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ADVISORY GROUP FOR AEROSPACE RESEARCH & DEVELOPMENT

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Results of Space Experiments in Physiology and Medicine and Informal Briefings by the F-16 Medical Working Group

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NORTH ATLANTIC TREATY ORGANIZATION

ADVISORY GROUP FOR AEROSPACE RESEARCH AND DEVELOPMENT

(ORGANISATION DU TRAITE DE L'ATLANTIQUE NORD)

AGARD Conference Proceedings No.377

RESULTS OF SPACE EXPERIMENTS IN PHYSIOLOGY AND MEDICINE AND INFORMAL BRIEFINGS BY THE F-16 MEDICAL WORKING GROUP

Papers presented at the Aerospace Medical Panel Symposium held in Istanbul, Turkey, 25—27 September 1984.

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PREFACE

At irregular intervals the Aerospace Medical Panel (AMP) of AGARD has organized Specialists' Meetings in which selected topics from Space Physiology and Medicine were discussed. The last meeting of this kind was held in Brussels in January 1979. At that time the USA and Europe were preparing for a new era of manned exploration and utilization of space with the reusable Space Transportation and Spacelab System.

Meanwhile, a number of Shuttle flights as well as the first co-operative NASA-ESA mission of the Space Laboratory (SL) were carried through. With 72 experiments from different disciplines (including 16 from the Life Sciences) and 4 Science Astronauts on board the latter carried the greatest scientific payload ever flown in space operations. Also, new information had been obtained during a French-Soviet collaborative project on Salyut 7.

In view of this development the AMP considered it to be appropriate to familiarise its members in another meeting with objectives, methods and results of recent medical research in space and give the specialists' knowledge on human adaptation to the space environment a wider dissemination.

The one-and-a-half-day Symposium was held at Istanbul, Turkey, on 25—26 September, 1984. The programme contained 13 invited presentations. It was opened with a report and film of Dr Ulf Merbold on Spacelab Mission 1 and his experience as a Science Astronaut. The other papers focused on the following topics.

Session I — VESTIBULAR AND SENSORI-MOTOR RESPONSES
Five reports dealt with the consequences of weightlessness on gravity perception and posture, with the cause and symptomatology of space motion sickness, and with mass discrimination.

Session II — CARDIOVASCULAR RESPONSES
Cephalic fluid shift and subsequent cardiovascular changes were addressed by three speakers.

Session III — SLEEP, IMMUNOLOGICAL AND RADIOBIOLOGICAL RESPONSES
There was one presentation on each of the following subjects: the electrophysiological recordings of eye-movements and muscle-activity, the significance of gravity on lymphocytes' activation, and the biological effects as well as the impact on man of heavy particles of cosmic radiation.

The Proceedings contain the papers together with the comments and remarks of the discussion periods. For those who wish to obtain a deeper insight into the matter reference is made to some recent publications: Science 225, 205-234, July 1984, and "Life Science Research in Space", ESA SP-212, Paris, August 1984.

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RESULTS OF SPACE EXPERIMENTS
IN
PHYSIOLOGY AND MEDICINE

INFORMAL BRIEFINGS BY THE F-16 MEDICAL WORKING GROUP

OPENING ADDRESS

by

Major General Ahmet Çörekçi
Commander
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Mr Chairman, ladies and gentlemen,

I am very glad to welcome all members of the Aerospace Medical Panel who have been invited to attend their respective committee meetings in Istanbul and I am very happy and honoured to make an opening speech to the distinguished members of the Aerospace Medical Panel who will discuss the "Results of Space Experiments in Physiology and Medicine".

First of all, I cordially congratulate the members who decided to hold this meeting in Istanbul during your previous meeting in London in October 1983. We feel very happy to host you, to get to know you in our country, and we are sure that you will make the best decisions and discussions concerning the body's responses in space and related subjects.

As we all know, knowledge changes now at a rate unparalleled in human history. More than two thousand years ago, the Greeks imagined Daedalus, the man who fashioned wings for himself. Leonardo Da Vinci drew sketches of flying machines and a Turk named Hazarfen Ahmet Çelebi flew with his wings for 3,000 metres from the Galata Tower across to the Anatolian side of Turkey in the 17th Century. But for centuries man remained earthbound. Just over fifty years after the Wright brothers had sold the United States its first military aeroplane, man set foot on the moon.

Not only in aerospace technology but in all areas, our world is changing with unprecedented rapidity, and there is no reason to believe that the rate of change will slow. In all environments — technological, medical, economic, social, political — our society is becoming increasingly complex, diverse, specialized and dynamic.

As you mentioned in your programme announcement, "With man's presence in space continuously increasing, a better comprehension of adaptation mechanisms to the space environment and of their consequences for readaptation to terrestrial conditions is urgently required".

For that reason, the members of the Aerospace Medical Panel committed to human responses will show more effort than before in order to maintain human superiority and avoid technological surprise.

As we know, even though the technology improves very rapidly in all areas, the human factor has never lost its position in every condition and situation. Man should have a complete education and training, discipline and a high morality, and should progress psychologically and mentally. Otherwise, those environments, especially weapons, machines and means, will not be any more valuable than a pile of iron or steel.

Mr Chairman, NATO and the scientific community will eventually obtain the results of your very important and highly valuable discussions and experiments and I am also sure that the informal briefings to be given by members of the F-16 Medical Working Group will be most useful to all of us, especially the Turkish Air Force. Turkey is planning to purchase the F-16 aircraft in the near future and any operational experience gained by our NATO allies will be of considerable use to us in our aeromedical training and operational flying programmes.

In conclusion, let me thank all of those individuals who worked very hard in organizing the scientific programme and arranging the many administrative, accommodation, transportation and social activities details.

I am sure your symposium will be a great success and I hope you will enjoy yourself in Istanbul and return home from our country with many beautiful memories.

Thank you.

TECHNICAL EVALUATION REPORT

by

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The exploration of space exposes man to a unique environment since it contains features which do not exist naturally and can hardly be simulated on earth. Prominent in this respect is the relative absence of gravity which initiates changes in the human organism mainly through three modes of action

- the specific effects on gravity sensing organs
- the lack of hydrostatic pressure affecting fluid compartments
- the reduction of deformation forces on load-bearing tissues.

Data collected during previous space flights demonstrated that almost all physiological systems are affected by the space environment. Some of the most significant changes which have become known so far involve the vestibular, the cardiovascular and the musculo-skeletal system as well as blood and metabolism.

However, many important scientific questions remained unanswered and many areas of research have been neglected, since the number of launches was limited, the subjects' number small and often operational programme requirements were not compatible with scientific research objectives. In this respect the situation is rapidly changing. The Symposium impressively demonstrated the progress which presently is being made in some areas of space physiology and medicine.

Particularly this is true for the system responsible for spatial orientation, the functional disturbance of which in microgravity evokes space motion sickness in almost 50% of the crews. But also other physiological consequences of space flights become gradually clearer.

These are the main conclusions which can be drawn from the Symposium Proceedings.

Session I

Since pitch and roll in microgravity do not result in otolith displacement, a sensory rearrangement becomes necessary in which the CNS reinterprets all otolith outputs as linear motion (otolith tilt-translation reinterpretation hypothesis).

The inability of otoliths to provide information on spatial orientation of head and body is compensated mainly by the increased utilization of visual cues.

Spaceflight-related redistribution of EMG activities in muscles responsible for posture control occurs in agreement with changes in otolith function.

Space motion sickness is most likely provoked by sensory conflicts, in particular during pitch and roll motions; individual susceptibility still can not be predicted, however, the easiness of adaptation to head movements while wearing reversing prisms may be indicative in this respect.

For the time being, the mechanisms behind the unexpected finding of a caloric nystagmus in the absence of thermal convection during orbital flight remains inexplicable.

Session II

Left ventricular size and volume, in particular end-diastolic and stroke volume, transiently increase in-flight and decrease post-flight; findings with respect to heart contractility are still controversial and need further clarification.

As judged by the changes of central venous pressure and hematocrit the fluid redistributions after launch and landing are highly dynamic processes, the physiological principles of which are far from being understood.

Cerebral and femoral blood flow seem to stay fairly constant in microgravity; this has given rise to the speculation that in view of an increased cardiac output renal and/or splanchnic blood flow might rise.

New data support the idea that extensive pre-flight athletic training might be the reason for a pronounciation of cardiovascular deconditioning, e.g. of post-flight end-diastolic volume decrease, and for longer recovery times.

Session III

Cells are gravity dependent, e.g. microgravity strongly depressed lymphocytes' activation; the implication for astronauts' immune system has to be clarified.

Heavy particles of cosmic radiation may include dramatic changes in individual cells, however, the risk for man with respect to orbital flight characteristics and time in orbit has yet to be assessed.

Future development of space activities will be characterized through (I) growing opportunities for research and development, (II) widening potentials for commercial and other ways of utilization of space, and (III) expanding presence of man in space with respect to the number of individuals and the duration of stay. Its implementation requires a deeper insight into the principles and mechanisms of physiological responses to space flight, allowing a clear definition of hazards for health and performance and the development of preventive measures and protective devices for man's work in orbit and his return to earth.

The AMP should closely follow this development. The results will have a bearing not only on aerospace medicine but should be of general significance to the medical sciences. For instance, they should contribute to a better identification of man's adaptive capabilities and will improve the definition of permissible ranges of variation in human physiological space research. It should be worth while to discuss the progress again in 2—3 years time.

INTRODUCTION A LA PARTICIPATION FRANCAISE AU SYMPOSIUM SUR LES RESULTATS DES EXPERIENCES SPATIALES EN PHYSIOLOGIE ET EN MEDECINE

par

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La mission franco-soviétique sur Soyouz T-6 et Saliout 7 s'est déroulée du 24 juin au 02 juillet 1982, dans le cadre d'une collaboration C.N.E.S.-INTERCOSMOS. Elle a permis le vol du premier spationaute français, le Colonel J.-L.Chrétien et la réalisation avec succès du programme scientifique prévu.

Pour permettre de cadrer les exposés français dans l'ensemble de la mission franco-soviétique, nous rappellerons succintement les aspects scientifiques et techniques principaux de cette mission.

1. PROGRAMME SCIENTIFIQUE

Le programme scientifique comprenait des expériences effectuées dans quatre volets:

1. **Science de la Terre et de l'espace**
   - PIRAMIG: chambre photographique à haute sensibilité pour l'étude dans le visible et le proche infra rouge du milieu interplanétaire, des galaxies et de l'atmosphère terrestre;
   - P.C.N.: photographie des sources de faibles luminosité du ciel nocturne;
2. **Elaboration de matériaux dans l'espace**
   - calibration du four MAGMA-F destiné à l'obtention de cristaux dans l'espace;
   - DIFFUSION: étude de la vitesse de dissolution d'un alliage solide dans sa propre phase liquide;
   - IMMISCIBLE: étude de la solidification d'alliages de composés non miscibles en microgravité;
3. **Biologie**
   - CYTOS-2: comportement en microgravité de différentes espèces bactériennes vis-à-vis de divers antibiotiques;
   - BIOBLOC-3: étude des effet des rayons cosmiques sur des oeufs d'Artenna Salina et des graines de tabac;
4. **Médecine**
   - ECHOGRAPHIE: étude en vol par un appareil à effet Doppler et un échotomographe à balayage électronique de la fonction cardiovasculaire;
   - POSTURE: étude de l'adaptation des ajustements posturaux liés à la mobilisation volontaire du bras ou du corps entier à la microgravité;
   - METABOLISME hydrominéral et calcique: étude sur des échantillons de sang et d'urine prélevés avant et après le vol.

2. SELECTION ET SURVEILLANCE MEDICALE DES SPATIONAUTES

La sélection médicale a été effectué avec le concours des experts et des moyens du Service de Santé des Armées. Sur 400 candidats, 193 ont été retenus, sur lesquels 5 ont été sélectionnés (dont une femme) à la suite des différentes étapes d'évaluation physique, médicale et de connaissances scientifique et techniques. En 1980, le choix final se portait sur J.L.Chrétien et P.Baudry, pilotes de l'Armée de l'Air. Ces deux candidats se sont rendus en septembre 1980 à la Cité des Etoiles pour suivre l'entrainement des cosmonautes.

La surveillance médicale a été assurée, du côté français, par le Médecin Chef des Services Carré, du Service de Santé pour l'Armée de l'Air. Cette surveillance s'est exercée avant le vol, pendant le vol, à l'atterrissage, et après le vol.

3. DEROULEMENT DU VOL

Le vol du Soyouz T-6 s'est dans l'ensemble déroulé conformément aux plans établis, exception faite d'une panne de l'ordinateur de bord du Soyouz qui a obligé le pilote V.Djanibekov à effectuer la phase finale du rendez-vous avec le Saliout par les commandes manuelles.

A bord du Saliout 7, toutes les expériences prévues ont été réalisées, mais il a été nécessaire d'aménager le programme initial de réalisation des expériences, le temps nécessaire pour les effectuer s'étant révélé nettement plus long que celui prévu par les scientifiques français.

4. BILAN DU VOL

Sur le plan scientifique et technique, le programme de recherches a été réalisé avec succès de Monsieur Lestienne sur l'expérience POSTURE, et du Professeur Pourcelot sur l'exprience ECHOGRAPHIE démontreront tout l'intérêt de leurs expériences dans le domaine de la médicine spatiale, à la fois par les résultats acquis au cours de la mission franco-soviétique, et par ceux que l'on peut attendre des expériences prévues dans un avenir proche sur la navette spatiale en coopération avec la NASA.

Mais hormis les résultats des expériences scientifiques, le vol de J.L.Chretien aura aussi permis aux spécialistes français d'acquérir une expérience dans le domaine des vols habités. Cette expérience sera précieuse car le C.N.E.S. envisage un vol humain tous les deux ans environ, soit avec les Américains, soit avec les Soviétiques. Dans un avenir plus lointain, cette expérience sera également précieuse dans le cadre d'une collaboration européenne pour des programmes tels qu'Eureca (plateforme mise en orbite à 500 km) ou Hermès (planeur hypersonique habité lancé par Ariane 5).

EXPERIENCE OF SCIENCE ASTRONAUT ON THE SPACELAB-1 MISSION

by

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1. Introduction

The first Spacelab flight, also called STS 9, took place during the period 28th Novembe through 8th December, 1983.

Its primary objective was to verify Spacelab as a new platform for experimental space sciences in orbit. The configuration flown on the first mission comprised the long module and one pallet.

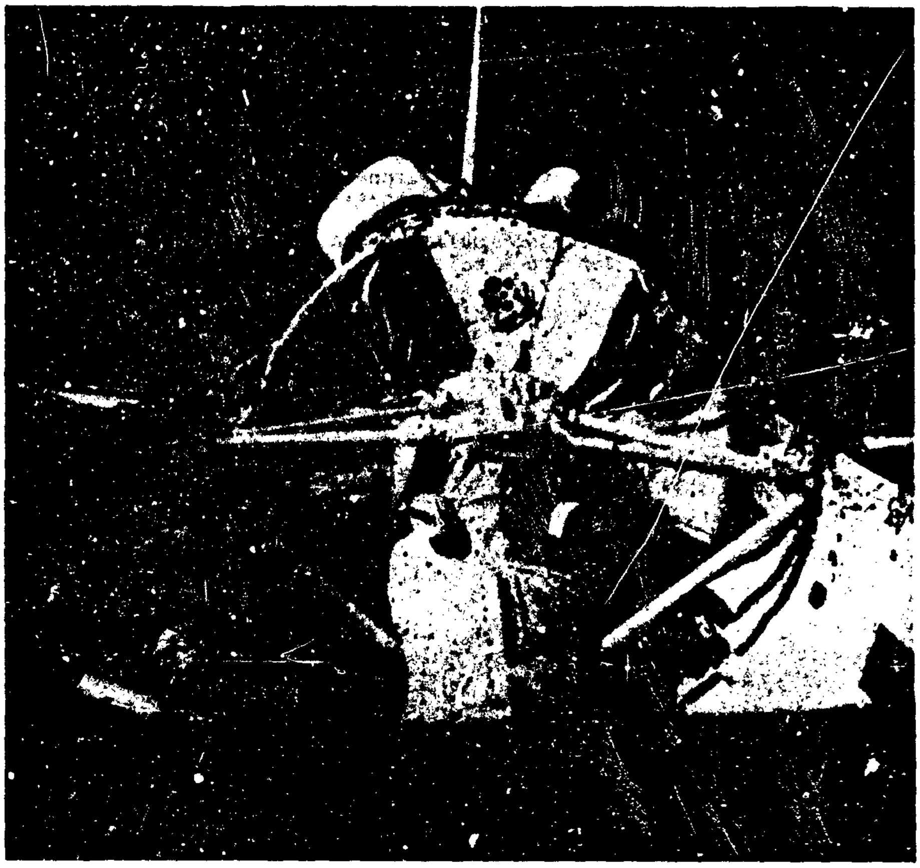

Fig. 1: Spacelab's long module in Columbia's cargo bay

The secondary objective of the flight was to carry out 72 experiments selected from 8 different science disciplines.

Table 1 summarizes the basic mission parameters.

Launch:	**28 November 84 16:00:00 GMT** **Kennedy Space Center/Florida**
Landing:	**8 December 84 23:47:24 GMT** **Edwards Air Force Base/California**
Orbit:	**circular** **altitude : 24o km** **inclination: 57°**

Table I - STS 9 Mission Parameters

2. SL Flight Performance and Mission Peculiarities

Originally, the mission was planned to last for 9 days, but because Spacelab and the scientific instruments flown consumed less power than anticipated, the flight could be extended to 1o days, 7 hours and 47 minutes. The mission thus established the long-duration record for Space Shuttle flights. Some other "firsts" related to Spacelab 1 are described below:

i) It was the first time that NASA had launched a large system on a manned flight which was not built in the United States. With the first flight of Spacelab, which was built by the European Space Agency (ESA), the era of manned space flight with European involvement began.

ii) The inclination of 57° (the typical inclination for a low earth orbit of the Shuttle is 28.5°) caused a ground track oscillating between 57° northern and 57° southern latitude.

The primary objective - verification of Spacelab - could be achieved with a great deal of success. Spacelab, as a system and a platform to utilise the Shuttle's potential for experimental space research, worked superbly and proved the soundness of the design and the high standard of workmanship. Spacelab supported the experiments exactly as planned and provided an excellent and pleasant working environment for the crew inside the habitable module. As a general summary, it can be stated that:

> Spacelab (built by ESA) is now a proven platform for space science. It is very versatile and supports a large variety of experiments. Its working environment is excellent.

3. Crew

The crew who flew on STS 9, comprising 6 astronauts, can be split into the Shuttle crew and the Payload crew.

The Shuttle crew was made up of Commander John Young and Pilot Brewster Shaw; the Payload crew consisted of Mission Specialists Owen Garriott and Robert Parker and the two Payload Specialists Byron Lichtenberg and Ulf Merbold

Fig. 2 : Crew of STS 9

For the first time the crew on STS 9 worked in two shifts around the clock.

> The flight demonstrated that two-shift operation works extremely well and enhances the scientific return substantially.

The Payload Specialists were non-career astronauts. They were selected by the Principal Investigators and worked on board as their surrogates. The Payload Specialists were the prime operators of the experiments and exclusively dedicated to the science.

The Mission Specialists were responsible for the maintenance of Spacelab as a system and for the verification objective. Since there were almost no problems associated with Spacelab, they were also heavily involved in experiment operation.

The payload crew conducted the experiments interactively so as to optimise the scientific return and at least ensure high quality. data.

First analysis of the enormous amount of data acquired during the SL-1 Mission (more than 10^{12} bits) reveals many spectacular discoveries, such as the observation of caloric nystagmus in weightlessness (1), the appearance of circumnutation during the growth of sunflowers (2), the observation of beam-plasma interactions (3, 4) and suprathermal electrons (4), the successful growth of large protein single crystals (5) or the observation of Marangoni flows in large columns of silicon oil (6).

The scientific success of the mission proves the concept:

> The best guarantee for acquiring good science on a scientific spaceflight is to send scientists (Payload Specialists) into orbit.

As a personal remark, I'd like to mention that all crewmen aboard worked hand-in-hand to form an effective team.

3.1 Crew Training

The training programme was aimed at enabling each member of the Payload Crew to conduct any experiment, e.g. full crew training.

The consequence was that all of us were forced to study new disciplines, starting from their basics and ending in an area between the known and the unknown from where good experiments come from.

Training was decentralised, which means that the Payload Crew went to the sites of the Principal Investigators. The disadvantage of the heavy travel load was more than compensated by the advantage of being able to meet not only the Principal Investigator in his laboratory but also his co-workers and experts on optics, electronics, data acquisition, software, etc. For that reason it can be said:

> For a complex mission (like Spacelab 1), decentralised training is optimal.

4. Control of Experiments and Operations

As mentioned above, Spacelab offers for the first time the capability to perform experiments interactively; that is to say, the data acquired by an instrument can be analysed in real-time and, based on the result, commands can be issued so as to optimise science return. In other words, close-loop control is typical for the operational philosophy of Spacelab experiments.

A total of 5 different control loops can be identified (Figure 3) (7).

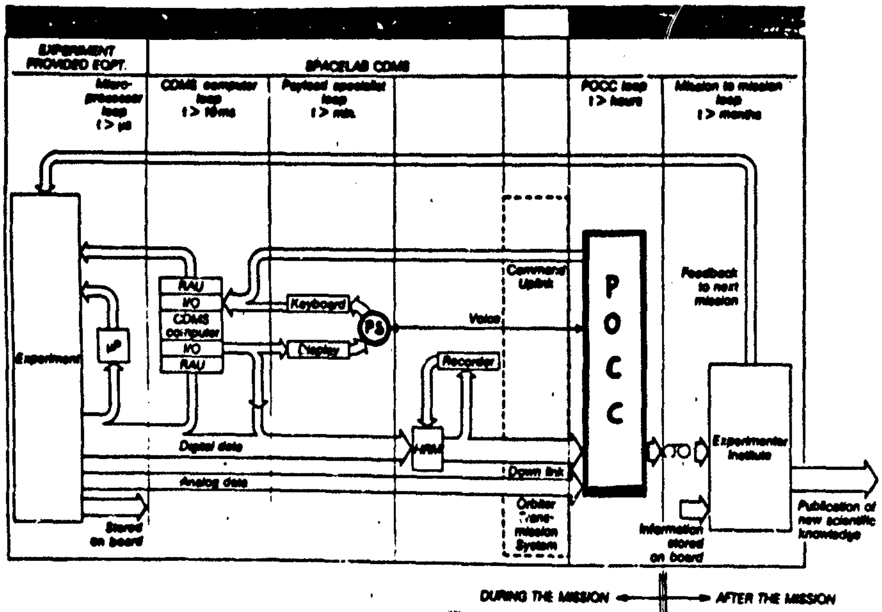

Fig. 3: Data flow and control of Spacelab experiments

The fastest control over an instrument is achieved by a dedicated microprocessor which is considered as being part of the experimental hardware. Typical response time is in the order of t ≥ µsec.

In case more complex software is needed for optimal control the experiment computer (CDMS = Command and Data Management System), provided by Spacelab, can be utilised and is an example of the support given to the experiments.

The scientific instrument communicates with the CDMS via the Remote Acquisition Units (RAU's) which are standardised interface boxes.

The RAU can cope with analog and discrete signals, as well as with serial information. All channels are serviced via the General Measurement Loop (GML) with a frequency of typically 1 Hz. The reaction time of this loop is in the order of t ≥ 1o msec.

The third loop brings the Payload Crew into play. The scientists aboard receive information from a display unit. They issue commands from a keyboard.

The ability of a human being to learn and react flexibly is an essential ingredient for mission success.

An automated system can only act as progra[illegible] pre-flight, and should be used for routine operations. However, in situation[illegible] [illegible]re things happen in an unforeseen way (such as in fluid physics on Spacelab 1), [illegible] [illegible]mputer will not ensure a meaningful approach.

But a trained Payload or Mission Specialist in this situation is extremely successful in acquiring good science. The typical response time of the scientist on board is t ≥ min.

The forth way of experiment control is based on a downlink data channel. Its digital data transmission capability is 5o Mb/sec. This high rate of data allows control of experiments from the Payload Operations and Control Center (POCC) on the ground in real time. The uplink channel is available to send commands from POCC to the experiments. The response time is typically t ≥ hours, but it can be much shorter.

A shortcoming of the control by POCC is that the downlink and uplink are only available during periods of contact via relay-satellite.

The last loop is non-interactive during the mission. It is based on samples or exposed film brought back from space which are analysed post-mission. The only way to react on results obtained is to repeat the experiment in a modified way on another flight in the future.

In summarising, it can be stated that the most important lesson learned on SL-1 is the following:

> In order to optimise the scientific result of space-science experiments or to ensure at least good-quality data, they should be performed interactively in realtime.
>
> (Two methods are feasible:
>
> - The trained scientist on board conducts the experiment.
> - Data are sent to POCC in realtime where the Principal Investigator conducts his experiment (limited to periods of contact).

5. Scientific Disciplines on Spacelab 1

The Spacelab-1 Mission was unique because of its complexity and the many scientific disciplines involved.

Table 2 gives an overview of the relative numbers of experiments per discipline and splits them between experiments selected by NASA and those selected by ESA.

DISCIPLINE	NASA	ESA	TOTAL
Astronomy	1	2	3
Atmospheric Physics	1	3	4
Earth Observation	-	2	2
Life Sciences	7	9	16
Material Science	-	37	37
Solar Physics	1	2	3
Space Plasma Physics	2+	4	6
Technology	1	0	1
	13	59	72

+ INS 002 : SEPAC experiment
Principal Investigator : T. Obayashi
University of Tokyo

TABLE 2 - SCIENTIFIC DISCIPLINES

Table 2 reveals that the number of European experiments (59) was more than four times higher than the number of US experiments (13).

The resources of the flight, e.g. mass, energy and crew-time, were shared between NASA and ESA on a 5o:5o basis. In spite of the resulting smaller average resource budget allocated to an average European experiment, the scientific accomplishments are quite spectacular.

5.1 Human Physiology Experiments

Eleven of the experiments from the life sciences discipline dealt with human physiology. They all were special for the crew because the crewman was operator and test subject at one and the same time.

The human physiology experiments can be divided into three categories:

I. Vestibular Organ and Neurophysiology

1 NS 1o2 : L. Young et al. / MIT Cambridge
" Vestibular Experiments"

1 NS 1o4 : M. Reschke et al. / NASA-JSC, Houston
"Vestibular-Spinal Reflex Mechanisms"

1 ES 2o1 : R. V. Baumgarten et al.,/ Universität Mainz
" Effect of Rectilinear Acceleration etc."

1 ES o25 : H. Ross, University of Stirling
"Mass Discrimination during Weightlessness"

1 ES o3o : H. - L. Green / Clinical Research Center, Harrow
"Personal Miniature Electro-Physiological Tape Recorder"

II. Cardiovascular Adaptation and Blood Volume Regulation

1 ES o26 : K. Kirsch, Freie Universität/Berlin
"Central Venous Pressure"

1 ES o28 : A. Scano, University of Rome
"Ballistocardiographic Research in Weightlessness"

1 ES o32 : K. Kirsch/L. Röcker, Freie Universität/Berlin
"Collection of Blood"

1 NS 1o3 : C. Leach/ NASA-JSC, Houston
"Influence of Space Flight on Eurythrokinetic in Man"

III. Immune System

1 ES o31 : A. Cogoli/ ETH, Zürich
"Effect of Weightlessness on Lymphocyte Proliferation"

1 NS 1o5 : E. Voss, University of Illinois
"Effects on Prolonged Weightlessness"

All of the human physiology experimenters established a sound set of baseline data by pre- and post-flight tests so as to observe the impact of the space environment by comparison. Baseline data were acquired on each individual member of the Payload Crew 9o, 6o, 3o and 15 days prior to flight and also during the week following the landing. The testing was so excessive that some crewmen were test subjects for 13 consecutive hours. Since the load of testing is accumulative, the subject might become exhausted after such a period of time. In this case, the scientific significance of data would be impaired. Therefore:

> Medical testing should be limited to such an extent that subjects do not become exhausted.

6. Summary

My experience on Spacelab 1 can be summarised as follows:

- The Spacelab-1 Mission was highly successful because the verification of Spacelab demonstrated the soundness of the design and the quality of workmanship.
- The scientific results obtained to date are very good.

The major reasons for the scientific success were:

- The interactive method of performing and optimising the experiments
- The presence of trained scientists on board
- Two-shift operation
- The capability to interact with the POCC and the very close cooperation between the Principal Investigator on the ground and the Payload Crew.

I am honored to have been part of the S1-1 Mission, which started a new era in space science. I'd like to thank the Principal Investigators who patiently trained us for years and who finally delegated so much responsibility to the Payload crew.

I think this way of conducting operations combined with the capabilities of the Shuttle/Spacelab opens up new horizons for basic research and its application.

7. References and Notes

1) R.v.Baumgarten et al., Science 225, 2o8 (1984)

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The European vestibular experiments of the Spacelab-1-mission

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ABSTRACT

The European vestibular experiments on Spacelab 1 were decigned to explore vestibular adaptation to the space environment and re-adaptation to the ground by conducting a series of vestibular tests which were repeated several times at different stages before, during, and after the mission. The tests included the threshold for linear oscillation, eye movements triggered by angular acceleration, optokinetic and caloric stimulation, and measurements of posture. Slow-phase velocity of caloric nystagmus was increasing in the course of the mission. The results of most tests could be interpreted as indicating a decreasing gain of CNS-processing of otolithic information during vestibular adaptation to the space environment.

A series of vestibular tests were performed 120, 90, 60, 30 and 11 days before the Spacelab-1-mission and again during the first 6 days after recovery of the space craft. Similar experiments were performed during the mission on board Spacelab by the "red shift" of the Spacelab scientific crew.

After our linear acceleration device "Space-Sled" was descoped for the SL 1-mission and postponed to the D 1-mission a body restraint system (BRS) was constructed which allowed linear oscillation of the experimental subject in three different axes by hand operation of the operator. The test subject wore our vestibular helmet, which contained the electrooculography amplifiers and a device for insurflation of heated or cooled air into the ears during the caloric test. An infrared sensitive CCD-camera (EMIR) allowed to record the movements of the right eye including eye-rotation. The EMIR- system was computing the XY-displacements of the eye for display on a stripchart recorder in the payload operation center. In front of the left eye was a TV-monitor mounted in a visor of the helmet for optokinetic stimulation, calibration and target cross resetting.

MEASUREMENTS OF LINEAR THRESHOLD

A linear oscillation device was constructed using air bearings to minimize noise and vibration. The subject was oscillated on it during pre- and postflight tests at a frequency of 0.3 hertz in the X,Y- and Z-body axes. The accelerating stimulus could be increased or decreased stepwise by 0.5 dB when the subject indicated by joystick deflection that he crossed the threshold. Detection of motion was tested seperately from detection of direction of motion. The inflight data on threshold are at present still fragmentary. Only measures taken on days 4 and 6 are available now. They show, that linear threshold on both crew members in all three axes was inflight considerably elevated as compared to the pre- and postflight control data. However we don't have the threshold yet at the very early part of the flight. The postflight threshold values were not significantly different from the preflight ones except for the Z-axis, which was significantly elevated early postflight as compared to preflight. The threshold for detection of direction of motion was, as expected, always higher than the threshold for motion regardless of direction.

ANGULAR ACCELERATION

Response to angular acceleration was tested on a hand driven rotating chair pre-, in- and postflight in the X- or Z-axis of the head. The eyes were either closed during the tests, or a fixed collimated light was observed. The VOR gain was found to be comparable pre- and postflight when measured with closed eyes. However, when measured with open eyes and fixation of a target, the gain of the VOR at 1 hertz was significantly lowered postflight as compared to preflight. This could indicate an increased dependence of visual as opposed to vestibular mechanisms in the course of space adaptation.

Head movements in the pitch axis with closed eyes revealed a smaller gain of the VOR inflight than on the ground. This experiment suggests that the otoliths significantly contribute to the gain of the VOR in the pitch axis and that in the space environment the vestibular contribution as compared to the visual contribution decreases during space adaptation. Possibly the unusual pattern of impulses from the otolithes during head movements in space contributes to space motion sickness, which stated by the astronauts as being exacerbated during all pitching head movements.

OCCULAR COUNTER ROLLING TESTS

Occular counter-rotation was measured pre- and postflight at lateral tilt angles of 90 degrees left and right. PS1, PS2 and MS1 had significantly less occular counter-rotation than preflight. Any preflight assymetry between counter rotation when tilting to the left and to the right was increased postflight. These findings agree with counter rotation data already found after the STS8-flight.

LUMINOUS LINE TESTS

Measurements of the deviation of the subjective vertical from the true vertical (luminous line tests) at different tilt angles of the body were conducted pre- and postflight. The deviation from the true vertical at steep tilt angles was larger postflight than preflight. Again all subjects exhibited considerably more bi-lateral assymetry when tilting to the left and to the right postflight as compared to preflight.

CALORIC STIMULATION

Insuflation of air heated to 44°C into one ear and of air cooled between 35° and 20°C resulted in strong nystagmus occured already after one to two minutes and changed readily its direction when interchanging the warmed with the cooled ear. The experiment was performed successfully on two crew members with the same results. The nystagmus was supressed on the first day, but increased in strengh during the mission. The recorded caloric nystagmus in space cannot be explained by Bárány's theory of thermoconvection since the latter does not exist in orbital weightlessness.

Our preliminary vestibular data from the SL1-mission suggest the adaptation to the space environment includes a decrease of gain in the processing of otolith-signals and increasing dependence on visual information. Furthermore any bilateral assymmetries of the otolith apparatus which were well compensated on the ground, may be miscompensated in 0 g environment until recompensation takes place. The compensation to 0 g possibly leads to temporary miscompensation again during the readaptation period on the ground.

SOME RESULTS OF THE EUROPEAN VESTIBULAR EXPERIMENTS IN THE SPACELAB-1 MISSION.

by

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SUMMARY.

A series of experiments were performed during the flight of Spacelab 1 to explore changes in vestibular function and visual-vestibular interactions associated with adaptation to micrgravity. Tests were also conducted on the ground during the four months before flight and over the six days post-flight. Measurements were made of the threshold for detection of linear oscillation and of vestibulo-ocular reflexes elicited by angular and linear accelerations and by optokinetic and caloric stimuli. These revealed changes associated with the modified otolithic afference in micrgravity, though the most unexpected finding was that caloric stimulation in orbital flight evoked nystagmus comparable to that obtained on earth.

INTRODUCTION.

Spatial orientation in the atypical force environment of orbital flight, as on the surface of earth, is dependent upon information provided by the eyes and by vestibular and somaesthetic mechanoreceptors. In micrgravity the greatest change will occur in those sensory systems whose receptors are stimulated on earth by the linear acceleration of gravity, notably, the specialised end-organs of the vestibular apparatus - the utricular and saccular maculae (more commonly called the otolith organs). In micrgravity the otoliths no longer provide information of the orientation of the head in pitch and roll, though they will be stimulated by the transient linear accelerations generated by voluntary movements of the head and locomotor activities. Indeed, it is the presence of atypical signals from the otoliths, in the presence of veridical information from the semicircular canals, that is regarded as the primary aetiology of space motion sickness (Reason & Brand, 1975; Benson, 1977; Oman et al. 1984) - a disability which has afflicted some 50% of astronauts during the first few days of space flight. Adaptation to the weightless environment is thus likely to involve, primarily, a modification of the neural processing of signals from the otoliths, though this may also impact those visual and vestibular mechanisms (and their interactions) which are intimately involved in equilibratory function.

The set of experiments (coded ES201) proposed by the consortium of European investigators to be performed on the First Spacelab Mission (SL-1) was designed to provide a better understanding of the effect of micrgravity on vestibular function and visual-vestibular interactions in man, and of the process of adaptation to this atypical force environment. The absence of significant linear acceleration in orbital flight also afforded an opportunity to test directly the theory that the nystagmus induced by thermal stimulation (caloric response) was caused by anisotropic changes in density (sic thermal convection) of the endolymph within the stimulated semicircular canal.

METHODS.

Apparatus. The principal equipment employed in the flight experiments consisted of a peri-cephalic structure - the 'Vestibular Helmet' - and a skeletal collapsible seat - the 'Body Restraint System' (BRS). The 'vestibular helmet' (fig 1) was equipped with two eye movement recording systems. One employed conventional electro-oculography (EOG) to transduce vertical and lateral eye movements, the other (the EMIR system) consisted of a CCD (charge-coupled device) television camera which relayed a digitised image of the subject's left eye, illuminated by IR emitting diodes, to ground equipment where the X and Y co-ordinates of eye position were computed in real time. The helmet carried in front of the subject's right eye a collimated cathode ray tube display which was used to present either optokinetic stimuli or a target cross, the latter display also being used for calibration of the eye movement recording systems. Caloric stimulation was achieved by insufflation of air, heated or cooled by Peltier elements to controlled temperatures, into the external ear canals via small tubes located in the ear-cups of the helmet. Also within the helmet were signal conditioning amplifiers for the triaxial servo-accelerometers which were mounted either on the helmet or on the subject's dental bite. In those experiments where the subject had to signal his responses, a small two-axis joystick or a rotary control, which were mounted in a small box held by the subject in one hand, was employed.

The test subject's head was securely located within the helmet by adjustable pads and by an individually moulded 'goggle' which interfaced with the optics of the EMIR camera and the CRT display. In most experiments the test subject was seated in a yogic position in the BRS and restrained by a five point harness. The helmet was clamped to the backrest of the BRS so dynamic stimuli could be given without significant relative movement between the subject and the experimental hardware. The BRS could also be fixed in different orientations to a simple bearing located on the floor (centre aisle) of Spacelab. This configuration was employed in those experiments where responses to angular motion stimuli were investigated.

For the ground-based tests, performed pre- and post-flight, a 'vestibular helmet' similar to the flight model was employed. In addition, a tilt-table able to orientate the subject in the roll axis in incremental positions of up to 90° from the vertical was used to study ocular counter-rolling and perception of the vertical. Thresholds for the detection of linear motion were determined with the aid of a 1 m stroke, horizontal linear oscillator (the BLTDD) fitted with an air bearing carriage to minimise adventitious motion cues. Oculomotor responses to angular oscillation were elicited on a hand driven turntable on which the subject could be orientated so that the X or Z axis of his head was either co-axial with, or 1 m distant from, the centre of rotation.

Procedure. The battery of tests, to which the two Mission Specialists and two Payload Specialists were subjected pre and post-flight, were carried out in the Baseline Data Collection Facility Laboratory at NASA Dryden FRF, Edwards AFB, Ca. The ES201 experiments were integrated with those of other investigators and were performed according to a fixed schedule in order to stabilise order and circadian effects. Pre-flight measures were taken on five occasions (nominally, 120, 90, 64, 43 and 11 days before launch), and post-flight measures were taken on the first, second, fourth and sixth day after landing.

During the flight of Spacelab-1, experiments were conducted throughout the mission, with major blocks of time allocated on the first and the sixth day for the ES201 experiments. These were performed, principally, by the two crew members (coded for anonymity) C and D. Further details of the equipment and procedures employed accompany the description of the separate experiments which follow.

RESULTS AND DISCUSSION.

Thresholds for Detection of Linear Oscillation.

Studies carried out by Walsh (1961) indicate that the perception of whole-body linear oscillation of liminal intensity at frequencies below 1 Hz is primarily dependent upon the integrity of the otolith organs. Thus, measures of the threshold of detection of such motion stimuli provide information on the processing of otolithic signals within the central nervous system and of how this may be altered by exposure to microgravity.

Determination of the thresholds for detection of linear oscillatory motion at 0.3 Hz in the X, Y and Z body axes were made both in-flight and on the ground. For pre-and post-flight tests a servo-controlled, air-bearing, mini-Sled (BLTDD) was employed to generate a continuous oscillatory stimulus which increased or decreased in intensity by 0.5 dB per half cycle. The psychophysical procedure was a single staircase, with threshold being determined by the method of limits (Engen, 1972). Typically, in each test sequence of 48

Fig 1. Photograph of the 'Vestibular Helmet' used for the ES201 experiments.

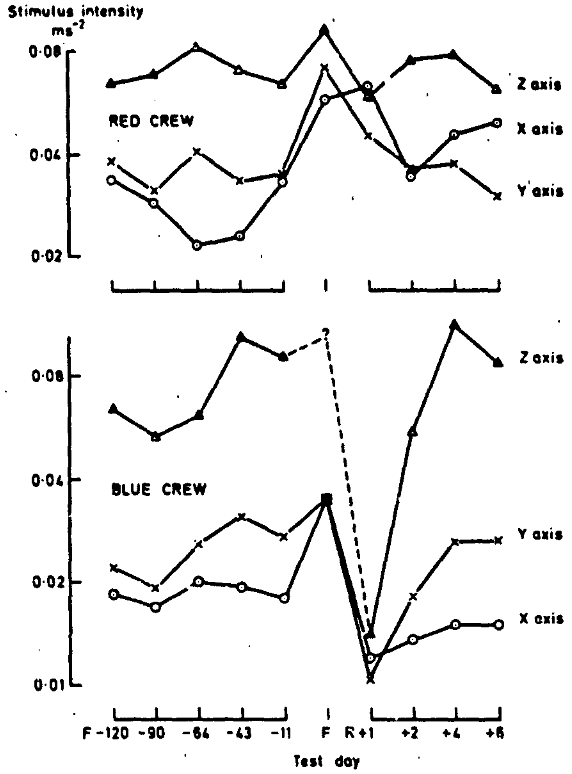

Fig 2. Thresholds for the detection of whole-body linear oscillation at 0.3Hz determined by the Mode 1 procedure. Ordinate values are peak half-amplitude of the stimulus at threshold, averaged for the two astronauts in each crew.

oscillatory cycles there were 8-12 reversals of the stimulus intensity trajectory. Two test procedures were employed: in Mode 1 the subject indicated, by means of a key switch, whenever he could detect the oscillatory motion, in Mode 2 the subject had to signal the direction of the perceived motion. In flight, an attempt was made to replicate the ground-based procedure. The test subject, restrained in the BRS, was moved by another crew member in an approximately sinusoidal manner at 0.3 Hz. As on the ground, the amplitude of the linear oscillatory motion was increased until the subject signalled detection of motion and decreased until he ceased to signal.

Analysis of variance of the pre and post-flight threshold data revealed a significant overall difference in the responses of the Red Crew (astronauts C and D) and the Blue Crew (astronauts A and B) which was caused, principally, by their differing behaviour in the first post-flight test (R+1). The reason for this difference is uncertain, though as the Red Crew were always tested at the beginning of each test day and the Blue Crew some 6 hours later, there is *a priori* justification for analysing and displaying (fig 2) the results of the two crews separately.

Base-line measures of threshold determined by the Mode I procedure exhibited reasonable test-retest reliability without consistent trend except for the Z and Y axis thresholds of the Blue Crew which tended to increase with repetition of the test procedure. Z axis threshold was, as expected (Gundry, 1978), consistently (P=0.001) higher than the X and Y axis thresholds, the latter not differing significantly from one another.

Currently, data from the flight experiment are confined to one set of observations made on subjects C and D on Mission Day 7 and on subject B in the X and Y axis on Mission Day 5. The reliability of these data is suspect because of a possible 1 or 2 bit error in the digitisation of the accelerometer signals. However, with this caveat, all the measures obtained in flight were higher than any of the base-line values for the respective subject and stimulus axis. Relative to the mean base-line thresholds, the thresholds determined in flight were raised by a factor of 1.5-4.3.

On the initial post-flight test (R+1), the Red Crew showed a significant elevation, with respect to base-line, of both the X axis (P=0.01) and Y axis (P=0.05) thresholds, but the Z axis threshold did not differ from base-line. In contrast, the Blue Crew exhibited a significant (P=0.05) reduction in X and Y axis thresholds and an even more intense (P=0.01) reduction in Z axis threshold relative to the base-line measures.

On R+2, the X, Y and Z axis thresholds of both crews did not differ significantly from base-line, though on R+4 and R+6 the X axis threshold of the Red Crew was elevated (P=0.05). The Z axis threshold of the Blue Crew was also raised (P=0.05) on R+4. With the exception noted above, all thresholds had returned to base-line by the sixth post-flight day.

Responses recorded during the Mode 2 procedure in pre and post-flight tests were used to calculate 50% detection thresholds, but the restricted number of stimulus cycles performed in flight did not provide adequate data on response frequency as a function of stimulus intensity from which detection thresholds could be derived. Comparison of the thresholds obtained by the Mode 1 and Mode 2 procedures revealed a significant (P=0.05) correlation between the two measures in the Y and Z axes though not in the X axis. Thus the changes observed in the Mode 2 thresholds, post-flight, exhibited similar features to those found using the method of limits. Notably, the Red Crew had an elevation (P=0.05) of X and Y axis thresholds on R+1 but no change in the Z axis, whereas the Blue Crew showed lowered Z (P=0.01) and Y (P=0.05) axis thresholds, on the initial post-flight test. Subsequent measures on both crews failed to yield thresholds which differed significantly from base-line.

Angular Vestibulo-ocular Reflex: Canal-otolith Interactions.

Vestibulo-ocular Reflex in Pitch and Yaw. It has long been recognised that the semicircular canals are of prime importance in the stabilisation of eye position, but the contribution of the otoliths to the vestibulo-ocular reflex (VOR) is relatively poorly understood. Some modulation of the VOR in the horizontal plane by a changing linear acceleration vector has been demonstrated (Benson, 1970) as has the induction of a horizontal nystagmus by linear oscillation in the Y axis of the skull (Niven et al. 1966). However, it is in the VOR responses to to angular head movements in pitch and roll that the otoliths might be expected to be of greater functional significance. On earth, head movements in pitch and roll, apart from stimulating the vertical semicircular canals, concomitantly stimulate the otoliths by virtue of the change in their orientation to gravity. In contrast, head movements in yaw do not necessarily alter the direction in which gravity acts on the otoliths. It is difficult, on the ground, to assess the exact contribution of the otoliths to the vertical VOR. However, microgravity provides a privileged situation because the normally correlated otolithic signal during an angular head movement in pitch or roll is absent. It was hypothesised that in space the gain of the pitch VOR would be lower and that there would be larger phase errors than in the normogravic environment, whereas the yaw VOR would be little affected. This hypothesis was tested by an *ad hoc* experiment which the crew were instructed to perform following failure of the optokinetic pattern generator on the first day in orbit.

The subject was asked to shake his head, with eyes open, at 1 Hz. Head movements were measured by linear accelerometers and eye movements recorded by EOG and EMIR. When the subject reported no oscillopsia with eyes open, it was assumed that head and eye movements were nearly the same (i.e. gain of VOR=1). Head oscillation was then repeated at this amplitude, but with eyes closed. An approximate value of VOR gain was obtained by comparison of the eye movements made with eyes open and eyes closed. Two methods of analysis were employed to determine the VOR gain in pitch and yaw. In one, the peak to peak values of the EOG were compared between samples of head oscillation of comparable amplitude and frequency as indicated by the accelerometer signals. In the other, the amplitude of the eye displacements was computed from the reconstructed sinusoidal component for 20 cycles after elimination of saccades.

The mean values of the VOR gain in pitch and yaw for subjects C and D obtained on flight days 5 and 7, and on the four post-flight tests are presented in Fig 3. Individual values of the yaw VOR gain ranged from 0.4 to 0.69 in microgravity and from 0.5 to 0.85 in the post-flight tests. These values are comparable to the population norm in ground-based studies (Jell et al. 1982) and suggest that weightlessness, at least in the adapted subject, is not associated with a change in the yaw axis VOR. Measures of pitch

VOR gain during flight ranged from 0.45 to 0.75 and were similar to the VOR gains in yaw, but on the first post-flight day, pitch VOR gain was elevated (range 0.95 to 1.11). On subsequent test days it declined towards the more normal values obtained during flight. Whereas on the ground phase errors were small (mean 1°, SD.0.3°), in microgravity the compensatory eye movements exhibited considerable and variable phase lag (mean 20°, S.D. 8°).

The absence of data on VOR gain before the subjects were adapted to weightlessness makes interpretation of these preliminary findings difficult. They do, however, suggest that on earth the otoliths contribute to the oculomotor responses elicited by angular movements of the head in pitch. In the absence of the normal otolithic signals, pitch VOR gain, but not phase, can be restored to its normal value. On return to the 1g environment, the presence of otolithic information initially engenders an enhanced oculomotor response.

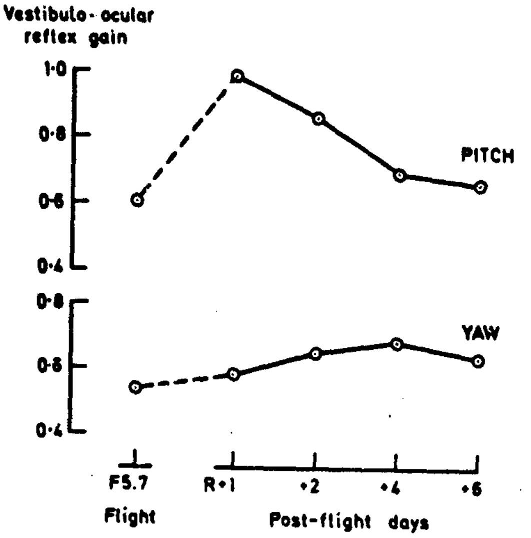

Fig 3. Vestibulo-ocular reflex gain during voluntary head oscillation at 1Hz with eyes closed. Mean values for astronauts C & D.

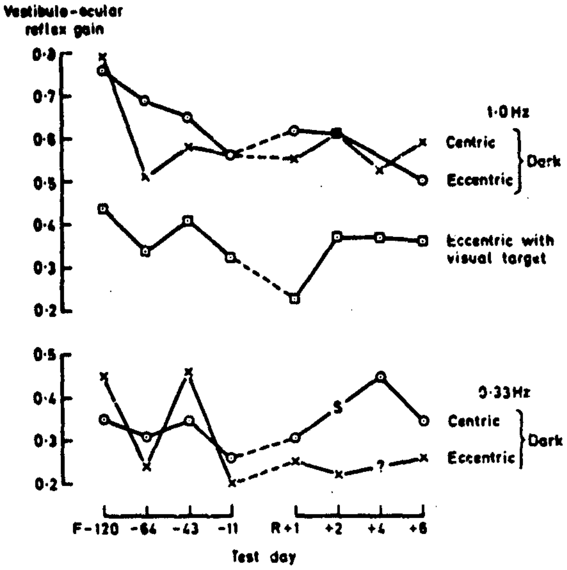

Fig 4. Yaw axis vestibulo-ocular reflex gain of astronaut C, during passive oscillation at 0.33 and 1Hz in centric and eccentric configurations.

Canal-otolith Interaction and Visual Suppression in Yaw. Another facet of vestibular adaptation to microgravity was studied in an experiment which explored the interaction between angular and linear motion stimuli, as well as the suppression of vestibular nystagmus by visual fixation. The angular stimulus was achieved by a hand-driven oscillation of the test subject at approximately 0.3 Hz and 1 Hz. Tests were conducted with the subject orientated so that the rotation axis was either co-axial with the Z axis of his head (centric mode) or 1 m distant (eccentric mode). In the latter orientation the vestibular stimulus was not only a changing angular acceleration but also a changing tangential and radial accereration. In addition, further tests were conducted in the Z eccentric mode with the subject fixating on a head-fixed visual target. Eye movements were recorded in darkness by IR, CCTV and by EOG; turntable angular velccity was also recorded.

Analyses performed, to date, (Fig 4) have been confined to the lateral eye movements evoked by the Z axis stimuli in one crew member (C). Using the technique developed by Barnes (1982), measures of vestibulo-ocular reflex (VOR) gain, phase and offset were determined over ten stimulus cycles in each of the five experimental conditions.

Inspection of the data obtained during the four pre-flight test sessions failed to show any significant difference between the VOR responses evoked by centric and eccentric oscillation in darkness, though, as was to be expected, (Benson, 1970) the VOR gain at 1 Hz (mean 0.65, range 0.51-0.79) was higher than at 0.3 Hz (mean 0.33, range 0.20-0.46). The values obtained on post-flight days 1, 2, 4 and 6 were comparable to the pre-flight measures, the mean VOR gain being 0.58 (range 0.50-0.62) at 1 Hz and 0.32 (range 0.22-0.55) at 0.3 Hz. In particular, the responses obtained in darkness on the first post-flight day (R+1) yielded measures which were within the range of those recorded pre-flight. In contrast, the gain of the VOR at 1 Hz, when reduced by the presence of single collimated fixation target (subtending approx. 0.3° at the subject's right eye), was significantly ($P<0.05$) lower on R+1 than on any other pre or post-flight test.

It would be hazardous to attach undue weight to the finding of a greater suppression of the VOR response by vision in a single crew member when tested 14 hours after landing. However, if confirmed by future experiments, it does suggest that one aspect of adaptation to microgravity is an increased dependence of visual as opposed to vestibular mechanisms in the stabilisation of the retinal image during head movement.

Ocular Counter-rolling.

Information on the functional state of the 'static' otolithic component of the vestibulo-ocular reflex was provided by measures of ocular counter-rolling made pre- and post-flight. There is good evidence that on earth the counter-torsion of the eye, during sustained body tilt in roll about a horizontal axis, is dependent upon the stimulation of the otolith organs by the gravitational acceleration (Bárány, 1906a; Fischer, 1930; Woellner & Graybiel, 1960). Linear oscillation in the Y axis of the head also evokes a cyclical counter-rolling response

(Lichtenberg et al. 1982) and an attempt was made to elicit this reflex response in Spacelab-1 by manually oscillating the test subject in the BRS at 0.3 Hz, at an amplitude of approx ±2 ms^{-2}. Unfortunately, the quality of the video image provided by EMIR precluded the quantification of dynamic eye movements in roll. However, measures of static counter-rolling were successfully made on the ground from 35mm colour transparencies of the eye of the test subject.

For these pre and post-flight tests the subject was restrained within a framework which allowed him to be rotated in roll about a horizontal axis at angles of up to 90°, to the right or left from the vertical position. A 35mm camera and ring flash were clamped to the framework and positioned so that a full-frame photograph of the subject's left eye could be taken. The tilt-table was moved in 15° increments from the upright (0°) position initially to the left and then to the right. In each orientation two photographs of the subject's eye were taken at not less than 15 sec after positioning. Measurement of the angular position of the eye in roll was achieved by projecting an enlarged image of the eye onto a graphics tablet and entering the co-ordinates of 10 iris landmarks into the computer. The X axis reference was a line joining internal and external canthi, and the calculated centre of gravity of the pupil defined the origin of the co-ordinate system.

Figure 5 compares the mean ocular counter-rolling responses of the four Spacelab Crew (A, B, C and D) obtained 120, 90 and 64 days before flight with those on days 1 and 2 post-flight. Statistical analysis demonstrated a significant (P<.05) reduction, post-flight, in the magnitude of ocular torsion on body tilt to the left in all but one (astronaut B) of the test subjects. In contrast, when tilted to the right there was no significant difference between the pre and post-flight responses.

These findings imply that adaptation to microgravity involves a reduction in the gain and increased asymmetry in the 'static' compensatory eye movements engendered by signals from the otoliths.

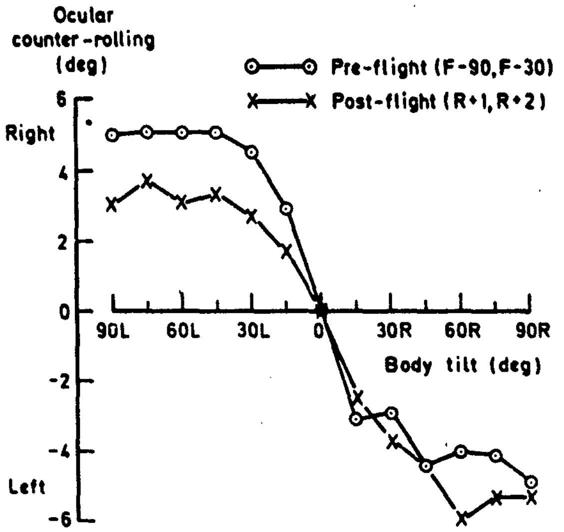

Fig 5. Comparison of pre and post-flight ocular counter-rolling induced by body tilt about the X axis. Mean values from astronauts A,B,C & D.

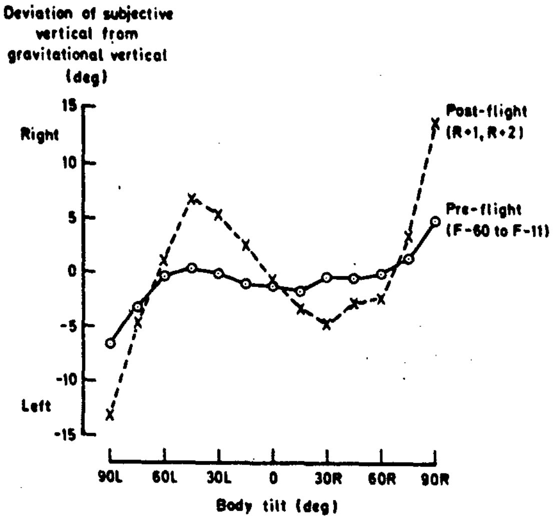

Fig 6. Comparison of pre and post-flight results of luminous line test. Mean values from astronauts A,B,C & D.

The Subjective Vertical: Luminous Line Test.

Perception of the gravitational vertical during whole-body tilt is dependent upon sensory inputs from the vestibular apparatus, in particular, the otolith organs, somaesthetic inputs arising from contact between the body and the surfaces which support it, and kinaesthetic inputs from the joints and musculature of the body. Microgravity modifies the neural information in all of these sensory systems, so it is possible that adaptation to the weightlessness will modify the astronaut's ability to perform a spatial orientation task on return to earth. One such task, performed pre and post-flight by the crew of SL-1, involved the setting of a luminous line to the perceived 'vertical' at different angles of body tilt about the X roll axis.

Body tilt, over the range 90° left to 90° right in 15° increments, was achieved with the same apparatus as was employed for the measurement of ocular counter-rolling. At each body orientation the subject was required to set, by means of an electrical control, the angular position of a luminous line (1.1m long at a distance of 3.5m) so that it was aligned with what he considered to be the gravitational vertical. Deviations of the setting of the luminous line from the true vertical were transduced by a potentiometer and displayed by a digital voltmeter. Between each change in body position, made when the subject's eyes were closed, the position of the luminous line was arbitrarily perturbed by the experimenter.

The results of the pre and post-flight tests conducted on the four Spacelab-1 crew members are summarised in Fig 6. The measures obtained pre-flight exhibit only modest deviation of the subjective vertical from the true (gravitional) vertical, with relatively small A (Aubert) effect at large angles of body tilt and no discriminable E (Muller) effect. (See Howard, 1982 for a review of the effects of body tilt on the visual vertical and A and E effects). On the first and second post-flight days there were significantly larger errors in the judgement of the apparent vertical, with a well defined E effect (max at 45° tilt) and A effect at angles of body tilt greater than 60°. Subject B had the largest deviations in the subjective vertical (20° at

45° tilt), though the errors made by subjects A and C were also greater than those made in the pre-flig tests. As with the measures of ocular counter-rolling, there was a marked asymmetry in the responses, with smaller E effect on tilt to the right than to the left.

Its most likely that this asymmetry in judgement of the vertical, like the asymmetry in ocular-torsio is the manifestation of an order effect (cf. Miller et al. 1965), for the tilt positions were not randomise They were always performed in a set order, all tilt left positions being tested before the subject w returned to the vertical and then tested at increasing angles of tilt to the right. However, the larger A a E effects found post-flight indicate that, having adapted to microgravity, the astronaut on return to earth less well able to judge his orientation with respect to the gravitional vertical. Indeed, the increase in A a E effects is not dissimilar to that found in individuals with bilateral vestibular deficit (Miller et al. 196 The process of adaptation to microgravity may thus involve a reduction in the 'gain' in the relaying otolithic signals within the central nervous system, or, perhaps more likely, a re-interpretation of those sign which in weightlessness do not convey useful information, as they do on earth, about spatial orientation wit the co-ordinate system in which the astronaut operates.

Visual-vestibular Interaction.

One approach to the study of how visual orientation cues interact with those of vestibular origin is examine an individual's perception of the vertical whilst he views a wide field, textured display which rota in roll about his line of sight (Dichgans et al. 1972; Held et al. 1975). The rotating visual stimulus induce sensation of body motion in the opposite direction to that in which the pattern rotates and the subject, w head erect, feels as if he is tilted, albeit to a limited extent, in the same direction as the continu sensation of self-motion. Constraint on the angle of perceived tilt is probably due to inputs from the otoli and somatosensory gravireceptors being in conflict with the visual stimulus, so any modification gravireceptor cues is likely to be manifest by a change in the magnitude of the induced tilt. The latter be measured by requiring the subject to set a small line (or cross) within the centre of the rotating disp to the apparent vertical.

The vestibular helmet had provision for making such measurements. The visual stimulus, displayed on CRT in front of the subject's right eye and subtending a[illegible]x 60°, was a random dot pattern which rota at 40°/sec in either the clockwise or anticlockwise direction. Superimposed upon this display was asymmetric cross, subtending 10°, the orientation of which could be adjusted by the subject via a rotat control located in the hand-held, 'response' box.

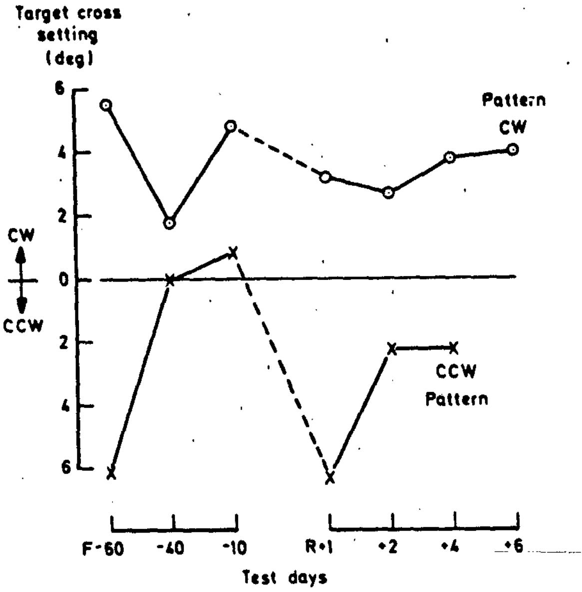

Fig 7. Apparent vertical during roll axis optokinetic stimulation at 40°/sec with the head vertical. Mean values of astronauts C & D.

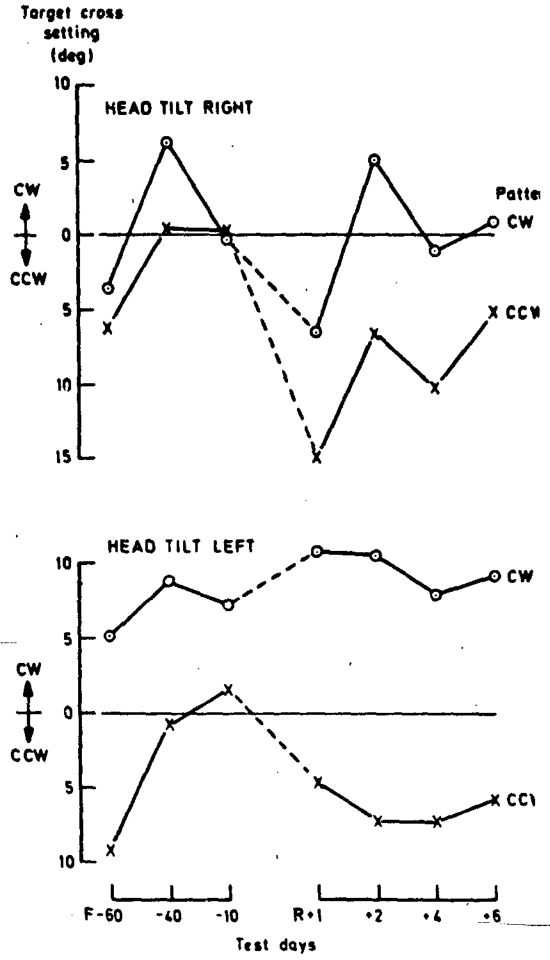

Fig 8. Effect of lateral head tilt on the apparent vertical during roll axis opto-

In-flight, the video replay unit, in which the optokinetic patterns were stored, ceased to function after one pass of the video tape, so only data from pre and post-flight tests are available on the two crew members (C and D) who were investigated.

Figure 7 summarises the results of the ground-based tests, performed with the subject's head in the vertical position. The dispersion of the pre-flight measures precludes statistical significance being attached to any change in the responses obtained post-flight. However, the individual records show that subject D had a greater deviation in his perception of the vertical on R+1 during clockwise (CW) pattern rotation than on any of the pre-flight or subsequent post-flight tests. Subject C behaved in a similar manner on R+1 except that the outstanding response occurred when the visual stimulus rotated in the counter-clockwise (CCW) direction.

The test procedure was also performed with the subject's head tilted in roll some 45° to the right and to left, for it has been shown (Dichgans et al. 1974) that the deviation of the subjective vertical is enhanced when the otoliths are placed in a less favourable position, the greatest potentiation occurring when the stimulus moves in the opposite direction to that in which the head is tilted.

The effect of lateral head tilt on the apparent vertical during optokinetic stimulation in roll is summarised in fig 8. This shows that in the experimental conditions where the response is optimally potentiated (i.e. CCW visual stimulus, head tilt right, and CW visual stimulus, head tilt left), on R+1 there was a larger deviation in the setting of the target cross than on any of the pre-flight tests. The responses obtained in the complementary conditions did not exhibit such a difference between pre and post-flight.

These results, whilst they lack statistical rigour, imply that the astronaut on return to earth has a modest impairment in the utilisation of gravireceptor information and hence experiences a larger deviation in the apparent vertical when presented with a visual stimulus which induces vection in roll.

<ins>Vestibular Responses to Thermal Stimulation (Caloric Test).</ins>

Whereas the experiments, reported above, were intended to enhance our understanding of vestibular adaptation in microgravity, one experiment was specifically designed to test the theory that the nystagmus evoked by caloric stimulation is caused by 'thermal convection'. This theory, initially advanced by Bárány (1906b) and consolidated by Brünings (1911), is that the temperature gradient within the temporal bone engendered by irrigation of the external ear canal with water above or below body temperature, causes circulation of the endolymph within the semicircular duct by thermal convection. This circulation of endolymph, in turn, deflects the cupula and hence alters the activity of the sensory cells in the ampulla. We now know that the cupula occludes the ampulla and endolymph is not free to circulate by convection, so the more modern concept is that the unequal alteration of the density of the endolymph, produced by the temperature gradient, deflects the cupula by virtue of the differential pressure which develops across it.

Although there is a substantial body of both theoretical and experimental work to support the density gradient model (reviewed by Proctor 1975), several authors have expressed doubts about the adequacy of the theory. In particular, the relationship between the intensity of the evoked nystagmus and the orientation of the stimulated semicircular canal to the Earth's gravitional field exhibits certain disparities (Coats & Smith, 1967). These suggest that a component of the response is due to an alteration of the resting discharge of the sensory cells brought about directly by the heating or cooling of the sensory epithelium. In microgravity, anisotropic changes in mass per unit volume of the endolymph should not produce a differential pressure across the cupula, and so a thermal stimulus should not evoke nystagmus, unless a linear acceleration is imposed in the plane of the canal in which a thermal gradient is induced.

The experiment performed in Spacelab on astronauts C and D entailed sustained binaural stimulation with air at temperaures ranging from 15°C to 44°C. At each temperature setting (detailed in Table 1) nystagmus was recorded with the test subject stationary and during whole-body oscillation in the X axis at

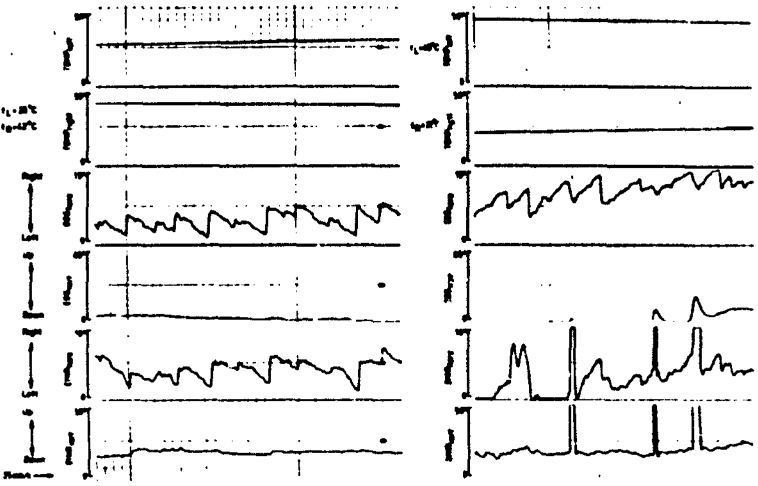

Fig 9. Records of nystagmus induced by binaural thermal stimulation in microgravity of astronaut C on mission day 8. The traces, from above downwards, are: temperature of insufflated air on left and right; eye position recorded by electro-oculography (EOG) in horizontal and vertical axes; eye position recorded by IR, TV

0.3 Hz. Pre- and post-flight tests were conducted with the subject's head in the vertical position (i.e transverse (X,Y) plane of his head horizontal) and the NASA 'Sled' (a horizontal linear oscillator) was used to generate the dynamic, X axis stimulus (0.3 Hz, ±5 ms^{-2}).

The records of eye movements (EOG and EMIR) obtained during caloric stimulation on the first and third day of flight revealed a minimal nystagmic response which was too small to evaluate quantitatively, and the addition of the dynamic stimulus did not potentiate the eye movements to a discernable extent. However, when the test procedure was repeated later in the mission (F+5, F+8) well defined nystagmus (fig 9) and vertiginous sensations were elicited in the absence of any whole-body oscillatory motion. It is noteworthy that the nystagmus recorded on these tests was similar, both in direction and peak slow phase velocity, to that obtained pre and post-flight (fig 10). Indeed, on reversal of the thermal stimulus, the intensity of the response in flight was somewhat greater than that obtained on the ground. However, during the pre-and post-flight tests the subject's head was not in the optimal position (i.e. plane of lateral canal vertical) for the induction of a maximal response. Evaluation of the caloric nystagmus during dynamic stimulation, both on the ground and in flight, revealed no significant changes or modulation.

Temperature (°C) of Insufflated Air		Activity
Right Ear	Left Ear	
37	37	Start of experiment
44	30	Static 120s, Dynamic 30s
44	20	Static 120s, Dynamic 30s
44	15	Static 120s, Dynamic 30s
20	44	Static 180s, Dynamic 30s
15	44	Static 120s, Dynamic 30s

TABLE 1. Protocol of Caloric Experiment.

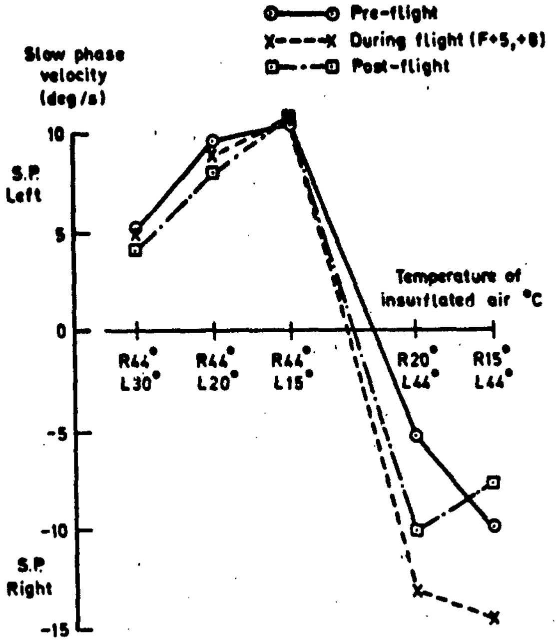

Fig 10. Comparison of peak, slow phase velocity of nystagmus evoked by binaural thermal stimulation pre, per and post flight. Mean values of astronauts C & D.

The demonstration of a substantial response to thermal stimulation in microgravity raises more questions than it answers. It suggests that mechanisms other than 'density gradient' are responsible, though to what extent, if at all, these contribute to caloric nystagmus when the test is performed on earth has yet to be determined. Certainly, the similarity of the nystagmus, in respect to both its direction and magnitude, elicited in orbit and on the ground, suggest a common mechanism. However, any postulated mechanism must account for the fact that on the ground the direction in which the nystagmus beats is determined by the orientation of the head to gravity (Coats & Smith, 1967). There is also a possibility that pulsatile pressure changes of the air blown into the ear by the pump in the helmet could have generated a cyclically fluctuating force environment within the fluid systems of the inner ear which permitted differences in the specific mass of the endolymph to deflect the cupulae of the semicircular canals. This is an inchoate hypothesis, but one which will be put to the test on the D-1 Spacelab mission, when another method of thermal stimulation will be employed. The lack of nystagmus to the caloric stimulus early in the mission may represent a suppression of vestibular responses, similar to that seen during the transient weightlessness of parabolic flight (Oosterveld & van der Laarse, 1969), but it is perhaps more perhaps more likely that it was caused by the drugs taken by the astronauts as prophylaxis against space-motion sickness (detailed in Oman et al. 1984). By the third or fourth mission day, the crew had adapted to microgravity, so that when the caloric tests were repeated later in the mission responses were not suppressed by anti-motion sickness drugs.

Although the experiment performed in Spacelab-1 has brought into question an established theory about how thermal stimulation induces nystagmus, it does not degrade the clinical utility of the caloric test. This widely used procedure remains an effective means of testing the functional integrity of vestibular apperatus and its central connections, and it will continue to be of value in localising lesions within the vestibular sensory system.

CONCLUSIONS.

The conclusions to be drawn from the findings of these experiments, which probed various aspects of the adaptation of vestibular and visual-vestibular mechanisms in microgravity, must of necessity be tentative; primarily because the number of subjects upon whom measurements were made is small, and insufficient data were acquired to determine with statistical rigour the significance of an apparent change in a particular microgravity involves a modification in the utilisation of gravireceptor information by the central nervous system.

Post-flight, the reduction in ocular counter-rolling, the impaired judgement of the vertical during body tilt, and the greater deviation of the apparent vertical during optokinetic stimulation, all point to a decrement in the use of gravireceptor information, primarily from the otoliths, to determine the orientation of the head and body with respect to the gravitational vertical. This could have been brought about by an attenuation in the transmission of the signals from the otoliths or even a modification of end-organ sensitivity by efferents. However, it is more likely that these changes are the manifestation of a 'sensory rearrangement' in which otolithic cues are re-interpreted, rather than any overall loss of sensitivity, for in those situations involving more dynamic stimulation of gravireceptors, responses were enhanced in early post-flight tests. In our experiments, this was revealed in the eye movements evoked by oscillation of the head in pitch and in the thresholds for detection of linear oscillation of two of the four SL-1 astronauts. Other SL-1 investigators also found increased sensitivity post-flight to dynamic linear acceleration stimuli. Notably, there was an improved ability to null random Y axis linear accelerations (Young et al. 1984) and a greater facilitation of the H reflex during an unexpected vertical drop (Reschke et al. 1984), although the latter finding must be tempered by the fact that electromyographic studies failed to demonstrate any modification of otolithic-spinal reflexes evoked by this type of transient vestibular stimulation (Young et al. 1984).

The dissociation of the adaptive changes in otolithic responses to static and dynamic stimulation does not conflict with the hypothesis of Parker (1983); namely, that adaptation to microgravity involves a 'sensory rearrangement' in which signals from gravireceptors cease to be interpretated by the brain as changes in angular position in pitch and roll but rather as linear movements of the head and body. In addition to such a reinterpretation of gravireceptor signals, there may also be a shift in the 'weighting' given by the central nervous system to signals from the otoliths. Experimental evidence suggests that this 'weighting' is is dependent upon the frequency content of the transduced stimulus, high frequency dynamic inputs being given greater weight than the low or zero frequency inputs which normally signal the 'static' orientation of the head to gravity.

The inability of the otoliths to provide information on the spatial orientation of the head in microgravity is likely to be compensated by the increased utilisation of orientational cues provided by other sensory systems. In particular, it appears that visual cues have greater dominance, as evidenced, post-flight, by larger errors in the perception of the visual vertical on the rod and frame test (Young et al. 1984) and by the enhanced visual suppression of vestibular nystagmus.

ACKNOWLEDGEMENTS.

We wish to express our gratitude to the Mission and Payload Specialists of Spacelab 1 - Dr. O. Garriot, Dr. B. Lichtenberg, Dr. U. Merbold and Dr. B. Parker - for conducting the experiment in-flight and for their co-operative participation in the pre and post-flight tests. The assistance of Dr. H. Bauer, Dr. M. Lampton, Dr. W. Oekels and Mr. M. Timm in performing pre-flight tests, and Dr. A. Belyavin in statistical analysis, is also gratefully acknowledged, as is the support of the staff of the Baseline Data Collection Facility, under the supervision of Dr. R. Clarke, at NASA Dryden, Edwards AFB, Ca.

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DISCUSSION

PARKER, USA

I would like to comment on the results Dr. Benson presented with respect to subjects' variability in the response to straight line motion by showing data we have been able to obtain from other missions.

THRESHOLDS FOR DETECTION OF LINEAR OSCILLATION FOLLOWING PROLONGED WEIGHTLESSNESS

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INTRODUCTION

Dr. Benson has reported that linear self-motion detection thresholds, which were recorded as part of the European Vestibular Experiments, varied across subjects. This varibility is consistent with observations following the STS-8 and STS-11 Shuttle missions.

METHOD

Three astronauts who participated in the STS-8 and STS-11 (41-B) missions served as subjects in this experiment.

The apparatus employed was the Miami University Parallel swing. This apparatus is described in Paper No. 3--REINTERPRETATION OF OTOLITH INPUT AS A PRIMARY FACTOR IN SPACE MOTION SICKNESS.

Nominal amplitudes of parallel swing motion were determined by recording the displacement of a pointer attached to the swing bed relative to a scale taped to the floor. These nominal amplitudes were compared with those determined with a three-axis accelerometer and strip-chart recorder.

The subject indicated his perception of self-motion ("yes" or "no") by manipulations of a joystick that was connected to one channel of the strip-chart recorder.

A small signal lamp was mounted on an ear-pad support and was controlled by the experimenter's hand-held microswitch.

The procedure used to determine self-motion thresholds was similar to that used in tracking audiometry. The swing was set in motion at a relatively high amplitude (about 20 cm/sec/sec). In response to a signal from the experimenter, the subject reported whether or not he perceived that he was moving. When his report was affirmative, the swing was stopped and then set in motion at an amplitude 5 cm/sec/sec smaller. Conversely, if the subject failed to detect motion, the swing amplitude was increased on the subsequent trial. The direction of stimulus amplitude change (increasing or decreasing) was altered after two affirmative or negative responses from the subject. Threshold tracking was continued until ten stimulus amplitude direction reversals had been completed or seven minutes had elasped.

The experimenter controlled the swing motion manually. She/he slowly increased the amplitude of swing motion until the desired level was reached. After one or two oscillations at the desired level, the subject was requested to report his self-motion perception.

RESULTS

The results of these observations are illustrated in Figs. 1-4. The data from Astronaut 1 suggest a nearly three-fold elevation of the self-motion detection threshold. Virtually no threshold change was seen with Astronauts 2 and 3.

DISCUSSION

Prolonged weightlessness appeared to produce elevated self-motion detection thresholds in one astronaut. However, a similar threshold elevation was not obtained from the other two astronauts. The basis for this discrepancy is unknown but it may be related to altered detection threshold criteria on the part of the astronaut who exhibited the threshold change.

Failure to record threshold changes following prolonged weightlessness is consistent with our otolith tilt-translation reinterpretation hypothesis. This hypothesis suggests that the sensitivity of the otolith receptors is not altered by weightlessness; rather the way in which the brain interprets otolith information is changed.

Our procedure required the subjects to report ANY motion. The subject was not required to distinguish between linear motion and tilt. Consequently, the presence in the central nervous system of any "above-the-noise" signal from the otolith receptors would result in a motion report by the subject.

The otolith tilt-translation reinterpretation hypothesis would predict improvement in performance on a task that requires the subjects to detect and respond to linear motion. This predicition derives from the postulate that following prolonged weightlessness, all otolith output is interpreted by the brain as indicating linear motion. Professor Young's report that performance improved on the "otolith closed loop nulling task" supports this predicition.

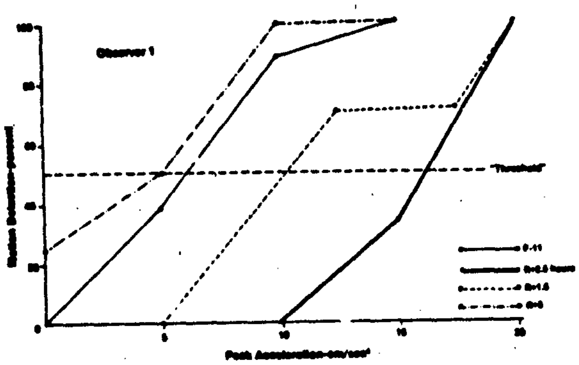

Fig. 1. Thresholds for detection of whole-body, Y-axis linear oscillation from Astronaut 1. The ordinate indicates percent detection and abscissa values are peak half-amplitude of the stimulus. The R+O data were obtained 2.5 hours after landing.

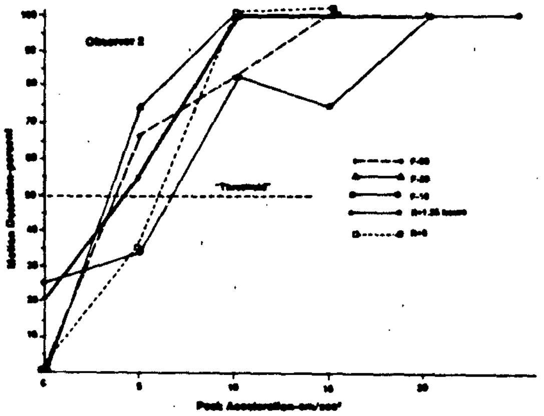

Fig. 2. Thresholds for detection of linear oscillation for Astronaut 2. The R+O data were obtained 75 minutes after landing.

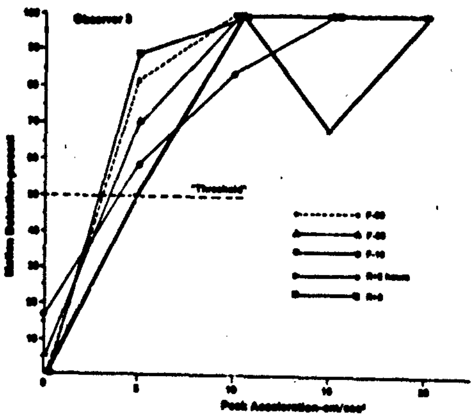

Fig. 3. Thresholds for detection of linear oscillation for Astronaut 3. The R+O data were obtained 2 hours after landing.

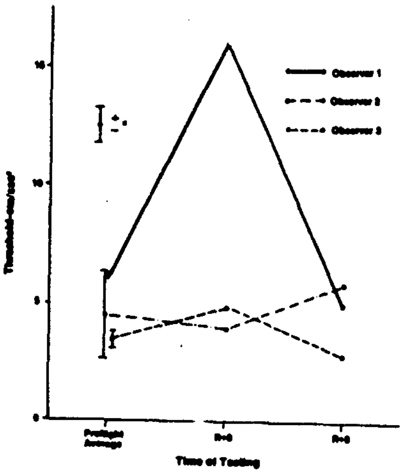

Fig. 4. Summary of thresholds for detection of linear oscillation recorded from Astronauts 1,2, and 3.

AUTHOR'S reply

Thank you, Don. I think your comment was adequately explained by yourself.

KLEIN, FRG

When you pointed out the differences between the red and blue crew I wondered what influence on the results the time of day might have had, since the one group was on day shift, the other one on night shift.

AUTHOR'S reply

We do not know the answer to that, although in the work we have done in the laboratory there do not appear to be large circadian variations in the threshold we are talking about. I think it is much more likely that these effects are either an individual difference or a reflection of the other stimulation that they have been given.

MERBOLD, ESA

I think the threshold is one of these measurements which might be influenced by fatigue. I should mention that the Body Restrained System (BRS) - maybe because it gave us some back pressure - put us asleep more or less immediately. And the same is also true if you sit on that machine on the ground; it is a comfortable rocker-chair and makes you sleepy. I do not know what we can do to avoid that problem.

AUTHOR'S reply

Well, there are a number of things we could do to keep you awake. We are looking at a different psycho-physical proceduring which would take care of people going to sleep.

(SPEAKER unidentified)

A comment regarding the pulsatile pump. If you change temperature in space, you still have that basic pulsatile flow in the same direction. Would that not mask any thermal effects you had? In other words, can you rule the pulsatile pump out, because you do get the increase?

AUTHOR'S reply

No experiments to my knowledge have been done on the characteristics of the pulsatile pulse in terms of producing or modifying responses. The experiment that should be done is using the same stimulus but in different head positions in 1 g. That would be much more critical.

(SPEAKER unidentified)

Was the same testing used pre-flight?

AUTHOR'S reply

Basically the same system was used for pre-flight, in-flight and post-flight tests.

Spatial Orientation in Weightlessness and Readaptation to Earth's Gravity

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ABSTRACT

Unusual vestibular responses to head movements in weightlessness may produce spatial orientation illusions and symptoms of space motion sickness. An integrated set of experiments was performed during Spacelab 1, as well as pre and postflight, to evaluate otolith organ and semicircular canal mediated responses by a variety of measurements, including eye movements, postural control, perception of orientation and motion sickness susceptibility.

INTRODUCTION

A novel set of sensory cues is produced by head movements in weightlessness. Voluntary head tilts are no longer confirmed by static changes from the otolith organs to signal head orientation with respect to the vertical. Indeed, with average linear acceleration equal to gravity during free fall, the linear accelerometers of the non-auditory labyrinth transduce only transient linear acceleration and no longer indicate head pitch or roll angle. We hypothesized that vestibular afferent signals, particularly from the utricular and saccular maculae, are centrally reinterpreted; for example, to represent linear acceleration rather than tilt.(1) It was further supposed that this central adaptation underlies the amelioration of symptoms of space adaptation syndrome, the special form of motion sickness which afflicts roughly half of all space travellers during the first two to four days on orbit. In order to localize this presumed adaptation, a set of interrelated experiments were performed on four Spacelab 1 crewmembers. Pre and postflight tests of postural control and motion perception, as well as of the inflight protocols, are used to evaluate readaptation to earth's gravity after reentry.

Visual-Vestibular Interaction (2)

When viewing a full field rotation about his sagittal (roll) axis, a subject on earth with head erect normally perceives a sensation of continuous self rotation in the direction opposite to the field motion (circularvection) combined with the paradoxical perception of a steady angle of tilt. This limitation has been attributed to graviceptor signals, particularly those from the otolith organs, which do not confirm the visual input suggesting continuous roll rate. (3) Visually induced tilt is enhanced when the head is placed in positions other than the erect (4) and can be continuous about a vertical axis when a subject lies supine. In weightlessness the absence of any inhibiting otolith signals might be expected to produce stronger and more compelling visually induced roll although the absence of confirming signals from the semicircular canals might be expected to delay the onset of circularvection. Subjects viewed the polka-dot patterned inside of a drum ("dome") which rotated at speeds of 30, 45, or 60 deg/sec about their roll axis. The head was fixed by a biteboard and ocular torsion (5) was recorded by a video camera. (Torsion results not yet available.) The subject's body alternately floated free or was restrained by standing against stretched elastic cords which created an upward force on the feet. Self-rotation illusion was manually indicated by magnitude estimation using a potentiometer and by qualitative descriptions from each subject. There was considerable variability among the four crewmembers in their reactions on the ground, as well as in space. There was evidence for some degree of enhancement of the vection during weightlessness, relative to ground erect or supine tests, for at least 3 of the 4 subjects. Reactions varied from a sense that the subject and Spacelab together were rotating about a stationary dome to feelings of incomplete vection. Latency to onset of vection and average intensity of the self-motion indication generally confirmed the subjects' reports of stronger visual effects in Spacelab than on the ground.

Early in the mission, elastic cord loading produced inhibition of visually induced tilt in 2 of 3 subjects. By MD 5, the inhibitory influence of these localized somatic cues disappeared. Body sway and neck torque in response to dome rotation was sensed by two subjects, but clearly visible only in one, whose trunk and legs rotated slowly by up to 30 deg in the direction opposite to dome rotation. Upon closure of the eyes for 3 of 4 subjects, circularvection unexpectedly ceased immediately, despite the absence of any sensory cues to signal body deceleration. Its onset was hastened by free rolling head movements. During post-flight rotating dome experiments, two subjects indicated self motion illusions not previously experienced lasting for up to five days postflight.

Visual cues concerning orientation appear to take on an increasing role in weightlessness. Localizable tactile cues, which may partially substitute for static otolith cues early in the mission for some subjects, no longer seem to play this role once vestibular adaptation has taken place.

Space Sickness Monitoring Experiment (6)

Symptoms and signs of space sickness and fluid shift were observed and documented by four specially trained crewmembers during this physically demanding flight. An example of one subject's discomfort index magnitude estimation is shown in Fig. 1. Two subjects wore head mounted accelerometers, but quantitative analysis of head movement data is not yet complete. Three of four crewmen experienced persistent overall discomfort, and vomited repeatedly. Symptoms diminished by the end of the third day, but still could be elicited with vigorous head movements through days 4-5. One subject who explored different types of head movement found pitching and rolling head movements particularly provocative. However, on MD 8 he was asymptomatic after performing 5 minutes of vigorous head to knee movements. Symptom pattern was generally similar to that seen in the same individuals preflight, except that: prodromal nausea was brief or absent in 2 of 3 cases; facial pallor and cold sweating were usually absent; one subject experienced uncomfortable "stomach elevation" and difficulty burping. There is evidence that "sudden" vomiting is characteristic of long duration motion sickness, and also of the responses of relatively resistant subjects. (7) We tentatively attribute absence of pallor and sweating to the presence of physiological fluid shift, and to the cool, dry environment of Spacelab, respectively. Subjects reported that symptom intensity was clearly modulated with head movement, and was exacerbated by reorientation illusions caused by ambiguous visual cues (as when assuming - or viewing another crewman in - an unusual orientation or when travelling through the tunnel connecting Spacelab with the orbiter). Tactile and proprioceptive contact cues provided by "wedging" the body into a corner or a bunk cubicle were palliative, as was closing the eyes, provided these contact cues were simultaneously present. Drugs (0.5 mg scopolamine/ 2.5 mg dexedrine or 25 mg promethazine/ 25 mg ephedrine) known to be effective in preventing motion sickness were eventually taken by all, and were judged helpful in reducing discomfort with only minimal side effects. One subject was asymptomatic. Among the others, only 2 of 12 vomiting episodes occurred during the presumed period of maximal drug effectiveness. Although all reported persistent head fullness and congestion, and "fluid shift" faces were evident throughout the mission, subjects denied difficulty with hearing or clearing their ears. Altogether, we believe these results support the view that space sickness is a form of motion sickness.

Pre and Post Flight Tests of Motion Sickness Susceptibility (8)

In the past, single preflight tests have not been predictive of space sickness (9). Beginning four years preflight, we conducted six different formal tests of motion sickness susceptibility; horizontal lateral oscillation, heavy water ingestion, a dynamic visual-vestibular interaction test (10), horizontal axis rotation in pitch and head movements in parabolic flight. The latter two were repeated in the year preceding flight. Modified Coriolis Sickness Susceptibility tests were conducted by NASA-JSC. These tests failed to predict relative susceptibility in flight (11). Four days post flight all four subjects performed more than 140 forehead to knee head movements during the zero-g phases of parabolic flight without eliciting any symptoms, whereas all had shown some symptoms in one or the other of the preflight tests.

Otolith-Spinal Reflex (12)

The burst of gastrocremius-soleus electromyographic (EMG) activity occurring 50-150 msec after the onset of a sudden fall is considered to be predominantly otolith-spinal in origin. It is of short and relatively invariant latency, too early for a voluntary response, and is time-locked to the acceleration stimulus. (13) It can also be selectively abolished by labrinthectomy in cats (14) and baboons (15) and is absent in labrinth-defective human subjects (16).

Previous studies have demonstrated that (1) the size of this otolith-spinal response is proportional to the acceleration stimulus, (2) the response may be reduced significantly by rotating the gravity vector 90 degrees relative to the body (subject supine), or by free fall as in parabolic flight in an aircraft (17), and that (3) the response steadily increases in size during prolonged exposure to the supine position (18). The present experiments were designed to measure adaptation and readaptation of the otolith-spinal system during and after prolonged weightlessness.

Pre and post-flight, the subjects were exposed to sudden, unexpected vertical falls of 15 centimeters, with stimulus amplitudes of 1.0, 0.67 and 0.33 g. The lesser accelerations were obtained using a counter-weighted parachute harness. Testing of two subjects was done on-orbit, substituting for gravity with suitably adjusted elastic cords running from a torso harness to the floor of Spacelab. We recognize that the mechanical consequences to the otolith organs of being accelerated downward by elastic cords from free fall are not equivalent to those of being dropped in 1-g. Although starting from a different bias position, however, the in-flight and ground stimuli are similar step changes in vertical acceleration.

Post-flight, all subjects experienced difficulty maintaining balance when landing from falls. This was dramatic initially, but returned to normal within a few days. Contributing factors suggested by the subjects included leg muscle weakness, slower reaction to the falls and landings, and some difficulty telling where the legs were, with the result that the feet were often forward of or behind the body center of gravity on landing. The latter phenomena seemed to be present late in the flight as well. At that time, one subject also described "pins and needles" sensations in his legs.

Despite impressions of the subjects, careful comparison of pre and post-flight EMG data obtained no earlier than R+3.5 hours did not appear to show any significant changes in latency or amplitude of the early otolith-spinal response to sudden falls. These results are compatible with previous ground-based studies on otolith-spinal adaptation to the supine position. (18) The lack of change post-flight could be the result of a readaptation time course which was too rapid to be detected by the present experiment, including the possibility of a nearly instantaneous readjustment of the response back to normal upon return to the familiar 1 g environment. It is also possible that post-flight changes in otolith function can only be demonstrated by lower frequency stimuli. These results suggest, however, that post-flight postural instability is more a reflection of altered proprioceptive or tactile sensation, or possibly muscle wasting, and less the result of modification of the vestibulo-spinal reflexes studied here.

Awareness of Position Experiment (19)

Subjects were strapped blindfolded to a flat surface and after 5-15 minutes rest were asked to point to preestablished targets and to describe the position of their limbs. If straps were left loose, uncertainty of orientation with respect to the laboratory grew slowly, as might be expected due to the possibility of body drift. However, even with tight straps, there was an apparent increase in variability of limb position estimate with muscles relaxed, as compared to pre-flight. Post flight, occasional very large errors pointing at high elevation targets were found through R+5.

Pre-Post Flight Posture and Orientation: (20)

Post-flight postural instability, especially with eyes closed, has been noted previously (21) and is related to the duration of weightless exposure. In a sharpened Romberg test, all subjects showed considerable difficulty in eyes closed standing post-flight, exhibiting growing body oscillations prior to falling off the 2 1/4 (5.7 cm) inch rail. As shown in Fig. 2A, standing time dropped to 25-35% of pre-flight on R+1 and improved only gradually over the following week. The one subject tested on R+0 indicated performance even poorer than on R+1, suggesting that a considerable amount of readaptation had taken place during the first twelve hours after return, as borne out by the crew's comments concerning instability in the dark and movement illusions.

Additional experiments were performed while standing, eyes open and eyes closed, on a posture platform which is rotated rapidly and unexpectedly in a step disturbance of 3-5 deg about the ankles. Measurements were made of platform torque, EMG activity from the tibialis anterior and the gastrocnemius muscles and of body position. Four hours post-flight, crew members were unsteady: They adopted a wide stance, and for the first time lost their balance during step disturbances on the posture platform (tilt-up; eyes closed). As seen in Fig. 2B, post-flight activity in both muscles was not significantly changed in latency or amplitude up to 250 ms following each tilt, but stronger beyond 250 ms. By R+4 EMG, responses returned to pre-flight levels. Despite previous reports of increased spinal activation post-flight (22), no increase in antagonist EMG was found during platform tilts.

Visual field dependence was measured by the rod and frame test (23) whereby subjects set a luminous line to the vertical under the influence of a luminous frame in a darkened room. Figure 3 shows that all four subjects were more field independent than the population average. The two most field dependent (A and D) pre-flight both shifted toward increased field dependence post-flight, returning gradually but not completely back toward their baseline by R+6. Subject A, who showed particularly large variability and asymmetry post-flight, also showed large asymmetry in the post-flight luminous line test (24). The two least field dependent showed no changes post-flight. An increase in time to make judgements of the vertical was noted for all subjects.

Perception and control of lateral acceleration was measured using a servo controlled sled which provided accelerations up to 0.7 g's over a 4 m track. The time to detect low step accelerations (0.001-0.08 g's) increased slightly in variability post-flight and showed some examples of long delays and direction errors, but presented no consistent trends in either thresholds or the time to detection of linear acceleration (25). For closed loop nulling of random disturbances in lateral acceleration on the sled, the two subjects who were tested on the evening of the return performed very accurately using only non-visual cues. Their performance far exceeded pre-flight, and approached their accuracy for the task with full visual cues. This ability decayed gradually over the week of post-flight testing. Dynamic ocular counterrolling, measured during lateral sinusoidal oscillation at 0.6 g (0.42 Hz and 0.83 Hz) appears to be reduced in gain on R+0.

DISCUSSION

The preliminary nature of the findings reported in this paper make conclusions and discussion neccessarily speculative. Nevertheless, all of the major findings are consistent with the principal hypothesis: During the course of adaptation to weightlessness the nervous system reinterprets signals from the graviceptors (primarily the otolith organs) to represent fore-aft or left-right linear acceleration, rather than pitch or roll of the head with respect to the vertical. Maintenance of this reinterpretation during the post-flight period is maladaptive, resulting in postural instability with eyes closed, increased reliance upon visual information for orientation, and improved ability to null lateral linear motion. Independent refinement of the otolith reinterpretation hypothesis was proposed by Parker et al (26) to explain their post-flight findings with STS-8 and STS-11 astronauts. Self motion reports and eye reflexes during roll motion showed primarily linear translation and reduced ocular counterrolling post-flight, relative to pre-flight. The adaptation is presumably not reflected at the more peripheral end organ responses or in fast reflex loops such as the otolith-spinal reflex. One consequence of the presumed linear acceleration sensor reinterpretation in-flight is the increased use of local visual cues for spatial orientation and, at least early in the flight, the increased attention to tactile and proprioceptive information regarding both body orientation and sense of body movement.

FOOTNOTE

We gratefully acknowledge the outstanding cooperation of the Spacelab 1 science crew and support from NASA (NAS9-15343), the Defense and Civil Institute of Environmental Medicine (Canada) and the Medical Research Council (Canada). We are grateful for the guidance and assistance of G. Melvill Jones, F. Guedry, A. Weiss, R. Donahue and especially R. Clark and G. Salinas for extraordinary support in the entire program. We also thank W. Mayer, Project Manager, and the staff of the Laboratory for Space Experiments of MIT's Center For Space Research. A. Arrott directed the sled protocols, R. Renshaw coordinated the MIT activities in the Baseline Data Collection Facility (BDCF), S. Modestino ran the rails and the rod and frame tests, R. Kenyon, the posture platform and M. Shelhamer, the rotating dome experiment. BDCF tests were performed 152, 122, 65, 44 and 10 days pre-flight, on the day of landing and 1,2,4 and 6 days after return. Several eye movement experiments require further data processing and are not covered in this report. The horizontal vestibulo-ocular reflex was measured during angular oscillation, post rotatory-nystagmus and pitch down nystagmus dumping. Ocular torsion was recorded during eccentric z-axis sinusoidal angular oscillation performed at high and low frequencies.

Complete reports on all our Spacelab vestibular experiments are being submitted for publication in a special issue of Experimental Brain Research.

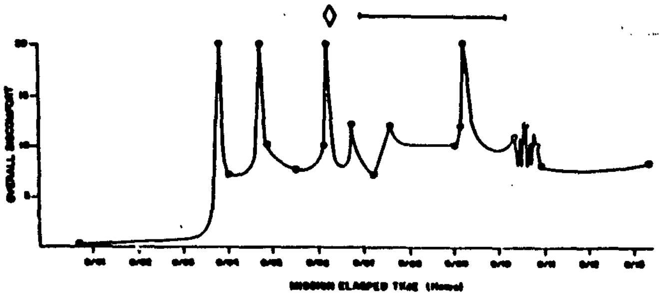

Fig. 1. Magnitude estimate of discomfort (26) for one subject during the first 14 hours on orbit. A score of 20 indicates vomiting. Curves between data points interpolated by subject. Diamond represents medication (scopolamine/dexedrine), followed by horizontal bar representing period of presumed maximal effectiveness.

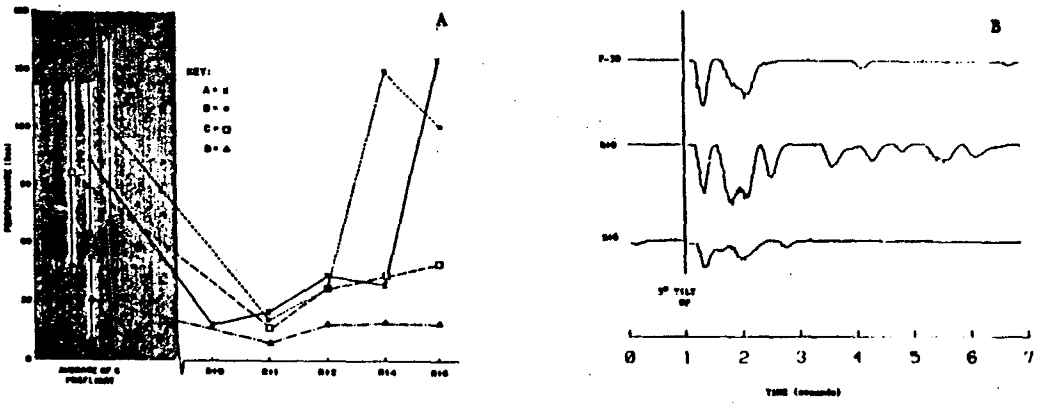

Fig. 2. Posture control with eyes closed showed marked decrement immediately post-flight when challenged by standing on a 2 1/4" (5.7 cm.) rail (A) or responding to unexpected toe-up tilt of a posture platform (B). Modified sharpened Romberg test (A) measured total time standing on rail for the best 3 of 5 one minute trials. In (B) one subject's filtered EMG activity (arbitrary units) from the tibialis anterior muscle during the first eyes closed 5° toe up platform tilt shows, for R + 0, increased magnitude and duration of the late response. The drop in magnitude below pre-flight, seen for R + 0, was not seen for the other three subjects.

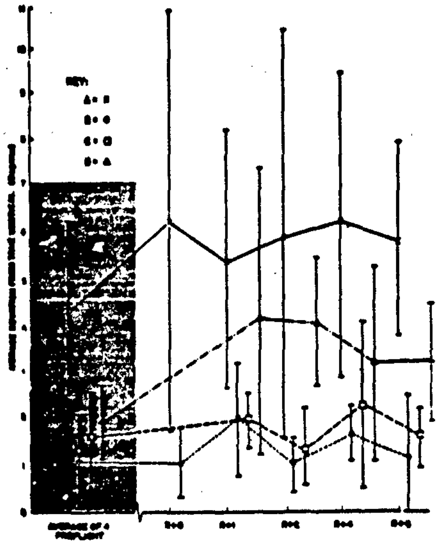

Fig. 3. Rod and frame measurements of field dependence, average absolute deviation and standard deviations. Subject A also showed increased asymmetry in visual field dependence as well as in body tilt (24) post-flight.

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DISCUSSION

BENSON, UK

You showed the ocular counter-rolling responses at 0.8 Hz. What I was postulati this morning was, that there would be a different form of reinterpretation otolith signals which may of itself be frequency dependent. Have you any informati on ocular counter-rolling gain at frequencies other than 0.8 Hz?

AUTHOR'S reply

The question of the frequency dependence of the changes in all of the otolit dependent responses is an interesting one, because one possibility is that only t low frequency portion, the tonic portion of otolith responses, would reinterpreted, whereas the high frequency, phasic portion, remains adequate a would not be reinterpreted. We performed therfore the ocular counter-rolli testing pre-flight and post-flight at two frequencies, 0.42 Hz and 0.83 Hz. For t two subjects analysed so far the gain decrease at both frequencies was about t same.

TERZIOGLU, TU

What were your tactile cues which temporarily substituted otolith no responsiveness?

AUTHOR'S reply

Local pressure cues were applied to the soles of the feet during the dome experime by counterpressure from stretched elastic cords attached to a shoulder harness.

TERZIOGLU, TU

Which drugs did you use to alleviate the overall discomfort in space moti sickness?

AUTHOR'S reply

Three crew men used 0.5 mg scopolamine and 2.5 mg dexedrine oraly in repeat doses. Two also used metachlopromide, one crewman used 25 mg promethazine and 25 ephedrine. These were drugs which have been selected by the crew members on t basis of pre-flight testing for maximum effectiveness and minimum side effects.

REINTERPRETATION OF OTOLITH INPUT AS A PRIMARY FACTOR IN SPACE MOTION SICKNESS

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SUMMARY

It is hypothesized that exposure to prolonged free fall is a form of sensory/motor rearrangement rather than a direct change in otolith sensitivity or sensory compensation for a reduced otolith input. The rearrangement of stimuli will force a new interpretation by the CNS of otolith input. This reinterpretation is necessary for a structured and meaningful interaction with the new environment.

Data from two flight experiments are presented which support an otolith reinterpretation hypothesis. The first experiment measured vestibulo-spinal reflex changes as a function of sustained free fall. Findings indicate that when a monosynaptic reflex (H-reflex), measured from the major postural muscles (soleus), is used adaptation to space flight includes a change in how the CNS interprets a fall. In a normal gravity environment a sudden unexpected fall will produce a potentiated H-reflex. After seven days in flight an equivalent fall does not potentiate the reflex. Postflight a greatly increased reflex is observed in those crewmen most susceptible to space motion sickness.

In the second experiment self motion perception and torsional eyemovements were modified as a function of exposure to sustained free fall. Preflight roll motion (about the X axis) was perceived as pure roll, and the eye movements recorded were countertorsional. Postflight, roll stimulation was perceived as linear translation (side to side movement) with a small angular motion component. Eye movement measurements confirmed significantly more horizontal motion.

INTRODUCTION

Exposure to sustained free fall results in rearranged relationships between signals from visual, vestibular, and proprioceptive receptors. Motor performance and spatial orientation perception are altered as a consequence of adaptation to this rearrangement. Space motion sickness is a frequent by-product of the adaptation process.

The normal relationships between visual, vestibular and proprioceptive receptor signals are rearranged in space because of removal of the constant acceleration due to gravity. The relationships between motion/orientation stimulation detected visually and by the otolith receptors differ from those experienced on earth. Touch and pressure receptors can be used to signal mass and velocity as the crewperson pushes off of a solid surface. Proprioceptive input has new meaning as the legs are drawn up to modify the body's center of gravity and the postural muscles are relieved of the task of supporting upright posture.

The sensory rearrangement produced by space flight results in reinterpretation of otolith signals. Otolith reinterpretation is revealed by changes in postural responses, eye movement reflexes, and self-motion and orientation perception.

To support the concepts present above, this paper presents results from two separate studies. One of these deals with vestibulo-spinal responses and the modification of these responses as a function of space flight. The second is concerned with the effects of prolonged free fall on vestibulo-ocular reflex activity and perceived self-motion. The results of both studies support an hypothesized central reinterpretation of otolith input following prolonged space flight.

EXPERIMENT I:
VESTIBULO-SPINAL REFLEX MECHANISMS

Two of the most dramatic changes related to orbital flight have been postural disturbances (1) and modified reflex activity in the major weight-bearing muscles (2). Taking advantage of the powerful and established anatomical pathways that link the otoliths and spinal motoneurones, our laboratory at the Johnson Space Center has employed the Hoffmann reflex (H-reflex) as a method of monosynaptic spinal reflex testing in conjunction with linear acceleration to assess otolith-induced changes in one group of

Early in the nineteenth century, investigators began systematically to link the vestibular apparatus to posture. Flourens observed disturbances of posture in pigeons when the vestibular apparatus was ablated. However, it was almost a century later that Magnus published his classic work describing vestibular function and body posture. These papers include a description of the Sprungbereitschaft reflex. This reflex consists of an extension of the hind and fore limbs in response to sudden downward acceleration, which disappears following ablation of the labyrinths. An English summary of these early works is contained in Camis (3).

More recently Money and Scott (4) have used the Sprungbereitschaft reflex as a qualitative measure of otolith function. They have also reduced the possibility, through surgical blockage, that the semicircular canals could contribute to this response. Under these conditions the postural reflex to a sudden drop is still exhibited. However, following bilateral labyrinthectomy the response is abolished.

Recent experiments (5) have demonstrated a short latency EMG response, recorded from the gastrocnemius in man, to the sudden unexpected initiation of a short fall. This response had a very consistant latency of approximately 75 msec regardless of the height from which the subjects were dropped. Cats were found to exhibit a similar short latency response which is permanently abolished by bilateral labyrinthectomy, but not by surgical blocking of the semicircular canals (6).

Greenwood and Hopkins (7-9) have extended this earlier work to find that in longer falls (200 msec), the initial short latency EMG burst was followed by a second peak of activity time to occur before the moment of landing. These same investigators (8) also have shown that the early burst of EMG activity is not present when labyrinthectomized man is suddenly dropped, confirming the earlier animal work of Watt (6).

An effective means of measuring changes in this vestibulo-spinal system may be with a clinical testing procedure which uses electrical stimulation to elicit, from the calf muscles, a monosynaptic reflex known as the Hoffmann, or H-reflex. In contrast to the short latency EMG activity elicited from an unexpected drop, the H-reflex would be particularly useful as a measure of central vestibular adaptation. That is, otolith organ sensitivity may not change, but the lower spinal motoneurone pool may be subject to charged presynaptic influences, and perhaps parallel descending vestibulo-spinal information.

The procedures for eliciting this reflex have been well documented by Hugon (10). Using this method Watt (11) investigated in decerebrate cats the effects of vertical acceleration on motoneurone pool excitability in the lumbosacral spinal cord. A significant reflex effect requiring a change in acceleration of 0.1-g or more, of the otolith apparatus on the postural mechanisms was observed.

Matthews and Whiteside (12) dropped human subjects in a seated position to investigate both stretch reflexes and the H-reflex as a function of zero-g. Their results indicated a decrease in amplitude of the H-reflex which occured from 50 to 100 msec after the subject was dropped. We feel that their results are open to question. Because increased muscle activity in the soleus and gastrocnemius begins from 75 to 100 msec following an unexpected fall, it appears unlikely that H-reflex amplitude (gain changes in the motoneurone pool) would be attenuated in the same time frame. It is possible that the result from Matthews and Whiteside were due to the manner in which the subjects were restrained or other methodological and mechanical problems.

In contrast, Greenwood and Hopkins (13) exposed their subjects to an unexpected drop while they were either seated or hanging in a parachute harness. Unlike Matthews and Whiteside they found an overall facilitation (200-500%) over control in the soleus H-reflex which began approximately 30 to 40 msec after release.

More recently, research in our laboratory (14-15) supports the findings of those investigators who show a potentiation of the H-reflex response as a function of free fall and reduced gravity loads. Using human subjects we have employed Soleus/Spinal H-reflex testing procedures in conjunction with an accelerative stimulus of approximately 1.8-g through 1-g to free fall (provided by NASA's KC-135 parabolic airplane) to assess changes in the vestibulo-spinal motoneurone pool as a function of variable background acceleration on the otoliths.

Based on the results of these studies where the H-reflex was modulated as a function of gravity, it was hypothesized that exposure to free fall for a prolonged period of time would reduce the necessity for postural reflexes in the major postural muscles, and that postural modification would reflect a change, not in the peripherial vestibular organs (otolith), but more centrally (brain stem). This postural adjustment would reflect a sensory/motor rearrangement where the otolith input was reinterpreted to provide an environmentally appropriate response.

METHOD: EXPERIMENT I

Four of the six crewmembers assigned to the Spacelab-1 mission served as subjects for this investigation. Preflight data were collected 151, 121, 65, 44 and 10 days prior to the flight (F-151, F-121..., etc.), on day 2 and day 7 of the flight (MET-01 and

A later data point was collected on one of the crew at R + 120. All four crewmembers participated in the preflight and postflight testing. However, only two crewmen were tested on R + 0. H-reflex data in conjunction with the linear acceleration was obtained inflight with one crew member on MET-01 and from two crewmembers on MET-06. The Spacelab-1 flight lasted for a total of 9 days.

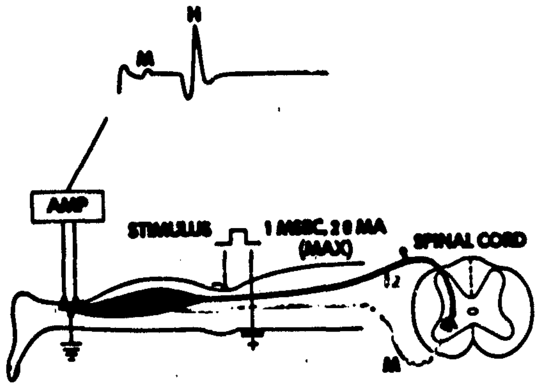


Figure 1

Hoffmann Reflex

The H-reflex as shown in Figure 1 was obtained through elicitation of a monosynaptic reflex recorded from the soleus muscle by electrical stimulation of the large group Ia fibers in the popliteal nerve. A needle electrode (modified 20g hypodermic needle), which served as the cathode was inserted in the popliteal fossa at a predetermined and permanently marked (tattoo) location on the right leg. The anode, a plate electrode, was secured just above the patella. A 1 msec constant current peak limited to a maximum of 20 mA was delivered through an isolation unit under computer control. A differential amplifier and bipolar electrode configuration was used to record the reflex from the soleus muscle. The reflex was a two-part response: a direct orthodromic muscle response (M-wave) with a latency of 5 to 10 msec that was followed 15 to 20 msec later by the monosynaphtic H-reflex. Because the M-wave represented a direct muscle response, it was used as a control during vestibular (otolith) stimulation. The H-reflex amplitude reflected the sensitivity of the lower spinal motoneurone pool as set by the descending postural control signals. Prior to vestibular stimulation, the H-reflex was established at 50% of the maximum value, and the M-wave was minimal but detectible.

Vestibular Stimulation

Vestibular (otolith) stimulation during preflight and postflight testing (Figure 2) was provided by unexpectedly dropping the subject in a special harness, designed to leave the arms and legs free, from a quick-release helicopter cargo hook. For each drop the subjects were shocked three times. Shock sequence consisted of a conditioning, control and test shock. The conditioning shock established the condition of the neural tissue. Three seconds later the control shock was delivered. Three to 5 sec later the test shock was delivered during the drop. Shocks during the drop occurred coincident with the drop (0 msec delay) or at 10 msec intervals up to 80 msec following initiation of the drop. An experimental session was comprised of four drops at nine delay times (randomized) for a total of thirty-six drops. The averaged response to the test shock was normalized with respect to the averaged control shocks and presented as a percent change in H-wave (or M-wave) amplitude.

A dedicated microcomputer (LSI-11) was used on-line to control the experiment. Four programs were supplied with the computer. These included: (1) control of the drop mechanism, (2) H-reflex stimulus sequence/delay, (3) data collection and analysis, and (4) graphics.

Inflight, we used the Canadian "hop and drop" station, a special harness arrangement, drop apparatus and calibrated bungee cords to pull the subject to the floor of the Spacelab (17). The drop-to-shock delay times employed inflight also differed from those used preflight and postflight. An experimental session was comprised of eight shock-to-drop delays ranging from 0 to 70 msec in 10 msec increments. On MET-01 four responses at each of the eight delays were recorded. This was reduced on MET-06 when only two responses at each of the delay times were obtained. The inflight computer (a modified PDP-8e) was used to control the experiment, release the drop mechanism, time the electric shock and collect the data. The data was either "dumped" real time to the ground, or stored on digital tape until it could be dumped.

Responses Recorded

In addition to the H-reflex response, a number of other parameters were recorded. Table I shows these parameters and when they were obtained.

TABLE I

Parameter Recorded	Preflight	Inflight	Postflight
Skull Acceleration	X	X	X
Body Position	X	X	X
Gastrocnemius EMG	X		X
Vertical Eye Movements	X		X
Release Time	X	X	X
Landing Time	X	X	X
Shock Delay	X	X	X

Body position was obtained by filming the drop preflight and postflight at 1000 frames/sec. In flight the drop was recorded with a video system on video tape. Every 10th film frame was analyzed to determine the angle of the head, trunk, hips, knees and ankles. Resolution of the video tape for analysis was limited to approximately 20 frames/sec. Using the body angles (Figure 2) obtained from the film and video recordings, stick figures were created and plotted in sequence to aid in visualization of the sudden drop. The angles were also used to determine percent change in a selected body angle during the drop when compared with that angle just prior to the drop. This calculation was referred to as the change in absolute body angle. A second percent change measurement was computed where each angle was referenced to the angle which just preceded it during the drop. This method yielded a running percent change in body position or the dynamic percent change.

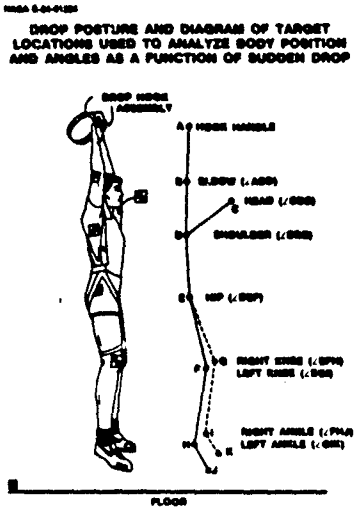


Figure 2

Preflight and postflight skull acceleration was obtained, with a linear Z axis accelerometer attached to a bite board and held in the subjects mouth during the drop. Inflight, the accelerometer was attached to the back of the head with a velcro strap arrangement. The signal from the accelerometers was digitized at approximately 100 samples/sec.

EMG activity recorded from the gastrocnemius muscles of the subject's left leg was amplified and digitized in real time at 100 samples/sec. The RMS amplitude of the EMG activity was then detemined by starting at 70 msec from before the initiation of the drop, to 170 msec into the drop. The electrodes used to record EMG activity were placed on the belly of the gastrocnemius muscle over tattoo marks.

Drop Sensation

In addition to recorded electrophysiological parameters, the subjects were asked to described sensations associated with the sudden and unexpected falls. In particular, they were to compare the inflight drops with those experienced preflight, and the postflight drops with those preflight and inflight. The subjects were also asked to describe and report any differences or difficulty in landing from the fall and any postflight difficulty in walking.

RESULTS: EXPERIMENT I

The results of the vestibulo-spinal reflex experiment are presented below in a graphic format. A detailed statistical analysis is currently in progress and not available at this time. However, the data indicate considerable differences between subjects and within subjects as a function of the Spacelab-1 flight.

Motoneurone Pool Excitability

Figure 3 shows a typical set of responses to a brief unexpected fall from 1g to free fall (a step acceleration of 9.8 m/sec^2). The time scale at the bottom of the figure has not been adjusted for a 20 msec delay that was inherent into both the ground and flight hardware. Between the time that a command to drop had been sent to the drop mechanism and data collection began or the shock initiated, approximately 20 msec elapsed. Because of this, a time of 0 msec should be read as 20 msec. This correction applies to all drop-to-shock delay times presented in the graphs of these results unless it is specifically noted that an adjustment for the 20 msec delay has been included in that graph.

The response in the top trace of Figure 3 is the control H-reflex response that was obtained approximately 3 to 5 sec prior to the actual drop. The second trace shows the test H-reflex in response to the drop. In this case the test shock was delivered at 70 msec with the drop (an unadjusted drop-to-shock delay of 50 msec). Note the large potentiation of the H-reflex, with no change apparent in the M-wave response, as a function of the drop. The third trace represents the EMG data obtained from the gastronemius muscles of the right leg. The fourth trace is the vertical position of the eye in response to the drop. The fifth trace from the top represents Z axis acceleration, and the bottom trace is a blank channel with no data recorded. Landing time relative to the release of the subject at 0 msec is indicated by the vertical dashed line at 147 msec.

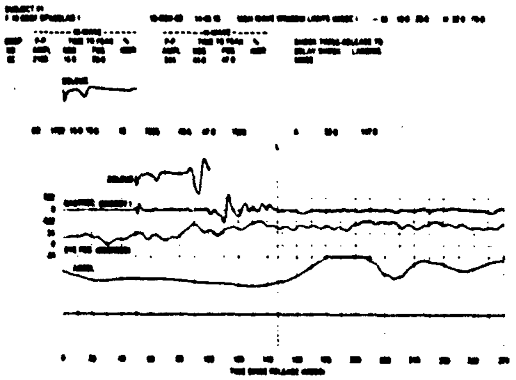


Figure 3

Figure 4 is a typical drop-to-shock response curve showing the potentiation of the H-reflex as a function of delay time. The variability (Standard Error of the Mean) indicated on this graph is representive of the typical variance associated with data collected with this method. Each data point that represents a shock-to-drop delay time is the average response of 20 H-reflex responses obtained over five preflight test days from one subject with four responses recorded during each day. Note that potentiation of the H-reflex begins between 40 and 50 msec (20 msec adjustment) and reaches a maximum peak value at 80 msec. The percent change on the Y axis represents a difference percentage where the test H-reflex response is a difference of the average (N=160) control response:

$$\% \text{ Change From Average Control Response} = \frac{\overline{HT} - \overline{HC}}{\overline{HC}} \times 100$$

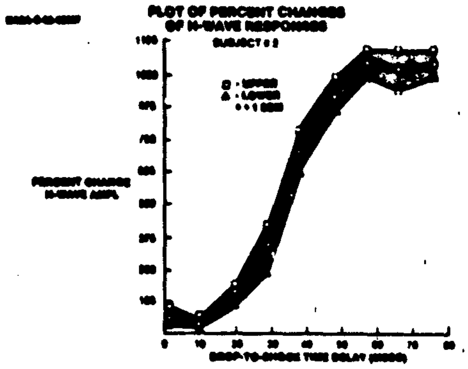


Figure 4

Figure 5 represents a preflight summary of the four crewmen tested. Again each drop-to-shock delay point represents an average of 20 H-reflex responses for each of the four subjects. This family of curves shows that there were considerable preflight differences in the motoneurone pool excitibility for each of the crewmen tested. The maximum response from subject D was less than 300% change in H-reflex amplitude over control values, while that for subject A was as high as 1100%. This difference in magnitude was correlated with inflight motion sickness susceptibility (see below).

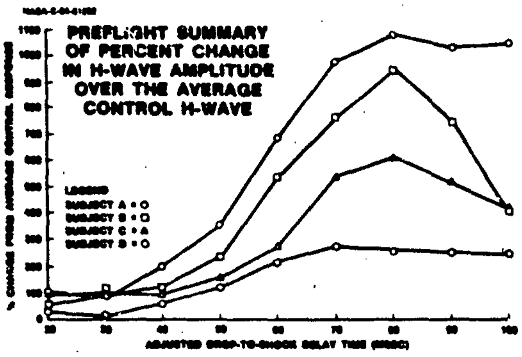


Figure 5

[illegible]light, Inflight and Postflight H-Reflex Summary

Figures 6, 7, 8 and 9 represent the summary of H-reflex amplitude changes for each of the four crewmen as a function of drop-to-shock delay and test day. Figure 6 shows preflight, inflight and postflight response curves for subject A. This is a complete family of curves with two inflight measurements. Figure 7 presents the data for subject B and includes only one inflight measurement (MET-06). The crewmen (subjects C and D) whose data are presented in Figures 8 and 9 include only preflight and postflight measurements.

The data presented in Figure 6 indicate that when the amplitude of the H-reflex (motoneurone pool excitibility) was obtained approximately 24 hours in free fall that the response was about the same as the preflight average. By the seventh day in flight (MET-06) it was clear that a significant change had occurred. The H-reflex no longer showed potentiation to the later drop-to-shock delays as it did preflight. In contrast, the R+0 data (approximately 2.5 hr. after landing) showed a large, three-fold, potentiation of the H-reflex over preflight averages. By R + 1 there was a response decrease indicating a tendency for return to baseline. However, the data for R+2 showed a rebound with a maximum potentiation above R+1 and R+0. This rebound continued on R+4 and R+6 with approximately a four-fold change in amplitude over the preflight maximum. No additional data were collected for subject A following the R+6 test. A return to baseline is assumed based on the data obtained from subject B (see below).

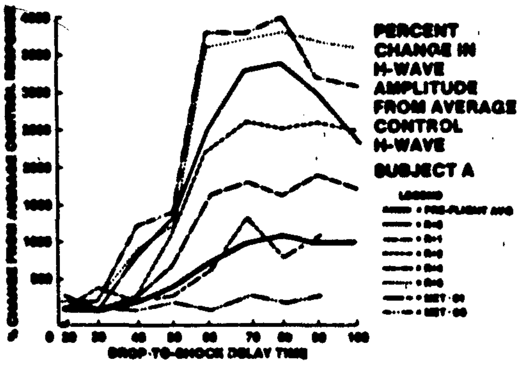


Figure 6

The H-reflex data for subject B are presented in Figure 7. The solid line represents the preflight average percent change in H-reflex amplitude over the control responses as a function of the drop-to-shock delay. Inflight, H-reflex amplitude changes obtained on day seven (MET-06) of the flight are equivalent to those obtained from subject A. That is, the H-reflex does not show potentiation as a function of drop-to-shock delay. Postflight, on R+0 there was a significant change in peak H-reflex amplitude going from 900% to approximately 1900%. On R+1 the maximum amplitude had dropped below the R+0 value to 1700%. As with subject A, there was a rebound on R+2 and R+4 which resulted in peak amplitudes near those obtained on R+0. By R+6 subject B was showing a tendency to return to baseline values with a maximum drop-to shock amplitude of approximately 1300% over the average control response for that day. Subject B was again tested on R+120, and showed responses equivalent to the preflight values (not indicated on Figure 7). Because of the long interval between R+6 and R+120 it cannot be determined when the return to baseline actually occurred.

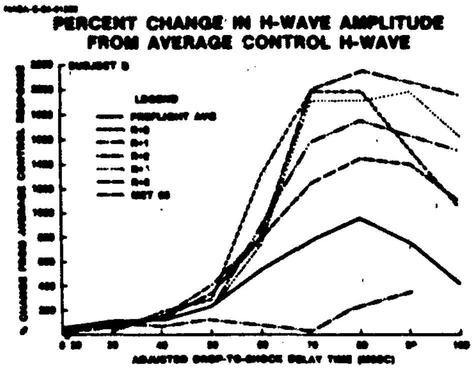


Figure 7

As indicated above, subjects C and D were not tested inflight, or postflight on R+0. Figure 8 shows the data for Subject C. The H-reflex amplitude shows a potentiation of approximately 800% over control values for R+1 and R+2. This is an increase of about 200% to 300% above the preflight value. By R+4 subject C had returned to baseline. Subject D (Figure 9) showed little change on R+1 from preflight, and quickly returned to baseline by R+2.

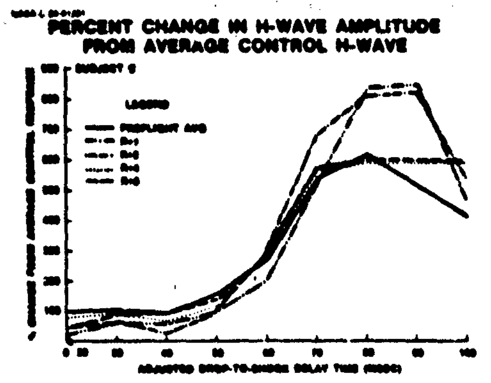


Figure 8

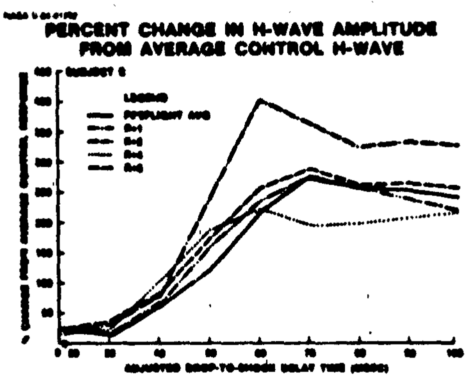


Figure 9

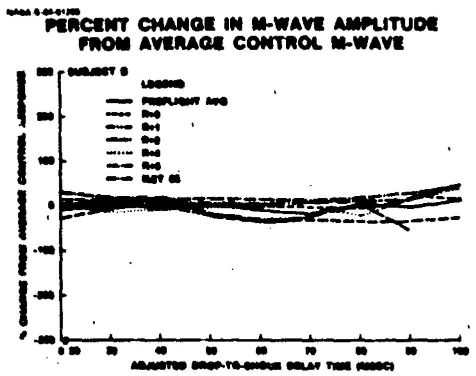


Figure 10

Figure 10 shows the percent change in M-wave amplitude from the average control M-wave for one subject (B) as it was measured preflight, inflight and postflight. Note that there is no real change in amplitude as a function of drop-to-shock delay for any of these test periods. These data indicate that the amplitude changes observed in the H-reflex reflect the excitibility of the motoneurone pool, and not local effects in the reflex arc or artifact. The curves in Figure 10 are representative of the M-wave data obtained for subjects A, B and C. It was very difficult to elicit a recordable M-wave from subject D with electric currents set to obtain the 50% maximum H-wave amplitude required for testing. However, a stable M-wave for subject D was verified by using supramaximal shocks.

Gastrocnemius EMG Activity

Presented in Table II are the latency of the EMG activity relative to the start of the drop (adjusted for the 20 msec delay), and the RMS amplitude of that activity taken from 70 msec to 170 msec into the drop. There is some question about the data on R + 0 for subject B. In the analog output there was evidence of amplifier saturation with a long time constant, which tended to increase the RMS amplitude value. Based on data from the remaining three subjects who showed little change on R+0 relative to the other test days, we suspect that the higher amplitude recorded for Subject B does not indicate an increased motoneurone pool activity. Note that the standard deviations for all measurements are high.

TABLE II

GASTROCNEMIUS EMG ACTIVITY

SUBJECT	TEST DAY	LATENCY	RMS APLITUDE
A	F-151	90.9(4.0)	164(40)
	F-121	92.2(4.3)	193(50)
	F-65	96.8(4.9)	257(58)
	F-44	100.0(4.1)	232(59)
	F-10	96.0(5.5)	259(66)
	F-All	95.1	221
	R+0	93.3(3.2)	217(64)
	R+1	94.2(3.7)	252(62)
	R+2	96.2(4.6)	218(59)
	R+4	93.9(3.6)	228(60)
	R+6	91.1(5.6)	268(74)
	R+All	93.8	237
B	F-151	92.4(9.1)	127(37)
	F-121	93.7(5.6)	207(72)
	F-65	91.0(3.6)	212(53)
	F-44	96.7(5.4)	210(41)
	F-10	95.6(5.4)	176(36)
	F-All	93.9	187
	R+0	94.2(6.2)	327(129)
	R+1	99.8(3.6)	175(50)
	R+2	97.4(5.3)	125(49)
	R+4	96.6(5.1)	131(51)
	R+6	97.1(5.0)	103(31)
	R+All	97.0	172
C	F-151	94.8(5.6)	198(63)
	F-121	94.2(5.5)	199(76)
	F-65	91.8(4.5)	333(95)
	F-44	95.2(4.4)	273(100)
	F-10	96.2(3.2)	182(46)
	F-All	94.4	237
	R+1	97.1(3.6)	149(68)
	R+2	93.7(4.4)	105(23)
	R+4	91.9(3.8)	195(56)
	R+6	92.3(3.3)	438(96)
	R+All	93.8	222
D	F-151	93.4(5.4)	351(53)
	F-121	93.8(4.2)	405(62)
	F-65	92.4(5.0)	376(42)
	F-44	90.3(6.9)	312(38)
	F-10	92.8(8.1)	352(57)
	F-All	92.5	359
	R+1	90.2(4.8)	397(66)
	R+2	89.9(5.4)	321(45)
	R+4	90.9(5.7)	289(47)
	R+6	88.8(5.3)	365(49)
	R+All	89.9	343

Vertical Eye Movement

The vertical eye movement recorded in response to the sudden fall was ballistic in nature. No visual tracking was apparent in the data. Both latency and velocity measurements showed no change from preflight to postflight tests. Varability of these data were similar to those observed with the EMG data.

Body Position

Using the body angles as defined in Figure 2, the drop position of the subject's falling body was plotted as the stick figures in Figure 11. This figure is a graphic representation of Subject's A fall on F-10 which showed very little change in limb position or head position as a function of the drop. This figure is representive of all subjects tested. Figure 12 plots head and limb angles from the stick figures as a dynamic percent change (the angle at 0 msec is compared with the angle at 10 msec, and the angle at 10 msec with that at 20 msec, etc.), and Figure 13 is a plot of absolute angle change (all angles are compared to that at 0 msec). Note that there is relatively little or no change in position during the fall. When these data are compared with these in Figure 14, it is apparent that the falls following the flight were no different than those preflight for a period of 220 msec.

However, Figures 15 shows a plot of stick figures for a longer duration, and compares preflight and postflight fall. In this case the analysis was continued for 1 sec after release of the subject and each stick figure represents a 50 msec increment. The landing occurred at approximately 200 msec after start of the fall. Note that preflight the subject appears to be stable and maintains balance after landing. Postflight, the subject show considerable change in posture and balance. Following the landing, the subject begins to fall backwards and hops off of the floor raising the knees. Without aid, the subject would have fallen. Data from this one subject is representive of that obtained from all four subjects. Instability after the landing for all subjects was evident until approximately R + 4.

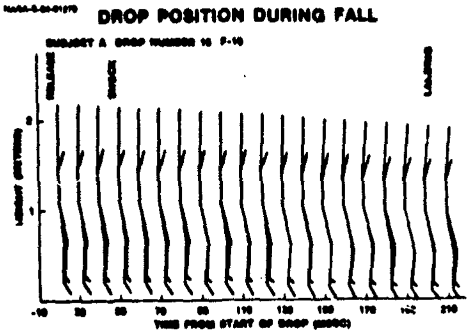


Figure 11

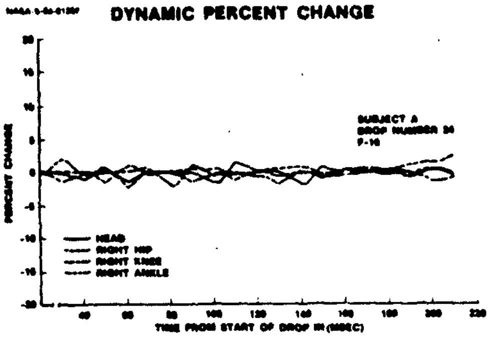


Figure 12

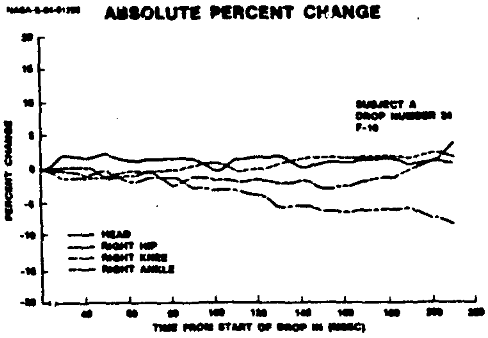


Figure 13

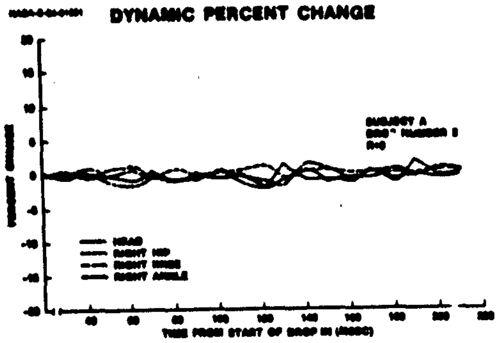


Figure 14

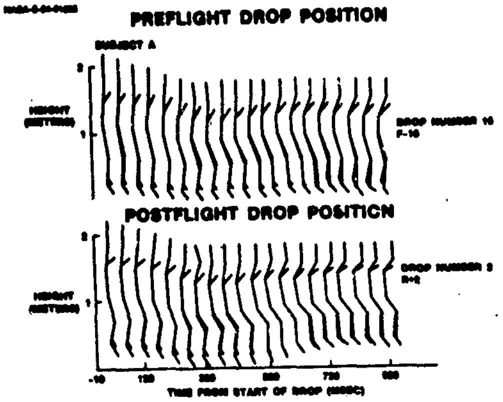


Figure 15

Perceived Motion and Sensations

When questioned about their sensation to the sudden drop inflight, the two subjects tested reported that on day seven (MET-06) the drop did not feel as though they were falling when compared to that experienced on the ground, or with those drops on flight day two (MET-01). By MET-06 the sensation was as if "being shot out of a cannon", or "very abrupt and unpleasant"and "they (the drops) were a surprise when it happened." The subjects also reported that the landings on MET-06 were very hard, and that they were not prepared when the landing did occur. This was confirmed from video tapes taken of the inflight drops. It frequently appeared as though the crewmen did not know where their feet or legs were, and were unprepared to land. One subject "fell" (failed to maintain his balance) several times during the MET-06 drops.
The postflight drops on R+0 and R+1 were reported by the crewmen tested inflight to be similar to the inflight drops on MET-06. That is, the fall was hard, abrupt and the landing was a surprise. All crewmen reported that postflight the sensation was not a fall, but that the floor came up to meet their feet. These sensations continued through testing on R+2 and R+4.

Space Motion Sickness and the H-reflex

The degree and severity of space motion sickness experienced by the four crewmembers who participated in this experiment was monitored as part of another experiment (17), and in a less controlled fashion by our experiment and mission operations. A brief summary of the results indicated that three of the four subjects experienced frank sickness (vomiting) more than once during the first three days of the flight. The fourth crewmember was asymptomatic. All crewmembers did take antimotion sickness medication. When ranked (by our experiment) for severity of symptoms experienced during flight we found symptom strength to be greatest in subjects A and B, and least in subject C. This rank order was then compared with the peak H-reflex drop-to-shock preflight average for each crewman and with the postflight H-reflex curves. The results show that subjects A and B (stronger symptoms) both had the greater H-reflex potentiation preflight and postflight. Subject C, ranked third, had less preflight H-reflex potentiation, and postflight changes quickly returned to baseline. Subject D, who was asymptomatic had a very low H-reflex potentiation preflight when compared with subjects A, B and C, and showed no change postflight over his preflight H-reflex maximum drop-to-shock amplitude.

EXPERIMENT II:

PREFLIGHT AND POSTFLIGHT VESTIBULO-OCULAR RESPONSE AND SELF-MOTION PERCEPTION

This study addressed changes in otolith receptor responses during space flight. Possible effects of prolonged weightlessness on spatial orientation system (18) responses have been the subject of numerous discussions during the past two decades (see ref 19). Some have focused on the consequences of altered stimulation of the otolith receptors while others have suggested changes in the "gains" assigned by the brain to orientation information from visual, vestibular and somatic receptors (20, 21, 18).

The vestibular otolith receptors respond to linear motion and gravity. If motion cues from visual and skin receptors are reduced or eliminated, responses to roll and linear translation attributable primarily to the otolith receptors can be examined. The Miami University parallel swing and its associated restraint system allow this to be done.

This investigation examined two types of responses associated with roll and linear translation stimulation: perceived self-motion path and eye movements. These responses were examined before and after orbital flight. Because the otoliths are gravity receptors, it was hypothesized that removal of stimulation due to gravity during flight would alter responses to which the otoliths contribute.

Both perceptual and motor responses associated with the vestibular receptors adapt to rearrangements of either vestibular or visual stimulation. Rearrangements that have been investigated previously included ocean travel, slow rotation, image reversing glasses and weightlessness (22-25). (This adaptation phenomenon accounts for the observation that motion sickness symtoms resolve during the initial 48 to 72 hours of orbital flight.) Return to a "normal" stimulus environment following prolonged exposure to rearranged stimulation is associated with a period of readaptation. Responses seen during readaptation suggest mechanisms of response change during the initial adaptation to the rearrangement (e.g., consider complementary color after-images).

After preliminary observations (19), an "otolith tilt-translation reinterpretation hypothesis" was proposed. On earth, information from the otolith receptors is used by the brain to signal linear motion or head/body tilt with respect to gravity. The brain adapts to weightlessness by reinterpreting all otolith receptor output as linear motion (because tilt interpretations are meaningless during space flights (see Figure 16). Immediately following return to earth and before the brain readapts to the normal gravity environment, the interpretation that otolith signals indicate linear motion persists.

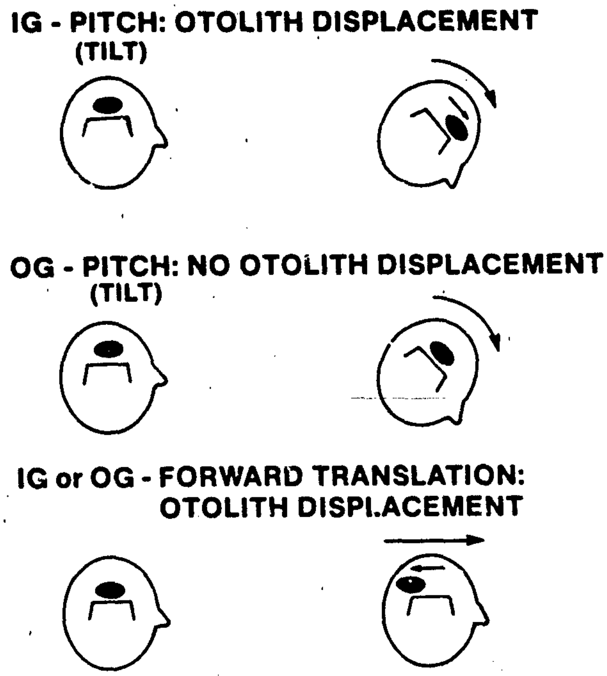


Figure 16

Following this otolith tilt-translation reinterpretation hypothesis we predicted that roll stimulation would produce roll self-motion perception preflight, but that this stimulation would be associated primarily with linear translation self-motion perception immediately postflight. We predicted also that horizontal eye movements during roll motion would be greater, and that ocular counterrolling would be reduced immediately postflight relative to the preflight and later postflight observations. If the free-fall-adapted brain interprets otolith signals as indicating translation, the appropriate compensatory eye movement during roll would be rotation in the horizontal plane.

METHOD: EXPERIMENT II

Three astronauts participated in this experiment. One was from the STS-8 flight and two were from the STS-11 mission. As described below, these three crewmen were asked to described their perceived self-motion path. Only two participated in the vestibulo-ocular measurement phase of the investigation (STS-11).

Perceived Self-Motion Path

Linear aceleration was provided by using the Miami University Parallel Swing. The swing is a four-pole pendulum which produced "linear" (translation) oscillation at 0.26 Hz. For translation, the swing was moved manually by the experimenter. The swing restraint system included an aluminum cylinder which was connected to a motor drive and could be rolled at amplitudes up to +/- 20° and frequencies between 0.1 and 0.5 Hz. Objective measures of translation and roll motion were provided by appropriate transducers.

The subject was restrained inside of a styrofoam body mold and incased in the aluminum cylinder. Head restraint was provided by ear pads and a bite board. The subject was placed in the restraint in the prone position and his head was dorsal-flexed about 50 deg. A cloth shroud enclosed the head-end of the cylinder and eliminated motion cues from light and air currents.

Responses to three motion stimuli were obtained. These were linear translation at 100 cm/sec/sec, roll at +/- 5 deg, and phase-locked, combined roll and linear motion. Translation was in the direction of the subject's Y axis. Roll motion was around the subject's Z body axis (X head axis). For both types of motion, the oscillation frequency was 0.26 Hz.

Three cycles of each type of motion stimulus were presented. The subject's reports consisted of drawings and verbal reports of his perceived self-motion path.

Vestibulo-Ocular Response

The apparatus was the same as that used in the self-motion perception study with the addition of eye movement recording capability. Eye movements were recorded using an experimental RCA video camera. The peak sensitivity of the camera was 890 nm. The subject's left eye was focused with the aid of extender rings. The light source was an array of 12, 100-mw infrared-emmitting diodes mounted on the camera lense. The camera output was recorded on one-half inch tape with a VHS system.

Eye movements were recorded during roll (+/- 15 deg) and Y axis linear translation oscillation (200 cm/sec/sec). The oscillation frequency was 0.26 Hz. The goal was to record during five consecutive cycles of movement.

RESULTS: EXPERIMENT II

Perceived Self-Motion Path

Drawings indicating perception of self-motion path during roll are illustrated in Figure 17. Preflight, the three astronauts reported that cylinder roll produced nearly pure roll self-motion perception, which they illustrated by drawing a "U" shape with arrows at the ends, and that linear translation oscillation was perceived as nearly pure linear self motion. Immediately postflight, roll stimulation was perceived as translation self motion with a small angular motion component. Their verbal reports corresponded to the drawings.

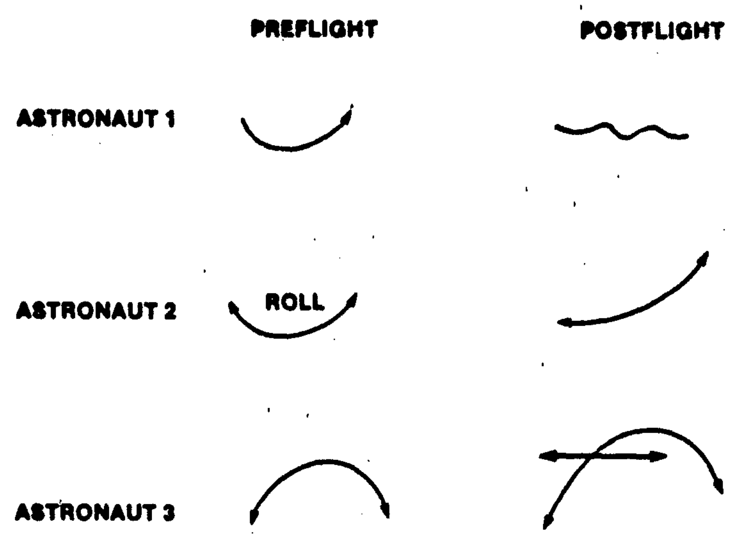
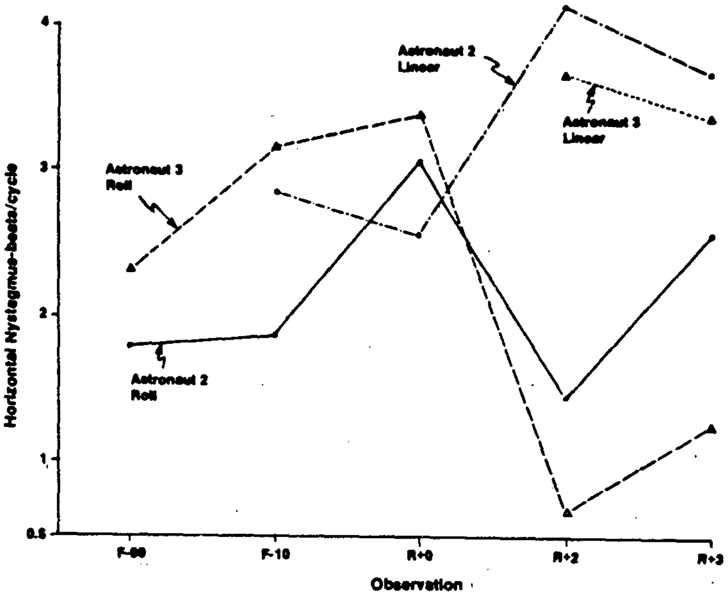


Figure 17

Vestibulo-Ocular Responses

Analysable data during roll oscillation were obtained from both observers on F-60 and F-7 days prior to flight, between R+70 and R+150 min following landing and on R+2 and R+3 days after landing. Fewer usable data were obtained during linear translation. Quantitative analysis of the video tape records focused on the horizontal eye movements. The average number of horizontal nystagmus beats per cycle of roll or translation stimulation for both observers is illustrated in Figure 18. Horizontal nystagmus during roll stimulation was greater immediately postflight than on R+2 or R+3 or preflight. The data suggest depression of horizontal eye movements during roll on R+2 after landing and some rebound on R+3. The data obtained during translation stimulation suggest enhancement of the horizontal eye movement response on the second and third days after landing.



Qualitatively, the recording during roll from Astronaut 2 immediately postflight appears different from the other recordings. This record shows the "classic" phase-reversing horizontal nystagmus seen ordinarily during oscillation around the Z head axis.

Eye movements were difficult to assess because of the movement of the astronaut's head in the restraint relative to the camera, poor image quality and the inability of the observers to maintain eye fixation.

The video tape records indicate a clear ocular counterrolling in Astronaut 3 during roll stimulation. The counterrolling was observable at +150 min after landing as well as preflight and on the second and third days after landing. Because of the poor image quality, no attempt has been made to analyse these data quantitatively.

DISCUSSION

Otolith Reinterpretation

We postulate that exposure to prolonged free fall is a form of sensory-motor rearrangement. We hypothesize that adaptation to this rearrangement results in reinterpretation by the brain the otolith input rather than reduction of otolith sensitivity. This reinterpretation is required for structured and meaningful interaction with and reaction to the altered environment.

Melvill Jones (20) may have been the first to note that adaptive changes during orbital flight could leave the brain temporarily unresponsive to otolith stimulation by the steady "g" vector. Young, Oman and their colleagues (21, 17) suggested "otolith reinterpretation" as one of several possible consequences of prolonged weightlessness which they examined in the MIT-Canadian Spacelab 1 experiments.

Experiment 1

Data from the vestibulo-spinal experiment support the otolith reinterpretation hypotheses. Under normal gravity conditions, sudden free fall elicits an otolith-spinal reflex if the body's Z axis is parrallel to the gravity acting on the body mass and are in the direction of the gravity vector. This reflex response preparesthe body for the impact deceleration of landing following the fall.

During space flight a fall, defined as linear translation parallel to gravity, is meaningless because gravity is absent. (The "drops" produced on orbit by our aparatus were linear translations but were not falls.) Consequently the adaptive brain learns to interpret all otolith signals as indicating linear translation not as falls, and reflex responses ordinarily elicited by falls are lost.

Perceptual and physiological data from Experiment I support this hypothesis. During space flight before adaptation, sudden drops were perceived as falls, but following adaptation the drops were perceived as linear translations. The crewmen reported that drops early in the flight felt much as they did preflight. The H-reflex changes associated with these drops also were similar to those obtained preflight. Later in the flight the drops perceived as sudden, fast and hard. The crewmen were not aware of where their legs and feet were and exhibited difficulties in maintaining "balance" following "landing." Late in flight the H-reflex was not potentiated by the drops.

Otolith reinterpretation also was supported by the postflight perceptual responses. The drops postflight were perceived just as they were at MET-06 inflight. That is, the crewmen were unaware of where their feet were and the drops were perceived as sudden. They did not feel as though they were falling; rather, "the floor came up to meet them."

Evidence for otolith reinterpretation was not seen in the postflight physiological response data. We suggest that the H-reflex would not have been potentiated by drops immediately after landing and that reflex would not have been potentiated by drops immediately after landing and tnat reflex readaptation had occured prior to our first postflight observations. Apprently some reflex responses readapt to normal gravity very rapidly.

The H-reflex responses reported here were modified by prolonged free fall, whereas the direct vestibulo-spinal responses recorded by Watt (17) apparently did not change as a consequence of this environmental alteration. We suggest that the apparent conflict between the two sets of data might be resolved as follows. Watt's direct vestibulo-spinal response may reflect primarily changes in otolith sensitivity, whereas our drop-moduated H-reflex may reflect primarily indirect excitatory and inhibitory influences from the brain stem vestibular nuclei. Several observations are consistent with the view that otolith sensitivity does not changes in the direct vestibulo-spinal response would be expected. On the other hand, our indirect H-reflex responses would reflect plastic changes in the vestibulo-spinal nuclei associated with otolith reinterpretation; therefore, changes during prolonged space flight in the drop-modulated

Experiment II

Postflight reports of self motion during roll stimulation indicate that the subjects perceived a complex motion composed of both linear and angular motion. Also, the eye movement recordings indicated that both horizontal rotation and ocular counterrolling were present within the 150-min period after landing. These results are interpreted as follows. As above, following retrun to the normal-gravity encironment, the brain appears to persist in interpreting any change in otolith signal as linear motion. Therefore, the otolith response change produced by roll (tilt) was perceived as linear motion and elicited horizontal eyeball rotation. Because oscillatory roll also stimulates the semicircular canals, the motion path was perceived as a combination of roll and translation and ocular counterrolling was present.

Adaptation to weightlessness could take place at cortical or subcortical levels. The observations that both perceptual and eye-movement reflex responses during roll stimulation were altered following prolonged space flight suggests that adaptation took place at the brain-stem level.

Other Spacelab 1 Observations

Results from four other Spacelab 1 observations are congruent with those reported here. Immediately postflight the Spacelab 1 crewmembers exhibited decreased postural stability with their eyes closed, increased reliance on visual cues for orientation and improved ability to null lateral linear motion in the "closed loop otolith nulling task" (17). One of us (BKL) noted that the "rooftop illusion" ordinarily experienced during translation on the U. S. Lab Sled was absent during the immediate postflight period. These observations led Young et al (17) to propose an hypothesis nearly identical to the one developed independently by us following the STS-8 mission (19, 26).

Space Motion Sickness

Motion sickness is among the problems associated with space flight. A substantial body of evidence suggests that this problem may be related to alteration of vestibular responses following prolonged weightlessness (22, 23).

Sensory conflict appears to be the basic mechanism whereby space motion sickness is produced (23). During the initial period of exposure to weightlessness, signals from the otolith receptors would conflict with those from the semicircular canals would indicate that the expected head motion had occured; however, an appropriate signal from the otolith receptor response during prolonged weightlessness also could be related to disorientation following return to a normal gravity environment.

Many astronauts have reported that pitch head motions during the initial period of orbital flight evoke motion sickness symptoms (24, 25). These reports provide additional support for the sensory conflict approach to space motion sickness as well as for an otolith reinterpretation hypothesis.

The results from Experiments I and II support the hypothesis that space motion sickness is related to otolith activity. Because of the small number of subjects and limitations of the data, proposal of procedures for predicting space motion sickness incidence and severity is not possible at this time. Further standardized investigation is required.

Certainly the data from the space experiments conducted to date are not ideal and firm conclusions based on observations from the several directions appears to support an otolith reinterpretation hypothesis.

NOTES

The experiment in this paper dealing with vestibulo-spinal reflexes has been targeted for publication in Experimental Brain Research, and if accepted will appear sometime in 1985. The Vestibulo-ocular and self-motion experiment has been submitted to Aviation Space and Environmental Medicine for publication later this year.

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DISCUSSION

KLEIN, FRG

As cause for the space motion sickness there is only the sensory conflict mentioned. What could be the contribution of fluid redistribution with the consequence of the "puffy face" to the symptomatology of space motion sickness?

AUTHOR'S (PARKER) reply

In our paper, we have described a major class of sensory conflict associated with weightlessness as well as evidence for a neural response - otolith reinterpretation - to that conflict. It is well known, that analogous sensory conflicts on earth elicit motion sickness from a large proportion of subjects. Consequently, it seems likely that sensory conflict associated with discordant signals from the otolith receptors and other spatial orientation receptors is the primary course of space motion sickness.

Parker et al (Aviation Space and Environmental Medicine, 1983) have reviewed possible mechanisms whereby fluid shifts might produce space motion sickness. One of these is associated with possible biomechanical changes in the labyrinth which would result in sensory conflict as a consequence of altered semicircular canal activity. A second mechanism involves changes in angiotensin levels that could affect the chemoreceptor trigger zone directly.

However, as reported by Lackner and Graybiel, there is no evidence for increased motion sickness susceptibility following prolonged head-down tilt on earth. I submit that the primary cause of space motion sickness is the sensory conflict produced by the discordant otolith input. If there are effects associated with fluid shifts, I suggest that they are, at most, tertiary.

TERZIOGLU, TU

Which basic mechanisms are involved in the reinterpretation by the brain of otolith sensitivity? I think this hypothesis should be investigated by animal experimentation.

AUTHOR'S (PARKER) reply

This is a very interesting question, and your suggestion that animal experiments be pursued seems to be quite appropriate.

We postulate that weightlessness produces a form of sensory rearrangement and that otolith reinterpretation is a response by the central nervous system to this rearrangement. If this postulate is correct, then the results of research on other types of sensory rearrangements should give us clues regarding the basic mechanisms underlying otolith reinterpretation.

Adaptation to sensory rearrangement (discordant stimulation) has been investigated and discussed for over hundred years, starting with scientists such as von Helmholtz in Germany and Stratton in the United States. I.P. Howard (Human Visual Orientation, John Wiley & Sons, 1982) recently reviewed the literature on sensory rearrangement and concluded that during the adaptation process neural changes occur at different levels and different times in the brain. Changes appear to occur initially at "higher" levels and to consolidate at "lower" levels after the adaptation process is complete.

A class of research that may give us specific clues concerning the basic mechanisms of otolith reinterpretation relates to investigation of vestibular-ocular reflex (VOR) adaptation. The site of VOR adaptation is the subject of vigorous research and debate among vestibular neurophysiologists (see Wilson and Melvill-Jones, Mamalian Vestibular Physiology, Plenum Press, 1979). Recent research by Oman at al. (Science, 1980), which demonstrated that self-motion perception adapted to prism-produced visual field reversal before eye movement reflexes, is congruent with Howard's view that adaptation may occur at different levels in the brain.

Finally I suggest, that reliable physiological and behavioral observations are

AJUSTEMENTS POSTURAUX ASSOCIES AU MOUVEMENT DU BRAS EN APESANTEUR

par F. Lestienne et G. Clément

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RESUME

L'adaptation des ajustements posturaux liés à la mobilisation volontaire du bras a été étudiée chez deux sujets au cours d'un vol spatial de sept jours.

En apesanteur, on observe une redistribution des activités électromyographiques entre muscles fléchisseurs et extenseurs de la cheville. L'analyse des données cinématographiques montre une inclinaison importante du corps vers l'avant au début du vol, suivie d'un retour progressif à une position identique à celle observée en situation de gravité terrestre.

Ces résultats sont interprétés selon l'existence d'un schéma corporel.

INTRODUCTION

Cette étude entre dans le cadre d'une recherche fondamentale sur les interactions sensori-motrices liées au contrôle postural. Cette expérience a pour but l'étude de la réorganisation de ces interactions au cours d'un séjour de courte durée (7 jours) de l'homme en situation d'apesanteur (Clément et Lestienne 1981).

Le contrôle de la stabilité du corps est une fonction très complexe pour l'homme. En effet, le centre de gravité du corps est placé très haut par rapport à un polygone de sustentation très étroit. Par ailleurs, l'ensemble des articulations entraîne la présence d'un nombre important de degrés de liberté.

La stabilisation du corps en position debout dans un champ de gravité nécessite une activité musculaire antigravitaire et un équilibre dynamique. Ces deux mécanismes sont sous la dépendance du système nerveux central (SNC) qui contrôle l'activité des muscles croisant chaque articulation. Le contrôle de ces effecteurs est assuré par la présence de récepteurs proprioceptifs, comprenant les récepteurs fusoriaux et tendineux, les récepteurs articulaires et les récepteurs tactiles qui informent le SNC sur la position relative de chaque segment par rapport à des référentiels intra et extra corporels (Droulez et Lestienne 1981, Matthews 1972). L'appareil vestibulaire de l'oreille interne possède des organes sensibles à l'accélération lui permettant de détecter des changements de position du corps (Wilson et Melvill Jones 1979). Enfin la vision, et surtout la vision périphérique, joue un rôle important dans le contrôle de la posture en informant le SNC sur les déplacements du monde visuel par rapport au sujet (Lestienne et al. 1977, Dichgans et Brandt 1978, Berthoz et al. 1979). Ainsi, chaque mouvement du corps est la source d'un processus complexe d'intégration et de traitement d'informations qui parviennent au SNC.

La mobilisation active d'un membre (par exemple l'élévation d'un bras) met en jeu des forces de réaction qui déstabilisent le corps. Les messages sensoriels des récepteurs décrits ci-dessus informent le SNC qui déclenche, au niveau des muscles impliqués dans le contrôle de l'équilibre, les ordres moteurs appropriés pour lutter contre cette déstabilisation. Des études en laboratoire, en condition de gravité terrestre, ont montré que ces "programmes" moteurs schématiquement sous tendent deux catégories d'ajustements posturaux : ajustements anticipés et ajustements réactionnels. Les ajustements posturaux anticipés correspondent à une "préparation" au mouvement, tandis que les ajustements réactionnels peuvent être assimilés à des "corrections" posturales résultant d'une perturbation (Belenkii et al. 1967, Cordo et Nashner 1982).

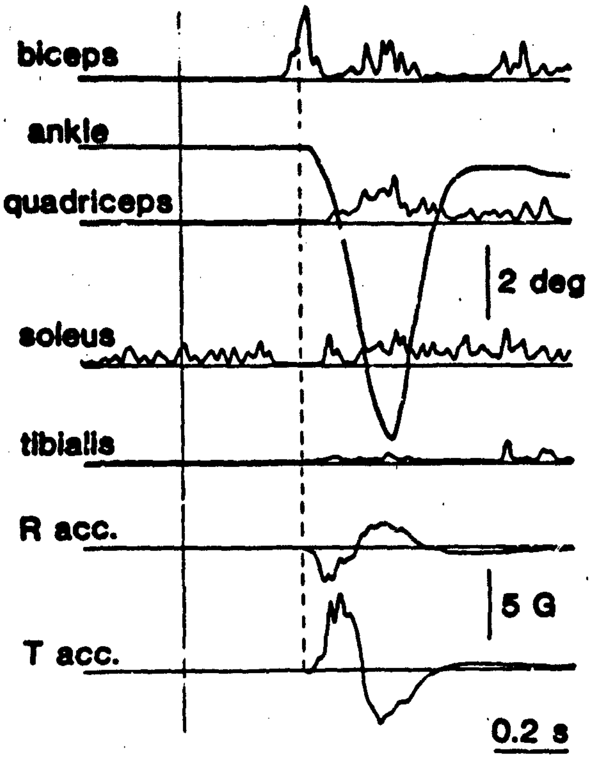

Figure 1 : activité EMG et paramètres biomecaniques enregistrés en laboratoire chez un sujet au cours d'un mouvement du bras en vision normale. Le trait vertical continu représente l'instant d'apparition du top sonore.

La figure 1 montre les modifications de l'activité électromyographique (EMG) de 4 muscles de la jambe (Biceps femoris, Quadriceps, Soleus, Tibialis anterior) et les paramètres biomécaniques (angulation de la cheville et accélération du bras) observés lors d'un mouvement du bras en condition de vision normale. La désactivation précoce du Soleus et l'activation du Biceps qui précèdent respectivement d'environ 80 ms et 50 ms le départ du bras peuvent être interprétées comme des ajustements posturaux anticipés. Le mouvement d'élévation du bras s'accompagne d'une inclinaison de la cheville vers l'arrière (d'environ 6 degrés) qui commence 30 ms après le départ du bras. L'activation du Quadriceps, contemporaine de cette inclinaison de la cheville, est un exemple d'ajustement postural réactionnel.

Les résultats que nous présentons ici ont été sélectionnés autour de deux thèmes qui nous paraissent fondamentaux :

1) En apesanteur la notion de base de sustentation n'a plus de réalité physique. Par ailleurs dans cette situation il n'est plus possible d'utiliser la composante gravitaire pour compenser en partie les forces inertielles responsables de la perte d'équilibre. Enfin cette situation libère le verrouillage articulaire. Autrement dit, le sujet peut utiliser une gamme très étendue d'angles d'ouverture articulaire. Aussi peut-on s'interroger sur le degré de persistance des programmes moteurs et de l'attitude posturale terrestre.

2) Il est admis que la neutralisation de la gravité affecte le point de fonctionnement de tous les récepteurs sensoriels sauf les récepteurs visuels. Peut-on alors considérer que la situation d'apesanteur est assimilable à une "déafférentation fonctionnelle" ? Dans cette situation les récepteurs visuels auraient une fonction prépondérante tant au niveau des interactions sensori-motrices liées au contrôle postural qu'au niveau des processus d'orientation.

METHODES

Le sujet, les bras le long du corps, est en position érigée, les pieds fixés sur une plateforme. Deux accéléromètres solidaires du poignet mesurent respectivement les accélérations tangentielle et radiale du mouvement d'élévation du bras droit. Un potentiomètre mesure le déplacement angulaire de la cheville. Une caméra filme (32 images/s) le profil du sujet qui porte des points-cibles au niveau de la tête, de l'épaule, du coude, du poignet, de la hanche, du genou et de la jambe. Les activités EMG du Soleus, du Tibialis anterior, du Biceps femoris et du Quadriceps du côté droit sont simultanément enregistrés. Une paire de lunettes permet soit d'occulter totalement la vision soit de rétrécir le champ visuel du sujet (vision centrale ou tubulaire)(Fig.2).

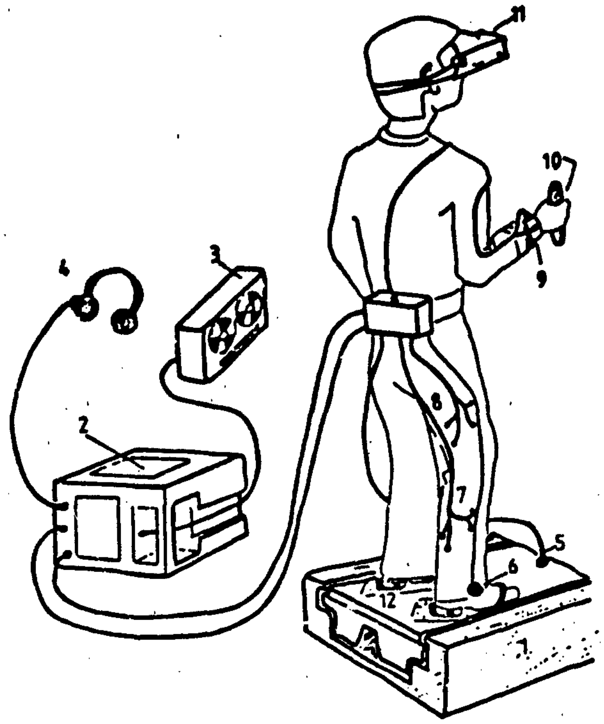

Figure 2 : Dispositif expérimental. 1 Plateforme. 2 Boitier électronique. 3 Enregistreur magnétique. 4 Ecouteurs. 5 Potentiomètre de plateforme. 6 Potentiomètre de cheville. 7 et 8 Capteurs EMG. 9 Accéléromètres de poignet. 10 Lunettes.

Le sujet a pour consigne d'être perpendiculaire par rapport à la plateforme. Un top sonore constitue le signal d'élévation rapide du bras en direction d'une cible placée devant le sujet.

Chaque type de mouvements a été répété 10 fois. Deux sujets ont été utilisés pour l'expérience au cours du vol. Jean-Loup Chrétien (JLC), qui n'avait jamais séjourné en apesanteur, a réalisé l'expérience le 2e, 3e et 7e jour du vol spatial (respectivement le 1er, 2e et 6e jour d'orbite à bord de la station spatiale). Vladimir Djanibékov (VD), qui avait déja participé a deux vols spatiaux de huit jours, a servi de sujet uniquement le 5e jour du vol (4e jour en orbite). Des études systématiques utilisant le même protocole expérimental ont été effectuées au sol 30 jours et 3 jours avant le vol spatial, ainsi que 3 jours après l'atterrissage avec les deux sujets.

RESULTATS

1) Mouvement volontaire d'élévation du bras et activité musculaire posturale.

Les ajustements posturaux consécutifs au mouvement d'élévation du bras au cours du séjour en apesanteur chez les 2 sujets sont illustrés respectivement sur les figures 3 et 4. Les tracés sélectionnés pour chaque jour d'expérience sont des enregistrements représentatifs des 10 mouvements effectués en situation de vision normale et de rigidité forte. Ces tracés représentent l'activité EMG des muscles Biceps femoris, Quadriceps, Soleus et Tibialis, le déplacement de l'angulation de la cheville dans le plan saggital, et les accélérations radiale et tangentielle du bras.

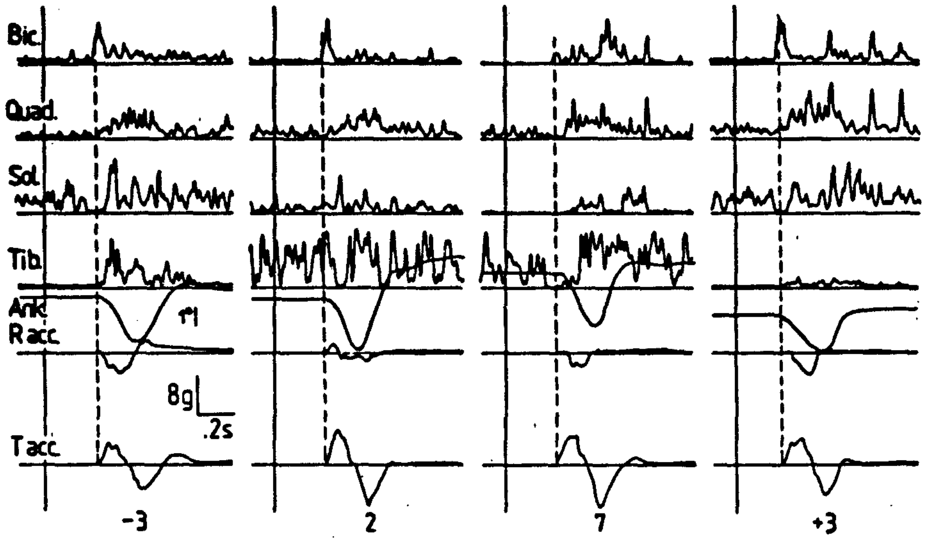

Figure 3 : Activité musculaire liée à l'élévation du bras chez le sujet JLC : 3 jours avant (-3), le 2é jour (2), le 7é jour du vol (7), et 3 jours après le vol (+3).

a) Sujet JLC : l'analyse des enregistrements de la figure 3 fait apparaître les points suivants :

- avant le mouvement du bras, l'activité tonique de repos des muscles croisant l'articulation de la cheville (Soleus et Tibialis) est profondément modifiée au cours du vol. En effet le 2e jour du vol l'activité tonique du Soleus a considérablement diminué par rapport aux données de base, et l'activité tonique du Tibialis est devenue très importante. Les activités musculaires toniques du Biceps et du Quadriceps ne semblent pas être modifiées au début du vol spatial. Le 7e jour du vol, l'activité musculaire tonique de l'ensemble des muscles étudiés a sensiblement diminué par rapport au début du vol.

- lors du mouvement du bras, les programmes moteurs des muscles posturaux sont modifiés au début du vol et évoluent tout au long du séjour en apesanteur. On constate notamment la disparition de la désactivation anticipée du Soleus, désactivation que l'on retrouve au niveau du Tibialis anterior au début du mouvement du bras. La durée de cette désactivation devient plus importante à la fin du vol (jour 7) et se manifeste clairement avant le début du mouvement du bras. La bouffée anticipatrice du Biceps femoris, qui est présente le 2e jour, diminue le 3e jour du vol et disparaît presque totalement le 7e jour du vol.

- le tracé du déplacement de la cheville montre que l'amplitude de la perturbation posturale consécutive au mouvement du bras au cours du vol est peu modifiée par rapport aux données de base. Cependant, le 2e jour du vol il est fréquent que l'articulation ne retourne pas à sa position initiale à la fin du mouvement du bras.

- les enregistrements effectués 3 jours après le vol, sensiblement identiques à ceux des données de base, attestent d'une réadaptation de l'ensemble des paramètres à la situation de gravité terrestre. Il est intéressant de noter que l'on retrouve cependant des bouffées phasiques d'activité EMG qui caractérisaient les enregistrements effectués à la fin du vol spatial.

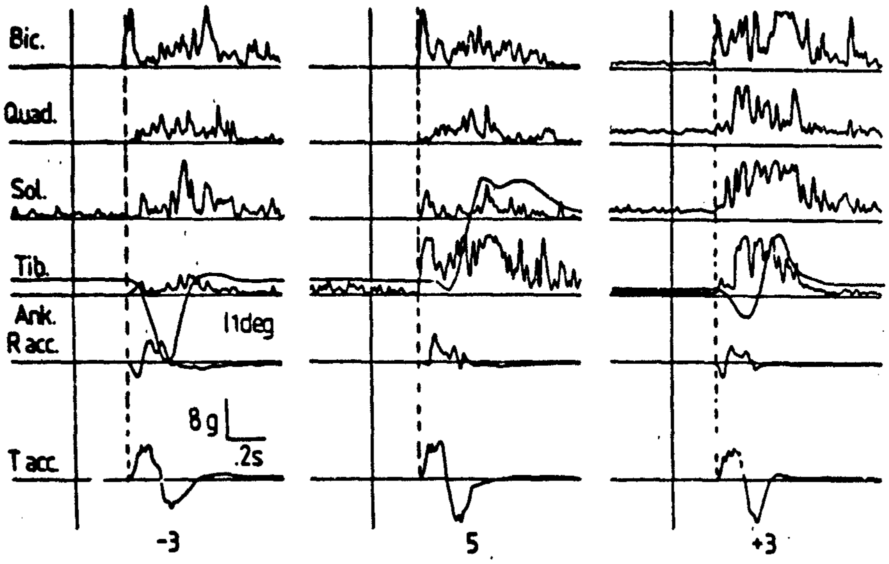

Figure 4 : Activité musculaire liée à l'élévation du bras chez le sujet VD : 3 jours avant (-3), le 5é jour (5), et 3 jours après le vol (+3).

b) sujet VD : les enregistrements de la figure 4 mettent en évidence les points suivants :

- avant le mouvement du bras, l'activité tonique de repos des muscles croisant l'articulation de la cheville est inversée au cours du vol par rapport aux données de base. Le niveau d'activité tonique de ces muscles est moins élevé que chez le sujet JLC : en effet on observe chez le sujet VD aucune activité tonique du Soleus, et une activité tonique faible (puis inexistante en fin d'expérience) du Tibialis avant le mouvement.

- lors du mouvement du bras, les programmes moteurs observés sont peu différents de ceux enregistrés avant le vol, sauf pour le Tibialis qui se désactive environ 50 ms avant le départ du bras et qui présente une forte activité pendant toute la durée du mouvement.

- le déplacement de la cheville indique la présence d'une importante perturbation posturale créée par le mouvement du bras, qui se traduit par une forte inclinaison du corps vers l'avant (environ 6 degrés) durant la 2e phase du mouvement.

- les enregistrements effectués après le vol montrent que cette perturbation est encore présente (inclinaison prononcée du corps vers l'avant précédant le retour à la position initiale) et que les programmes moteurs sont caractérisés par des bouffées phasiques simultanées des quatre muscles étudiés. Il faut néanmoins noter que de tels programmes moteurs ont été parfois observés lors des tests effectués avant le vol.

2) Attitude posturale

Les résultats de l'analyse des données cinématographiques confirment la présence d'une posture initiale différente chez les sujets, comme le suggère la différence entre le niveau d'activité tonique de leurs muscles.

a) sujet JLC : la figure 5 permet de comparer la position relative des différents segments corporels avant et pendant le mouvement du bras. En apesanteur on constate une augmentation de l'inclinaison initiale du corps vers l'avant. Le 2e jour cette inclinaison, sensiblement identique pour tous les segments corporels, est de 13 degrés en moyenne. Il est important de souligner que le sujet était persuadé qu'il respectait la consigne c'est-à-dire : être perpendiculaire par rapport à la plateforme. Le 3e jour du vol on observe un redressement du corps plus important pour la partie inférieure. Cette inclinaison se maintient pendant toute la durée du mouvement. Enfin, en comparant ces données avec celles enregistrées au sol, on n'observe pas de modification de la position des différents segments les uns par rapport aux autres.

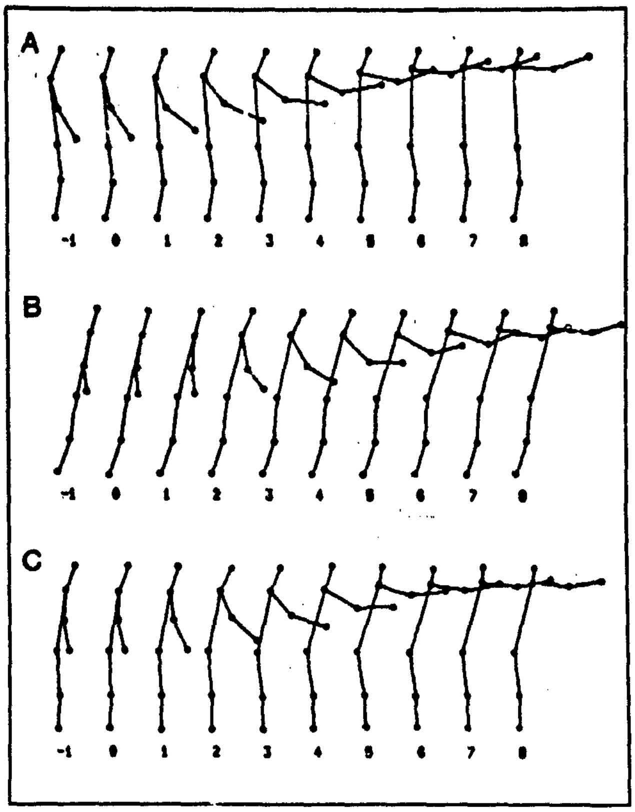

Figure 5 : Reconstitution de la posture du sujet JLC au cours d'un mouvement d'élévation du bras 3 jours avant le vol (-3), le 2é jour (2) et le 3é jour du vol (3).

L'influence de la situation visuelle du sujet (vision normale VN, vision tubulaire VT, vision occultée VO) sur la position initiale et pendant l'élévation du bras est illustrée sur la figure 6. Avant le vol la situation VT provoque une augmentation de l'inclinaison du corps vers l'avant d'environ 2 degrés par rapport à la situation VN. Cette augmentation est identique lorsque le sujet passe de la situation VT à VO (+2 degrés). Le 2e jour du vol nous avons vu que l'inclinaison initiale du corps était très prononcée vers l'avant. Il est cependant intéressant de noter que les situations VT et VO accentuent encore cette inclinaison dans les mêmes proportions que celles enregistrées avant le vol (de 2 à 3 degrés). Le 3e jour du vol la position initiale du sujet en VN est sensiblement perpendiculaire à la plateforme ; la situation VT entraîne une augmentation de l'inclinaison générale du corps de 6 degrés vers l'avant ; la situation VO induit une inclinaison du corps vers l'avant de 12 degrés environ.

Les déplacements de la tête, de la hanche et de la cheville pendant le mouvement du bras montrent peu de différences entre toutes les conditions expérimentales. Cependant, on peut noter que les déplacements de la tête sont les plus importants en apesanteur lorsque le sujet est placé en situation VN.

b) sujet VD : l'analyse des données cinématrographiques montre que le sujet VD a une posture différente de celle du sujet JLC en apesanteur. En effet la posture du sujet VD est caractérisée par une position semi-fléchie de l'ensemble des articulations. L'axe général du corps est légèrement incliné vers l'arrière.

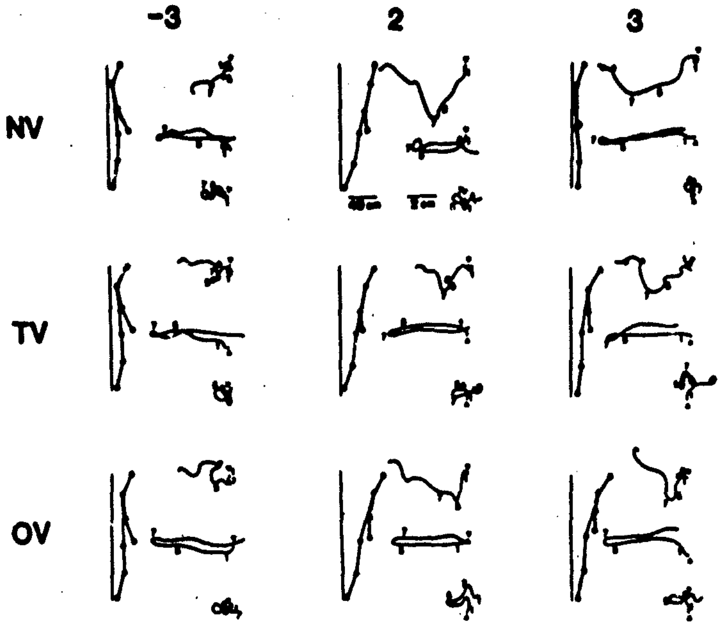

Figure 6 : Reconstitution de la posture initiale et des trajectoires de la téte, de la hanche et de la cheville du sujet JLC en situation de vision normale (NV), de vision tubulaire (TV) et de vision occultée (VO) : 3 jours avant (-3), le 2é jour (2) et le 3é jour du vol (3).

DISCUSSION

Le paradigme expérimental utilisé dans cette expérience permet d'évaluer l'importance fonctionnelle des interactions entre les systèmes sensoriels et moteurs impliqués dans le contrôle postural. Les résultats observés mettent en évidence des modifications de la posture du sujet JLC au début du vol spatial. Ces modifications se traduisent par une forte inclinaison vers l'avant et par la redistribution de l'activité electromyographique des muscles fléchisseurs et extenseurs de la cheville. Plusieurs arguments nous empêchent d'attribuer ces résultats à une désorientation du sujet : la position des différents segments corporels entre eux, l'effet des différentes situations visuelles et l'amplitude du déplacement de la cheville pendant le mouvement du bras sont identiques à ceux observés en situation de gravité terrestre (Gouny et al. 1977). De plus, la reproductibilité de cette inclinaison au cours de tous les essais de chaque segment expérimental effectué le 2e jour va à l'encontre d'une telle interprétation.

Le 3e jour du vol, on constate que le sujet JLC a une posture sensiblement identique à celle observée au sol, uniquement dans la situation de vision normale. L'intégralité des récepteurs visuels est donc nécessaire pour la récupération complète de cette posture le 3e jour du vol. Ces résultats soulignent l'influence des récepteurs visuels dans la recalibration des systèmes sensoriels affectés par la situation d'apesanteur.

La redistribution des activités toniques entre muscles fléchisseurs et extenseurs de la cheville pourrait s'interpréter par un processus lié à une déafférentation otolithique. En effet, la déafférentation des otolithes provoquerait la défacilitation de l'activité des muscles antigravitaires (extenseurs)(Jeannerod, 1981). Cependant, en considérant les contraintes mécaniques mises en jeu par l'apesanteur, cette redistribution de l'activité tonique entre fléchisseur et extenseur pourrait s'expliquer différemment. En effet, dans cette situation, la position erigée exige une activité tonique des muscles extenseurs (Bogdanov et al. 1970). Dans notre situation expérimentale où le sujet a les pieds fixés à un support, les forces élastiques du muscle extenseur de la cheville entrainent une inclinaison passive du corps vers l'arrière. L'activation du Tibialis (le muscle fléchisseur de la cheville) est donc nécessaire pour ramener et maintenir le corps vers l'avant. Cette dernière interprétation est en accord avec nos résultats qui montrent que l'activité tonique du Tibialis est la plus importante le 2e jour du vol lorsque le sujet est fortement incliné vers l'avant. En apesanteur, le sujet VD adopte une posture qui, comparée à celle observée au sol, présente une légère inclinaison vers l'arrière et une fermeture plus importante de l'angle du genou. Cette position ne nécessite pas la mise en jeu d'une activité musculaire importante des fléchisseurs et extenseurs de la cheville. Cette position semi-fléchie très économique sur le plan énergétique, est la mieux adaptée à l'apesanteur (Bogdanov et al. 1970, Thornton et Rummel 1977).

Le transfert des programmes moteurs, et notamment de la désactivation anticipée du muscle qui exerce la fonction de support du corps (les extenseurs en gravité normale, les fléchisseurs en apesanteur) témoigne d'une adaptation rapide de ces programmes à la situation d'apesanteur qui relève d'un "processus opératoire". La question reste posée de savoir si cette brève désactivation a effectivement un rôle dans la stabilisation poturale ou si elle a un rôle plutôt informationnel que fonctionnel. Une adaptation à plus long terme est mise en évidence à la fin du vol par la disparition de l'activité anticipatrice du Biceps, et par la présence de bouffées d'activités phasiques présentes pour tous les muscles étudiés. Ces résultats suggèrent une adaptation lente à la situation d'apesanteur par la disparition des programmes nécessitant trop d'énergie et devenus inutiles dans cette nouvelle situation. Ces données mettent en évidence l'existence de processus conservatifs.

En apesanteur, l'inlinaison vers l'avant du sujet JLC témoignerait de la persistance d'une attitude posturale terrestre qui amène le centre de gravité du corps vers l'avant pour assurer une meilleure stabilité. La posture du sujet VD est comparable à celle observée au sol. Les déplacements des différents segments corporels au cours du mouvement du bras sont peu modifiés par l'apesanteur. De plus, contrairement aux résultats obtenus chez un sujet fixé à un support, pour lequel on observe une disparition rapide et totale des programmes moteurs posturaux, on retrouve en apesanteur des modifications d'activité EMG au cours du mouvement du bras parfaitement structurées. Ces programmes moteurs sont très reproductibles d'un essai à l'autre et d'un segment expérimental à l'autre.

L'ensemble de ces résultats suggère qu'en apesanteur le système qui contrôle la posture et les mouvements utiliserait un schéma corporel élaboré en situation de gravité terrestre pour adapter ses stratégies motrices à ce nouvel environnement (Gurfinkel et al. 1979). Selon l'hypothèse du schéma corporel, la modification du point de fonctionnement des récepteurs impliqués dans le contrôle postural n'entraînerait pas de modifications notables des ajustements posturaux en situation d'apesanteur. Ce concept nous amène à discuter de la possibilité d'une déafférentation NON fonctionnelle des récepteurs sensoriels. En effet, si l'on admet que l'apesanteur provoque une déafférentation des récepteurs otolithiques, ou modifie les informations afférentes des récepteurs tactiles ou musculaires du fait de la réduction de la masse et du volume des muscles, on constate cependant que les conséquences de ces modifications sont peu importantes sur la posture. Par exemple, nos résultats montrent que la diminution de l'activité réflexe lors de l'ouverture de la cheville (réflexe d'étirement) ne s'accompagne pas de perturbation posturale plus importante. En outre, l'occultation de la vision en apesanteur (VO), qui représente la situation extrême, n'induit pas de modifications posturales fondamentalement différentes de celles observées en situation de gravité terrestre en ce qui concerne la position des segments corporels entre eux.

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MASS-DISCRIMINATION DURING PROLONGED WEIGHTLESSNESS

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SUMMARY

An experiment to compare weight and mass discrimination was conducted using 5 of the crew of STS-9 (Spacelab 1) as subjects. Thresholds for mass discrimination under microgravity in flight were found to be higher by a factor of about 1.8 than for weight discrimination before the flight, and there was no consistent improvement throughout the 10 day mission. This suggests that inertial cues to mass (gained through accelerating objects) are not as effective as weight cues. The crew showd an aftereffect for two or three days on return to Earth, when their bodies felt heavy and their weight discrimination was impaired. This suggests that some adaptation to weightlessness occurred during the flight, probably early in the mission before the majority of the mass discrimination tests were conducted.

When comparing the weights of objects, it is normal to pick them up and "jiggle" them. This method yields lower discrimination thresholds than does static pressure (1). The improvement is partly due to the involvement of the kinaesthetic senses in addition to the pressure receptors (2). It may also be due to the availability of inertial cues to mass, sensed through the force required to accelerate the objects (3). In a 1-G environment it is difficult to distinguish between the contributions of weight and mass to what is usually called "weight-discrimination". In a 0-G environment weight cues are effectively absent, and the discrimination can only be made by accelerating the objects and using inertial cues. An experiment was therefore conducted to compare thresholds for the same test, when performed on the ground and under weightless conditions in Spacelab.

The apparatus consisted of a box containing 24 weighted balls and a set of record cards (Fig. 1). It is described in greater detail elsewhere (4). The balls had a diameter of 30 mm and varied in mass from 50-64 g in 2 g steps, with several duplicates. They were fabricated from lead and epoxy resin, the lead being in the form of a spherical shell, the diameter and thickness of which was formulated to yield balls which all had a measured polar moment of inertia of 4.0 to 4.1 x 10^{-6} kgm^2 irrespective of their mass. (We have found the Weber fraction for the discrimination of polar moments of inertia to be at least 0.70 for cylinders of comparable mass and polar moment of inertia to the test spheres). The balls were stored in holes in the box under retaining straps, and were labelled with letters. The box also contained record cards, listing 72 pairs of letters. The lists comprised 18 repetitions of 2, 4, 6 and 8 g pair intervals, with the heavier mass equally often first or second, in random order. No letter combinations were repeated. For each test session the subject opened the box and fastened it to a worktop. Using his left hand, he picked out the first ball on the list from its hole, shook it and replaced it. He then did the same for the second ball of the pair. He decided which felt heavier, and marked the corresponding letter on the list, using his right hand. All subjects were right handed. The subject repeated this for all 72 pairs, then posted the completed record card in a slot in the box. The test lasted about 12 min on the ground and 17 min in space.

Two Payload Specialists and two Mission Specialists were thoroughly trained to perform the test. Baseline data were then collected on 4 occasions between 5 months and 3 days before the flight. The Pilot was also tested at one month and 3 days before the flight. During the flight performances were made by these crew on 2-5 occasions each. The earliest was at 8 hours after liftoff, and the last were on the tenth flight day. Postflight data were collected at the Baseline Data Collection Facility 5 hours after landing for one Payload Specialist, and for all 4 Spacelab crew on 1, 2 and 4 days after return. The Pilot was retested in London 2 months later.

The mean number of preflight errors was 18.0 (25%), and in flight 24.7 (33%). All subjects gave more errors in flight ($p = 0.031$, sign test, 1 tail). Errors were also high after the flight (mean 23.0 on R+1), but returned to baseline level by R+4. There were, however, no systematic changes with time in error rates of the tests performed before flight or during flight. There was considerable variation in error rates between subjects, those with vigorous shaking techniques giving fewer errors (particularly the Pilot, who also used his right hand for both preflight and inflight tests). Group Differential Thresholds (DLs) (75% correct level) were derived from preflight and inflight data, by calculating the percentage of correct judgements for each step interval and subject, and weighting all 5 subjects equally. The percentages were converted to z scores, and a straight line fitted through the origin (5) (Fig. 2). There were insufficient data to derive reliable DLs for each

Fig 1. A Payload Specialist tests himself using the mass-discrimination apparatus.

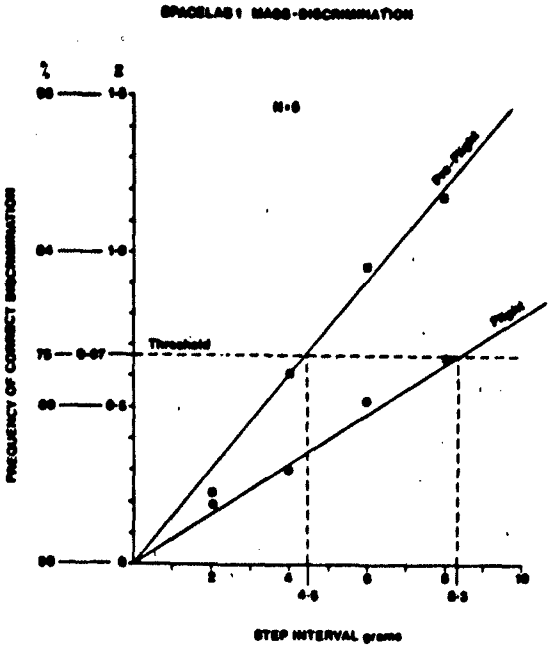

Fig 2. Mass-discrimination thresholds under 1-G pre-flight and 0-G in flight.

All subjects showed poorer performance under 0-G, by an average factor of 1.84. This appears to be less than the factor of 2.15 found during brief periods of 0-G (< 25 sec) in parabolic flight (6), though there were too few data to compare the results statistically. The difference may be due to fluctuations in the microgravity level in the KC-135 aircraft, or to the brief time available for adaptation to loss of arm weight. Sudden changes in arm weight are known to impair weight-discrimination, but the effect is reduced if time is allowed for adaptation (7). However, discrimination remained impaired even after 9 days in orbit, when adaptation should have been complete.

In so far as the sense of heaviness is related to force, objects judged through inertial mass alone should feel like very light weights. Indeed objects were judged to be about half their weight during the 0-G phase of parabolic flight (6), but there was also a tendency to "mass-constancy" despite changes in the force environment (7). The Weber fraction is roughly constant for the middle range of weights, but increases for weights below 50 g (8). Poor discrimination under 0-G may therefore be an artefact of the low range of masses used. Higher masses might yield equal DLs under 1-G and 0-G, though simulations with air-bearing tables and horizontal arm movements suggest that this may not be so (9).

Results from postflight tests on four of the crew suggest that the state of adaptation is also an important variable. The crew reported feeling heavy, and they also suffered from other postural aftereffects (10, 11) for a few days after return to Earth. Their weight DLs were also raised, but returned to baseline within three or four days. This poor discrimination may have been due to tiredness. However, the aftereffect was exactly that predicted from experiments on adaptation to arm buoyancy in water (7), as well as from the reported feelings of heaviness of the crew and other astronauts on landing (6). It is possible that this was a genuine phenomenon, mirroring some adaptation to weightlessness that occurred during the first day or two of spaceflight before the majority of the mass-discrimination tests were undertaken.

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CHANGES IN CARDIOVASCULAR FUNCTION: WEIGHTLESSNESS AND GROUND-BASED STUDIES

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SUMMARY

Echocardiographic measurements were taken on members of four Space Shuttle missions before (F-10 to F-12) and twice after (L+0 and L+7 to 14 days) 7- to 9-day space flight missions. Such recordings allowed for determination of left ventricular chamber dimensions and subsequent calculations of left ventricular volume and stroke volume. Resting ventricular volume could be shown to significantly decrease 23% ($p<.01$) on L+0 ($N=7$) and to be associated with a significant 28% decrease ($p<.01$) in stroke volume. Studies 7 to 14 days later ($N=17$) showed amelioration of effects, but persistence of end-diastolic volume change (11% decrease, $p<.01$). Such findings occurred despite ability to fully ambulate and exercise during the post-flight period. Comparison of findings with bed rested subjects (athletic and non-athletic) showed similar changes, but changes after bed rest were of smaller magnitude compared to the flight crews. It is concluded that space flight induces significant changes in heart volume even after short duration (7-9 days) missions. Heavy athletic conditioning pre-flight may contribute to the severity of the observed changes in the flight crews and to the apparent slow post-flight process of recovery. This will need to be followed closely in subsequent studies.

INTRODUCTION

The Soviet and American space programs have demonstrated that exposure to weightlessness, even for short periods, induces significant changes in the cardiovascular system (1). A loss of adaptive capacity (deconditioning) can be shown to occur during flight with provocative testing and becomes clearly apparent and troublesome with return to earth. Findings have included the presence of tachycardia and narrowed pulse pressure and the inability to adequately control blood pressure when in the vertical position (2-6). If an upright body position is allowed to continue in the early post-flight period, presyncope and even frank fainting have occurred in certain crew members (1,2,7). Much of this has been attributed to a loss of intravascular volume, leading to a decrease in heart size. Such changes are thought to be physiological consequences initiated by the headward shift in body fluids occurring during flight. During the present studies, echocardiographic measurements of left ventricular volume were obtained before and after flight in selected Shuttle crew members to gain insight into the magnitude of these changes following 7- to 9-day flights and to document the time course of the recovery process.

BACKGROUND

Since the first manned space flight in 1961, the United States has successfully completed 40 manned missions and the Soviet Union 60. The two programs have launched more than 140 individuals (3 women) into orbit, some as many as five times. Space flights have lengthened from the one hour and 48 minutes of Gagarin's initial flight to the more recent record Soviet stay of 211 days in December 1982. Cardiovascular changes have been regularly observed both during and after all flights (1-7).

Figure 1 presents a schematic summary of observed in-flight cardiovascular changes during the early period (24 to 48 hours) of weightlessness. Principle events include a redistribution of body fluids, associated neurohumoral steps to adapt to the redistribution and eventual loss of apparent perceived excess intravascular volume leaving the body more prone to orthostatic stress. The triggering mechanism is the loss of body weight during exposure to zero gravity. Under such conditions hydrostatic pressure is eliminated and fluids that would normally reside in the lower parts of the body are displaced to the upper regions. During this early period head fullness is sensed and facial edema appears. These changes have been consistently reported by all cosmonauts and astronauts and persist regardless of flight duration (5). From in-flight measurements of leg girth it is estimated that 1,000 to 1,500 ml of fluid shift to the upper body, compared with a 600 to 700 ml shift when changing from the standing to the lying position while on earth. This shift is believed to cause the observed increase in jugular venous pressure (central venous pressure has not yet been directly measured) and lead to the orthostatic intolerance and cardiovascular deconditioning that is regularly

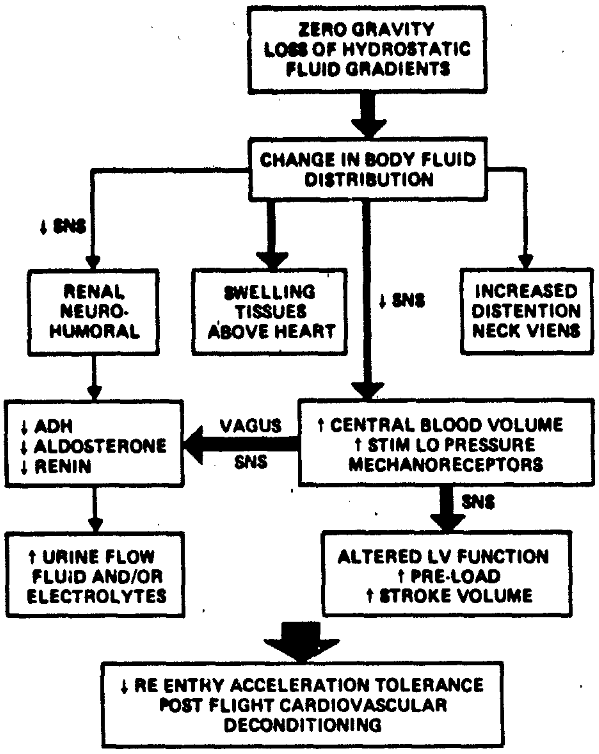
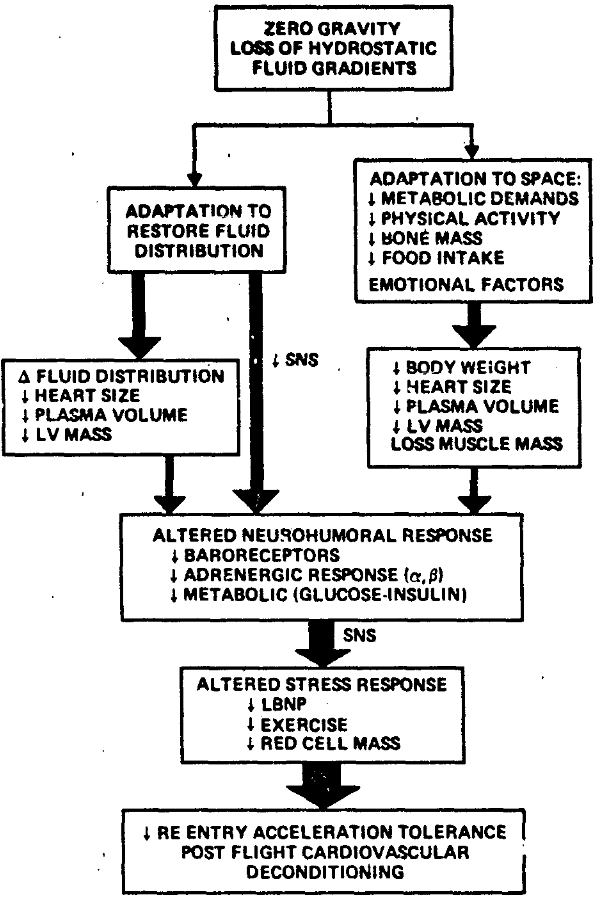


FIGURE 1 Schematic representation of changes associated with early period of weightlessness (24-48 hours).



activity, loss of bone and muscle mass and altered neurohumoral responses. Post-flight a decrease in heart size has been found by X-ray or ultrasound (8,9).

Cardiovascular deconditioning has been regularly observed after space flight exposures, manifested mainly as depressed exercise capacity and orthostatic intolerance. In the Skylab missions, lower-body negative pressure (LBNP) testing was undertaken during flight for the first time and provided greater cardiovascular stress during weightlessness than before flight. In Skylab 4 such responses became less severe after 30 to 50 days of flight (4). During re-entry all Skylab crewmen wore G-suits which were designed to provide counterpressure to the lower extremities to reduce postural hypotension after landing and while standing at 1-G. Although the suits produced a decrease in heart rate and maintained blood pressure at or near supine levels during standing, the SPT of Skylab 2 nonetheless experienced postural hypotension. Similar findings have occurred after Shuttle flights (7). These latter observations occurred despite the use of ingested water-salt supplements prior to re-entry.

Since the Skylab missions, Soviet investigators have undertaken and completed a series of six consecutive flights of considerably longer duration, remaining in orbit for periods from 96 to 211 days. At the time of writing this report, the Russians have a three-man crew that has been in orbit for 190 days and may well exceed their previous space endurance record of 211 days set in December 1982. Figure 3 summarizes echocardiographic findings of left ventricular end-diastolic volume obtained from Soviet crews following flights of 96 to 175 days (10). All subjects, as shown, had flight-induced changes in volume. Decreases ranged from 12 to 65 ml, representing falls of 8 to 50% from resting values. Similar findings, but of lesser magnitude, were reported after the 84-day Skylab flight (9). Measurements in previous shorter US or USSR flights have either not been taken, or reported to date. All crews have been able to perform in-flight tasks without evidence of limitations from cardiovascular deconditioning. Of interest are recent findings of echocardiographic studies performed during flight by French cosmonaut, Jean Paul Chretien (11). Figure 4 illustrates reported changes in left ventricular and left atrial size measured by echocardiography during a 7-day mission. Chamber dimensions changed little during the first 2 days of flight, peaked by Day 4 and then returned to baseline just prior to re-entry. These findings suggest that in-flight heart size changes occur rapidly, with heart volume returning to baseline levels by the first week. Post-flight changes and orthostatic tolerance for this subject have not yet been made available in the open literature.

To avoid deconditioning during long-term flights, all Soviet crewmen wear "Penguin" constant-load suits during waking hours which contain elastic cords attached to the arms and legs in order to supply an "earth-like" resistance to motion. Countermeasures prior to flight include intensive physical training and one week of sleeping in a head-down (-6° to -12°) position. During flight, extensive bicycle or treadmill exercises are used (up to 2 to 2.5 hours daily), incremental LBNP for 5 to 7 days before re-entry and ingestion of water-salt additives just prior to re-entry. These countermeasures have provided subjective improvements in state of well-being, decreases in weight loss and improved performance during exercise testing. They have not been entirely successful since the cosmonauts continue to show significant decreases in heart volume post-flight, as shown in Figure 3, and to experience significant post-flight cardiovascular deconditioning as judged by heart rate response to a 5-minute passive stand test (75° back angle). For the crews participating in the 75-, 96-, 140-, 175-, and 185-day flights, pre-flight heart rates during such tests ranged from 48 to 60 beats/min at rest, increasing to 60 to 72 beats/min on standing; after flight resting heart rates ranged from 60 to 87 beats/min and increased to 90 to 128 beats/min on standing. The largest post-flight orthostatic change occurred for V. Ryumin after his historic 185-day flight; he had completed the previous 175-day flight as well with a 6-month break between missions. None of the Soviet crewmen experienced frank syncope, but tests were limited to 5 minutes or less. An unknown variable is the magnitude of change in heart rate that would have occurred if no countermeasures had been used. Similar findings have occurred for Shuttle crews (7).

MATERIALS AND METHODS

Data were collected on changes in cardiac size and function for four Shuttle crews. Paired t-test values were compared for echo ultrasound measurements obtained 10 to 12 days pre-flight (F-10 to F-12), immediately after landing (L+0) and then at 7 to 14 days post-flight (rec). Due to operational constraints only seven crew members could be studied immediately after flight, while 17 subjects could be measured in the 7- to 14-day recovery period. Resting two-dimensional echos were obtained using a portable ADR 4000S ultrasonoscope which allowed for video tape recording of data for subsequent analysis. Recordings were made of each crew member during the 5-minute supine control period immediately preceding a 5-minute stand test, used as a standard medical test procedure. Standard parasternal long axis, short axis, and apical 4-chamber views were obtained with crew members in the left lateral decubitus position. Data were transferred to a Sony video disc recorder (SVM-1010, Video Motion Analyzer) for computer data processing. The use of a time base corrector (to correct disc time base errors) and a video mixer allowed superposition of the output from the computer character generator on the video image. This facilitated the use of a video-caliper (Step Engineering and Hewlett Packard HP 77020-AC, HP-77020-A Video Analysis Systems) to estimate endocardial end-diastolic and end-systolic ventricular diameters directly from the display video sector images. Maximal and minimal diameters were used to designate end-diastole and end-systole. Derived diameters (D) of the outline were stored in the computer for volume

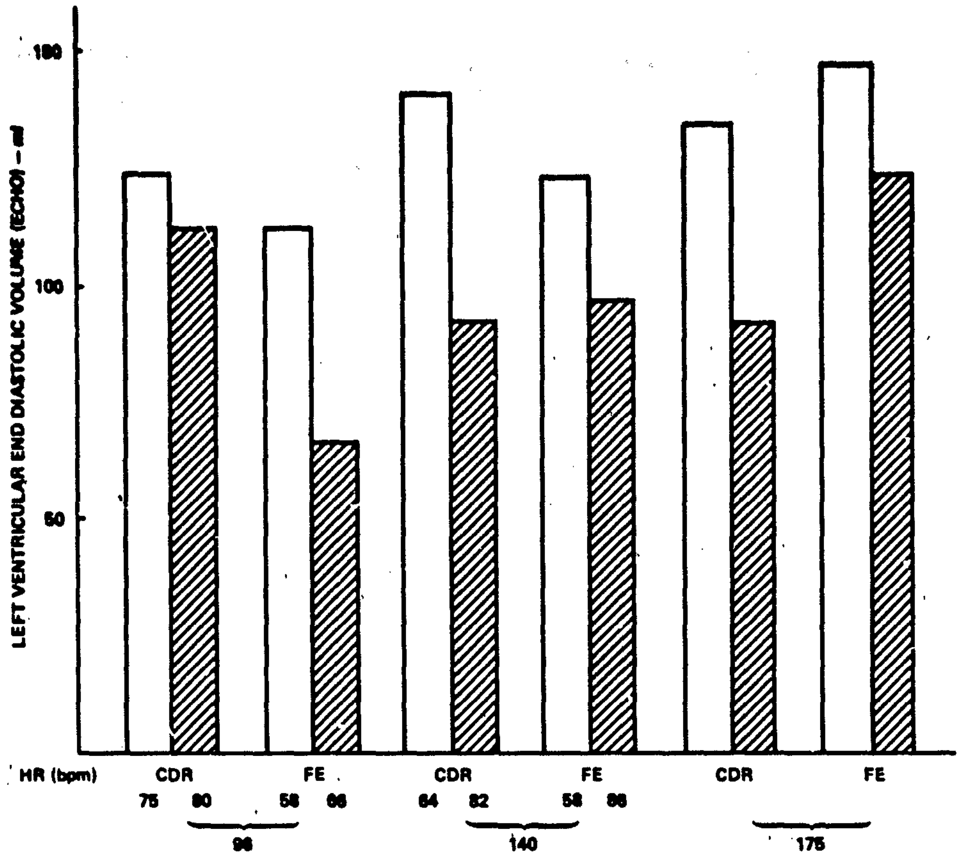


FIGURE 3 Echocardiographic changes of left ventricular end-diastolic volume in Soviet crews before (open bars) and immediately after (scored bars) long-term space flight. Heart rate changes at the time of measurement are given below each bar graph, duration of flight given beneath each bracket, and consisted of 96, 140, and 175 days.

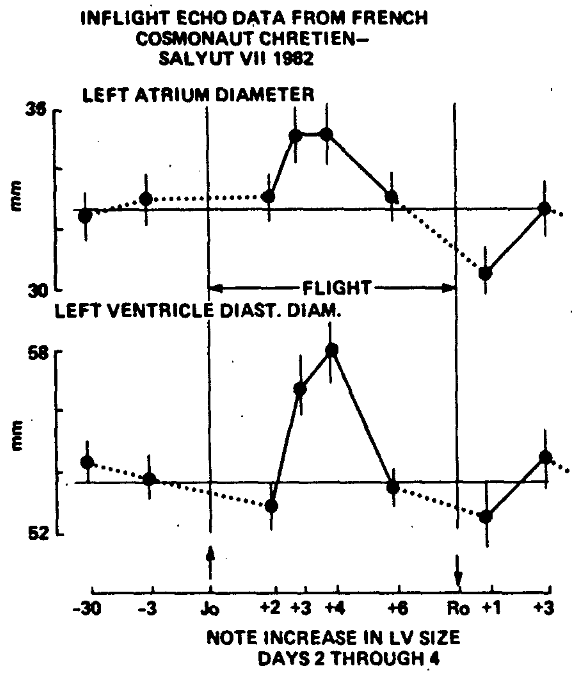


FIGURE 4 Inflight echo data from French cosmonaut Chretien -- Salyut VII 1982. Data taken from Reference #11.

(V) was calculated as:

$$V = \left(\frac{7}{2.4+D}\right) D^3 \qquad (1)$$

This approach assumes the ventricle to be ellipsoid. Five to six beats from each recording were analyzed and the average end-diastolic volume (EDV) and end-systolic volume (ESV) calculated. Left ventricular stroke volume (SV) was derived as:

$$SV = EDV - ESV \qquad (2)$$

Cardiac output (CO) was derived as:

$$CO = SV \times HR \qquad (3)$$

All values were converted to indices by dividing by body surface area in order to normalize for difference in body size. An ejection fraction (EF) was derived from the relationship:

$$EF = SV/EDV \qquad (4)$$

Sternal ECG's and blood pressure (cuff and microphone) were simultaneously recorded with the echos.

RESULTS

The seven crewmen studied at L+0 when compared to pre-flight state evidenced increases in resting heart rate (HR) of 16 bpm (30.5%, $p<.05$) changing from 52 ± 1 to 68 ± 4 bpm, and increases in mean aterial pressure (MAP) from 74 ± 2 to 82 ± 2 mmHg (12%, $p<.01$). End-diastolic volume index (EDVI) fell 17 ml/M^2 (23%, $p<.01$) from 73 ± 4 to 56 ± 5 ml/M^2. The magnitude (percentage) of changes in EDVI are shown in Figure 5. Similar changes also occurred for derived stroke volume index (SVI), which decreased 15 ml (28%, $p<.05$) from 52 ± 4 to 37 ± 5 ml/M^2. Changes in SVI were almost entirely due to the decreases in EDVI, ESVI showing almost no differences. Due to the almost similar decreases in SVI and EDVI, EF tended to increase, but the changes were not significant. Cardiac index (CI, L/M^2) failed to show significant change (2.7 ± 0.2 vs 2.4 ± 2 L/M^2, NS).

The 17 subjects studied 7 to 14 days post-flight showed amelioration of most changes induced by space flight exposure. Most parameters now showed small and insignificant changes compared to pre-flight levels. Heart rate was slightly increased from preflight values (56 ± 2 vs 60 ± 1 bpm, NS), MAP was still slightly elevated (74 ± 1 vs 75 ± 2 mmHg, NS), CI slightly elevated (2.6 ± 1 vs 2.7 ± 1 L/M^2, NS) and SVI a slight 4% decrease (48 ± 2 to 46 ± 2 ml/M^2, NS). However, EDVI, as shown in Figure 5, still demonstrated a small, but significant, 7 ml/M^2 loss (11%, $p<.01$) from 70 ± 2 to 63 ± 3 ml/M^2.

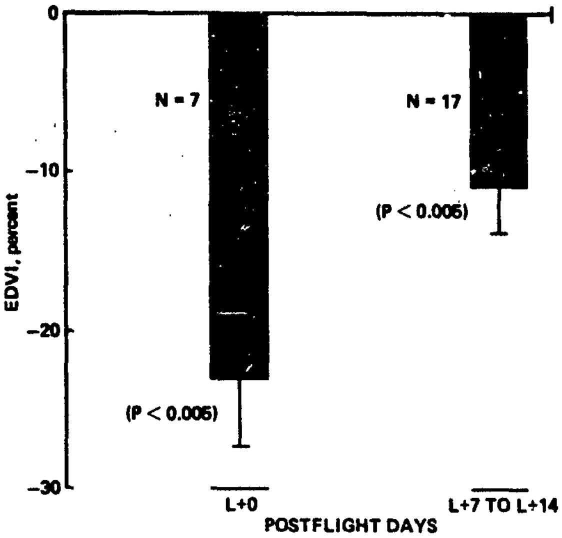


FIGURE 5 End-diastolic volume changes registered immediately after flight (L+0) and 7-14 days later (L+7 to L+14). Percentage change represents difference after flight compared to pre-flight level.

DISCUSSION

A significant decrease in EDVI occurred after space flight. The range was similar, but of smaller magnitude, to that seen after previous longer duration US and USSR space flights. A finding of interest in the present study was the persistence of change at 7 to 14 days of recovery. Since the subjects were fully ambulatory during the recovery period, it would be expected that plasma volume loss induced by fluid volume shifts would have been restored (13). This was certainly the case following the Skylab missions (14). Plasma volumes, however, were not determined during the course of these investigations.

Some insight into the mechanisms of these changes may be gaged from similar findings following bed rest simulations of weightlessness (1). Studies in our laboratories of resting left ventricular volume before and after 2-week periods of bed rest have shown similar changes to that observed in the flight crews. In one group of seven athletically-trained male subjects, ages 19 to 25 years, EDVI was initially 70 ± 2 ml/M^2 and decreased to 62 ± 3 ml/M^2 (11%, $p<.01$) after 2 weeks of horizontal bed rest. In another group (similarly aged) of seven males, who were non-athletic (sedentary college students) and experienced an identical 2-week bed rest exposure, EDVI changed from 62 ± 3 ml/M^2 to 58± 3 ml/M^2 (6%, $p<.05$) (1). Left ventricular volumes in these cases were measured by single crystral echocardiography and processed in a manner similar to that used in the present study. Change in EDVI for this study was, therefore, twice to three times greater than that observed in these previous bed rest studies. EDV after 7 days of recovery for the non-athletic bed rested subject was 60 ± 2 ml/M^2 and 70 ± 3 ml/M^2 after 3 weeks of ambulation for the athletes, thus returning to or towards pre-bed rest levels so as to be statistically indistinguishable from pre-bed rest levels. Changes in volume for the flight crews persisted during recovery and differed from that previously seen with bed rest. However, such changes must be interpreted with caution, since echocardiographic measurements can produce a 10 to 20% measurement error from subject to subject or for the same subject. This variation was minimized, however, by having the same team and data processing scheme involved in the serial measurements. Of note is the higher absolute mean values for EDVI for the flight crews and athletic males (70 ml/M^2) as compared to the non-athletic males (62 ml/M^2). It is known that athletic conditioning can lead to both a significant increase in intravascular plasma volumes, as well as to an increase in absolute size (mass) of the heart (14,15). All members of the flight crew are known to participate in an active physical education program, including both isotonic and isometric exercises. This would explain the higher EDVI's recorded for the athletes in the bed rest study and for the flight crews. This heavy athletic conditioning may also explain the apparent long recovery period. Saltin and co-workers (16) were the first to show that such athletically-trained individuals may have a more prolonged period of recovery following bed rest exposure, as compared to sedentary individuals. Figure 6 illustrates data taken from the Saltin study showing the time course of recovery of heart volume in a group of three sedentary subjects, as compared to two athletic individuals. A clear difference was present with the athletes requiring a 3-4 week post-bed rest period to regain lost heart volume and max VO$_2$ capacity in order to return to their higher pre-bed rest levels. Based on findings such as these and the observations that athletically trained subjects are more prone to syncope after water immersion exposure, Klein and co-workers (18) have raised a question regarding the benefits of heavy exercise training for space flight crews.

Further examination of the above athletically-conditioned subjects during bed rest also indicated that the severity of the deconditioning process may not be manifest soley by observations made at rest as done in the present study. These subjects experienced not only a single bed rest period, but a series of three consecutive 2-week horizontal bed rest exposures, separated by a 3-week ambulatory recovery period between exposures. Data was collected at rest and following LBNP testing. Changes in left ventricular volumes were measured by single crystal echocardiography, as shown in Figure 7. Values recorded for each pre-bed rest (control) period are shown on the left. Values after bed rest on the right. Subjects were studied at rest and following -20, -30, and -40 mmHg vacuum. The surprising finding was that control responses (left panel) were not similar, indicating that the subjects had not returned to initial pre-bed rest state. In fact, LBNP response during the third pre-bed rest study (left panel) was almost identical to that seen after the first or second bed rest period (right panel). The third bed rest period shows the greatest changes in both cases. Results show that 3 weeks of ambulation was not sufficient to promote recovery. Time period for ambulation was slightly longer for the bed rested subjects (3 weeks) as compared to the flight crews (1 to 2 weeks). Plasma volume levels measured at these times (control period) failed to indicate the presence of significant differences from pre-bed rest levels for the bed rest subjects (13). It is concluded from such findings that the recovery period following bed rest and space flight requires a longer time interval than previously postulated. Evidence for the presence of a deconditioned state and study of the course of recovery will require other measurements than those based on resting heart rate and blood pressure and should include some form of stress testing such as a stand test, LBNP, or exercise. The results of the present study also support the conclusion that greater cardiovascular change occurs for the flight crews than with bed rest. Beneficial or detrimental effects of flight can only be gaged after appropriate data becomes available in a greater number of individuals and such groups contain individuals not participating in a regular heavy exercise program. It appears from the data to date that athletes show the larger changes in physiologic parameters, both at rest and on stress testing.

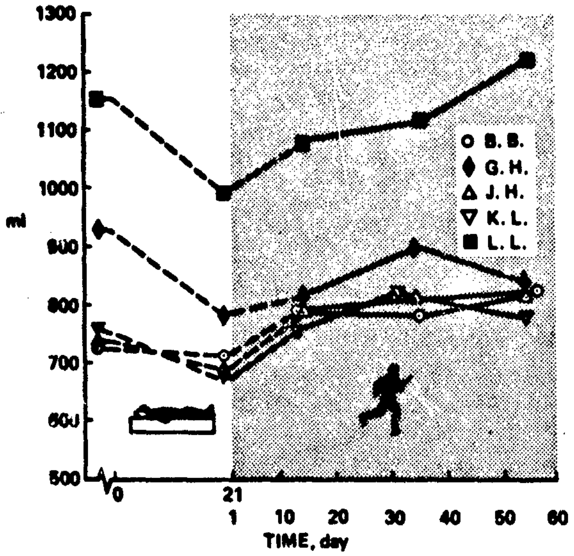


FIGURE 6 Total heart volume changes occurring after 3 weeks of horizontal bed rest and time duration of recovery. Figure taken from Reference #17.

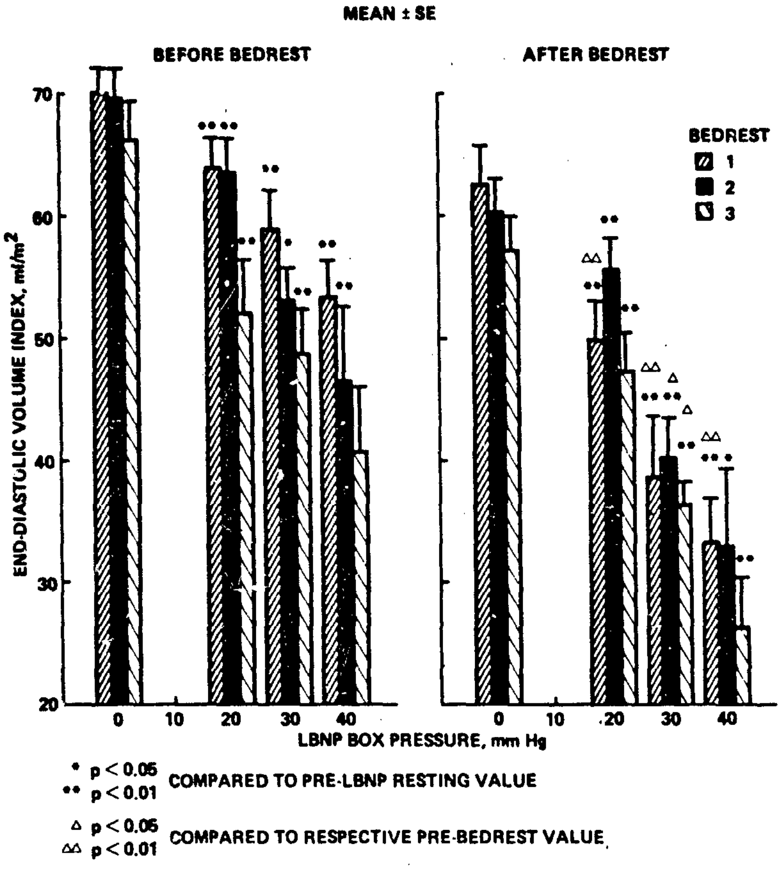


FIGURE 7 End-diastolic volume index changes at rest and during LBNP (5-minute consecutive steps at -20, -30, -40 mmHg vacuum). Scored bars represent changes before and after first bed rest, solid bars after second bed rest, striped after third bed rest. Three weeks of ambulation occurred between each bed rest exposure.

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DISCUSSION

KLEIN, FRG

Did you investigate heart contractility in your studies?

AUTHOR'S reply

Data from the echos are still being analysed. As judged by the ejection fraction $\left(\frac{\text{stroke volume}}{\text{end-diastolic volume}}\right)$ contractility decreased on L + 0 and recovered by L + 7 to L + 14.

PSIMENOS, GR

What you have shown must have an implication on the astronauts' physical exercise program and it sounds, as if over-training is a hazard rather than a benefit. I remember Neil Armstrong saying "I will not run", refusing to participate in the physical training program of Apollo astronauts.

AUTHOR'S reply

There is no question that excessive exercise training is detrimental. E. Burchard at the end of my talk mentioned, that astronauts in Skylab 4 stopped exercise for 2 - 3 weeks before flight and did better than members of Skylab 2 and 3 crews. In bedrest, subjects who do not exercise before bedrest have smaller fall of $\dot{V}O_2$ max and LBNP tolerance than athletes.

BONDE-PETERSEN, Denmark

As both positive and negative hydrostatic pressure gradients are abolished in weightlessness (both above and below the heart), the arteriolar and capillary pressure above heart level will increase resulting in oedema formation in the face, while below the heart capillary pressure will decrease. The puffy face might therefore not be the result of a continued central venous stasis but might be the result of an increased arteriolar pressure which cannot be handled by the "low pressure vascular bed" of the face with thin walled arterioles which will not adapt to the weightlessness-dependent increase in the local arteriolar pressure.

ETUDE DU SYSTEME CARDIOVASCULAIRE EN MICROGRAVITE : RESULTATS ET PERSPECTIVES

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RESUME

Une étude du système cardiovasculaire a été réalisée en microgravité lors du vol commun franco-soviétique à bord de la station Saliout VII en juin 1982. Un système à ultrasons a été spécialement développé pour cette application et fonctionne sur les modes Doppler, imagerie rapide et temps-mouvement. Les changements de volumes et de fonction cardiaques, les débits dans la carotide et la fémorale, le temps de transit de l'onde de pression, ainsi que la circulation veineuse, ont été étudiés chez l'astronaute français avant, pendant et après le vol. Différents tests ont également été réalisés au sol et en vol afin de tester la réponse dynamique du système cardiovasculaire et de comparer les résultats obtenus en apesanteur et au cours des tests de simulation.

INTRODUCTION

Les grandes fonctions physiologiques de l'organisme humain sont perturbées par un séjour en microgravité (1), (2). Ces perturbations apparaissent plus ou moins précocément après la mise en apesanteur, et s'expriment par des signes qui peuvent être cliniques, comme le mal de l'espace, ou qui restent le plus souvent à un stade infraclinique, tout du moins pour des vols de courte durée. Dès la mise en apesanteur c'est le système neurosensoriel (et en particulier le système vestibulaire) qui subit la plus forte perturbation, alors que la disparition de la pression hydrostatique entraîne une nouvelle répartition de la masse sanguine dans l'organisme. Plus tardivement, la désadaptation cardiovasculaire, les variations du volume sanguin, les troubles de l'équilibre hydrominéral et du métabolisme calcique, les phénomènes d'irradiation, prennent une importance croissante, en l'absence de contre mesure, au fur et à mesure que la durée du vol s'allonge.

Plusieurs études ont été rapportées sur le système cardiovasculaire des astronautes (3). La majorité de ces travaux ont été réalisés avant et après le vol, en raison des faibles moyens d'investigation non invasive dont on disposait jusqu'alors. Les techniques à ultrasons sont très intéressantes car elles permettent des évaluations qualitatives et quantitatives de l'hémodynamique et de la fonction cardiovasculaire. Un système à ultrasons spécialement développé pour les conditions spatiales (expérience Echographie) a été utilisé au cours du vol commun franco-soviétique à bord de la station Saliout VII du 24 juin au 2 juillet 1982. Les études en vol ont été réalisées sur l'astronaute français J-L. CHRETIEN avec la participation des astronautes soviétiques DJANIBEKOV et IVANTCHEKOV.

Dans les conditions de microgravité, l'absence de pression hydrostatique provoque le déplacement d'une importante masse de sang vers la partie supérieure du corps, et un changement dans la distribution de liquide extracellulaire. Ces mécanismes aboutissent, d'une part à une augmentation transitoire de la masse sanguine, et d'autre part à une variation importante de la pression veineuse dans presque tous les compartiments de l'organisme. Le nouveau gradient de pression qui s'établit alors, entraîne la formation progressive d'une oedème de la partie supérieure du corps (face, tronc,...), et peut être également une augmentation de volume liquidien dans le cerveau et le poumon. La stimulation des capteurs centraux peut alors déclencher le réflexe de Gauer-Henry avec baisse de l'ADH et de l'aldostérone, réduction de la soif et élimination accrue d'eau et d'électrolytes (4).

En apesanteur, l'activité de l'astronaute nécessite un travail relativement faible des muscles à action antigravidique. Les changements de position ne stimulent plus les réflexes vasoconstricteurs nécessaires au sol pour contrôler la masse sanguine et l'hémodynamique dans les membres inférieurs. Ces deux phénomènes sont essentiels dans le déconditionnement cardiaque et vasculaire.

OBJECTIFS

Les principaux objectifs de l'expérience Echographie étaient les suivants :

- étudier les mécanismes de régulation de l'ensemble de la fonction cardiovasculaire à la suite du remaniement de la masse liquidienne et de l'installation d'un nouveau gradient de pression ;
- évaluer le retentissement de ces régulations sur le coeur (dimensions, contractivité, fraction d'éjection) et les débits locaux (cerveau, membres) ;
- tester la réponse dynamique du coeur en microgravité lorsqu'on modifie rapidement le gradient de pression (manchettes) ;
- comparer les résultats de vol et ceux obtenus en sol sur les mêmes sujets lors d'épreuves de simulation ;
- enfin, étudier la phase de réadaptation précoce lors du retour à la gravité normale.

MATERIEL ET METHODES

L'appareil à ultrasons spécialement développé pour l'expérience Echographie (figure 1) a été construit par la Société Matra-Interélec (Paris), sous contrat C.N.E.S., à partir d'un prototype réalisé au Laboratoire de Biophysique de la Faculté de Médecine de TOURS. Il comporte 4 modes de fonctionnement différents qui permettent d'étudier la circulation superficielle, et de réaliser des examens du coeur et de l'abdomen : (1) Doppler à émission continue, 4 MHz ; (2) mode temps-mouvement (T.M.), 3.5 MHz ; (3) mode B temps réel à balayage électronique linéaire, focalisation dynamique, 3.5 MHz ; (4) système duplex (temps réel 5 MHz-Doppler continu) pour la débitmétrie transcutanée. Un électrocardiogramme est enregistré systématiquement avec chaque mode.

Les astronautes sont entraînés à utiliser les sondes sur eux-mêmes et peuvent contrôler au moyen d'un moniteur toutes les informations qu'ils désirent stocker (E.C.G., T.M., Doppler, images). Des enregistrements de référence ont été réalisés 30 jours et 3 jours avant le vol. Les mesures en microgravité ont été effectuées aux jours 2, 3, 4 et 6 du vol. La phase de récupération a été étudiée aux 1er et 3e jours après le retour au sol. Un enregistrement supplémentaire, associé à un test d'antiorthostatisme de 3 jours, a été pratiqué 2 mois après le vol afin de comparer les résultats obtenus avec ceux du vol spatial. Toutes les informations de vol ont été stockées sur bandes magnétiques pour être traitées au retour au sol. Les images 2D et le mode T.M. sont enregistrés en mode conventionel. Les signaux Doppler sont présentés sur le moniteur sous forme de courbes analogiques de la variation de fréquence moyenne dans un but d'orientation. Afin d'effectuer une étude précise, le signal Doppler audio, enregistré en parallèle sur la bande vidéo, est traité ensuite par transformée de Fourier rapide (analyse spectrale). Il faut souligner la bonne qualité des documents obtenus, consécutive à un bon fonctionnement de l'équipement Echographie et à l'entraînement des astronautes.

A partir des résultats d'échocardiographie, les études ont porté sur les variations de volume des cavités cardiaques, les modifications de la fonction d'éjection du ventricule gauche et de la contractilité du myocarde. Les principaux paramètres étudiés sont les suivants :

- temps d'éjection simple ET (s) et corrigé CET (s) ;
- volume diastolique LVDV (ml) et systolique LVSV (ml) du ventricule gauche ;
- volume d'éjection SV (ml), fraction d'éjection EF (%) ;
- fréquence cardiaque HR (puls./mn) ;
- débit cardiaque (l/mn) ;
- pourcentage de raccourcissement du diamètre ventriculaire gauche ΔR (%) ;
- vitesse moyenne de raccourcissement circonférentiel des fibres myocardiques MVFC (s^{-1}) ;
- débit systolique moyen MSER (ml/s).

Ces études portent sur les examens faits au repos, ainsi que pendant l'épreuve des manchettes pratiquées au sol 30 et 4 jours avant le vol, les 4e et 6e jours de vol, le 3e jour de la période de réadaptation. Le schéma de ce test est le suivant : une contre-pression est établie au niveau des membres inférieurs à l'aide de brassards gonflables placés sur les cuisses, à la racine des membres inférieurs + 40 mmHg pendant 20 mn ; + 60 mmHg pendant 20 mn.

Tous les résultats présentés sont les moyennes obtenues à partir de plusieurs mesures. La déviation standard a été calculée et un test de Student pratiqué. Sur les courbes, les points dont la variation par rapport aux valeurs de base est significative avec $P < 0.05$, sont notés d'une étoile.

A partir des résultats Doppler et de l'imagerie vasculaire, différents paramètres sont accessibles qui renseignent sur les résistances périphériques, les débits, et la vitesse de propagation de l'onde de pression. Les principaux paramètres étudiés sont les suivants :

- vitesse instantanée systolique ou diastolique v : elle est calculée à partir de la formule de l'effet Doppler :

$v = \frac{\Delta F.c}{2F.\cos\theta}$ avec ΔF = variation de fréquence Doppler ; F = fréquence des ultrasons (4 MHz);
θ = angle entre l'axe du vaisseau et la direction du faisceau Doppler ;
c = célérité des ultrasons dans le milieu (1540 m/s).

- débit sanguin carotidien ou fémoral : l'imagerie vasculaire permet de mesurer le diamètre d de l'artère à l'endroit où le faisceau Doppler traverse le vaisseau. Par intégration de la courbe de variation de fréquence, on accède à la fréquence Doppler moyenne $\overline{\Delta F}$, puis à la vitesse moyenne $\bar{v}$. Le calcul du débit $Q = \bar{v}.s$ est effectué en supposant que la section s du vaisseau est circulaire. ce qui est vrai pour une artère, à distance des zones de bifurcation. (La mesure du débit dans une veine est plus compliquée puisqu'il faut connaître à tout moment sa section exacte qui évolue souvent au cours des cycles respiratoires et cardiaques).

- index de résistance circulatoire carotidien : le flux carotidien est constitué d'un débit continu, sur lequel se superpose le débit systolique à chaque cycle cardiaque. La proportion de débit systolique dans le débit total est d'autant plus importante que la résistance circulatoire périphérique est élevée. Sur la courbe de vitesse instantanée du flux carotidien on détermine la valeur maximale A et la valeur minimale diastolique D. L'index de résistance s'écrit alors : $R = \frac{A - D}{A}$.

- index de résistance circulatoire des membres inférieurs : le flux fémoral est constitué essentiellement d'un pic systolique A suivi d'un reflux B en débit de diastole, l'ensemble ayant l'allure d'une oscillation amortie. La proportion de reflux diastolique B est directement liée à la résistance circulatoire périphérique lorsque la souplesse vasculaire reste constante. L'index de résistance s'écrit donc :

$$R = \frac{B}{A} = \frac{\text{Amplitude reflux diastolique}}{\text{Amplitude pic systolique}}.$$

- mesure du temps de propagation de l'onde de pression : sur l'enregistrement simultané de l'ECG et des courbes de variation de fréquence Doppler, il est possible de mesurer le temps qui sépare le début de l'onde R et le début de l'onde systolique. Ce temps s'allonge au fur et à mesure qu'on s'éloigne du coeur et ceci en fonction de la vitesse de propagation de l'onde de pression. La vitesse de cette onde dépend de la compliance vasculaire, et augmente lorsque la rigidité s'élève. On peut donc étudier l'évolution de la compliance vasculaire globale sur chaque grand territoire, en analysant le temps de transit de l'onde de pression dans ce territoire.

Tous les résultats de l'exploration vasculaire correspondent à l'analyse de nombreux complexes avec, pour chaque paramètre, la détermination de :

- la valeur moyenne obtenue sur l'ensemble des mesures correspondant à un enregistrement ;
- la déviation standard ;
- l'écart par rapport à la valeur de base, avant le vol, exprimée en % de cette valeur de base.

RESULTATS

1. Cardiologie :

Les principaux résultats obtenus avant, pendant et immédiatement après le vol sont rassemblés dans la figure 2. Le rythme cardiaque HR reste en permanence à une valeur élevée pendant le vol et lors de la phase initiale de récupération. La première mesure en vol (2e jour) montre une chute du volume ventriculaire systolique (LVSV), associée à un rythme cardiaque élevé, ce qui peut être la conséquence d'une réaction neuro-émotionnelle. Les valeurs des volumes diastoliques (LVDV) et systolique (LVSV) sont élevées aux 3e et 4e jours, avec retour aux valeurs de base le 6e jour. Le volume d'éjection (SV) suit une évolution assez parallèle à celle des dimensions ventriculaires. Ceci entraîne une forte augmentation du débit cardiaque (CO) qui atteint près de 40 % au 4e jour de vol. Le débit cardiaque reste élevé durant la période de récupération surtout en raison du rythme cardiaque supérieur à sa valeur de base.

Aucune altération de la contractilité cardiaque ne se manifeste durant le vol, comme le montre l'absence de changements importants de la fraction d'éjection (EF), du raccourcissement relatif du diamètre ventriculaire (ΔR) et des temps d'éjection simple (ET) et corrigés (CET). Cependant on note une augmentation de la vitesse de contraction des fibres (MVFC) et du débit systolique moyen (MSER) certainement consécutive à l'augmentation du rythme cardiaque.

L'ensemble des phénomènes observés est vraisemblablement la conséquence de l'accroissement de remplissage sanguin des cavités cardiaques, provoqué par la redistribution du sang vers l'extrémité céphalique. Une évolution similaire des paramètres cardiaques est décrite par de nombreux auteurs lors des expériences de simulation de l'impesanteur par la position antiorthostatique, l'augmentation du remplissage des cavités cardiaques étant fonction de l'angle d'inclinaison des sujets lors de ces études.

Afin de préciser les conséquences, sur le système cardiovasculaire, des modifications de répartition de la masse sanguine, un test dynamique a été réalisé en vol aux jours 4 et 6, au moyen de brassards placés autour des cuisses. Ce test permet de retenir le sang dans le système veineux des membres inférieurs. Afin de clarifier la présentation (figure 3), seuls les résultats obtenus le 4e jour sont présentés ici. La rétention du sang dans les membres inférieurs normalise les paramètres hémodynamiques centraux en réduisant le remplissage des cavités cardiaques et en provoquant une assez forte baisse du débit cardiaque (20 %), associée à une légère décroissance du rythme cardiaque, et surtout, à une chute du volume d'éjection et du diamètre ventriculaire diastolique. Ces modifications montrent que le gonflage des brassards permet de réduire les effets de la redistribution de masse sanguine en apesanteur, et peut-être d'avoir une efficacité identique à celle du LBNP (Lower Body Negative Pressure).

Un test d'antiorthostatisme (bed-rest) a été réalisé sur l'astronaute français le 60e jour après le vol, à -6° pendant 3 jours. La réponse obtenue montre que le volume ventriculaire gauche, le volume d'éjection et le débit cardiaque ont tendance à augmenter, mais ces variations sont plus faibles qu'en vol. On note de plus une baisse du débit cardiaque et peu de modifications des paramètres de la contractilité myocardique. Le rôle du stress peut partiellement expliquer la différence entre les résultats de simulation et ceux de microgravité.

A partir des résultats obtenus chez un seul sujet, on ne saurait tirer des conclusions définitives concernant les mécanismes d'action de l'impesanteur sur l'hémodynamique cardiaque, la fonction d'éjection et la contractilité myocardique. Pour résoudre ces problèmes, ainsi que pour décider des conditions optimales d'utilisation des manchettes dans un but prophylactique, il est nécessaire de poursuivre des études identiques pendant les vols spatiaux et les expériences de simulation au sol.

2. Vasculaire :

Le débit de la carotide primitive de l'astronaute reste constant dans une limite de quelques % durant le vol, en dépit de variations importantes du débit cardiaque, ce qui traduit une excellente régulation du débit sanguin cérébral (figure 5). Il faut cependant noter que les composantes de ce débit évoluent pendant le vol puisque le débit systolique augmente, alors que le débit diastolique diminue. Il semble exister une bonne corrélation entre la vitesse de contraction des fibres myocardiques et le débit systolique carotidien. Cette variation des composantes du flux sanguin cérébral est bien mise en relief par l'index de résistance $P = \frac{A - D}{A}$ traduisant la proportion de flux systolique dans le flux total de la carotide. Cet index augmente en vol dans les carotides primitive et interne (deux points de mesure seulement ont été demandés au commencement sur la phénomène à un éventuel oedème cérébral de moyenne importance.

La circulation dans l'artère fémorale évolue pendant le vol (figure 6), mais dans des proportions modestes qui ne dépassent pas 20 %. On note cependant une nette augmentation du débit fémoral le premier jour de la phase de récupération, ce qui peut s'expliquer par une difficulté de contrôle vasomoteur lors du retour en gravité normale. Les composantes du flux fémoral évoluent elles aussi avec une tendance à l'augmentation du débit systolique mais surtout du débit diastolique (reflux) pendant toute la période de vol. L'index de résistance R = B/A qui traduit l'amplitude relative du reflux fémoral augmente de manière très nette au cours du vol (+ 20 %) pour redescendre très vite lors du retour au sol.

Pendant le vol, le diamètre de la veine jugulaire est nettement augmenté par rapport à sa valeur au sol en décubitus à zéro degré. A aucun moment cette veine ne se collabe (comme cela arrive parfois au sol), ce qui traduit la présence d'une pression veineuse toujours positive. Les dimensions de la veine fémorale commune restent beaucoup plus stables lorsqu'on compare les résultats en vol et au sol.

L'analyse des flux veineux instantanés révèle des modifications très importantes des conditions hémodynamiques, en particulier au niveau des veines jugulaires. On note au sol une courbe de vitesse typique, qui est nettement modulée par les différentes phases du cycle cardiaque (contraction auriculaire, contraction ventriculaire, remplissage rapide, etc...), retrouvées sur la courbe de pression auriculaire droite $P_a(t)$. La courbe de vitesse en jugulaire est alors assez voisine de la fonction $- \frac{dp_a(t)}{dt}$. Pendant le vol, le flux jugulaire montre un débit permanent en diastole, et un arrêt brutal contemporain de l'onde P de l'ECG : cette courbe de vitesse semble bien refléter une augmentation de la pression veineuse centrale, et éventuellement de la résistance pulmonaire. Ce type de tracé est observé pendant toute la période de vol. Dès le 3e jour après le retour au sol les tracés jugulaires sont comparables à ceux de référence enregistrés avant le vol.

La circulation veinuuse fémorale de référence présente essentiellement une composante continue faiblement modulée par la respiration et le rythme cardiaque. Au cours du vol, ce flux fémoral apparaît beaucoup plus rythmé par les cycles respiratoires et cardiaques avec des arrêts circulatoires assez longs. Au premier jour de récupération, la modulation se résuit pour redevenir identique à celle de référence dès le 3e jour après le vol.

La mesure du débit veineux en cm^3/mn n'a pas été réalisée en raison de la grande variabilité de la section de ce type de vaisseau. On note cependant que les vitesses dans la veine fémorale en vol, exprimés en cm/s, sont beaucoup plus faibles qu'au sol. L'ensemble des résultats obtenus au niveau de la circulation veineuse confirme les hypothèses de remaniement de la masse sanguine avec surcharge du coeur droit et modification de la pression veineuse centrale.

L'étude indirecte de la compliance artérielle à partir des caractéristiques de la propagation de l'onde de pression avait pour but d'étudier les changements du tonus vasculaire et des contraintes externes appliquées aux vaisseaux. Les résultats s'analysent en deux étapes successives :

- retard entre le début de l'onde R et le début de la mise en vitesse du sang dans trois artères : carotide primitive, artère férorale commune, artère tibiale postérieure. On note pendant le vol, ainsi que lors de la phase de récupération, une diminution nette de ce retard. Son évolution au niveau de la carotide traduit clairement une diminution du temps de prééjection cardiaque ;
- temps de transit de l'onde de pression : par soustraction des temps précédents on obtient le temps de transit dans l'aorte et les iliaques (temps fémoral-temps carotide) et dans les membres inférieurs (temps tibial postérieur-temps fémoral). Sur le trajet de l'aorte il n'existe pas de différence significative pendant le vol, mais par contre, on note une diminution du temps de transit supérieur à la déviation standard lors de la phase de récupération. Dans les membres inférieurs, le temps de propagation est diminué de manière très sensible en microgravité, et revient à sa valeur de base lors de la phase de récupération (3e jour) (figure 7).

L'augmentation nette de la rigidité du système vasculaire des membres inférieurs pendant le vol constitue une surprise, qui peut trouver son explication dans deux mécanismes : 1°, l'existence d'un tonus vasculaire important qui est révélé par l'augmentation de la résistance circulatoire périphérique ; 2°, l'augmentation du tonus musculaire des membres inférieurs en vol par rapport à la position de décubitus. Aucune explication n'a été trouvée à la variation de temps de transit dans l'aorte au cours de la phase de récupération.

Afin de contrôler l'aptitude du cosmonaute à visualiser certaines structures abdominales, il était prévu l'enregistrement d'images échotomographiques montrant le système porte intra-hépatique et les veines sus-hépatiques. Les résultats obtenus sont d'excellente qualité et montrent clairement que les veines sus-hépatiques sont soumises à des variations de calibre importantes à chaque cycle cardiaque pendant la période de vol. Ceci peut être la conséquence d'une augmentation de la pression veineuse centrale et d'une surcharge du coeur droit. Le système porte ne montre pas de variation de calibre décelable d'emblée sur les images étudiées.

Lors de l'épreuve d'antiorthostatisme réalisée 2 mois après le vol sur le cosmonaute français, il a été possible de montrer que certaines réponses hémodynamiques étaient semblables et d'autres très différentes des résultats de vol. Au niveau carotidien, on retrouve le fait que le débit reste dans les limites de 10 % de la valeur de base, avec augmentation de l'index de résistance lié à la diminution de la vitesse diastolique et augmentation de la vitesse systolique maximale (figure 8).

Au niveau des membres inférieurs, on note par contre une importante chute de débit fémoral (de l'ordre de 35 %), avec une variation inverse de celle enregistrée en vol pour le reflux et le temps de propagation de l'onde de pression (figure 9).

Ainsi, l'épreuve d'antiorthostatisme reproduit partiellement les conditions de microgravité et semble nettement mieux adaptée pour la cardiologie et la circulation cervico-encéphalique que pour la circulation dans la partie inférieure du corps. Ceci s'explique en partie par le fait qu'en microgravité le gradient de pression est symétrique de part et d'autre du coeur droit, ce qui n'est pas le cas en position à -6°.

CONCLUSIONS

L'expérience Echographie a été mise au point pour le vol commun franco-soviétique de juin 1982 à bord de la station Saliout 7 (vol de 7 jours). Les spationautes ont été entraînés à utiliser l'appareillage développé en commun entre le Laboratoire de Biophysique de la Faculté de Médecine de Tours, le C.N.E.S. et la Société Matra. Cet appareil basé sur l'emploi des ultrasons est capable de visualiser le coeur et les vaisseaux, d'enregistrer le mouvement des structures cardiaques et de fournir les paramètres nécessaires au calcul du débit sanguin dans les vaisseaux superficiels. La quasi-totalité du programme a pu être exécutée et les documents expérimentaux se sont avérés être de bonne qualité.

Des enregistrements ont été effectués sur J-L. CHRETIEN aux dates suivantes : à 30 et 3 jours avant le vol, aux jours 2, 3, 4 et 6 durant le vol, aux 1er, 3e, 60e jour après le retour au sol. Parmi les principaux résultats observés on note l'accroissement du débit et de la fréquence cardiaques en impesanteur, l'augmentation des dimensions auriculaires et ventriculaires gauches, avec conservation de la contractilité myocardique, les modifications du flux veineux et de la compliance vasculaire, le changement de la résistance périphérique et la stabilité du débit sanguin cérébral. La nouvelle répartition du volume sanguin lié à la disparition de la pression hydrostatique ainsi que la forte réduction du travail physique expliquent en partie les résultats précédents. L'utilisation de manchettes placées à la racine des membres inférieurs s'est avérée efficace pour réduire la surcharge du coeur en situation d'impesanteur. Aucune modification à caractère franchement pathologique n'a été observée pendant toute la période du vol.

Des simulations au sol par alitement prolongé en antiorthostatisme ont été réalisées. Les résultats montrent qu'il n'est pas possible de simuler complètement la situation de microgravité par la simple position antiorthostatique à -5 à -6°. Par ailleurs, des dosages hormonaux sanguins et urinaires très complets doivent compléter les informations cardiovasculaires obtenues avec l'appareillage Echographie.

Il est important d'insister sur plusieurs aspects qui ont été mis en relief au cours de l'expérience :

- l'ergonomie de l'appareil s'est avérée relativement bonne, ainsi que l'entraînement du spationaute J-L. CHRETIEN, puisque les documents obtenus sont de bonne qualité et que la quasi-totalité de l'expérience a été menée à bien dans les délais prévus ;
- l'augmentation du débit cardiaque sans modification majeure du débit cérébral et fémoral laisse supposer que la circulation rénale et/ou hépato-digestive augmente à certaines phases du séjour en microgravité. Il est essentiel d'analyser ce phénomène lors de prochains vols ;
- les caractéristiques du flux pulmonaire sont importantes à étudier car elles retentissent directement sur la pression veineuse centrale et sur les modifications de dimensions des cavités cardiaques ;
- les fortes modifications dans le retour veineux et leur répercussion sur la pression veineuse centrale nous incitent à étudier de manière plus approfondie le flux dans la veine cave.

Toutes ces remarques montrent la nécessité d'études complémentaires à partir de la technique par Doppler pulsé, ainsi que l'intérêt de répéter les expériences car il est difficile de généraliser les résultats obtenus sur un seul individu.

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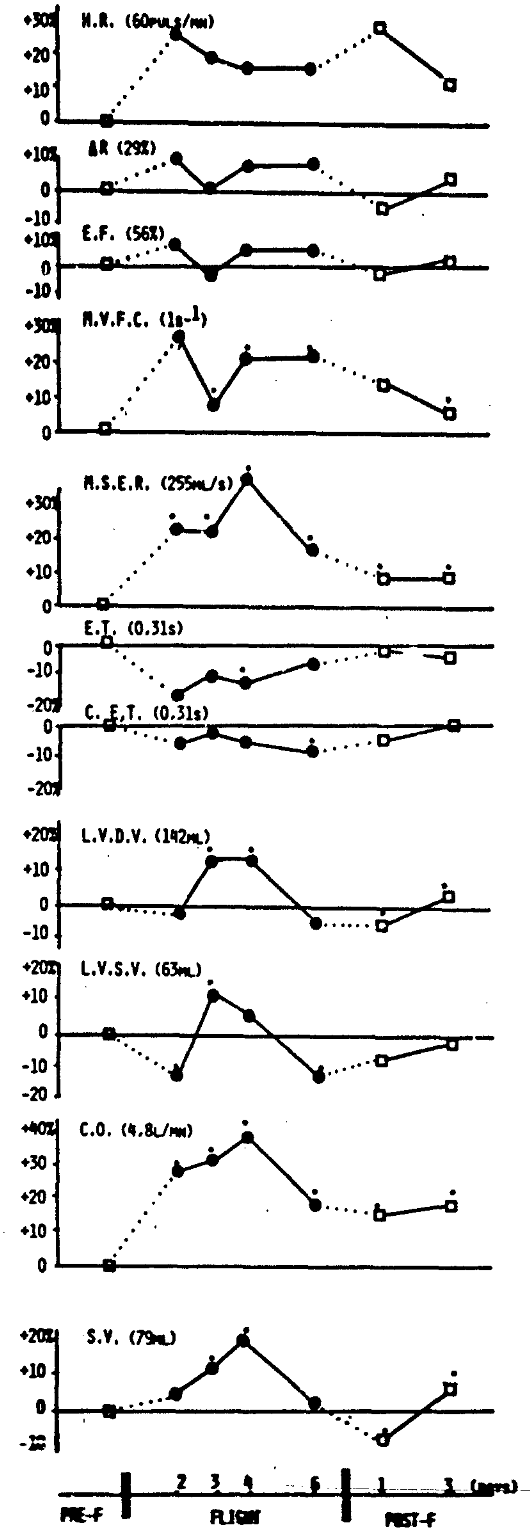

Figure 2 : Paramètres cardiaques mesurés avant, pendant et après le vol.

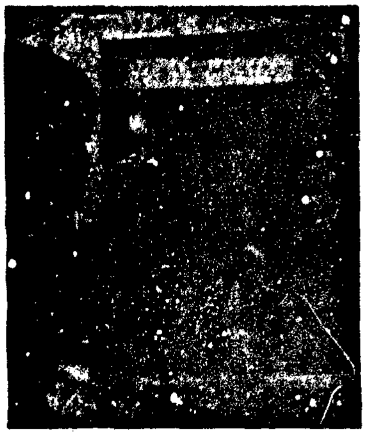

Figure 1 : Vue de l'appareil Echographie et d'une sonde duplex placée sur la carotide primitive.

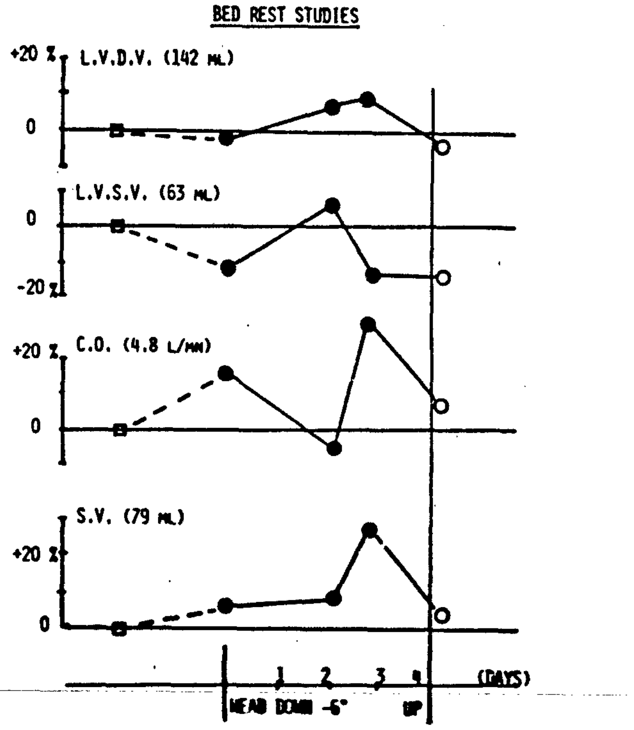

Figure 4 : Résultats du bed-rest à -6° (a comparer avec ceux de la figure 1).

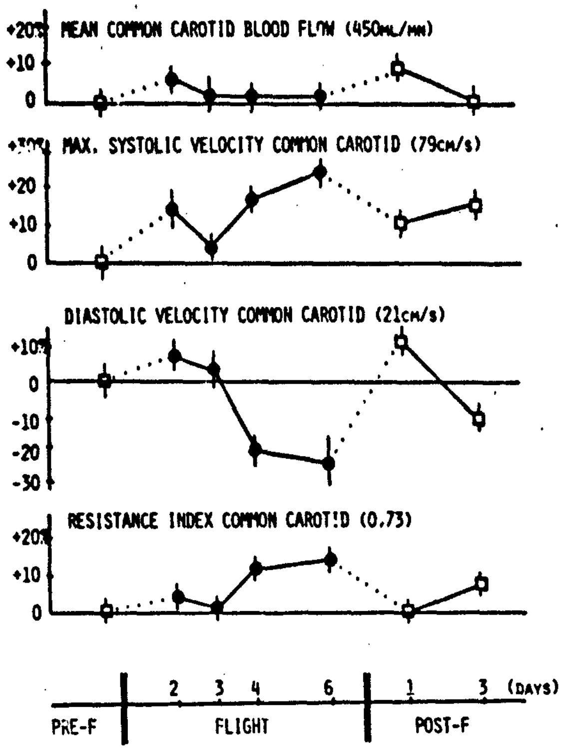

Figure 5 : Circulation carotidienne étudiée avant, pendant et après le vol.

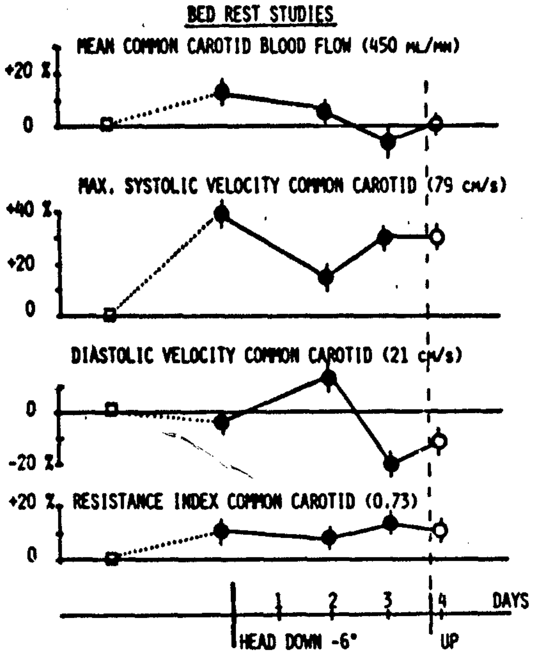

Figure 8 : Bed-rest à -6° (à comparer avec les résultats de la figure 5).

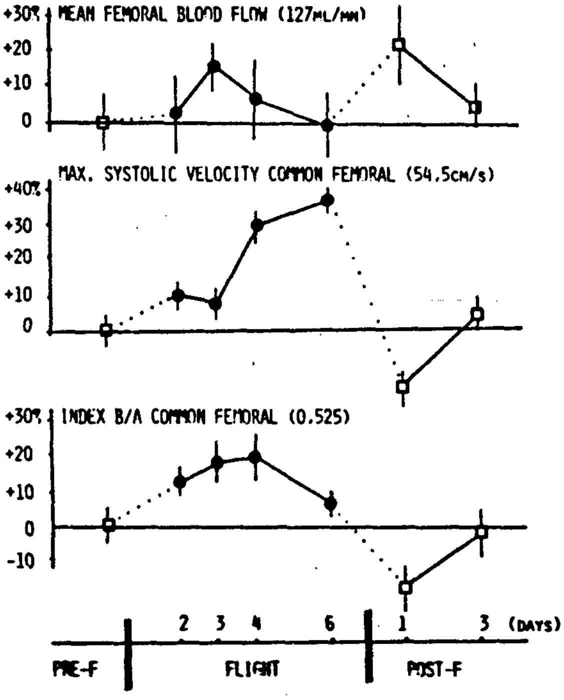

Figure 6 : Circulation fémorale étudiée avant, pendant et après le vol.

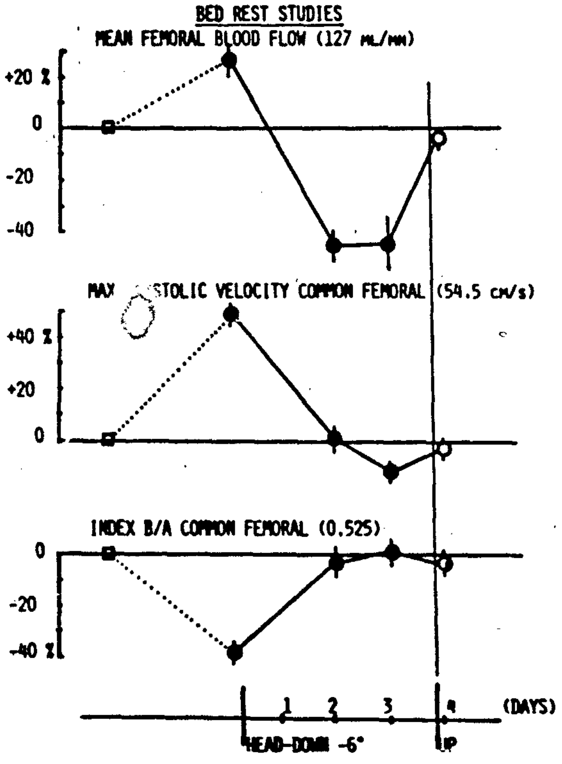

Figure 9 : Résultats de bed-rest à -6° (à comparer avec les résultats de la figure 6).

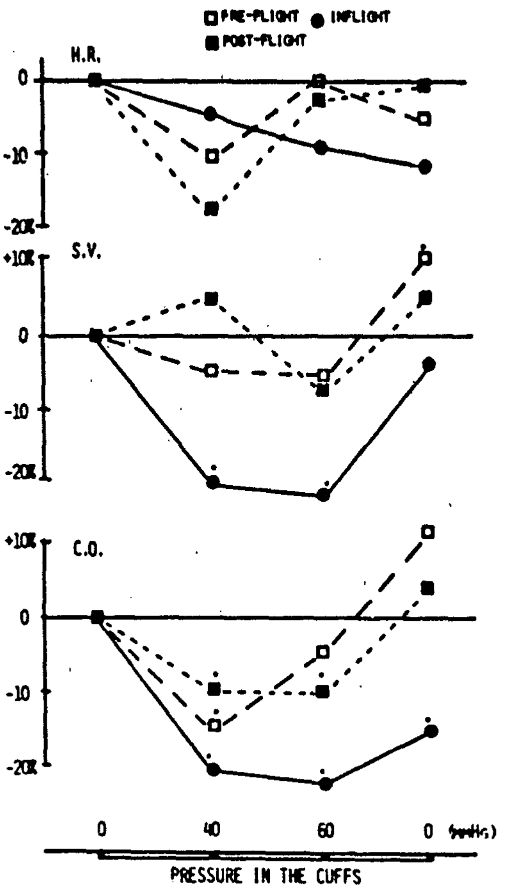

Figure 3 : Modifications des paramètres cardiaques induits par le test des brassards placés sur les cuisses.

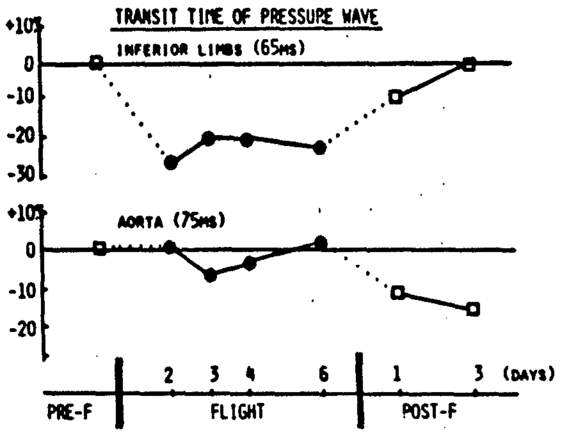

Figure 7

DISCUSSION

SCANO, Italy

C'est seulement une contribution au problème comme on l' a discuté jusqu' ici, en particulier aux données presentées par le Prof. Pourcelot.

Comme vous savez nous avons enregistré le ballistocardiogramme, qui est un phenomène complexe a interpréter, mais qui peut donner une idée sur l' activité mechanique du coeur et sur la condition des vaisseaux.
Alors, dans la diapositive (je crains que c'est difficile a voir) nous avons posé les données concernant la somme de quatre ondes du ballistocardiogramme (ce sont les ondes systoliques), enregistrées dans les jours précédants, dans la première phase du vol, dans la deuxieme phase du vol et six jours après l' atterrissage, pendant des conditions de repos et d' activité physique, une activité tres limitée en realité. Nous avons posé ici les données concernant le ballistocardiogramme le long des axes longitudinal du corps, le ballistocardiogramme le long de l' axe transversal du corps, Z et Y. On peut voir que pendant le vol, et en particulier dans les jours initiales du vol, il y a une augmentation nette et statistiquement significative de l' amplitude du ballistocardiogramme, sur les quatre membres sur lesquels nous avons travaille. Ce phenomène va s' atténuer pendant la deuxième phase du vol et il va disparaître après le retour au sol. Nous n' avons pas encore les données du premier jour. Ils seront les plus intéressantes mais en tout cas on voit qu' il y a une sensible différence aussi avec le données avant le vol. C' est très difficile dire que le ballistocardiogramme est l' expression du débit systolique, mais certainement il est une expression globale de la puissance ventriculaire et aussi des resistances vasculaires. Ça, c' est bien d' accord avec les données concernant la vitesse d' expulsion et le débit systolique.- Il y a une chose qui est différente, c' est a dire la fréquence cardiaque qui dans notre cas n' etait pas augmentée, plutôt diminuée mais pas significativement.
Les données après les exercices sont encore différentes: vous pouvez voir l' augmentation plus élevée de l' amplitude du ballistocardiogramme. Je pense qu' il serait utile voir s' il est possible les mettre en rapport avec le données du Prof. Pourcelot et du Dr. Sandler aussi.

Pourcelot, FR

Je ne connais pas suffisamment les données de vos ballistocardiogrammes pour pouvoir les comparer tout de suite avec nos résultats. Il semble cependant que les variations que vous avez observées sur l' axe z soient tout à fait dans l' ordre de grandeur des variations que nous observons au niveau du débit systolique moyen. Il y a donc une corrélation possible entre les deux résultats.

SCANO, Italy

This is actually not a question, but only a modest contribution to the interesting papers presented by Prof. Pourcelot and by Dr. Sandler.

As you know, we made ballistocardiographic recordings prior, during and after the Spacelab-1 Mission. During my presentation I showed a diagram with the values of BCG systolic waves collected along the Z and Y axes: It demonstrated a statistically significant increase of the whole amplitude of these waves during the first days in microgravity, a relative decrease by the end, and a further decrease 6 days after landing. It seems interesting to find a confirmation of your results through a completely different cardiovascular physiological exploration method.

AUTHOR'S reply

It could be of interest to compare on the same subject the results of echocardiography and ballistocardiography during microgravity exposure. The modifications you have observed could be correlated with increase in stroke volume, mean systolic ejection rate, and systolic velocities in vessels, which was demonstrated on the French Astronaut during the Salyut space flight.

Cardiovascular Research in Space: Problems and Results

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Summary

In order to see whether the headward fluid shift during spaceflight is followed by increased venous pressures in the upper half of the body in astronauts during the Spacelab 1 Mission pressures in an antecubital vein (PVP) was measured together with the hematocrit (Hct) and the ADH concentration pre-, in- and post-flight. Central venous pressure was followed pre- and post-flight, together with the body weight (BW). 22 hours after launch PVP was lowered as compared to pre-flight values and remained so during the whole mission, whereas Hct and the ADH were elevated. Apparently the space adaptation of the low pressure system is a highly dynamic process being over within 24 hours. The readaptation to ground conditions follows a similar time course.

Introduction

The physiology of space flight is characterized by two adaptive processes - the adaptation to weightlessness and the readaptation to the 1-g environment on earth. It is nowadays obvious that within the frame of these processes the cardiovascular and the endocrine system play a key role (3, 7, 14, 18).

The anthropometric measurements during the Skylab missions (21) showed a reduction of the tissue volume of the lower limbs due to a fluid mobilisation from the intra- and the extravascular compartment amounting up to 2000 cc. This fluid was shifted towards the upper parts of the body and accumulated predominantely in the intrathoracic compartment of the low pressure system elevating probably for a certain period of time the Central Venous Pressure (CVP). This in term should trigger the so called "volume reflex" described by GAUER and HENRY (5) with the consequence of an increased urine output due to lowered levels of the Antidiuretic Hormone (ADH). Since in space so far no elevated urine outputs could be detected, the normal urine excretion must be regarded as elevated because fluid intake is reduced (12, 13). Insofar the GAUER-HENRY-hypothesis should still be valid in space. It was the aim for our study to prove this hypothesis and therefore during the First Space-Lab mission (FSLP) the following experiments were performed. In the astronauts on ground before and immediately after landing CVP was measured with the help of the arm-down method (6, 9). In space the astronauts measured the pressure in an arm vein according the MORITZ-TABORA method (15). After the pressure measurements blood samples were taken for hematocrit measurements and hormone analysis (ADH).

The Experimental Environment

Before in the usual manner the methodology and results will be reported it seemed necessary to the authors to outline more in detail the special circumstances under which the data were elaborated. All the results obtained should be viewed under these special aspects.

Despite the technological progress made in the last two decades there is no denying the fact that the conduct of scientific programs concerning human physiology is very much subject to the operational constraints. The operational demands of the mission are responsible for the boundary conditions which often limit the experimental approach. Till now space physiology still is field physiology very often done under extreme conditions where the pencil and the notebook of the experimenters are more important than the analytical procedure later in the quiet laboratory.

What are the limiting factors?

1. Only 4 subjects took part in our venous pressure experiments and only from two subjects blood samples for hormone analysis in space were available; therefore no statistical analysis of the data was undertaken. The numerical results of each individual will be given. In some instances the arithmetic mean ($\bar{x}$), the highest (H) and lowest (L) values are given.

2. The age of the astronauts varied from 33 to 55 years. This should influence the life style to a certain extend. All but one of the astronauts had a training in technical fields what is important to know because in space subject and experimenter were identical. The astronauts were trained to perform venipuncture on themselves and did this task excellently.

3. The technical design of the equipment had to be simple and easy to handle even under extreme conditions. Safety requirements had also to be fulfilled. The equipment had to be ready three years before launch.

4. The venous pressure measurements and the blood sampling had to be done in space on 4 astronauts within 45 minutes. This time had to be shared with another group doing hematological experiments.

5. The ground bases data collection before and after the spaceflight took place in four different locations

Canaveral a warm, humid climate prevails. The astronauts had to travel between the locations and the danger of a more or less pronounced dehydration was always imminent (see Figure 1).

6. Two weeks before laun the crew was taken into quarantine which meant the astronauts had only limited contact to the outer wor They had time to rest and relax, and followed their usual eating and drinking pattern.

7. In two crew members a time shift of 12 hours was introduced, two of them were working whereas the two others were asleep. This time shift was maintained throughout the mission. The team was synchronized after landing. Since the measurements in space were taken in all crew members at the same time, two were in their morning cycle and the other two in their evening cycle.

8. Another inhomogeneity was introduced into our team by the fact that two astronauts were salt and water loaded shortly before landing. One liter of a balanced salt solution was given.

Nevertheless we are confident that despite these limitations useful informations could be gained which not only will shed new light on the physiology of the human body but also will improve the experimentation in future missions.

Procedure and Methods

Figure 1 gives further insight into the special circumstances of the experiments.

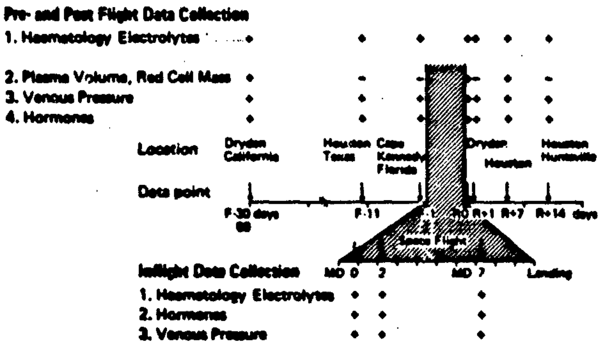

Figure 1: Time line of the pre-, in- and post-flight data collection. The locations of the data collection are also given.
F - 30 = 30 days before flight
MD 0 = First Mission Day, 22 hours after launch
R + 0 = 1 - 2 hours after recovery (landing)
R + 1 = 12 hours after landing

The experiments reported here were part of a program to which 3 different groups of investigators made their contributions. Our group was responsible for the venous pressure (3.) and the hormones (4.). The timing of the data collection is indicated by + - signs.

Originally the pre-flight control measurements were scheduled on F - 30, F - 15, and F - 1. Due to the repeated delays of the mission we finally had 4 - 5 pre-flight control values from each subject namely on F - 65, F - 55, F - 44, F - 7, and F - 1. These details are omitted on Figure 1 but will be seen in Figure 2.

In-flight measurements were planned on MD 0, MD + 2 and MD + 7. On MD + 2 only in two astronauts venous pressure measurements were taken. The whole mission lasted 9 days. In the recovery period after landing the data collection took place on R + 0, R + 1, R + 7 and R + 14.
The two Payload Specialists (PS 1 and PS 2) and the two Mission Specialists participated in the study.

On ground the data collection took place in the following manner: after voiding and taking the body weight (BW), a resting period of 15 - 20 minutes in supine position followed. After the venous puncture of an antecubital arm vein blood was drawn for the analysis of the hematocrits (Hct), the electrolytes and the hormones. The plasma volume (PV) and the red cell mass (RCM) were determined on three occasions (see Figure 1). Thereafter the venous pressure measurements were done. At first the peripheral venous pressure (PVP) was measured, the subject lying on his back keeping the arm almost perpendicular to his trunk (MORITZ-TABORA-method). No further corrections for hydrostatic factors were done. Then CVP was determined using the arm-down method of GAUER, HENRY and SIEKER (6). For this purpose the subject had to turn into the lateral decubitus position. This method permitted an estimation of the CVP level with adequate accuracy without intrathoracic catheterization. The measurements could be repeated ad libidum, so that over a period of several weeks a reliable baseline for each astronaut could be established. The measurements were done against atmospheric pressure using a small conventional strain gange (Fa. AME, Horten, Norway), a pre-amplifier, and a tape recorder to store the signals (Fa. Kayser & Threde, Munich, FRG). Pulse coded modulation was used for data acquisitation and a small oscilloscope to make the signals visible for the subjects. The flight unit and the unit used on ground were identical, battery driven, weighing 3 kg (9). In order to have correct CVP values on ground a correction for hydrostatic factors must be done with the help of simple anthropometric measurements 8, 9.

In space only the pressures in an arm vein were taken. Only 4 - 5 minutes were allowed for the venous pressure measurements in each subject on F - 1, in space on R + 0 and R + 1.

It is accepted that CVP or right atrial pressure cannot be considered as effective right ventricular filling pressure because pleural and pericardial pressures were not subtracted (2). However, this difference can be minimized by using only values obtained in the endexpiratory phase. In such a case, changes in CVP closely parallel the changes in effective filling pressure. A critique of the method will be given elsewhere (11).

For hematocrit (Hct) measurements a small microhematocrit centrifuge was used (Compur M 1100, Fa. Compurelektronik GmbH, Munich). Mean values out of 3 - 5 samples were used.

The Plasma AVP was determined twice on each sample by the radioimmunoassay technique of MOHRING (personal communication). The interassay coefficient was 15 % (1 - 5 pg/ml) and 10 % (5 - 10 pg/ml), respectively for 10 separately extracted samples. Extraction was performed with acetone and petroleum benzene. The overall recovery of AVP - J^{125} was 70 %. The antisera cross reaction with lysine vasopressin was less than 1 %. The limit of detection for this assay was 1.2 pg/ml plasma.
Only from 2 subjects blood samples for hormone analysis were available (Figure 6).

Results

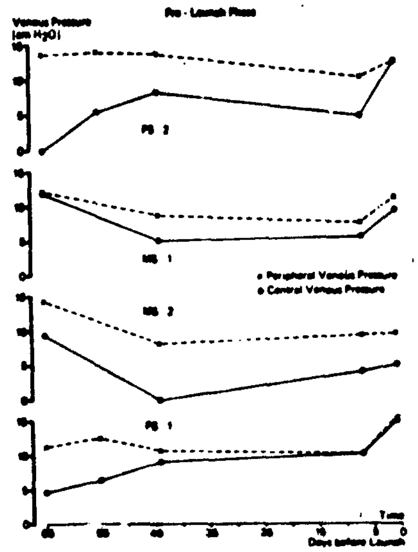

Figure 2: Pre-launch data collection of the PVP- and CVP values in 4 subjects. The data collection started 65 days before launch (abscissa left side), and ended 24 hours before launch F - 1.

In the pre-launch phase (Figure 2) the PVP values ranged usually between 10 to 15 cm H_2O and fluctuated to a much lesser extend than the CVP values. For instance in subject PS 2 on top of Figure 2 CVP ranged from 0.0 cm H_2O on F - 65 to +12.6 cm H_2O on F - 1. Despite these fluctuations of the CVP values each subject had more or less his individual CVP level (see Table 1).

Table 1: The arithmetic mean ($\bar{x}$), the highest (H) and the lowest (L) values for each subject of the PVP and CVP over the pre-launch phase.

		PVP			CVP			(cm H_2O)
	N	$\bar{x}$	H	L	$\bar{x}$	H	L	
PS-1	5	12.1	15.5	10.3	9.2	15.2	4.7	
PS-2	5	12.3	12.6	10.3	6.3	12.6	0.0	
MS-1	4	10.0	12.2	7.7	8.1	12.0	5.1	
MS-2	4	13.4	14.3	8.2	4.7	9.4	0.0	

When CVP values were low, the PVP values did not follow this trend. In these instances the venous pressure gradient PVP - CVP was rather high (see subject PS 2 and MS 2). On the other hand, when CVP values went up, they approached the PVP levels and in some cases both pressures were indistinguishable.

The most important information in this phase of observation was that within F - 7 and F - 1 in all subjects a more or less marked increase of the venous pressures was seen. In three subjects even the highest PVP and CVP values were reached. It is obvious that with lowered CVP levels the venous gradient increased which should be mainly due to the collaps occuring at the point were the veins enter the thorax. With increasing CVP levels the gradient gets smaller.

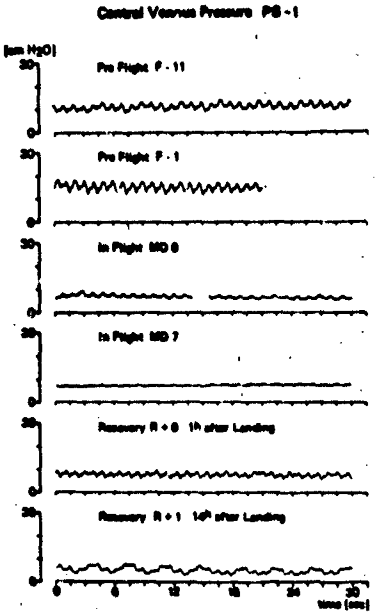

Figure 3: Typical examples of central venous pressure recordings in the pre- and post-flight period from one subject PS 1. In-flight the data from the antecubital vein were used.

The examples of a typical, original recording from one subject given in Figure 3 show convincingly that with the method applied characteristic CVP recordings could be gained. The high pressure level on F - 1 is seen easily. Most striking is the finding of MD 0. Firstly the pressure level is low (6.5 cm H_2O). Secondly despite of that, an almost complete CVP curve with all the characteric waves is seen. This is unusual in an peripheral vein and indicates an open connection between the intra- and extrathoracic compartment of the low pressure system. On MD 7 these characteristics disappeared, however, the venous pressure was low. One hour after recovery typical CVP recordings can be seen again, the values being rather high (+8.3 cm H_2O) in face of a dehydration being in this case 3.4 % of BW. 14 hours after landing the CVP was lowered but most important respiratory fluctuations clearly influence the CVP recording.

The results of the two subjects given in Figure 4 cover the most important time span of the study and are representative for the data of all of our subjects.

In the pre-launch phase from F - 8 to F - 1 an increase of the PVP and CVP went hand in hand with a decrease of the Hct and an increase of the BW. Taking all informations together, one can state that in this phase a filling of the extracellular space occurred. This raises the question what should be regarded as the baseline for the comparison with the in-flight data?

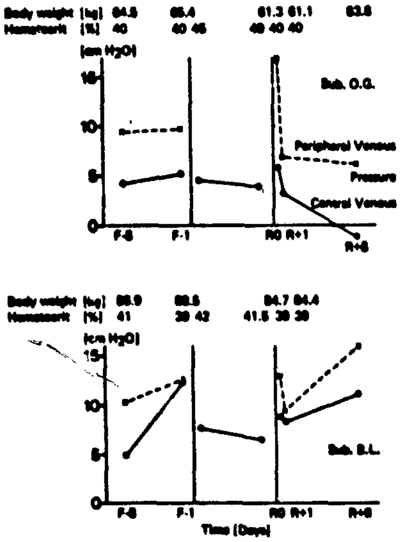

Figure 4: From the top to the bottom the data of the BW, Hct, PVP and CVP measurements of 2 astronauts over the period from F - 8 to F - 1, in-flight and in the early recovery period R + 0 and R + 1 are combined. For details see text.

As can be seen in the upper part of Figure 4, in-flight a lowered pressure level in an arm vein was seen in comparison to the PVP measurements on F - 8 and F - 1. The pressure decrease was most marked in the subject with the high pressure values on ground (lower part). Since the pressures were measured in a certain distance to the heart, the pressures in the right atrium must have been even lower than in the arm veins. In the two subjects the venous pressure levels were even lower than the CVP values immediately pre-flight. In PS 2 (lower part) the in-flight values were lower only in comparison to the F - 1 value, otherwise the in-flight values were always higher than the values on F - 8 or the x value in Table 1.

At the same time the Hct increased by 3 to 5 Hct%. In one subject the elevation remained on this level throughout the mission, whereas in the other subject Hct returned to the pre-flight level.

After landing in all astronauts a BW decrease was seen. Despite of this rather high PVP values were found which were on the level of the F - 1 data or beyond. The subject in the upper part was fluid loaded before landing, an increase of the PVP by 13.0 cm H_2O was seen. In the lower part the subject remained dry but the PVP increased by [illegible]3.3 cm H_2O. The CVP values on R0 were lowered compared to F - 1 but higher than the in-flight venous pressure levels.

In the upper example the Hct remained unchanged in the landing phase and thereafter, despite the fact of the fluid loading of the subject Below a decrease of the Hct was seen, which means that in this case fluid was added to the intravascular from the interstitial space. 12 hours after the first measurements between R0 and R + 1 a step decline of the PVP was seen, but also the CVP decreased.

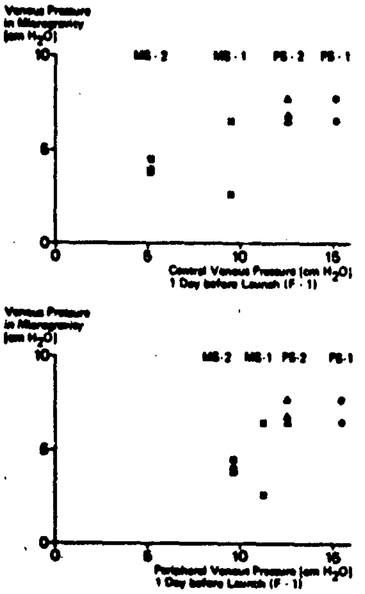

Figure 5: Upper part: Venous pressure in micro-g is plotted against CVP 1 day before launch (F - 1). Data from 4 subjects (MS 1, MS 2, P 1, P 2). Description see text.
Lower part: Venous pressure in micro-g is plotted against PVP 1 day before launch. Notice the low scatter of the data in space.

Not only that the venous pressures were lowered in micro-g, the range of the data between the subjects decreased (Figure 5 upper part). On the abscissa in Figure 5 the values extended from +5.2 to +15.2 cm H_2O, in space (ordinate) the values ranged from 3.9 to 7.7 cm H_2O. The range in space narrowed to 3.9 cm H_2O disregarding the one point of subject MS 1, whereas on ground the range was 10 cm H_2O. Even if one would compare the data in-flight with the PVP values on ground in the latter, the range would be 5.8 cm H_2O between the 4 subjects (lower part).

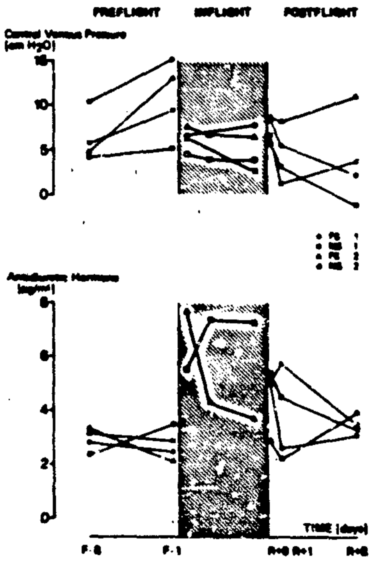

Figure 6: Upper part: CVP values pre- and post-flight are given together with the arm venous pressures in-flight.
Lower part: ADH values as collected over the same time span as above are included.

Figure 6 demonstrates in the upper part the lowered pressure level in the arm veins during space flight as compared to the pre-flight data of the CVP measurements. The time course of the values after flight between R + 0 and R + 1 is identical to what was seen on Figure 4. In face of these findings the AVP levels given below are understandable. In the pre-launch phase AVP levels ranged between 2.2 pg/ml to 3.7 pg/ml. All in-flight samples obtained showed higher values as compared to the pre-launch phase. The scatter of the data was higher than on ground. After landing (R + 0) in all cases higher ADH levels as compared to F - 1 were seen. In 3 subjects the values decreased within the next 12 hours (R + 1), but increased in one subject. 8 days later they were close to the pre-flight controls.

Discussion

All the scheduled experiments in the pre-, in- and post-flight phase could be performed and valuable data were obtained. They were published previously in a short communication (10). This must be regarded as a success having in mind the limiting factors outlined above.

The signal to background noise ratio is unfortunately rather low during such a study. However, the excellent support given by NASA and ESA and the initiative of the highly motivated astronauts kept the background noise on the lowest possible level. On the other hand, the experimenters have to separate the important signals from the background noise. In this respect the experimenters notebook is of utmost importance describing as closely as possible the environmental conditions under which the data were collected. Therefore no data had to be disregarded in our study. The simple rules in doing so were outlined excellently by ADOLPH et al. and his associates during their studies in the desert (1). This was especially important for our study since we were dealing with parameters of the salt-water physiology depending very much on the hydration level of the body and the temperatures.

The outcome of such a study also depends on the definition of the control values. As far as the CVP and PVP values are concerned, we had up to 5 data points in the pre-launch phase (Figure 2). Despite of the expected fluctuations of the values for each subject a baseline could be established (Table 1). Therefore the filling up of the extracellular space in the quarantine phase indicated by increasing BW's and venous pressures and decreasing Hct's (Figures 2, 3, 4, 6) could be detected and taken into consideration. Compared to the values on F - 8 and F - 1 the venous pressures in space were mostly substantially lower. At least for the first data point (MD 0) 22 hours after launch due to the fluid shift elevated pressures were expected. Russian authors described this in their subjects measuring the pressure in the ingular vein in their cosmonauts (16, 22). At this point it must be mentioned that the Russian cosmonauts have to undergo an adaptive training sleeping in head-down position in the pre-launch phase (KATHOV, personal communication). Thereby their extracellular space might have been depleted to a certain extend so that the control values for the venous pressures were lower than normal. The fluid accumulation in the upper half of the body in space might then lead to an increased venous pressure. Therefore their data cannot be used in connection with ours.

If we had based our expectations on the results of BLOMQVIST and his group (3, 4, 17), who used the head-down tilt model to simulate the fluid distribution in space, our results would not have been a surprise. These authors only found a short CVP increase during the first 90 minutes of the head-down tilt, later the values fell even below the controls. The latter was seen by us even if we would compare the arm vein values against the CVP values on ground (Figure 4). POURCELOT et al. (18) measuring cardiac dimensions with echocardiography found on the second day of spaceflight a reduced left ventricle systolic and diastolic diameter. The elevated Hct at this point of the mission indicates a reduced plasma volume (Figure 4). Apparently after the fluid mobilisation from the lower limbs an extravasation of fluids occurs into the upper half of the body mainly into the tissues of the head and neck and the lungs. Furthermore, a reduced fluid intake can be assumed. Despite the fact that exact data on this matter are not available, this can be deduced from the findings of the Skylab Missions. Here already very early a reduction of the body mass was observed, indicating a negative fluid balance (21). All factors together should keep the plasma volume low in space and hence the venous pressures (8).

The astonishing fact is that the low pressure system reacts in such a dynamic way to the stimulus of weightlessness. The space adaptation of this system apparently takes place during the first few hours. In this phase lasting probably only six hours the pressures in the upper parts of the body might well be increased as compared to ground values but this must be shown in future missions. In this respect our results will influence the time line of future missions. Later in-flight the values are not only lowered but also the scatter of data is reduced (Figure 5).

Is this due to the fact that the hydrostatic component of the intravascular pressure is eliminated? In space only the mean circulatory filling pressure which depends of the filling volume and the elastic properties of the vessel walls together with the hydraulic pressure generated by the heart determine the intravascular pressures. Not only that the hydrostatic factor on earth often introduces errors into the measurements, this factor also induces reflex mechanisms in order to maintain a proper cardiovascular function (19, 20). It might well be that with the elimination of the hydrostatic forces the cardiovascular system reaches an equilibrium with a minimum activation of reflexes so that the scatter of the data is reduced.

In the light of the data of venous pressure measurements the ADH data (Figure 6) fall in line with the GAUER-HENRY-hypothesis (6). In space the venous pressures are low and hence the ADH levels should be high, which was the case. However, this would be a very simplistic view. Other factors like the plasma osmolality might also influence the ADH levels. And it cannot be excluded that the symptoms of the space adaptation syndrome like vomiting and nausea might have had impact on the ADH levels. Much more data are needed to proof or disproof this hypothesis.

The following conclusions seem to be justified. As experimentation in space in the future becomes easier available to the physiologists, the difficulties reported can be overcome and a clearer picture of the human physiology under the conditions of weightlessness emerges. It is and will be a challenging field and will surely add to our knowledge about man on earth.

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DISCUSSION

COLLIN, FR

Pour mesurer la pression veineuse centrale, vous prenez la pression veineuse péripherique et mésurez la distance pour retrancher la pression hydrostatique. Il reste encore un facteur qui est la perte de charge. Comment pouvez vous la mesurer ou en tenir compte puisqu' elle varie suivant la vasomotricité veineuse?

AUTHOR'S reply

If I understand you correct, you want to say, there must be a pressure gradient between the peripheral and the central veins. There is a so called "dynamic factor" in the venous system. However, this gradient is rather low and should not be more than 1 or 2 cm H_2O.

COLLIN, FR

Ceci est trés faible, mais toutefois important vis à vis de la très faible pression veineuse centrale. L' erreur sur la pression veineuse centrale peut donc être importante.

SANDLER, USA

It is very important in making your measurements, to know the position of the heart within the chest. How did you determine where the heart position was before flight? And what, if the heart moved its position significantly inside the chest during weightlessness? Would this in any way alter your measurements?

AUTHOR'S reply

In Space the hydrostatic component of the pressure is eliminated therefore the problem you address is only important for measurements on ground. On ground you have to know where the heart is situated. We did this by usual anthropometric means. More important is, that you always have the exact distance between your point where the heart is and the pressure transducer. If this is defined and constant, the fluctuations you see are due to a physiological factor and not to a methodological error. I agree that the absolute height of the central venous pressure might be slightly different of what you might have obtained if you could have used an indwelling catheter in the right atrium. However the pressure changes you observe, the fluctuations during the time course, you can pick up easily with our method.

SANDLER, USA

How did you determine clinically the position of the heart?

AUTHOR'S reply

The usual way, by percusion and auscultation.

TERZIOGLU, TU

You say, there was an increase in venous pressure just before launch. Did you measure at that time arterial blood pressure and arterial blood flow? In other words, I would like to know, whether it is just an effect of stress.

AUTHOR'S reply

We measured arterial blood pressure which did not show any change. We did not measure blood flow. However, we measured cortisol hormon which tells us something about stress. The cortisol levels were slightly higher; there might be some stress involved.

TERZIOGLU, TU

My question concerns not only your presentation but, also, some of those delivered yesterday. I was quite surprised that in space only cardiovascular parameters are measured but obviously not parameters of the respiratory system. Did you follow pulmonary function in space?

AUTHOR'S reply

No, we did not, since we did not have time to do so.

TERZIOGLU, TU

There was an increase in the hematocrit values in space, which as you pointed out may be due to dehydration. Was plasma volume also measured?

AUTHOR'S reply

Plasma volume was determined before launch and immediately after return, not in space. It decreased about 10% - 15%.

TERZIOGLU, TU

Did you try to correlate your aldosteron levels with the levels of electrolytes?

AUTHOR'S reply

Electrolytes were determined by Carolyn Leach-Huntoon, NASA JSC, Houston. She found a slight increase in the sodium levels during space flights. This might be due to the hemoconcentration and the water loss the astronauts experienced. But this, of course, does not explain the most interesting findings after landing.

SANDLER, USA
Did you make any experiments on the ground where you have decreased plasma volume and see what this does to your measurement?

AUTHOR'S reply
No, we have not done such an experiment.

THREE-DIMENSIONAL BALLISTOCARDIOGRAPHY IN MICROGRAVITY *

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Summary

Some triaxial ballistocardiograms (BCG) and one electrocardiogram lead have been repeatedly recorded on 4 crew-members of the Columbia Shuttle (STS-9) before, during and after a microgravity period of 9 days.
In view of this project a miniaturized accelerometric equipment was designed and manufactured so as to pick-up the BCG signal from the dorsal region and to record it on a magnetic 4-track tape recorder. A special sequence was devised and implemented in the various flight and ground stages. The measurements carried out on numerous and long tracing samples, previously decoded and transcribed on paper, proved the reliability of this technique and also provided us with the following results.

1. The amplitude of the four BCG systolic waves is — as a rule — higher in microgravity as compared with the ground basal values, but it decreases together with the duration of the flight. This can be observed both in the accelerations along the body longitudinal axis (which are the most regular in all the explored conditions) and in the accelerations along the transversal and sagittal axes (the latter being almost always of lower amplitude).
2. Under microgravity conditions we noticed that also the ratios of the relative amplitude of the same 4 waves resulted to be modified so as to form a capital M pattern.
3. The sum of the mG amplitude of the 4 waves recorded along the 3 body axes, shows an inverse correlation with the heart-rate.

These results will be submitted to a computer processing as soon as an adequate program will be ready.
The Authors deem it necessary to carry out a second space experiment having the "targeted" objectives provided for by the experience resulting from this research, having a general character.

I. INTRODUCTION AND GENERAL DATA

The research that was carried out deals with one of the most peculiar and controversial non-invasive methods of cardiovascular function exploration, for which microgravity is a unique experimental condition that cannot be obtained on ground : the ballistocardiography (BCG).
Before presenting the results obtained during the study stage, we would like to provide you with some information and brief considerations on the specific technical and scientific aspects of this research, on the experience resulting from it and on some cardiovascular data of general interest.

1. Scientific and technical aspects

The main scientific objectives of this experiment were :

- numerous recordings of the BCG tracings along the 3 body axes, by means of accelerometric sensors secured to the back of the subjects during the whole microgravity period, together with one ECG lead ;
- Collection of the same data, from the same subjects, several times prior to flight and after re-entry, so as to compare the BCG recordings obtained under substantially equal conditions, the only difference being the gravity factor.

The aim of this programme was to obtain more information on cardiovascular and fluid adjustment phenomena during space flights (and on readjustment to earth gravity) and particularly to acquire deeper knowledge of the physiological

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*This research was carried out thanks to the financing of CNR-National Space Plan. Ground experiments have been carried out at the ISEF laboratory of Applied Physiology in Rome.

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meaning of the various waves that make up the BCG signal , after assessing their quantitative features. Due to these reasons we studied a particular recording sequence including periods of normal breathing , of breath-holding , of the Valsalva manoeuvre , of light dynamic exercise , of short-lasting isometric exercise , and also a change in body posture (crouched posture).

The implementation of this project, both on ground and in flight, implied our ability to overcome difficulties and technicalities that could hardly be thought of when physiological research was being carried out in a ground laboratory , and it also required our working out of new original procedures and techniques in order to attain the target aims. Another major drawback was the need to set and establish both the techniques and the procedures much before the actual execution of the experiment , and not being able to modify them in the light of the results obtained from ground experiments.

The materials and methods have already been illustrated on the occasion of the Second European Symposium of Life Sciences Research in Space (Porz-Whan , 4-6 June , 1984 , ESA), thus we will here simply illustrate the essential data. Due to fundamental weight and feeding requirements , that also led to the choice of the Medilog 4-2 recorder (Oxford Medical Systems) , we adopted the ENTRAN damped piezoresistive accelerometric sensors , though we knew about their thermal and aging characteristics. Both flight equipment and identical models were designed, manufactured and calibrated in Rome , by the CONEL Company , under the supervision of the Project Manager. The general features are :

Equipment made up of two parts :

a) "dural" plate suitably secured to the back of the subject, supporting the small box that contains the 3 sensors set in a triaxial configuration , their respective preamplifiers plus one ECG preamplifier.

b) box containing the amplifying system , active filters (passing band 0.2 ÷ 30 Hz), control systems and a 4-track miniature tape recorder connected to the other small box by means of a shielded cable measuring 3 metres in length.

Other features of our equipment were :

autonomous feeding ± 3 volts ; recording time of approximately four hours (3 standard cassettes of 90 minutes each); overall weight of 2,700 grams , alkaline batteries being included (Figs 1 and 2).

Ground recording **were** carried out by means of a suspended camp bed secured to four thin steel-cables having a natural frequency of about 0.29 Hz.

The recordings of the triaxial BCG sequences plus one chest ECG lead (each having an average duration of about 10 minutes) were carried out on the 2 Payload Specialists and on the 2 Mission Specialists , 11 days before (F-11) and then again 24 hours prior to the flight (F-1). These recordings were also carried out within 24 hours after re-entry (R+0) and then again 6 days after re-entry (R+6). During the first 8 days of flight some recordings were carried out on the PSs starting from the 16th hour after lift-off (F-I) , while the recordings carried out on the MSs began from the 5th day (F-E) onwards. The total number of the performances was 14.

The sequence was inclusive of periods of approximately 30 seconds of spontaneous breathing , of breath-holding , of a Valsalva manoeuvre lasting about 15 seconds , of a light physical exercise lasting 3 minutes , of 1 minute of recovery followed by 15 seconds of breath-holding , of a short-lasting isometric contraction of the lower limbs and , in the end , the assumption of a crouched posture.

2. Acquired experience

This topic involves some aspects that are common to all studies carried out on human beings , the constraints of which become more serious due to the space situation (potential danger of electric shock provoked by equipment or static discharges ; offgassing ; dangerousness of unsecured equipment and instruments ; risky manoeuvre execution ; use of chemicals ; etc.). Our experiment also involved some specific aspects , which can be listed as follows :

a) requirements that were not fulfilled during flight :

- protracted motionless of the subject who is not secured to fixed bearing systems (the body slowly drifts because of air conditioning system and of inertial phenomena due to slight body movements and to respiration) ;
- stretched body posture at rest (under microgravity conditions the subject assumes a spontaneous semi-crouched posture , in the guise of a primate , and a voluntary effort of the anti-gravity muscles is needed in order to maintain a stretched attitude) ;
- a good ECG recording (our recommendation to keep the adhesive chest electrodes during the entire flight was not attended ; in some other cases the electrodes or the connectors broke loose during physical exercise and were later reattached in a wrong position or with too much delay) ;
- reliable BCG tracings during or after certain **manoeuvres** in the experimental

sequence (Valsalva manoeuvre , isometric contraction , crouched posture) : we believe that this is a consequence of severe disturbances caused by the muscular movements necessary to implement such manoeuvres in the absence of ground supporting systems ;

- effective dynamic exercise (we had to give up a hard enough one in order not to compromise other experiments) ; in this case there has been a further drawback , which was pointed out by the PSs at the time of debriefing , namely the eccessive compliance of the elastic bungee that was on board.

b) Operational problems

- in more than one occasion the marker system acting on the ECG tracing proved to be unreliable due to the absence of this signal or due to occasional operating errors ;
- the recording of the single steps differ both on ground and in flight performances;
- certain performances were disturbed by , or postponed due to the needs of other experiments ;
- air-to-ground voice communications were inadequate ;
- the only televised communication took place at the end of the mission , thus the visual information was obtained with delay (for example : it was only at that time that we could observe the wrong position of one electrode).

These two last drawbacks proved to be particularly disturbing as our experiment could not be monitored or televised during the flight stage . The many difficulties and doubts that affect our research in its present stage , suggest us that the scientific return of further studies in this field , can be improved by real-time transmission of recording samples directly as electrical signals or by means of an adequate on-board monitor system.

II.GENERAL CARDIOVASCULAR AND METABOLISM-RELATED DATA

It is common knowledge that the heart-rate was the first physiologic parameter to be studied and monitored on space crews. We will here give a short account of this topic as we have obtained data that can prove to be of some interest for other experiments. As already described by other Authors , we noticed that under microgravity conditions all 4 subjects presented some decrease in heart-rate together with an increasedheart-rate variability at rest.

Table I shows the average values of the five conditions (resting , Valsalva , post-Valsalva , exercise , recovery) that were recorded in different days. The heart-rate trends reported during the various performances are shown in Figs 3-6 .

Without going into the details of these data , we will say that the average rate in microgravity — at rest — is lower than 11.4% , as compared with F-11 , and that during the 24 hours that followed landing this rate is higher than 10.1% , though it goes back to its normal values in the recordings that were made on the 6th day after re-entry. The response to the endothoracic pressure increase , related to the Valsalva manoeuvre , was of about +29% (min. 21.7 ; max. 38.3 — in the youngest subject) and there are no noticeable differences between pre-flight and post-flight heart-rates.

On the contrary , as could easily be expected according to the existing literature, even the slightest physical exercise caused in R+0 a major increase in heart-rate (+73%) , which becomes even higher (+86%) if compared to the pre-flight values at rest.

Anyway , we should say that these percentage oscillations are but trends , given the fact that a) it is very difficult to carry out the Valsalva manoeuvre obtaining always the same increase in endothoracic pressure , even in the case of well trained subjects as ours ; b) it is very difficult to uniformly carry out (especially during flight) the kind of physical exercise that was chosen to conciliate the various requirements ; c) before our experiment the subjects carried out various activities .

Table II shows the BTPS pulmonary ventilation , the O_2 consumption and the respiratory quotient values(*) that were recorded before and during the exercise consisting

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(*) These measurements were carried out in the NASA laboratories in the Dryden Flight Research Facility (Edwards AFB , California) and in the Kennedy Space Center (Cape Canaveral , Florida) by Mr. Mark Timm and Mr. Daniel Yost, Jr., to whom we would like to express our most felt gratefulness .

of the stretching an elastic bungee secured to the floor once every second , for a time period of 3 minutes. Due to time reasons the recovery period was not recorded and, in most of the post-flight exercises , the duration was reduced because the subjects found it difficult to perform them while standing.

So , as a matter of fact , these data proved to be useless as far as the BCG research was concerned , but in our opinion they are worth knowing because they might prove useful to other investigators.

III.BALLISTOCARDIOGRAPHY RESULTS

On the occasion of the Porz-Whan and Anacapri meetings (that took place respectively on June 4th and June 14th , 1984) , we illustrated the preliminary results of our research which we will here summarize and that will be followed by the presentation of the results obtained from the researches that were carried out in a later stage .

The work that has been carried out up to now , that is to say BCG complex by complex direct measure of the dimensions and ratios of the 4 (and sometimes 5) waves that make up the systolic fraction of the signal , was made on the 3 "leads" that were obtained and that correspond to the body accelerations along the longitudinal (Z) , transversal (Y) and sagittal (X) axes ; the exact timing of the first positive wave (H) was made — as usual — at the beginning of the S-T section of the ECG. The wave amplitude was calculated on the basis of the calibration factor of the recording , decoding and printing system (10 mm shift = 1mG). This measure (G-H , H-I , I-J , J-K) is relative , not absolute , given the fact that a stable base-line is not available.

A.Comparison of the amplitude of the tracings.

When considering the 4 subjects and the longitudinal BCG axis (Z) (which in general gave more regular signals) , during breath-holding and resting conditions , the sum of the systolic waves (from H to K) according to the final calibration factor , is as follows :

prior to flight (F-1) : 4.9± 0.9 mG

during the first 2 days of flight (F-I) : 8.4±1.9 mG

during the 2nd stage of the flight (F-E) : 7.5±1.3 mG

6 days after landing (R+6) : 4.4±1.3 mG

The tracings that were collected immediately after the exercise are — in general — of poor quality or they do not show the ECG signal. The sections that could be utilised show the expected increase , which is more evident during microgravity (about ± 3 mG as compared with the ground variation).

When considering the amplitudes in function of the age of the 4 subjects , we do not obtain any reliable relationship , at least under microgravity conditions , but it is not possible to make a final statement on the basis of just 4 subjects whose age ranges from 35 to 53 .

B.Comparison of the pattern of the BCG waves.

Under microgravity conditions , the trend of the systolic section of the BCG is similar to the one that was recorded on the ground , but the amplitude ratios of the 4 main waves are considerably different : in fact, in the first case , the Z axis shows a relative amplitude increase of the G-H and J-K sections as compared with the lower negativeness of I , thus the tracing assumes the shape of a more or less asymmetric capital M . This trend was described some 30 years ago by V. Masini who worked by means of the Starr table and interpreted it as the expression of a reduced ejection force of the left ventricle with protraction of the related time , so that the I wave results to be less deep than normal. This trend is more frequent on the Z axis and it is even more accentuated towards the end of the flight.

We studied more thoroughly the ratios of the same waves by extending our observation to the Y and X axes , which under microgravity conditions are not altered by the mechanical bearing systems.

The statistical means of 20 complexes for each condition are shown in Table III , and are also graphically represented in Fig. 7 which refers to the BL subject. The comparison refers to the amplitude ratios of the 4 waves , at the beginning (a) and at the end (b) of the flight.

A first result concerns the relative dimensions which are very similar as far as the Z and Y axes are concerned ; while we can observe that the amplitude on the X axis is practically half of the others (see Table III).

One intersting datum comes from Table IV which shows the sums of the 4 waves during the initial phase (a) and then from the fifth day onwards (b) : in the second phase there is a decrease in amplitude of about 28%.

When plotting the mG values of the sums of the BCG of the waves of the 3 body axes against the heart-rate measured on the same complexes , we obtain an inverse correlation which is more or less manifest in 3 of the subjects while we obtain none in the fourth subject (Fig. 8).

And finally , the ratio between the sum of the 4 waves and the body weight which could be correlated to the ventricular power(and partially to the vascular resistance) , gives a value that ranges from 0.24 to 0.36 , with the exception of one case .

This ratio shows the highest values at the beginning of microgravity and the lowest values at the end of microgravity , but the values of the body mass , during flight , are still missing.

IV. FINAL CONSIDERATIONS

The data obtained directly on the basis of the decoded tracings that were collected by means of the flight equipment , provided us with some results that in our opinion are quite reliable.

The first , though apparently obvious , is that the particular mechanical phenomenon , called ballistocardiogram , occurs in microgravity in a similar way to the one that occurs on ground. This coincides with the pioneer studies made by Beischer and Hixon (1965) , with the peculiar recordings of Baevsky and Funtova (1982) and with the remarkable self-observations made by O. Garriott and E.G. Gibson during the various Skylab flights.

A second fact is represented by the increased overall amplitude of the 4 BCG systolic waves during microgravity (about +71% at the beginning and +53% by the end). This fact had already been pointed out by us and it is still a reliable one also when considering the overall sum of the 3 axes.

We do not know whether this phenomenon is the expression of an increase in the ventricular contraction rate (which was also reported in the echocardiographic examinations made by Pourcelot), or of variation in the arterial resistance ; or of possible modifications of the body mechanical impedance due to muscular hypotonia , to a change in body posture , to the complete absence of any damping bearing system or , maybe , to all of these factors.

We can also confirm that when the microgravity period was extended this phenomenon tended to attenuate itself but was still above "ground" levels.

A third fact is represented by the inverse correlation (at least on 3 of the 4 subjects) between the overall amplitude of the BCG systolic waves and the heart rate. This fact could very well give rise to some considerations on the relationship between the BCG and the stroke volume , but we dare not discuss this matter , at least for the time being.

Some of the "oddities" and the considerable dispersion of our data can certainly be ascribed to the slight changes in the body posture during different recordings (or during the same recording) or even to the setting and position of the dorsal plate. They could also be ascribed to the physiological effects of the activities that were performed immediately before , or to the shift and consequent reduction of fluids , etc. As a consequence of this , only a computerized statistical processing of these data will be able to confer a higher reliability to our results. Unfortunately , we were not able to satisfy our requirements due to the many difficulties that arose during the preparation stage of a program capable of "recognizing" the reliable sections of a tracing and the different artifacts , to set a true baseline , to find out the magnitude of the reading " window ". This will enable us to extend our research to other factors that are involved in the BCG , the trend of the acceleration vector in the 3 space dimensions being included.

All this presupposes not only a further examination of the material that has been collected up to now , but also the carrying out of a new experiment , in microgravity , that should be free from most of the drawbacks that alter the BCG recording.

Table I

Heart rate measured on ECG recorded in the 5 conditions below

Date	Subject : BL					Subject : UM					Subject : RP					Subject : OG				
	Rest.	Vals.	Post-V	Exerc.	Rec.	Rest.	Vals.	Post-V	Exerc.	Rec.	Rest.	Vals.	Post-V	Exerc.	Rec.	Rest.	Vals.	Post-V	Exerc.	Rec.
18 Nov.'83 (F-11)	61	78	60	104 (138)	72	66	78	60	115 (144)	80	76	92	67	105 (114)	79	64	70	62	104 (120)	75
28 Nov.'83	66	102	60	116 (138)	78	57	67	50	104 (114)	66	58	65	52	103 (140)	69	69	91	66	103 (108)	78
28 Nov.- 8 Dec.'83	53	87	48	-	57	47	58	44	60 ?	52	69	92	70	-	79	67	80	61	-	72
8-9 Dec.'83 (R+0)	67	96	54	122 (162)	67	56	74	52	111 (140)	73	86	101	85	136 (160)	101	85	119	86	132 (147)	91
14 Dec.'83 (R+6)	56	56	51	78 (85)	65	60	86	51	67 (75)	55	78	97	80	99 (120)	87	68	95	55	99 (120)	73

Rest. : mean values relative to the minute prior to BCG sequence

Vals. : values of the last 5 sec of closed glottis forced expiration

Post-V.: value immediately following the end Valsalva manoeuvre

Exerc. : mean values of the whole period, lasting 2-3 minutes; between brackets, the highest value

Rec. : initial 30 sec. of recovery

Table II

Pulmonary ventilation, O_2 consumption, respiratory quotient, heart rate values in the conditions below

Date	Subject:BL;35 yrs;84,6 kg;182 cm					Subject:UM;42 yrs;68,2 kg;173 cm					Subject:RP;47 yrs;73,5 kg;175 cm					Subject:OG;53 yrs;61,2 kg;172,5cm				
	V_E BTPS 1/min	V_{O_2} STPD 1/min	$V_{O_2}^{MX}$	R	HR	V_E BTPS 1/min	V_{O_2} STPD 1/min	$V_{O_2}^{MX}$ 1/min	R	HR	V_E BTPS 1/min	V_{O_2} STPD 1/min	$V_{O_2}^{MX}$ 1/min	R	HR	V_E TPS 1/min	V_{O_2} STPD 1/min	$V_{O_2}^{MX}$ 1/min	R	HR
18 Nov.'83 (F-11)																				
Resting	11,6	0,462		0,81	61	10,1	0,357		0,86	66	9,66	0,296		0,85	76	10,3	0,339		0,89	64
Exercise	31,5	0,861		1,11	104	31,6	0,741		1,06	115	19,6	0,489		0,96	105	22,1	0,648		1,0	104
			1,0		138			0,947		144			0,608		114			0,788		120
8 Dec.'83 (R+0)		(+ 5h)					(+ 20h)					(+ 19h)					(+ 23h)			
Resting	13,1	0,465		0,83	67	10,1	0,371		0,80	56	10,6	0,323		0,76	86	9,1	0,304		0,93	85
Exercise	36,1	0,900		1,07	122	30,2	0,836		1,05	111	32,3	0,778		0,95	136	20,7	0,551		0,95	132
			1,118		162			1066		140			0,979		160			0,630		147
14 Dec.'83 (R+6)		(PM)					(AM)					(AM)					(PM)			
Resting	13,9	0,420		0,85	56	11,3	0,331		0,82	60	12,2	0,324		0,82	78	11,8	0,306		0,99	68
Exercise	29,0	0,790		1,15	78	32,4	0,764		1,10	67	29,2	0,738		0,92	99	21,3	0,543		0,99	99
			0,916		85			1125		75			0,952		120			0,662		120

Note : a) The two heart rate figures of the exercise represent respectively the mean and the maximum value (3rd figure, on the $V_{O_2}^{MX}$ LINE).

b) The hours shown in brackets are referred to the time elapsed after landing.

Table III

Statistical means of G-H, H-I, I-J and J-K waves of BCGs recorded during the STS-9 flight (Values in milliG)

		G-H		H-I		I-J		J-K			HR
		$\bar{x}$	σ	$\bar{x}$	σ	$\bar{x}$	σ	$\bar{x}$	σ	Σ	
Subj. : UM (a) MET 1:16:45 (Mission elapsed time : days, hours, minutes)	X	0,16	0,28	0,71	0,32	1,39	0,33	1,39	0,42	3,65	43
	Y	1,66	0,39	1,73	0,41	0,79	0,20	1,08	0,37	5,26	
	Z	2,38	0,20	2,13	0,26	1,30	0,27	2,47	0,35	8,28	
Subj. : BL (a) MET 2:03:59	X	1,07	0,34	2,53	0,37	3,64	0,42	2,79	0,38	10,03	50
	Y	1,26	0,43	1,93	0,47	2,68	0,41	1,71	0,49	7,58	
	Z	1,71	0,38	2,28	0,29	3,23	0,44	3,74	0,31	10,96	
Subj. : OG (a) MET 5:03:25	X	0,88	0,29	1,43	0,54	2,17	0,30	2,0	0,37	6,47	60
	Y	1,96	0,30	4,88	0,43	6,64	0,51	4,64	0,37	18,13	
	Z	2,31	0,25	1,99	0,32	1,81	0,59	3,88	0,43	9,98	
Subj. : RP (a) MET 5:15:20	X	0,46	0,20	1,21	0,22	1,90	0,42	1,17	0,24	4,74	61
	Y	1,89	0,52	3,64	0,97	4,59	0,92	3,01	0,70	13,12	
	Z	1,62	0,26	1,49	0,35	1,68	0,69	3,42	0,44	8,21	
Subj. : UM (b) MET 7:13:00	X	0,05	0,10	0,55	0,23	1,02	0,39	0,75	0,34	2,37	53
	Y	1,58	0,72	1,94	0,85	1,76	0,91	1,60	0,65	6,89	
	Z	2,76	0,33	2,40	0,24	0,47	0,19	1,37	0,22	7,0	
Subj. : RP (b) MET 7:13:20	X	0,32	0,15	0,67	0,29	0,91	0,37	0,79	0,22	2.69	69
	Y	1,58	0,51	1,73	0,46	2,34	0,67	1,87	0,57	7,52	
	Z	0,79	0,43	1,06	0,34	2,08	0,34	3,25	0,60	7,19	
Subj. : BL (b) MET 8:02:50	X	0,43	0,24	1,01	0,28	1,95	0,25	1,55	0,27	4,94	50
	Y	2,11	0,[illegible]	1,84	1,02	1,22	0,65	1,53	0,66	6,69	
	Z	2,12	0,31	1,43	0,25	1,44	0,26	3,91	0,47	8,69	
Subj. : OG (b) MET 8:03:05	X	0,67	0,22	0,98	0,32	1,35	0,34	1,39	0,33	4,39	69
	Y	1,53	0,52	3,01	0,56	3,53	0,86	3,31	0,71	11,38	
	Z	1,47	0,27	0,61	0,37	1,[illegible]	0,28	3,22	0,59	6,52	

Table IV

Relationship between BCG whole accelerations ($\sum_{xyz}$ systolic waves in milliG) and body weight in kg

		$\sum_{xyz}$ (H -K)	kg	ratio
Subj.: BL	a	28,6	85	0,34
	b	20,5	"	0,24
Subj.: UM	a	17,2	68	0,25
	b	16,3	"	0,24
Subj.: RP	a	26,1	73	0,35
	b	17,4	"	0,24
Subj.: OG	a	34,6	61	0,56
	b	22,3	"	0,36

Note: a = first record; b = second.record (se table III)

FIG. 1

FIG. 2

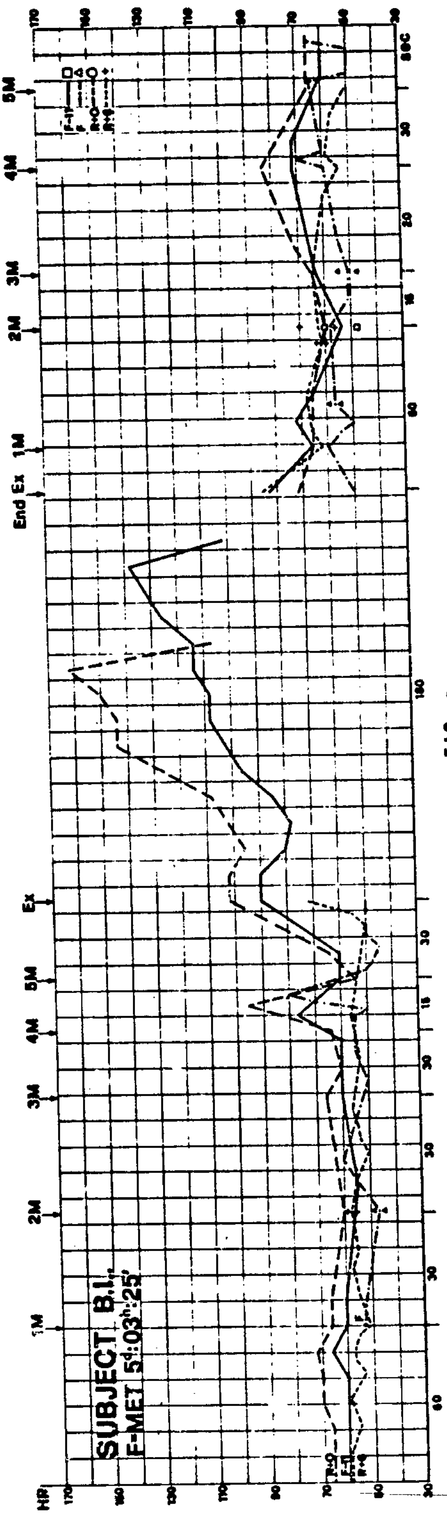
SUBJECT B.I.
F-MET 5d:03h:25'
HR
170
150
130
110
90
70
50
30
R+0
F-11
R+8
F
1M
2M
3M
4M
5M
Ex
End Ex
1M
2M
3M
4M
5M
F-11
F
R+0
R+8
SEC
60
30
30
30
15
30
180
60
15
20
30
SCHEDULED SEQUENCE

FIG. 3

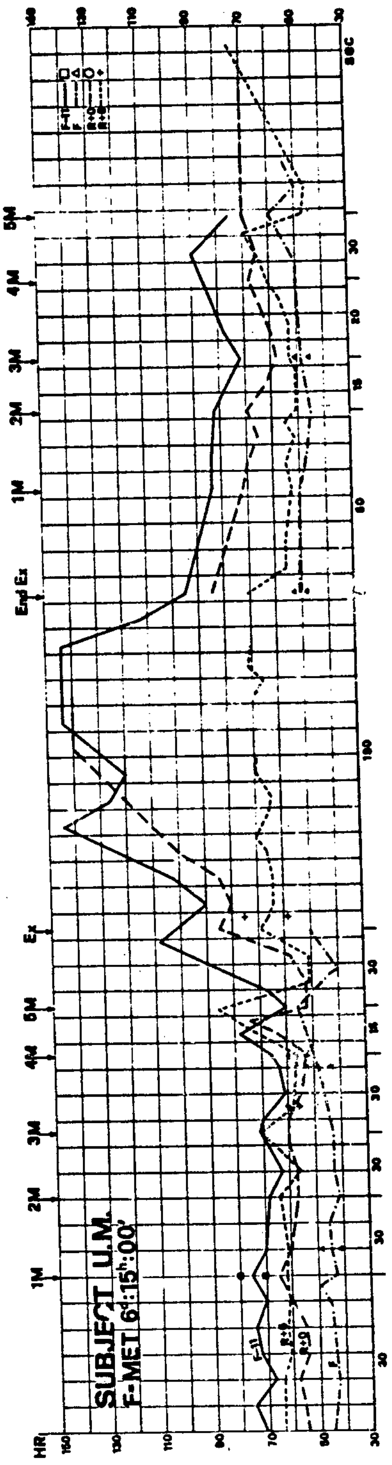
SUBJECT U.M.
F-MET 6d:15h:00'
HR
150
130
110
90
70
50
30
F-11
R+8
R+0
F
1M
2M
3M
4M
5M
Ex
End Ex
1M
2M
3M
4M
5M
F-11
F
R+0
R+8
SEC
30
30
30
30
30
15
30
180
60
15
20
30
SCHEDULED SEQUENCE

FIG. 4

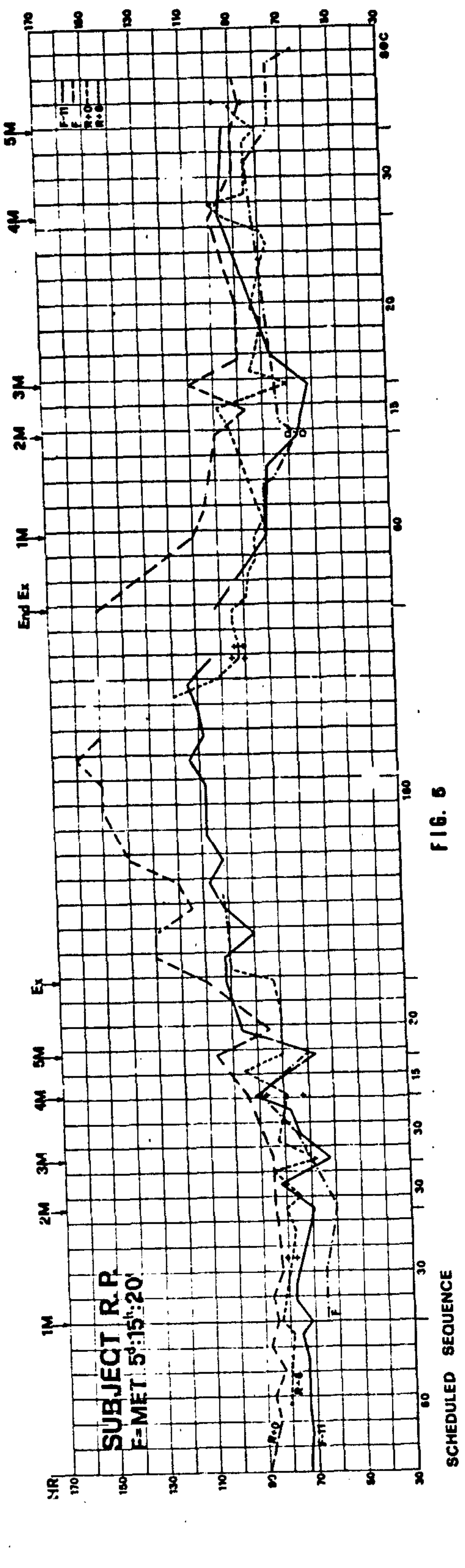
SUBJECT R.P.
F-MET 5d 15h 20'
HR
170
150
130
110
90
70
50
30
1M
2M
3M
4M
5M
Ex
End Ex
1M
2M
3M
4M
5M
SEC
F-11
F
R+O
R+S
SCHEDULED SEQUENCE

FIG. 5

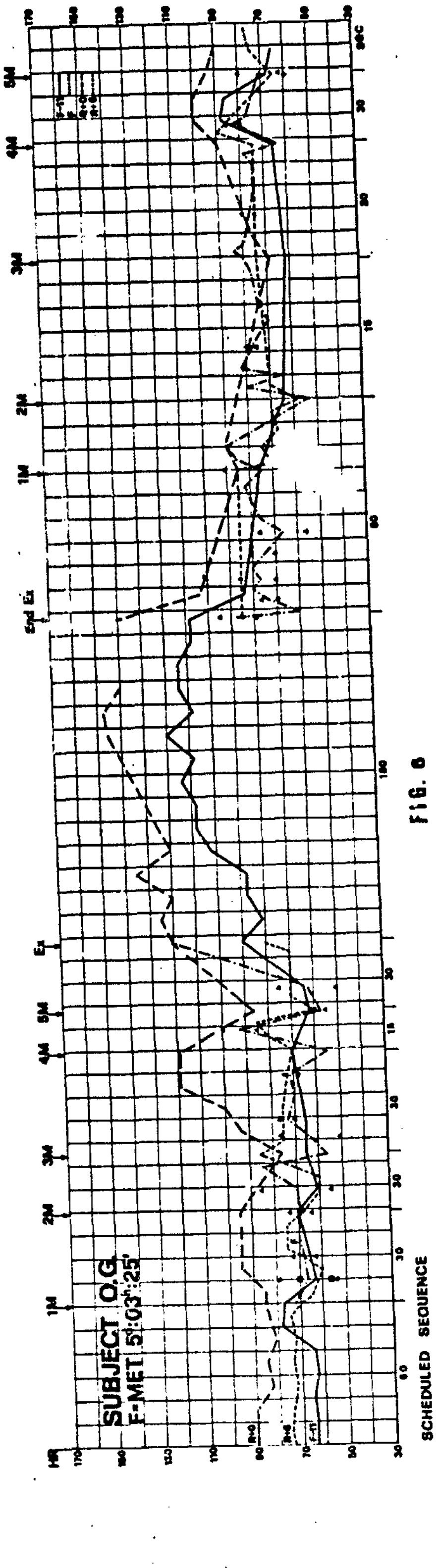
SUBJECT O.G.
F-MET 5d 03h 25'
HR
170
150
130
110
90
70
50
30
1M
2M
3M
4M
5M
Ex
End Ex
1M
2M
3M
4M
5M
SEC
F-11
F
R+O
R+S
SCHEDULED SEQUENCE

FIG. 6

SUBJECT B.L.

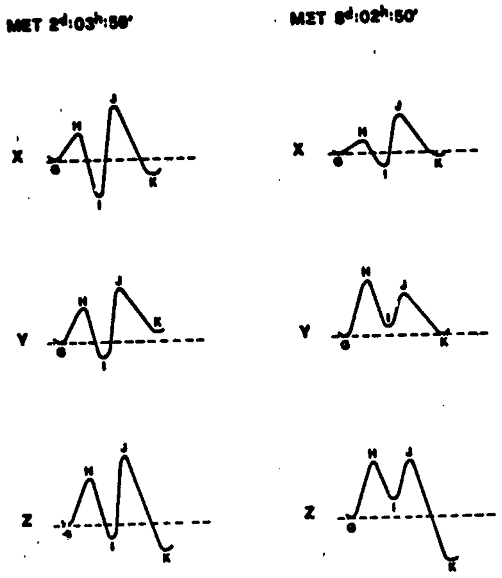

FIG. 7

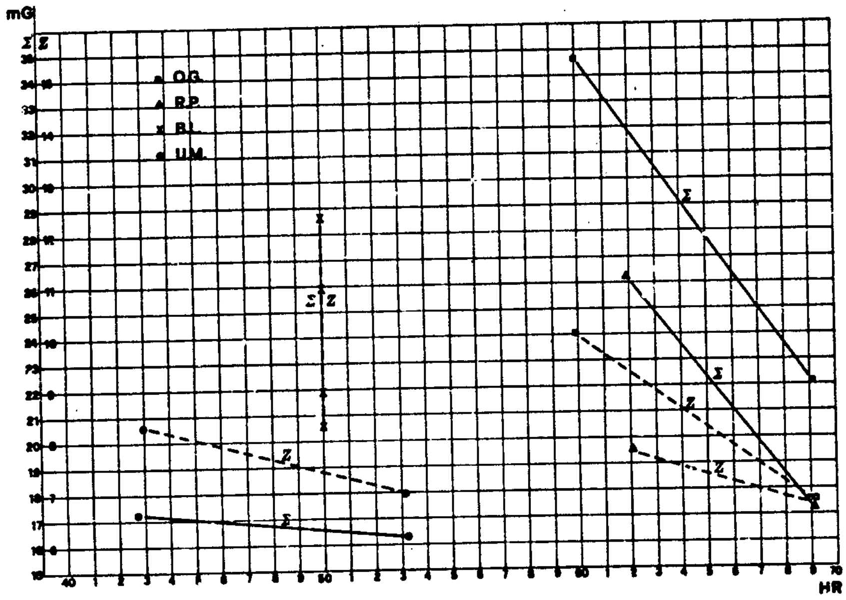

FIG. 8

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DISCUSSION

KLEIN, FRG

You mentioned almost no difference in O_2-uptake during exercise in space. What was the exercise level? Was it submaximal or maximal?

AUTHOR'S reply

In order not to disturb other experiments, it was unfortunately an extremely light exercise with the arms, only.

SLEEP AND WAKE PHYSIOLOGY IN WEIGHTLESSNESS.

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Summary.

Among the electrophysiological parameters which are used to define the sleep and waking states, the muscle activity (EMG) and the eye-movements (EOG) were recorded during sleep in the Spacelab 1 mission, allowing detection of Rem-sleep but precluding evaluation of slow wave sleep. The EOG evidenced an important increase in the number of eye-movements during night zero as compared to the pre- and postflight baseline data. The waking electroencephalogram (EEG) was recorded during parabolic flights and showed a significant increase in the theta frequency band during the acrophase of the parabolas.

1. Introduction.

The purpose of the experiment was to study the effects of weightlessness on the brain of a crew member during sleep and waking. In fact, during sleep, the muscle tone (EMG) and the eye-movements (EOG) have been recorded satisfactorily on the Spacelab 1 mission allowing evaluation of Rem sleep but the absence of a reliable electroencephalographic recording (EEG) precluded evaluation of slow wave sleep. The waking electroencephalogram was provided by recordings which were taken during parabolic flights with a different subject.

Contrary to the traditional assumption according to which the cortex becomes activated during wakefulness and inhibited during sleep, experimental evidence indicates that cortical reactivity is greater during the periods of sleep than during wakefulness.

Moreover, weightlessness implies a strong stimulation of the vestibular system. Animal experiments have suggested that the eye movements of Rem sleep reflect the phasic activity of central vestibular mechanisms in the evaluation of sensory input and motor output. During sleep the brain stores information for motor adaptation, for memory and for selective attention. Economic and optimality considerations lead to the hypothesis that all information must be stored in a manner which changes as the needs and environment of the organism change. That this happens by way a programme which gives rise to the storage of information has been first hypothesized by Dewan (1). At about the same time it was shown that Rem-sleep has the functional neuronal structure necessary for the "programming" or as a matter of fact, the "reprogramming" to occur. This programme is expressed by the temporal structure of the eye-movements of Rem sleep (2, 3).

The eye-movement frequencies of Rem-sleep have been utilized for measuring the changes in brain activity during sleep.

Examination of the Rem frequencies in normal and disordered systems has revealed patterned substrates underlying behavioral performances. In humans, there is evidence that in Rem sleep the eye movement frequencies higher than 1 per second and those lower than 1 per 2 seconds have different functions. Results indicate that the higher frequencies are related to the integration of sensori-motor information whereas the lower frequencies behave as random noise (2, 4). The higher oculo-motor frequencies are decreased when cognitive function is impaired (5). They are increased as a function of succesful learning (6). The ratio between the higher and the lower frequencies or oculo-motor index indicates the degree of mental entropy. Moreover the evolution of this ratio as a function of age puts it in the category of genetic functions. This is very suggestive of the synergetic function of the brain. The oculo-motor index is an order to noise ratio in the Rem function and strongly suggests that the diurnal equivalent of Rem sleep is attention. Attention implies a multiple input system which selects only that information which has a high probability of being useful and relevant to the needs of the organism (1). That particular information in space is obviously weightlessness.

2. Equipment and procedure

Standard Oxford Medical Systems "Medilog Mk 1" 4-channel recorders were used, but some modifications were necessary. The usual plastic coated cases were replaced by aluminium with an anodised finish. The major problem was the necessity to find an alternative to the mercury batteries normally used. Manganese alkaline batteries were adopted, which fitted exactly into the normal battery space after reassembly from 3-cell units to 4 cell units. Fireproof "Nomex" pouches were made to replace the normal leather ones. The electrode leads had to be constructed from PTFE rather than PVC for safety reasons.

The recorder was set up for the sleep study using 2 channels EEG, 1 EOG, and 1 EMG. There were 2 small EEG preamplifiers, 1x1x0.2 cm., attached next to the electrodes. The timelined maintenance required only two procedures per 24 hrs; these were just before and just after sleep periods, to allow change of tape and battery or to check the electrodes.

The EEG was provided by recordings which were taken with a Medilog tape-recorder similar to that used during the SL1 mission but with normal mercury batteries and PVC electrode leads.

3. Results

3.1. The eye-movements of sleep

In the evaluation of the sleep data, two variables were to be taken into account: a 12-hour time shift for the payload specialist (PS1) who carried out this experiment and zero gravity. Therefore, several baseline nights were recorded prior to flight at F-120, -60, and -30 days. A further night was recorded after the shift at -5 days. A 12-hour time shift started for PS1 two weeks prior to the launch. After return, further nights were recorded at R+2 and R+4, but we must bear in mind that the effects of return to gravity were compounded with the effects of a return to local time. For various reasons, it was only

corded satisfactorily and the rapid eye-movement sleep epochs (REM's) were perfectly clear.
The eye-movements of sleep increased significantly in number during night 0, but returned to baseline level on night 1 (fig. 1). On night 0, the quick nystagmic components and fast saccades with a frequency higher that 1 per second, outnumbered the slower eye-movements by 2 to 1, but the oculo-motor index remains within the pre-flight norms. On night 1, the slow and fast eye-movements were equal in number (fig. 2).

After return, the total number of eye-movements during Rem sleep decreased. However on R+2, the fast components outnumbered again the slow rolling eye movements and isolated saccades by 2 to 1 as they did on night 0 in Space. Their proportion returned to normal on R+4.

The very disclosure of a pattern in the Rems that clearly differ between the 1st and the 2nd night, yet clearly represent a similar pattern across the nights in-flight and post-flight is indeed challenging.

The electromyogram allowed to differentiate the eye-movements of Rem sleep from those of wakefulness. Muscle tone, which is always abolished during the Rems, can temporarely disappear during slow wave sleep but muscle artefacts are always present in wakefulness.

With the findings made in both the GEMINI and the SPACELAB missions, a complete picture of the brain activity can be reconstructed during wakefulness, slow wave sleep and Rem sleep, in the absence of gravity. The recordings were complementary indeed. In the Gemini flight, the electroencephalogram was successfully recorded during 6 hours of sleep and showed successive 90-100 min. cycles each descending into deep slow waves and brief periods of awakening between them. However, during the Gemini mission the eye-movements and the muscle tone were not recorded, precluding evaluation of the presence of Rem sleep (7).

3.2. The waking electroencephalogram (EEG).

Fourier analysis of the mean EEG amplitude spectrum in the 4-8 Hz., 8-12 Hz. and 12-16 Hz. frequency bands revealed a 90 seconds periodicity corresponding to the period of each of the parabolas. Carefull assessment of the records indicated increased amplitude in the 4-8 Hz. theta band by comparison with pre- and post parabolic records (fig. 3).

Increase in the EEG theta activity has been documented in the GEMINI flights and in Soviet cosmonauts in early exposure to space environment indicating that it is a physiological response to the weightless environment (7). Therefore we are entitled to assume that the 90 seconds periodicity found in the augmented theta activity during the parabolic flights correspond to the zero-gravity acrophase of the parabolas. Our knowledge of the significance of theta rhythm in normal man has remained small. They may arise in augmented orienting response to a quite unusual experience.

The subjects resting EEG was clearly normal with a well developed alpha rhythm at 8-12 Hz. having an amplitude spectrum at 20-25 µv (fig. 4).

At the same time, - and important in comparison with flight records, - amplitudes in the spectrum 4-8 Hz. were low. This 4-8 Hz. theta rhythm activity was increased in the pre-take-off period over baseline records. The increased density broadened to include higher frequencies (12-16 Hz.) as take-off became imminent. At the beginning of the parabolas the theta band remained with similar amplitude whereas a decrease in the alpha and beta bands became obvious. These findings are interpreted as related to strongly focused attention and orienting response in an undoubtedly novel situation. They closely resemble the normative library data in similar situation. During the parabolas however, the power in the theta band increased with no change in the alpha and beta frequency bands. Same phenomenon appears in the second series of parabolas performed the same day in the afternoon.

The alpha and beta frequencies decreased at landing indicating a renewal in focused attention. The EEG in the pre- and post nap recording closely resemble the baseline data.

In the afternoon series of parabolas the theta waves resume the same course of evolution. The alpha rhythm remains stable this time indicating that habituation has occured.

4. Discussion.

The very complexity of the rapid eye movement data in sleep has traditionnally limited their evaluation to the simplest parameters and the correlates with behaviour to the broadest classifications. Since mental processes are rapid and changing, we must use techniques and methods that are equivalently refined and effective with epochs of data only a second or so in duration - far shorter than segments of records that are analysed with most analog computation. Such an analysis has proven fruitfull in this and in other studies, where visual examination of a paper record could scarcely provide the basis for an interpretation (2, 3, 5, 6, 7). From an anatomical standpoint, the oculomotor system has components located at many different levels of the central nervous system and the organisation of the components is complex and not completely understood. Nevertheless it is possible to distinguish components operating at different functional levels. At the lowest level is the final common pathway, which for the eye movements of all kinds must be neurons in the cranial nerve nuclei, since the motor nerves to the extra-ocular muscles arise here. These nuclei are found in the brain stem. At the same anatomical level are found the vestibular nuclei which are well known to have a powerful influence on the generation of eye movements. The vestibular system is actively involved in the process of sensorimotor integration during the phasic activity (i.i. the eye movements) of Rem sleep (8). Stimulation of the vestibular system produces an increase in those Rem bursts (9).

Furthermore Kornhuber and Da Fonseca have shown that there is no cortical representation of vestibular nystagmus to be found at the cortex (10). On the other hand the visual cortex fires in a definite relationship to the eye movements of sleep (11).

Concerning our EEG data, it may be assumed that they reveal patterned substrates of behavioural performance to the extend that the brain's electrical activity mirrors transactional processes at the cortical level.

Some sleep EEG patterns may provide information on potential behavioural reactions. We should remind the extreme paucity in the 12-14 Hz. sleep spindles in the Payload Specialist's (PS1) baseline recordings. To the extend that these spindles may be considered as a corollary discharge signal, informing the subject about the relative head and body positions, their absence may shed some light on the astronaut's resistance to motion and space sickness.

The sensitivity of the brain to zero gravity has clearly revealed changing states of activity as a function of changes in the environment as provocative as any other in the age-old history of the evolution of man.

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We ow much thank and appreciation to Dr. K. Money for providing the EEG records during the parabolic flights.

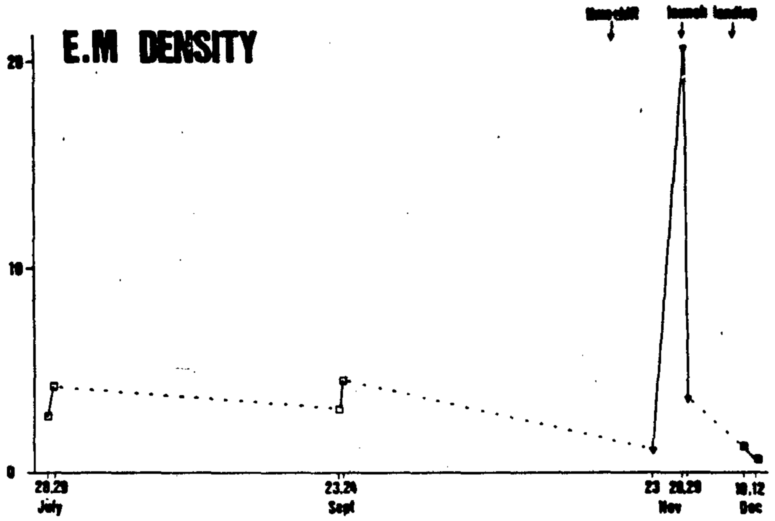


Fig. 1. Number of eye movements per 40 seconds of Rem sleep at various times.

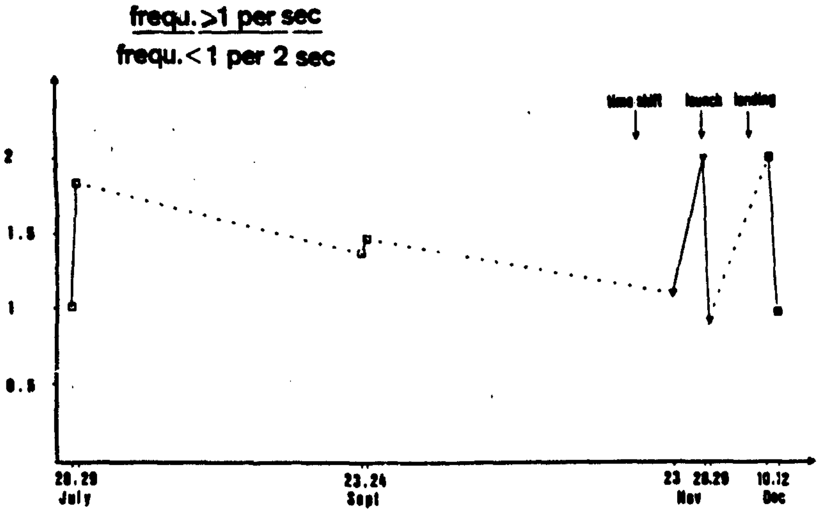
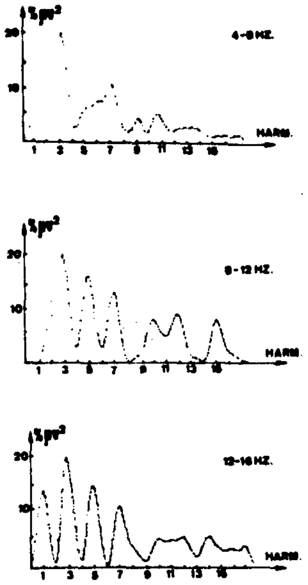


Fig. 2. Ratio of eye movement frequencies higher than 1 per second (nystagmus and quick saccades) to those lower than 1 per 2 seconds (isolated eye movements) at various times.



HARM.	T.SEC
1	280
2	140
3	93
4	70
5	56
6	47
7	40
8	35
9	31
10	28
11	25
12	23
13	22
14	20
15	19

Fig. 3. Discrete Fourier analysis of the mean amplitudespectrum during the parabolas.

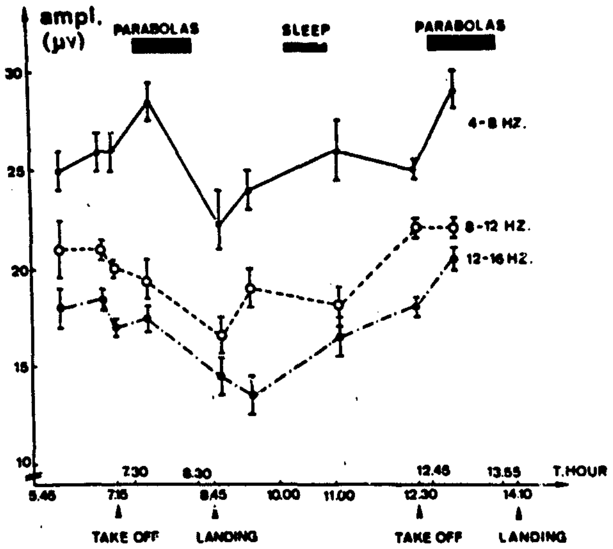


Fig. 4. EEG mean amplitude-spectrum (in µv) in parabolic flights. The data represent each the mean amplitudespectrum sampled over a period of 280 seconds at various times during and between the parabolas.

DISCUSSION

SCANO, Italy

My question is perhaps a naive one: Did you try to ascertain the dream contents of your subjects in the various conditions studied?
The question refers to the well known relationship between the dream subject and the daily activity, mental engagement or emotional situations, like those we can expect in a Scientist Astronaut.

AUTHOR'S reply

No, we did not. The reason is, that in order to get information on the content of the dreams, the subject has to be awawken during the phase of rapid eye movements. Therefore the sleep architecture has to be disrupted. The experiment on SL-1 aimed at collecting information on sleep with one variable only, namely microgravity, and to compare it with similar uninterrupted sleep epoches pre- and post-flight.

TERZIOGLU, TU

Besides EEG, EOG, EMG did you record cardiovascular, respiratory or other parameters in REM and NREM sleep stages?

AUTHOR'S reply

Yes, the ECG has been recorded in-flight during sleep and wakefulness, as well. The changes in the ECG frequency as a function of sleep have been well documented. They allowed us to determine in space the total sleeping time in one of the payload specialists. We must remind that in the absence of a reliable in-flight EEG recording during sleep, the total sleeping time was only evaluated by the EOG and the EMG and could not be but underestimated. Indeed, if a normal subject wakes up spontaneously during a REM-stage he always falls asleep in slow wave sleep. According to Oswald, the first REM-stage is preceded by 45 min of slow wave sleep.

TERZIOGLU, TU

How often did you observe REM stages in space?

AUTHOR'S reply

The number of REM-stages in space on night 1 was similar to baseline. On night 0 however the number of stages is meaningless, for REM sleep occupied 50% of the total sleeping time which was 120 min according to our EOG/EMG criteria and 147 min according to the ECG criteria.

TERZIOGLU, TU

How would you explain your results in terms of the new neuro-pharmacological theory of the sleep-wakefulness cycle?

AUTHOR'S reply

I am rather reluctant to interprate the SL-1 results on the eye-movements during sleep in neuro-pharmacological terms. The neurol-humoral theories have been established in animals, mainly rats and cats.

However, in previous studies, we have administred 5-Hydroxytryptophan (5-HTP), a Serotonine precursor, to mongoloids with the consent of their parents. We have noticed an increase in the number of sleep spindles and in the bursting of the eye-movements, as well, without changes in REM per cent. 5-HTP produces an increase in the rhythmic activity of the brain in REM- and in NREM-sleep, as well. The classification of sleep in stages or states is not refined nor effective enough to account for the features of brain activity. The rhythmic activity of the brain might be a mean by which the brain assures that the information is repeated. It may be a system by which engrams are formed (Andersen and Andersson, 1968). Implicit in this is the fact, that undisturbed spindle- and eye-movement-bursts are essential for learning (Petre-Quadens, 1969).

ROSS, UK

How important do you think were the circadian shifts for your Spacelab subjects?

AUTHOR'S reply

Since the circadian shift was in principle 180° for one of the crews, there was an important adaptation to be expected for most of the biological rhythms. Sleep is closely dependent upon the body temperature and interacts with the hormonal rhythms. Let me remind you, that the time shift was installed for our subject 2 weeks before launch.

It is now clear that at least four hormonal systems have temporal patterns of secretion that are closely linked to the 24 hour sleep-waking activity in man. No single principle or mechanism can explain these patterns but rather each system has its own temporal organisation and responses to manipulations of the sleep-waking cycle. For instance, growth hormon appears to be intimately associated with a specific sleep-stage in relation to the period after sleep onset, and its release can be readily shifted by shifting the time of sleep. Prolactin is released in large quantities throughout the night in an episodic manner with initiation at the time of sleep period (Weitzman et al., 1974). There is preliminary evidence that shift of sleep maybe accompanied by a shift in the release patterns. The importance of biological organisations of neuroendocrine systems in relation to time is clear.

ROSS, UK

The shift cannot have been 12 hours both in Houston and California, and probably was less in both. Does the precise timing matter? If so, can you find out from the crew or other sources exactly what the shift was in both directions ?

AUTHOR'S reply

Decrements of performance have been documented in East-West flights involving only an 8 hours transition. Hauty and Adams (1966) claim, that it is the time zone transition itself and not the mere fatigue of flying which is mainly responsible for the impaired performance following flights along the Est-West meridian. Preston (1974) has used an artificially controlled environment to stimulate the time change. Decrements in performance have been reported across tasks, ranging from 17% to 38%. Therefore, I do not think that the precise timing matters very much. However, there is good relationship between body temperature and performance such that when temperature is highest during the 24 hours, performance is most efficient (Kleitman et al., 1950). Furthermore, sleep onset can only occur with a lowering of the body temperature. When the temperature raises the subject wakes up.

SENSITIVITY OF HUMAN LYMPHOCYTES TO MICROGRAVITY IN-VITRO

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Laboratorium für Biochemie, ETH-Zentrum, CH-8092 Zürich

SUMMARY

The purpose of this paper is to describe our studies on the effect of gravity on lymphocytes, the cells responsible for the immune response. A decrease of lymphocyte reactivity has been observed since 1973 in Soviet and U.S. astronauts after space flight. Ground-based studies performed in hypergravity and in simulated low-gravity conditions suggest the hypothesis that low-g depresses, whereas high-g increases lymphocyte activation.

Cultures of human lymphocytes were flown in an incubator on the 1st Spacelab mission and exposed to the mitogen concanavalin A, a substance capable of activating lymphocytes in-vitro. The stimulation of the flight samples was less than 3 percent of that of the ground controls.

Although the results are very clear, it is premature now to draw conclusions from this experiment on the effect of space flight on the immune system of the astronauts. Future investigations on the D-1 and Spacelab-4 missions should clarify the problem on the behavior of lymphocytes during and after space flight.

INTRODUCTION

Over twenty years of manned space flight have demonstrated that man can easily survive and work in weightless conditions. However, a number of physiological changes may affect crew performance in space. Beside the well known disturbances of the vestibular and cardiovascular systems, bone demineralisation, and decrease of red blood cell mass, certain immunological alterations have been observed in space crews after flight. One of them is the reduction of lymphocyte reactivity to mitogens. This aspect was and will be the subject of our investigations in the Spacelab.

Although the immunological changes never had consequences on the health of astronauts, they clearly indicate that the efficiency of the immune system is influenced by space flight. Is it weightlessness per se? is it stress? We are trying to give an answer to these questions.

The advent of the space shuttle as an operational vehicle for working in space, the prove that Spacelab is a useful tool for performing scientific experiments in several disciplines, and the recent decision of building a permanent manned space station will require that a much broader community of scientists and technicians than in the past will spend prolonged periods of time in space. This may imply that the criteria for physical certification of astronauts will be less severe. In addition, physiological changes which were judged minor or not alarming so far, cannot be ignored in future.

Here I present the experimental approach and the results of our experiment with lymphocytes on Spacelab-1 and a description of the experiments to be performed on the D-1 and Spacelab-4 missions in 1985 and 1986 respectively. In addition I give an account of our ground-based studies in hypergravity and at simulated low-g.

WHAT ARE LYMPHOCYTES?

Lymphocytes are the cells in our blood responsible for the immune response, which reacts to body-foreign substances called antigens. Structures (receptors) that specifically recognise the antigens are localised on the cell surface. The interaction between antigens and receptors triggers lymphocytes to proliferate and to produce antigen-specific antibodies. The diameter of resting cells is about 7µm and increases in activated lymhpocytes to 15µm. Infectious bacteria are typical antigens recognised by lymphocytes.

A similar reaction can be triggered in-vitro when lymphocytes are exposed to certain substances called mitogens. In fact, lymphocytes are easily isolated from peripheral blood by density gradient centrifugation and kept alive in culture medium for several days. Mitogens are proteins or polysaccharides of plant or bacterial origin having the property of cross-linking sugar moyeties on the cell membrane and thus bringing about, through a still unknown mechanism, lymphocyte activation in-vitro. Lymphocytes can be divided in two major subpopulations, the T- and B-lymphocytes. The B-cells are involved in the synthesis and secretion of the antibodies (humoral immune response), the T-cells are regulating the cellular immune response, i.e. the rejection of grafts, the secretion of a number of factors like interferon, and they play a key role in the activation of B-lymphocytes. In our studies we use as mitogen concanavalin A (Con A), a protein isolated from jack beans, a widely used T-lymphocyte mitogens.

Maximum activation in-vitro is usually observed on the third day of culture. The activation can be accurately measured by incubating the cultures with a radioactive constituent of the cell. Tritiated tyhmidine is a component of desoxiribonucleic acid, a kind of biological software in which all information needed by the cell is stored. Thymidine is incorporated into activated cells at a much higher rate (100 to 200x) than into resting cells. ^{3}H-thymidine is easily measured in a liquid scintillation counter.

The transition from resting status to stimulated lymphocyte is an example of cell differentiation. The in-vitro activation of lymphocytes by mitogens can therefore be regarded as a good model for testing the efficiency of the immune response and for the study of the mechanism of cell differentiation, the latter being one of the most interesting topics in biology today.

CHANGES OF LYMPHOCYTE FUNCTION IN SPACE

In this paragraph I briefly describe what has been observed by other investigators on the effect of space flight on lymphocyte activity.
As described above, the test generally used is based on the activation of T- and/or B-cells with mitogens in-vitro, and the parameters measured are desoxiribonucleic or ribonucleic acid synthesis using radioactive thymidine or uridine respectively as precursor.
The first report on a reduction of the efficiency of lymphocytes after space flight appeared in 1973 by Soviet investigators (1): the lymphocytes from cosmonauts of the Soyuz 6,7, and 8 missions showed a depressed reactivity toward T-mitogens. Similar effects were later observed on several U.S. and Soviet missions and are summarised in Table 1. and reviewed in Ref.(2).

Table 1. Effect of Space Flight on T-lymphocyte Reactivity (2)

MISSION	DURATION (days)	DEPRESSION
Soyuz 6, 7, 8	5	YES
Apollo 7-13	6-12	NO
Skylab II, III, IV	28,59,84	YES
Apollo-Soyuz	9	YES
Salyut 4	30,63	YES
Salyut 6	140	YES
Salyut 6	96	NO
Space Shuttle STS-1, 2, 3, 4	2-8	YES (Ref. 3)

Cultures of lymphocytes purified from blood samples drawn from crew members before and after flight, but not during flight, were exposed to mitogens. Activation was measured by incorporation of labeled precursors into DNA or RNA.
In total, 41 U.S. astronauts and 12 Soviet cosmonauts were tested.

No manned U.S. space missions took place between the Apollo-Soyuz flight in 1975 and the 1st space shuttle flight in 1981. With the beginning of the shuttle-era lymphocyte efficiency is regularly tested after each flight. Taylor and Dardano have reported recently on the results obtained with lymphocytes from the blood of the 8 astronauts who participated to the first 4 flights (3): the post-flight activation is reduced by 18 to 61 percent at optimum mitogen concentrations and after optimum incubation times. According to the authors the post-flight changes are correlated with the subjectively-evaluated increase in the incidence of in-flight stress and not to hypogravity.
In general, recovery of lymphocyte performance to normal pre-flight levels is observed two weeks after landing.
Concentrations of immunoglobulins, the antibodies secreted by B-lymphocytes, were also determined in the blood of flight crews. No significant changes of IgG and IgM levels were found in the Apollo astronauts, the same is reported for all immunoglobulin classes after the Skylab missions. A large increase of IgA, IgG and IgM serum concentrations was observed after the 49-day Salyut flight. This effect has been put in relationship with the secretion of autoantibodies against degradation products from the atrophy of skeletal muscles occuring during space flight.
Immunoglobulin levels were also determined in the blood of 4 crew members of the 1st Spacelab mission. Specimens obtained prior to, during and after flight were analysed for total antibody content as well as for specific antibody activities. Quantitation of immunoglobulins G, M, A, D, and E indicated relatively minor fluctuations in the concentration of each class of immunoglobulin during the experiment. Thus, microgravity effects on immunoglobulin levels during the 10-day flight were considered insignificant (4).
T-lymphocytes can be induced in-vitro to produce α-interferon by a procedure similar to that used for mitogenic activation. A number of different substances, among them T-mitogens, can be used as inducers. α-interferon production has been studied in-vitro with lymphocytes drawn from cosmonauts prior to and after flight on the space station Salyut-6 (5). Newcastle Disease Virus, UV-inactivated was used as inducer. In two samples the production of interferon was significantly lower after flight, in the other two it remained unaltered. The same authors determined also the synthesis of interferon by lymphocytes from normal donors, i.e. not from crew members, cultured on board of Salyut-6 in the presence of four different inducers. In the flight samples production of interferon was almost five times higher than in the ground controls (5).

GROUND-BASED STUDIES

By ground-based studies I mean experiments which are performed in a common laboratory on earth and not in space. On the ground, hypergravity can be generated in centrifuges, whereas hypogravity can be simulated, but not reproduced, in clinostats. Experiments in space are much more valid when supported by studies performed in the ground laboratory.
In 1977, when our proposal "Effect of weightlessness on lymphocyte proliferation" was selected by the European Space Agency (ESA) for flight on the 1st Spacelab mission, we began with the study of the behavior of animal and human lymphocytes cultured in hypergravity (between 4 and 15xg). My interest in this subject was triggered by the thought that having been gravity constant throughout millions of years of biological evolution, altered gravitational conditions would have an important influence on living organisms. Soon we discovered that lymphocyte activation was remarkably enhanced in cultures exposed to Con A and kept at 10xg. The study was extended to other cell systems as described in Fig. 1. In any case tested cell proliferation was enhanced by 20-30% (6). However, to our great surprise, glucose consumption in the medium remained the same. An explanation of this apparent contradiction was found by tracking cell movements at high-g on the bottom of culture flasks coated with colloidal gold. With HeLa cells we found that cell motility is nil at 10xg, therefore more energy is available to proliferation (6). This is an important finding, suggesting that the cell is capable of adapting to hyper-g by changing some important functions like motility and division.

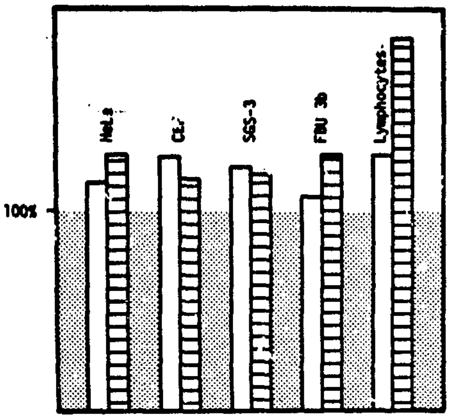

Figure 1. Effect of hypergravity at 10xg on cell proliferation. HeLa cells are a common and well kown line of human tranformed cells; CEF, chicken embryo fibroblasts, are an example of non-transformed cells; SGS-3 are cells from a sarcoma of a rat strain called Galliera; FBU 3b are Friend leukemia virus transformed cells, an example of slow growing cells.
Results are expressed as percent of the corresponding 1xg control, indicated by the shadowed area. In HeLa cells, CEF, and SGS-3 cells proliferation was measured after 24 h (void bars) and 48 h (hatched bars) incubation time respectively, in FBU 3b cells on day 4 (void bar) and 5 (hatched bar) of incubation. Human lymphocytes were activated by exposure to Con A, cell activation was measured on day 2 (void bar) and 3 (hatched bar) of culture. (from Ref. 6).

Hyper-g effects are more dramatic when whole blood cultures are exposed to Con A at 10xg. Whole blood cultures are obtained by diluting peripheral blood 1 to 10 with culture medium instead of purifying the lymphocytes on a density gradient. In whole blood cultures lymphocyte activation is more than trebled by hypergravity(A. Cogoli and A. Tschopp, unpublished observations). We do not know yet the reasons of this effect. It is possible that certain blood components, e.g. red blood cells or hemin, which are not present in purified lymphocyte preparations, have a co-mitogenic effect at hyper-g. In fact, hemin has been identified as a macrophage-dependent T-cell mitogen (7). The use of whole blood cultures is due to the fact that we will test the efficiency of lymphocytes from crew members in-flight on two Spacelab missions in 1985 and 1986. Limitation of equipment and of crew time make a purification of lymphocytes in-orbit impossible.
The rapidly rotating clinostat is a device designed to provide "functional weightlessness. In fact gravity is transformed from a vector into a scalar. Since flight opportunities for biological experiments in space are still rather rare, clinostats offer a useful way to perform exploratory investigations in simulated microgravity conditions. While the launch of Spacelab-1 suffered several delays between 1979, the year in which it was originally scheduled, and 1983, we investigated the behavior of human lymphocytes exposed to Con A in the rapidly rotating clinostat (8). As shown in Fig. 2 activation was depressed by 50% as compared to the 1xg controls.
In conclusion, the results of our ground-based experiments led us to formulate the hypothesis that microgravity depresses, hypergravity increasse cell proliferation rate. The effect appears to be more relevant in cells undergoing differentiation rather than in those undergoing normal division cycles.

HUMAN LYMPHOCYTES IN SPACELAB-1

We had the opportunity of testing our hypothesis under real microgravity conditions during the first Spacelab mission launched on November 28 1983. The main objective of the experiment was to establish if lymphocytes in culture are sensitive to microgravity per-se.
The whole design of the experiment, i.e. hardware and flight operations, was very sim-

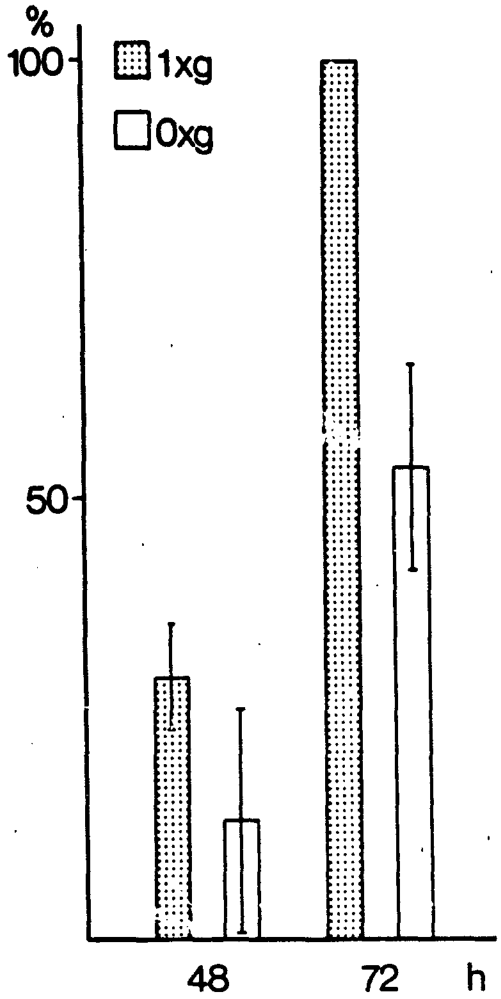

Figure 2. Effect of simulated 0xg on lymphocyte activation. Human lymphocytes were exposed to mitogenic concentrations of Con A. Activation was measured after 2 and 3 days of incubation. Microgravity was simulated in a rapidly rotating clinostat.
The results are expressed as percent of activation, taking as 100% activation that of the control at 1xg on the third day of cultivation. The standard deviations are calculated from 4 experiments with lymphocytes from different donors.

ple. In fact, complicated instruments are frequently subject to irremediable failures in space. This is due mainly to the fact that biological experimentation in orbit is still at the beginning. Therefore the biologist used to much more sophisticated experiments which are easily performed in his laboratory on the ground should be aware of the problems existing when working in a space laboratory. The situation will rapidly change in future since ESA and NASA are doing considerable efforts to improving the conditions for biological and biomedical experimentation in space.
The equipment used in this experiment was designed and manufactured in our laboratory. It consisted essentially of a carry-on incubator, a front panel and four cell culture chambers fixed in a block of aluminum (Fig. 3 and 4). In the incubator the temperature can be kept at 37°C either by means of a battery power (up to 24 h) or a Spacelab power (28V DC). The incubator can be fixed to its front panel mounted in a rack in the Spacelab module. The front panel carries the electronic box with the connectors to Spacelab's power bus and to the remote acquisition unit (RAU). The RAU connection delivers a temperature signal to the ground control station at Johnson Space Center. A crucial problem in developing the hardware was the design of the culture chambers. We had to satisfy the safety requirements of NASA, to select materials non toxic to lymphocytes, and to take into consideration the peculiar properties of the weightless environment in terms of mixing of fluids and air bubbling. After having tested about 50 materials (metals and plastics) for biological compatibility, we made culture flasks of Teflon reinforced with 25%

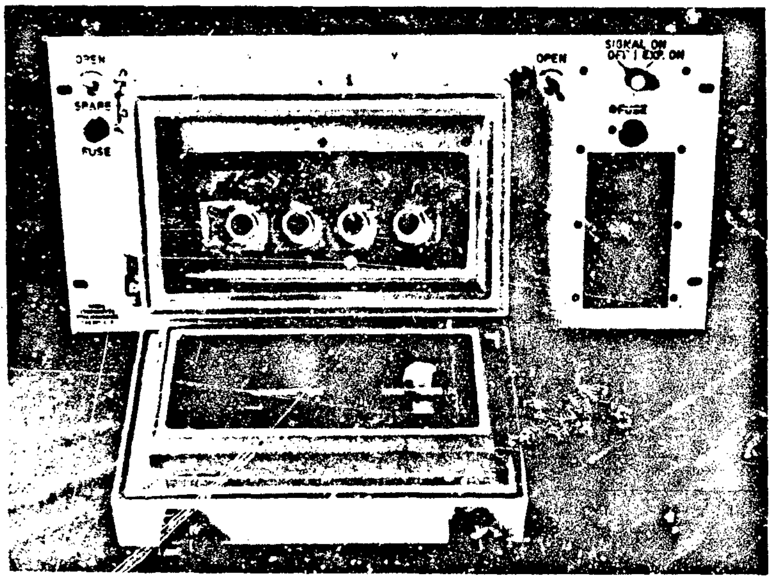

Figure 3. Flight hardware of the experiment in Spacelab. Open incubator mounted in its front panel. The incubator contains 4 culture chambers, one set of 12 syringes, 3 for each culture, and tools for inflight operations, in the lid.

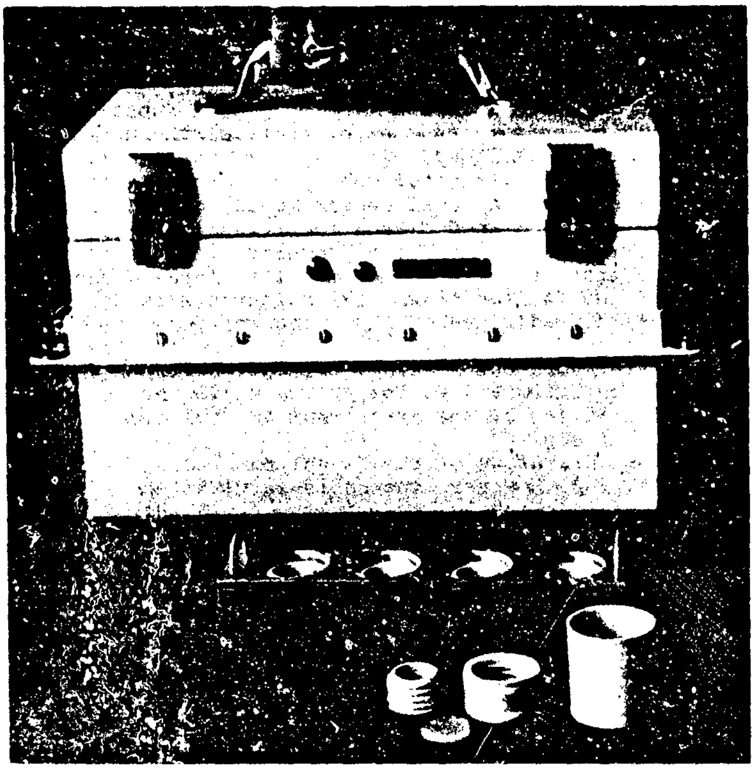

Figure 4. Flight hardware of the experiment in Spacelab. Carry-on incubator (25x17x17 cm^3 and weighing 3.5 kg), aluminum block with 4 cell culture flasks, and open flask.

Table 2. Protocol of the Experiment in Spacelab-1

TIME Hours before/after launch	ACTIVITY
L - 22 h	Blood draw from a healthy male donor
L - 13 h	Lymphocytes are purified on a density gradient by centrifugation
L - 7 h	The cultures are sealed in their containers, stowed in the incubator, and delivered to the launch pad
L - 6 h	The incubator is stowed in a middeck locker of Columbia
L + 6 h	The incubator is transfered into the module of Spacelab, installed in the front panel , and the experiment is activated by injection of Con A into the cultures
L + 75 h	After 69 h incubation at 37°C, labeled thymidine is injected into the cultures
L + 77 h	The experiment is terminated by injection of hydroxyethylstarch as cryopreservative of cell ultrastructure and the cultures are stowed in a liquid nitrogen freezer
1 h after landing	The flight samples are returned to the investigators after a 10-day mission

A synchronous control experiment was run in the ground laboratory at Kennedy Space center with cultures from the same batch of cells in an identical incubator. Data analysis was performed in Zürich 6 days after the end of the mission.

glass fiber. Basically, they consist of a cylindrical container (Fig. 4) which can be filled with maximally 12 ml of culture and hermetically sealed with a piston. Reagents can be injected into the chamber by means of syringes through a thick membrane made of silicone rubber. The piston can move up and down, thus compensating variations of volume. More details of the hardware are given in Ref. (9).

An incubator unit identical to that flown in Spacelab was tested 3 months before during the 8th space shuttle flight on board of Challenger. There, we investigated the

The experimental approach consisted essentially of exposing lymphocytes in culture to mitogenic concentrations of Con A during space flight, and of measuring activation by incorporation of tritium-labeled thymidine into desoxyribonucleic acid.

The incubator contained 4 cell cultures, syringes with Con A, ^{3}H-thymidine, and hydroxyethylstarch (HES). HES is a substance commonly used in solution as plasma substitute in transfusions and has also the property of preserving the integrity of the ultrastructure of human cells when these are frozen in liquid nitrogen. Pre- and in-flight operations are summarised in Table 2. 13 h before launch, lymphocytes were purified from human blood and resuspended in culture medium at a final concentration of 2 millions cells per ml. Portions of the culture were sealed in 8 flasks (8ml/flask): A,B,C, and D were the ground control samples and E,F,G, and H the flight samples. 6 h after lift off the experiment was activated by injection of Con A (25 µg/ml) into three flight and three ground cultures. The fourth ground (A) and flight (E) cultures were unstimulated controls. After 69 h of incubation, radiolabeled thymidine was injected into cultures to give 4 µCi/ml. Two hours later HES was added to a final concentration of 14%. Air was let into the flasks and, after vigorous shaking, the cell cultures were stored in liquid nitrogen freezers both on board and on the ground until the end of the mission. Finally, 13 days after completition of the experiment all cultures were simultaneously thawed and prepared for analysis.

The main results are given in Fig. 5. The activation of the flight samples, is less than 3% that of the ground controls (Fig. 5a). However, the cells survived the space flight, since the glucose consumption is only slightly lower in the flown than in the ground samples (Fig. 5b). A significant glucose consumption by unstimulated cells is not surprising since resting lymphocytes, like all other cells in culture, need a remarkable amount of glucose for survival. A further argument in favor of our results is that a relevant number of radiolabeled nuclei is detected by autoradiography in the lymphocytes exposed inflight to Con A. Again, this indicates that cells were viable throughout the experiment and that thymidine uptake was not altered in microgravity. See, for more details, Ref. (10).

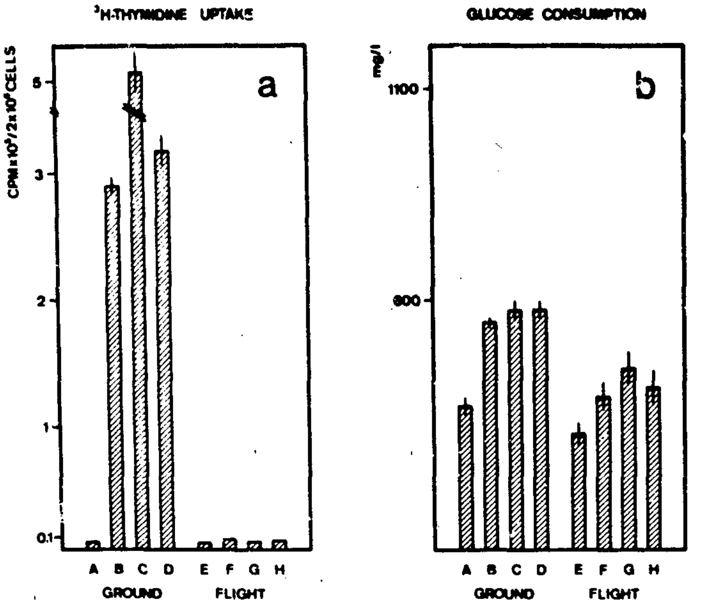

Figure 5. Lymphocyte activation induced in microgravity on Spacelab. Cultures of human lymphocytes were exposed to mitogenic concentrations of Con A in ground samples B,C, and D and in flight samples F,G, and H respectively. Samples A (ground) and E (flight) were unstimulated controls.
a. Activation measured after 69 h incubation at 37°C as ^{3}H-thymidine incorporation into desoxyribonucleic acid.
b. Glucose remaining in the medium measured by the glucose dehydrogenase method (6). The initial concentration of glucose in the medium was 1100 mg/liter. The standard deviation of triplicate samples is given, except for samples A,E,F,G, and H in a., for which it was too low to be shown here.

Although the results are unequivocal, I note that they are from a single experiment and therefore need to be checked on future missions.

In the discussion of our results I assume that the constituents of cosmic radiation which can penetrate the culture flasks - that is, high-charge and high-energy particles such as iron nuclei - do not play a relevant role in this experiment. In fact, the probability that a significant number of resuspended cells are hit by the radiation in cultures containing 16 millions cells per flask is extremely low.

As discussed above, a decrease of lymphocyte reactivity was expected, i.e. our hypothesis on the effect of gravity on cells has been confirmed, however, the extent of the depression is surprising. Lymphocyte activation is triggered by at least two signals. In this experiment, the mitogenic signal is delivered specifically to T-lymphocytes by Con A through its binding to glycosidic residues on the cell membrane followed by patching and capping. Patching and capping are typical phenomena due to the migration on the cell surface and to the cross-linking of the receptors recognised by Con A which carries four binding sites for mannose and glucose. The second signal may be delivered by factors produced by macrophages (which are always present in lymphocyte cultures) and/or by subpopulations of T-lymphocytes (interleukins). A third signal may be required and delivered through direct cell-cell contacts, although the finding of high activation in cultures diluted to as few as 50 thousands cells per ml does not support microgravity, the third signal may be hindered since cell-cell contacts may be less probable in lymphocytes suspended at Oxg. However, the following considerations indicate that cell contacts must also occur in microgravity: (i) aggregates of cells, a typical consequence of intercellular binding through Con A, were formed in microgravity (10), (ii) the experiment performed on the 8th space shuttle mission showed that contacts between cells and microcarrier beads are at least as effective in space as on the ground (A. Tschopp et al., unpublished results), (iii) passive cell movements in the medium, which may contribute to establish contacts, are not hindered by gravitational forces, (iv) calculations based on the volume of the flask and the cell concentration show that the average statistical distance between cells was less than 0.05 mm in our cultures, and (v) considering the various signals involved in activation, it is important to note that the comparative results in Fig. 5a are consistent with activation being an all-or-none phenomenon.

OUTLOOK

Although our observations are in agreement with the results found with lymphocytes taken from crew members after space flight, we cannot extrapolate the data derived from experiments in-vitro to changes occuring in-vivo. Experiments planned for the D-1 and Spacelab-4 missions in 1985 and 1986 should clarify the question of lymphocyte efficiency in space.

Both experiments consist of two different functional objectives:

1. Like the experiment on Spacelab-1, cultures of lymphocytes, prepared on the ground, will be exposed in-flight to Con A, however, activation will be determined after 24, 48, 72, and 96 h of incubation. This will permit to establish wheter the cell cycle, i.e. the biological clock of the cell, is modified by altered gravity conditions. On both missions, control cultures will be incubated in-flight at lxg in a reference centrifuge. In addition, three more g-levels will be provided on board Spacelab-4 by a "multi-g" centrifuge, namely 0.5, 1.5, and 2xg, thus permitting a broader study of g-effects on cells.
2. Whole blood cultures of samples from four crew members will be exposed to Con A pre-flight at launch - 10 days, - 1 day, in-flight at launch + 3 days, and after flight at landing + 1, +7, and +10 days. This approach should permit to discriminate between effects of stress and effects of weightlessness per se on the lymphocytes of astronauts.

CONCLUSIONS

Considering what is presently known about the behavior of cells at different g-values, we can see a relatively consistent picture into which our results from Spacelab-1 fit very well. At high-g, cells divide faster at expense of reduced motility, since energy consumption remains the same. In microgravity, lymphocyte show a dramatic reduction in proliferation rate, reduced glucose consumption, but a strong increase of interferon secretion. As seen in an experiment performed on Skylab in 1973 (11), WI-38 human embryonic lung cells, which differ from lymphocytes in that they do not undergo differentiation steps, grow and move normally at Oxg, but they also consume less glucose.

In conclusion, most of the cells investigated appear to be sensitive to gravity, the effect seems to be stronger with cells such as lymphocytes, which are transformed by mitogens from a dormant to an activated state.

The results we have obtained so far have contributed to an increase in the knowledge of the influence of gravity on basic cellular mechanisms, to clarifying certain biomedical aspects of the effect of space flight on the immune system, and to developing useful biotechnological processes. Although the mechanisms involved in gravitational effects on cells are still unknown and a gravity sensor has not yet been identified, we can conclude on the basis of results to date that cells are sensitive to gravity.

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DISCUSSION

(SPEAKER unidentified)

You said that high acceleration activates lymphocytes. It that also true for high pressure, for instance, during therapy in hyperbaric chambers?

AUTHOR'S reply

I am not able to answer your question, because I do not know. The only relation I have in my experiments to pressure is that we cultured lymphocytes under a column of water, because we thought that the effect we saw during centrifugation might be an effect of hydrostatic pressure which we have also on the centrifuge. But nothing happened in lymphocytes cultured under a column of liquid.

VAN DEN BIGGELAAR, NL

Is it possible, that other human cells than lymphocytes can be activated by G forces, for instance bone or cartilage forming cells?

AUTHOR'S reply

Yes, our experiments (Experientia 39: 1323-1329, 1983) at 10 G with HeLa cells (human tumor), CEF (chicken embryo fibroblasts), SGS cells (rat tumor), FBU cells (human virus transformed cells) confirm that generally hypergravity stimulates cell proliferation. The effect seems to be stronger on differentiating cells. We will extend our investigations to other cells and other methods. We want to understand what happens in the cells biochemically. We think that there is a change in the metabolism of the cell under high acceleration.

VAN DEN BIGGELAAR, NL

What is the most effective acceleration value for stimulating cell activity, and how long must the G force be applied?

AUTHOR'S reply

The G levels tested on human lymphocytes range between 2 G and 15 G; at 20 G lymphocytes do not survive. The cells were cultured for 3 days in the centrifuge. There is no correlation between G level and extent of the effect, i.e. it is an all or nothing effect. In preparing experiments for the German Spacelab Mission D-1, we have exposed whole blood without mitogen at 10 G for 24 hours. If you than go back to 1 G and add mitogen, the effect of high G is still there; obviously, the 24 hours "preconditioning" at 10 G are sufficient to prime human lymphocytes with a high G effect. But this is so only with whole blood.

BIOSTACK EXPERIMENTS ON STS-FLIGHTS AND THE IMPACT FOR MAN IN SPACE

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SUMMARY

The radiobiological properties of the heavy ions of cosmic radiation were investigated on Spacelab 1 by use of biostacks, monolayers of biological test organisms sandwiched between thin foils of different types of nuclear track detectors. Biostacks were exposed to cosmic radiation at several locations with different shielding environments in the module and on the pallet. Evaluations of the physical and biological components of the experiment to date indicate that in general they survived the spaceflight in good condition. Dosimetric data are presented for the different shielding environments.

INTRODUCTION

Humans in spaceflight are exposed to two important sources of potentially detrimental effects: (i) the cessation of the gravitational stimulus to which they are normally adapted, and (ii) ionizing cosmic radiation. On the earth people in industrial countries are exposed and possibly adapted to an average radiation dose-equivalent estimated as 2.4mSv per year /1/, whereas measurements in the near-earth orbits of Skylab yielded exposure levels between 200 and 800 mSv per year /2/. It is not this quantitative increase in intensity that merits special attention, however, since according to current radiation protection standards even this several hundredfold increase would not prohibitively limit man's sojourn in space. It is the radiobiological quality of numerically minor components of the cosmic radiation field which uniquely distinguishes it from the terrestrial radiation environment and which, since the beginning of manned spaceflight, has prompted the special attention of radiation biologists /3/. In the context of radiation protection the radiobiological quality is expressed in terms of the dimensionless quality factor Q, by which the amount of physically absorbed radiation as measured in grays (1 Gy=joule/kg) is to be multiplied in order to yield the biologically relevant dose-equivalent in sieverts (Sv) /5/. The physical quantity by which ionizing radiations of different quality are conventionally distinguished is the spatial density of ionizations engendered in the irradiated material, which in turn can be expressed by their linear energy transfer (LET), usually given in keV per micrometer of tissue or MeV·cm^2 per gram. The densely ionizing heavy ions (also called HZE (high charge and energy) particles) and the disintegration stars of nuclear reactions induced in irradiated matter present an obstacle to a comprehensive and consistent assessment of the radiation hazards in manned spaceflight. The LET of the cosmic heavy ions extends to such large values, where both the spatial and temporal pattern of energy deposition become extremely inhomogenous, that the very definition of absorbed dose as a measure of radiation exposure and also the concept of the quality factor become inapplicable /6/. The pragmatic approach of setting aside these fundamental conceptual difficulties and converting the measured macroscopic spatial and temporal "averages" of "absorbed dose" distributions over LET into biological "dose-equivalents" by means of accepted Q(LET) relation /7/ remains problematic, since (i) the data base on which these relations rest does not cover the ionization densities typical of cosmic heavy ions, (ii) LET alone does not provide a unique measure of radiation quality, and (iii) a unified theoretical understanding of radiation quality, which might allow extrapolations, has yet to be achieved. These problems were recognized in a report of the U.S. National Academy of Sciences on HZE particle effects. The report concluded that in order to assess the radiation hazards of these HZE particles to man experimental knowledge of their radiobiological effects must be advanced by spaceflight experiments and groundbased experiments at suitable particle accelerators (which at that time just became operational) and that these experiments must permit evaluation of the radiobiological effects of single HZE particles on individual biological cells /8/. The requirement was realized for the first time in space by the Biostack experiment onboard Apollo 16 /9,10/. The results of subsequent spaceflight experiments on the last lunar mission of Apollo 17 /11/ and the earth-orbital Apollo-Soyuz mission /12/ emphasize tne important role of single heavy ions onto dramatic changes in individual cells. On Spacelab 1 the most extensive Biostack experiment, the Advanced Biostack, has been flown.

EXPERIMENT DESCRIPTION

The Biostack Concept

The investigation of the biological effects of single heavy ions to individual biological objects requires a clear geometrical assignment of these particles to the test organisms. Sandwichlike combinations of monolayers of suitable biological test items, fixed in between nuclear track detectors permit to correlate the visualized tracks of the particles to individual biological objects in the vicinity of the track. The procedures adopted for this correlation depend on the properties of the track detectors used, on the nature of the test organisms as well as on the precision required. In addition to these radiobiological findings, the track detectors of the Biostack experiment yield detailed dosimetric results on the atomic composition and the LET spectra of HZE particles as well as the spatial density of nuclear desintegration stars. LiF-dosimeters measure the integral ionization of HZE particles and sparsely ionizing background radiation.

The Layout of the Advanced Biostack on SL 1

Following the results of the former Biostack experiments which have been flown inside the Apollo command modules it seemed worthwhile to fly 4 experimental units on SL 1 at sites of different mass shielding environment, two units in an experimental rack of the module, one unit beneath the flor of the module and one without any shielding from SL 1 (within $\sim 2\pi$) on the pallet. These data will contribute to predict radiation hazards in future long-term missions, once the problem of evaluating the radiation quality has had at least an operational solution. They also serve as tests of the rather involved models used to calculate radiation transport under the influence of the geomagnetic shielding effect /13/.

In order to provide a broad empirical basis for a check of radiobiological models a large variety of test organisms differing in systematic position, organization level, developmental stage, radiation sensitivity and size have been used in combination with track detectors with different chemical composition and sensitivity . This requirement was met by the contributions of many co-investigators working on these different systems. Table 1 shows the biological systems and their combination with track detectors used, the endpoints of biological evaluation and the investigators involved. Table 2 shows the radiation detectors used, their relevant properties and their investigators.

The Biological Stack

The use of AgCl-crystals as track detectors demands actinic light during the passage of the particle in order to stabilize the latent particle track. Since this requirement is not compatible with the use of nuclear emulsion two different biological stacks have been defined: a passive stack including plastic and emulsions and an active stack containing AgCl-crystals.

The passive stack. Every passive stack consists of about 15 sub-units, in any of which either a selected biological object is sandwiched with a certain track detector several times or a certain number of track detector sheets is stacked together for dosimetric purposes. A sub-unit consists of 1 to 80 sheets. The thickness of the biological sheets, given by the size of the biological object, varies from 1 µm in the case of Bac. subtilis (fixed on the detector with PVA) to 200 µm for seeds of Arabidopsis Thaliana or cysts of Artemia salina. In order to prevent the bigger objects

TABLE 1: Biological Systems

Biological system		Track detector	Effects under investigation	Investigator	Affiliation
Biomolecules	Hemoglobin Rhodopsin	CN	Influence on the optical absorption	S.L.Bonting	University of Nijmegen, The Netherlands
Uni-cellular	Bac. subtilis spores	CN Lexan AgCl	Influence on spore outgrowth, cell development, colony formation	R.Facius G.Horneck G.Reitz M.Schäfer J.U.Schott K.Baltschukat	DFVLR, Biophysk. Köln, FRG
Plants	Arabidopsis thaliana seeds	CN AgCl	Influence on germination, plant development and mutation induction	A.R.Kranz U.Bork	University of Frankfurt, FRG
	Sordaria fimicola ascospores	CN AgCl	Influence on germination, mycel growth reproduction and mutation rate	J.U.Schott	DFVLR, Biophysik Köln, FRG
	Nicotiana tabaccum seeds	K2	Influence on germination, growth and development, mutation induction	M.Delpoux	University of Toulouse, France
Animals	Artemia salina cysts	CN K2	Influence on early steps of development, metabolism (biochemical analysis), integrity of ultrastructure	G.Gasset Y.Gaubin H.Planel	University of Toulouse, France
		CN K2 AgCl	Influence on hatching, induction of development anomalies, histological anomalies	E.H.Graul W.Ruther	University of Marburg, FRG

from mechanical stress during stacking these objects are embedded in little holes of a plastic sheet of 250 /um thickness (grid) keeping a well defined distance between the neighbouring detectors. The thickness of the detectors varies from 100 /um for CN to 300 /um for emulsion. To prevent influence to each other, plastic foils of Makrofol, 40 /um thick, have been used between the sub-units and between emulsion and biological layers. For rhodopsin and hemoglobin little hermetically sealed gilded container have been used. The sub-units are mounted on a gilded stacking frame.

TABLE 2: Radiation Detectors

Cosmic Radiation Component	Detector	Range of information on Z and LET	Threshold	Tissue equivalence	Background noise	Time assignment	Investigator	Affiliation
Heavy Ions	Nuclear Emulsion: K2, K5	very broad	low	no	high	no	M.Francois R.Pfohl	CEA, Paris, France SADVI, Strasbourg, France
	Plastics: Cellulose-nitrate, Polycarbonate	medium	medium	yes	low	no	O.C.Allkofer R.Beaujean W.Enge B.Siegmon G.Sermon	University of Kiel, FRG
	CR 39	broad	low to medium	yes	low	no	W.Heinrich J.Beer	University of Siegen, FRG
							R.Facius G.Reitz M.Schäfer	DFVLR, Biophysik, Köln, FRG
							E.V.Benton	University of San Francisco, U.S.A
	AgCl-crystals	broad	low to medium	no	medium to low	yes	E.Schopper	University of Frankfurt, FRG
							J.U.Schott	DFVLR, Biophysik, Köln, FRG
X-rays, Protons	LiF Thermo-luminescence dosimeter	integrating dosimeter				no	M.Francois G.Portal	CEA, Paris, France
							G.Reitz	DFVLR, Biophysik, Köln, FRG

The active stack. In the active stack AgCl-crystals are used in combination with Bac. subtilis, Arabidopsis thaliana, Sordaria fimicola and Artemia salina. On 200 /um thick single-crystals, covered with a protective lacquer, the biological objects are fixed with PVA (Bac. subtilis and Artemia salina) or luviscol. The stack is illuminated by actinic light from a matrix of yellow and green light emitting diodes during the flight.

Flight Hardware

The flight hardware consists of two hermetically sealed containers housing one passive stack each (Typ A) and two hermetically sealed containers with a smaller passive stack on the bottom and an AgCl stack on top (Typ B). Fig. 1 shows one container type A and type B (left side) of the flight experiment.

Hardware type A: The design of the hardware for the passive stacks was similar to that of the Apollo missions. The container picks up a stack of 98 mm of diameter and 87 mm of height. One unit (A1) was mounted in an experimental rack, the other unit (A2) beneath the floor of SL 1.

Hardware type B: The middle part of container type B contains a matrix of light emitting diodes, which illuminates the AgCl-crystals in the hermetically sealed upper container through a glass window. Because of the hign importance of the temperature for the survival of biological samples two temperature sensors have been included, one in the wall of the container near the lower stack representing the temperature of the the passive stack and one in the AgCl-stack. An adequate data interface to SL 1 permitted to observe the actual temperatures and the status of the light source in near real time on ground during flight. One unit (B1) was mounted in rack no 4, the other unit (B2) on the pallet.

Flight Experiment

Due to the latest launch date delays the biological samples have been handled earlier in advance than foreseen. After covering the detectors with the biological objects in the biologists laboratories in June 1983 the stacks have been prepared at DFVLR in July and integrated into the containers. After a storage time of 6 weeks at 4°C the units have been mounted into the SL 1 payload in early September. During transportation to KSC as well as during flight, from 28. Nov. to 8. Dec. 1983 the

Fig. 1: Flight hardware: Pallet unit (type B) on the left side, rack mounted unit (type A) on the right side

temperature of both units has been monitored; it did not exceed 21°C during transportation. Except during the hot phase, where 34°C have been observed as maximum temperature in the pallet unit B2 for about 1 hour, the temperature did not exceed 28°C during flight in any unit. The lowest temperature observed has been 19,5°C on the module mounted unit B1. All module mounted units were returned to DFVLR on 10 Dec. 1983, the pallet mounted unit on Dec. 22. The disintegration and the delivery of the samples to the co-investigators involved was performed between 12 Dec. 1983 and 12 Jan. 1984.

Ground based control experiments. Extensive ground control experiments have been performed with the 4 identically prepared back up units. One unit type A and type B has been exposed to the transmitted temperature profile of the pallet unit during flight with a one day delay, another unit was irradiated with 400 MeV Fe-ions at Berkeley short time after flight. The results of these experiments render to exclude potential effects of the temperature onto the biological samples and contribute to the investigation of the influence of the sparsely ionizing fraction of the cosmic radiation.

RESULTS

Dosimetric Results

Preliminary measurements of fluxes (in ions per square centimeter per day) of heavy ions with an LET above 1 GeV·cm^2/g show an increase from about 0.15 beneath the floor to 0.25 inside the racks and 0.28 on the pallet in one substack of plastic

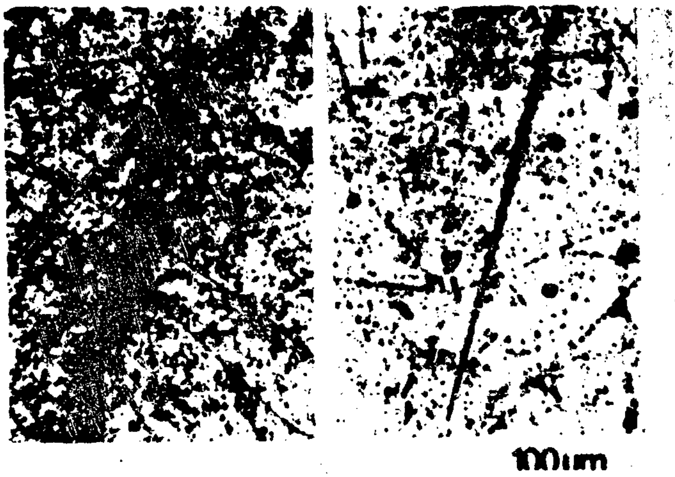

Fig. 2: Track of the heaviest ion ever detected in the Biostack experiments, on the left side penetrating through a 300 /um thick K5 emulsion, on the right side its stopping end in a 300 /um thick neighbouring K2 emulsion

detectors, and an increase from 0.20 in the floor to 0.34 on the pallet in another substack. In a somewhat more sensitive plastic detector the last two fluxes were measured as 0.36 and 0.54, respectively. In nuclear emulsions with a still lower registration threshold a flux of about 1 ion/cm^2-day with LET above about 400 MeV-cm^2/g was measured on the pallet, where a very heavy ion (atomic number probably twice as large as that of iron) was also detected for the first time in a biostack experiment (see Fig. 2)Lithium fluoride dosimeters measured average physical absorbed doses of 0.071, 0.088 and 0.085 mGy/d in stacks beneath the floor, within the racks, and on the pallet, respectively. These values, which represent the contribution of sparsely ionizing radiation, show a less marked dependence on the shielding than the heavy ion fluxes. 750 nuclear desintegration stars/cm^3 day have been registered in K5 emulsions on the pallet. Due to different solar cycles these dosimetric data are consistently somewhat lower than the values for the Apollo-Soyuz mission. A probable influence of different shielding is still under investigation. Table 3 summarizes the dosimetric results in comparison with the results of previous Biostack experiments. A detailed comparison must await the final calibration of all detector materials and the evaluation of complete LET and particle spectra. The first data from CR 39 for an LET spectrum of the SL 1 experiments in Fig. 3 are still preliminary.

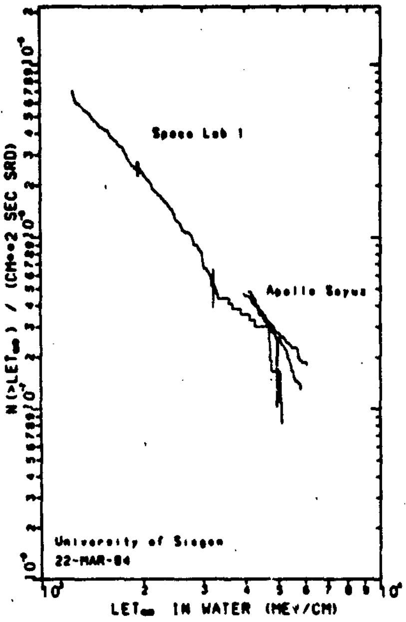

Fig. 3: Preliminary LET - spectra of the Spacelab 1 experiment in comparison with the Apollo Soyuz experiment

TABLE 3: Results of Dosimetric Measurements inside Biostack Containers

BIOSTACK EXPERIMENT		DOSE RATES IN LIF TLD-DOSIMETERS (MRAD/D)	HEAVY ION FLUXES LET-THRESHOLD (GEVCM^2/G)	FLUX (CM^{-2}D^{-1})	DENSITY OF NUCLEAR DISINTEGRATION STARS IN NUCLEAR EMULSION K 5 (cm^{-3}d^{-1})
Apollo 16		53.9 47.6 43.3	1.0 1.0	1.46 0.87	1360
Apollo 17		59.4 57.5 56.1	1.0	1.98	1000
Apollo-Soyuz		13.7 12.0 10.7	1.0	0.50	1400
SL 1§	Pallet	8.5	0.4 0.8 1	- 1.0 - 0.54 0.28 0.34	750
	Racks	8.8	1	0.25 -	-
	Floor	7.1	0.8 1	- 0.36 0.15 0.20	-

* VALUES ARE ARRANGED IN ORDER OF INCREASING SHIELDING WITHIN EACH EXPERIMENT

§ PRELIMINARY AND APPROXIMATE VALUES ONLY

Biological Results:

First biological results cannot exclude some influences to the test organisms which are not related to spaceflight factors. Some samples from the temperature stimulated ground control experiment and those which have been flown, but not hit by heavy ions (flight control samples) show a decrease of survival. This observation we trace back at least to some extent to an unusually long period of time between the preparation of the samples and the disassembly of the experiment of more than 5 month, caused by the two latest delays of the launch date, compared to 28 days with the Biostack experiment on ASTP. Flight control samples of cysts of Artemia salina for instance exhibit a survival of 50 percent only. The extent to which this inactivation is due to the long storage time or to radiobiological effects of nuclear desintegration stars within the cysts - the cysts of Artemia salina have the largest radiosensitive volume of all samples used - possibly in combination with other factors of spaceflight such as microgravity remains to be determined. The development of eggs, which were hit by heavy ions but still formed swimming larvae (~5 percent), appeared to be more strongly retarded than in previous spaceflight experiments by approximately a factor of 10 compared to normal cysts.

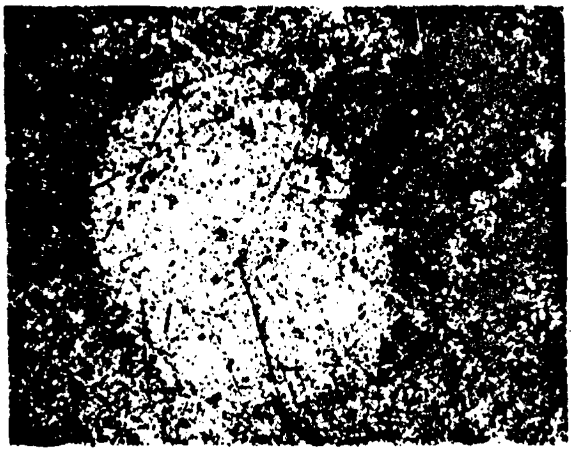

Fig.4: Shadow of a seed of Arabidopsis thaliana on K5 emulsion hit by a heavy ion

Figures 4 to 6 show photomicrographs of the physical evaluation of hit biological objects. In the case of Arabidopsis thaliana in combination with nuclear emulsion, the biological objects were outlined on the emulsion by weak illumination with actinic light before removing the seeds and development of the detector. Thus the particle tracks can be correlated to the negative shadow (Fig. 4). Fig. 5 shows the same object on CN, hit by a heavy ion, whereas Fig. 6 shows a spore of Sordaria fimicola on an AgCl-crystal hit by a secondary particle from a nuclear disintegration star. The focal plane of these photographs is a more or less worthwile compromise between a focused

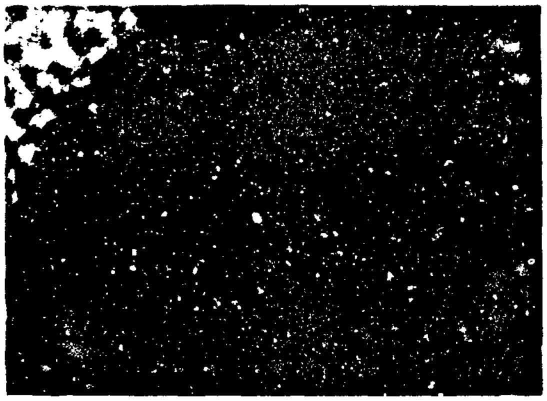

Fig 5: Seed of Arabidopsis thaliana on CN with the etchcone of a heavy ion

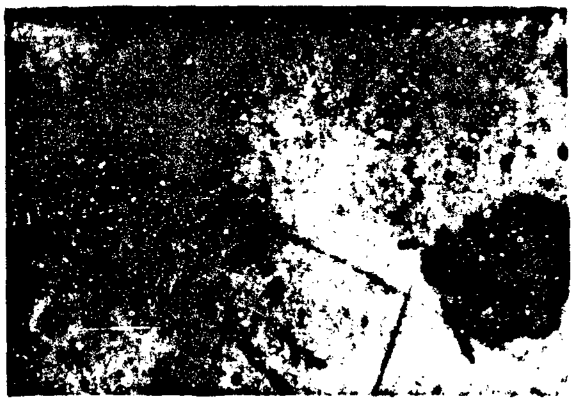

Fig. 6: Spore of Sordaria fimicola on AgCl with a nuclear disintegration star

picture of the biological object and the particle track. Thin layers of myoglobin and rhodopsin were included for the first time in the Advanced Biostack experiment as biochemical test system. Rapid, automated postflight scanning of the dry films at the wavelengths of peak absorbance with a spatial resolution of 2 /um has not revealed any new absorbance ascribable to heavy-ion trajectories so far. Experiments are in progress to determine whether postexposure wetting of the films will modify this finding.

FUTURE EXPERIMENTS USING THE STS

Within the life sciences space programs of NASA and ESA continuous effort will be devoted to experimental investigations of the radiobiological implications of the cosmic radiation, especially of its densely ionizing component. At present the following radiobiological experiments have been accepted for flight.

Already in orbit is the completely passive long duration exposure facility (LDEF) of NASA, which was launched into an orbit at 556 km altitude and 28 degrees inclination on April 6. 1984. The "Free Flyer Biostack Experiment" on LDEF is the first space flight experiment which probes the radiobiological effects of the cosmic HZE particles during long term exposure to the additional factors of the sapce flight environment, especially to microgravity. Its revovery is scheduled for March 1985.

The launch of the 7 day german D1 mission of the Spacelab into an orbit at 324 km altitude and 57 degrees inclination is scheduled for September 1985. Whithin its BIORACK facility two radiobiological experiments have been accommodated. The "Dosimetric Mapping inside BIORACK" experiment will provide dosimetric data for the ionizing radiation environment within the BIORACK. These data yield the background information, which may be necesssary to analyse and interpret findings from other biological investigations in the BIORACK, e.g. on biological effects of microgravity. The facilities of the BIORACK will allow to study the effects of HZE particles on development in the experiment "Embryogenesis and Organogenesis of Carausius morosus under Space Flight Conditions".

The european free flying long duration exposure facility EURECA will provide active temperature control and electric power for its experimental facilities, among which the Exobiology and Radiation Assembly (ERA) is designed to accommodate also radiobiological experiments. Its first flight is scheduled for March 1988. This mission in an orbit at 296 km altitude at 28.5 degrees inclination is planned to last six to nine months. This different orbit, as compared to the first LDEF mission, is expected to reveal the contribution of the nuclear disintegration stars to the observed radiobiological effects in the "Free Flyer Biostack " experiment on EURECA. The objectives of the experiment "Dosimetric Mapping on EURECA" in the ERA are the same as the one in the BIORACK.

Future missions, for which experiment proposals for radiobiological investigations have been or will be submitted are the following.

Scheduled for May 1987 is the launch of the NASA IML-1 mission with 7 days duration. The Spacelab will carry on this mission the BIORACK facility, for which a reflight of the two radiobiological experiments of the D1 mission has been proposed. In addition a proposal for a third experiment has been submitted, where the radiobiological effects of cosmic HZE particles on actively metabolizing organisms in contrast to organisms in a resting state will be investigated. The proposed experiment has the title "Response of Unicellular organisms to Heavy Ions of Cosmic Radiation During Spaceflight".

For the reflight of the LDEF, to be launched in August 1987 for a two year mission into an orbit at 450 km altitude and 57 degrees inclination, a refligth of the "Free Flyer Biostack" of the first LDEF mission will be proposed. So far this will be the mission with the longest exposure to the space flight environment.

A second german mission with the Spacelab (D2) is scheduled for July 1988. For this mission a reflight of the "Advanced Biostack Experiment on SL-1" will be proposed. A second proposal will be submitted for the "Dosimetric Record of Astronauts' Radiation Exposure". Apart from yielding personal dosimetry data for radiation protection purposes, in this experiment the specific contribution of the South Atlantic Anomaly of the geomagetic field to the radiation field in a near earth orbit will be studied.

For the progress of scientific research in space the availability of the Spacelab and the Space Transportation System STS obviously marks a major stepping stone. Apart from offering the interaction of human experimentators and more sophisticated and larger experimental tools it will allow to perform experiments in space more frequently and at more regular terms. Thereby scientific activities - especially biomedical research - in space will gradually approach the standards valid for terrestrial scientific work.

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PREFACE TO THE INFORMAL BRIEFINGS BY THE F-16 MEDICAL WORKING GROUP

The autumn meeting of the Aerospace Medical Panel has developed into a special format namely a mini-symposium on a timely subject, the annual business meeting and a "national half-day". The latter is a morning or afternoon session with papers of a less scientific and more practical nature, more like briefings on a certain theme or topic chosen by the host nation. As the briefings presented at the 1984 autumn meeting were of interest to a wider public, publication as Conference Proceedings was decided upon.

INTRODUCTION

Air Commodore G.K.M.Maat
The Netherlands

At the end of seventies, the F16 Falcon fighter came into the inventory of five nations at about the same time. That was rather unusual. In the past, when a new aeroplane came into operation in the smaller nations, the manufacturing country, for example the US, already had considerable experience with it, and the buying nations could use that experience.

In this case, the aeromedical community was alerted too. For news of the fantastic possibilities of the F16, the first high performance fighter, foretold that for the first time the pilot would be the limiting factor. The new concept of the high G environment, the high G cockpit, with its unknown consequences for the crew needed careful medical scrutiny.

The ensuing medical concern for possible acute and long lasting negative effects on man and the need to explore the nature of the human limitations led to two things. Firstly, flight surgeons from the five nations with occasional observers from nations that had joined the "high performance society" came together in a medical working group in order to pool information and to start common policies in selection and training in a most pragmatic way.

Secondly, the Aeromedical Working Party of the Military Agency for Standardisation conceived a Stanag on centrifuge training.

Turkey was the host nation for this autumn meeting. Turkey intends to purchase and manufacture under licence the F16. To deal with medical aspects of the F16 at the so-called "national-half-day" is appropriate. The Aerospace Medical Panel relayed the Turkish request to the F16 Medical Working Group, seeing an extra advantage in doing so. As the group is a practical one, the briefings would be operational rather than scientific and there is a need for more operational orientation within the Panel.

The topics covered in the following briefings speak for themselves. One topic, however, you will miss — equipment. The need for a proper lightweight helmet and a fast G-valve is still there.

This might be, with for example the practical consequences of the HUD and the strain on the neck muscles, a good subject for the next operationally-oriented session.

SELECTION PROCEDURES FOR F-16 PILOTS IN THE BELGIAN AIR FORCE

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I. Introduction

By the introduction of the high sustained G F-16 aircraft in our Air Force, the problem of the physical standards was raised.

These physical standards for flying must ensure that individuals selected for aviation duties are free from medical conditions or defects which could adversely affect flying safety, mission completion, or their own health.

Additionally, the standards should ensure that an individual selected for flying training is qualified for world-wide duty. That means that he should not only be capable of enduring the various stresses involved in flying, but also be capable of withstanding the considerable stresses involved in ejection or egress from the aircraft, and in escape and survival in a hostile environment.

The introduction at the end of the eighties of a new single seat, high performance fighter aircraft, such as the F-16, makes it essential that our physical standards, used for both selection and further qualification of pilots, by carefully reviewed and appropriately modified. These aircrafts are capable of rapid onset and high sustained +Gz which can easily exceed a pilot's physical limitations.

The maximum G available is no longer determined by the aircraft itself but by the human capabilities and physiologic limitations.

There exist a number of mild or subclinical medical conditions which could be aggravated by high sustained G or potentially result in sudden pilot incapacitation.

Our current flying physical examination must be changed to detect these conditions.

In developing new standards several factors should be kept in mind :

- these new aircrafts have been specifically designed in order to provide the pilot with an advantage in performance capability ;
- these aircrafts are single seat systems ; the pilot is alone ; he will have to see, interpret and respond to all instrument displays ;
- the fundamental and necessary requirement of excellent visual acuity for fighter pilot must be emphasized.

II. Pathology influenced by "high sustained +Gz"

There are a number of mild or subclinical medical conditions which could be aggravated by high sustained +Gz or potentially result in pilot incapacitation.

Among such conditions we can quote :

A. Cardiovascular pathology

1. Valvular lesions
   - Mitral Valve Prolapse
   - Aortic Insufficiency
   - Aortic Stenosis
   - Mitral Regurgitation
2. Arythmias
   - Supraventricular Tachycardia
   - Complex ventricular arrythmias

3. Coronary Artery disease (minimal to mild)
4. Other
    - Wolff Parkinson White Syndrome
    - Hypertension
    - Cardiomyopathies
5. Varicosites
    - Hemorroïds
    - Varicicoele
    - Varices of lower extremities

B. Non-cardiac pathology
1. Gastro Intestinal
    - Oesophagel varices and hernia hiatalis
    - Ulcer
    - Ulcerative Colitis/Proctitis
2. Pulmonary
    - Alpha 1 - Antitrypsine deficiency
    - Smoking

C. Musculoskeletal pathology
- Scoliosis
- Spondylolyse and spondylolysthesis
- Juvenile epiphysitis (Scheuerman)
- Degenerative joint disease
- Congenital abnormalities (Klippel-feil-and Sprengel's anormaly)

III. Kinds of Tests

Presently, in our center, we have added the following tests to our systematic revisional examination :

1) Phono-mecanogram
2) Echocardiogram
3) Holter monitoring in case rhythmic disturbances should be diagnosed.
4) Spiroergometry
5) EEG
6) Biological parameters - cholesterol and HDL cholesterol
    - triglycerides
    - CRP
    - Gamma GT
    - IGE
    - Carboxyhemoglobine
    - alpha -1- antitrypsine
7) RX full spine and RX cervical spine

IV. Discussion on pathology and policy followed in the BAF.

A. Problem of cardiovascular pathology

The valvular cardiac lesions which are aggravated by high sustained +Gz loading are mitral valvular prolapses, mild aortic insufficiencies, mild aortic stenose and mitral regurgitations. The lesion which is of greatest concern amongst this group is mitral valve prolaps.

Mitral valvular prolaps, is a valvulopathy, individualised by Barlow in 1963.

The fundamental physiopathological phenomenon is the more or less important prolaps of one or two valves in the auricle during the systole.

We wish to quote genuine prolapse and ballonisation according to the fact wether the free edge of the valve is located behind the level of the mitral ring or not.

The prolaps may be caused by an injury of the valvular tissue itself or of the sub-mitral organ. (cordage and pillars). The ausculatory semiology is characterised by one or more meso-tele-systolical clicks, connected with or without a tele-systolic murmur.

This murmur shows the existance of a mitral leak. The echocardiography objectivates the valvular lesion.

The difficulties in the decisions of flying-fitness are due to various factors :

1. The frequency of the disease, which ranks first amongst the valvulopathies, it amounts to 6 %.
2. The risk of complications is dominated by the rhythmic disturbances and consequently by thrombo-embolic accidents. The evolution towards mitral insufficiency is always possible. The risk of infectuous graft is much smaller.
3. There are asymptomatic forms which are strictly echocardiographic.
4. We still lack in our knowledge about the natural history of the disease.
   This should make us careful in our decisions.
5. The accelerations constitute definitely a damaging factor, for two reasons :
   a. they cause a decrease of the ventricular volume chaply due to a reduction of the base-point distance of the heart ; this on turn aggravates the prolapse.
   b. under high intensity, they are in itself arythmogenic and thus they increase the risk of rhythmic disturbances, typical of prolapse.

The most frequent complication being represented by rhythm disturbances, the latter should be detected by holter monitoring and by an effort ECG.

Their appearance should imply the fysical unfitness for High Sustained +Gz missions.

When the prolaps is isolated, i.e. without mitral insufficiency nor arrythmias the decision to be taken as to the flying fitness, is difficult and unclear.

Presently, considering the aggravating influence of accelerations, we declare the pilot unfit for High Sustained +Gz missions.

The possibility also remains that repetitive +Gz forces may have an adverse effect on the natural history of these lesions.

The most common non-valvular lesion which may reasonably be expected to be affected by high sustained +Gz loading would be mild coronary artery disease.

Under conditions of decreased cardiac output, reduced oxygen saturation, and marked tachycardia, even subclinical coronary disease may manifest itself under high sustained +Gz loading.

While subclinical coronary disease may not then manifest itself as angina pectoris, the propensity for arrythmias may be enhanced by a lowered arrythmia treshold.

Any condition which decreases an already compromised cardiac output, should be considered as a counter-indication to further high performance flying.

In that sense mild cardiomyopathies, with subclinical left ventricular disfunction, complex ventricular arrythmias, atrial fibrillation and supraventricular tachycardia may all be exacerbated by G stress.

In our center, the echocardiogram has not led to any rejections from flying status.

The holter monitoring, which we apply only when rhythm-disfunctions occur during the routine ECG or the treadmill-test, caused two rejections because of av block in the second degree, and total dysrythmia.

As to the hypertension problem, the standards applied on our rated pilots are :

- maximum systollic values : up to 160 mm Hg
- maximum diastolic values : up to 95 mm Hg.

A treatment restricted to hygienic and dietic measures, with the use of diuretics is tolerated.

The problem of the specific beta-blockers that exert a hydrofilic influence (cfr. atenolol), has not been thoroughly studied up to now so that we do not presently accept these farmaceutic agents as compatible with the flying status.

The purpose of the initial treadmill-exercice test is chiefly to screen out stress-induced arrythmias, rather than detect latent coronary disease.

Indeed the incidence of latent coronary disease is very low in this age-group.

In our center, we apply the treadmill test according to the Bruce-protocol. Using our standards, we have, untill now, not yet pronounced any rejections from flying status because of this test.

As to the vascular pathology, only serious and symptomatic forms of hemoroïds, varices, varicocoele, are to be considered as incompatible with high sustained +Gz flights.

B. Non cardiac pathology

1. Pulmonary

Two conditions which could be incompatible with flying high performance aircraft are alpha -1- antitrypsine deficiency and possibly smoking.

Alpha -1- antitrypsine deficiency induces early emphysema with deleterious effects on oxygenation. There exists a diffusion defect in the involved lung, the oxygen can not penetrate into the blood fast enough to maintain arterial oxygen-saturation.

The basic lesion of emphysema apparently results from the effect of proteolytic enzymes on the alveolar wall. Enzymes of this type can be released from leukocytes participating in an inflammatory process. Thus, any factor leading to a chronic inflammatory reaction at the alveolar level encourages development of emphysematous lesions.

Fortunately, most people have considerable ability to neutralize such enzymes as a result of antiproteolytic activity of the alpha -1- globulin fraction of their serum. In a rare condition known as homozygotic alpha -1- antitrypsine deficiency, however, the serum antiproteolytic activity is markedly diminished. In such patients emphysema may develop bij middle age even in the absence of exposure to substances known to interfere with lung defense mechanisms.

At the moment we envisage the introduction of the alpha -1- antitrypsine determination in the medical examination shedule of the applicant-pilots.

The remaining possibly disqualifying condition is heavy smoking.

This has two negative consequences upon the oxygen transport since :

a. carbon monoxide combines preferrentialy with hemoglobin, blocking sites of oxygen binding, and thus decreasing the oxyhemoglobin saturation.
   The normal concentration due to endogenous red blood cellmetabolism is 1 - 2 % Co Hgb.
   Average cigarette smoking increases this figure to about 5 % Co Hgb.
b. smoking alters the permeability of the airways and causes ventilation disturbances with partial oxygen desaturation of arterial blood.

In our center we measure the vital capacity and the one second forced expiratory volume by spirometry, and the residual volume by the Helium dilution method.

We determine the percentage of carboxyhemoglobin with chain-smokers (more than 20 cigarettes/day) and try to reduce via hygiënic measures the tabacco-usage of the pilots.

2. Gastro intestinal pathology

The presence of oesophagel varices, hernia hiatalis with or without ulcers, the gastric ulcer and the ulcerative collitis, disqualifies for high sustained +Gz.

C. Musculoskeletal pathology

It is felt that certain spinal column-anomalies, discovered by X-ray, represent an inherent mechanical weakness of spinal column architecture, able to be activated by back strain, and precipitating or aggravating underlying lesions.

Scoliosis

Scoliosis is defined as an abnormal lateral structural curvature of the spinal column which causes a deficiency in the thoracic spine flexibility. We distinguish two sorts of scoliosis :

1. a postural scoliosis, i.e. a curve that disappears by suspension or during recumbency.
2. a structural scoliosis, i.e. situation with vertebral body rotation, and with definite geometric and intervertebral disk changes in the individual vertebral body.

Spondylolysis

The malformation most commonly encountered in the vertebral arches is a cleft :

1. cleft in the pars interarticularis (spondylolysis)
2. cleft sagittal of the spinous process (spina bifida occulta)

Spondylolysis refers to a mechanical failure in the pars interarticularis without any relative vertebral body slippage and is most commonly found in the fifth, and less often in the fourth lumbar segments. Clinical evidence exists which suggests that an individual with a spondylolysis will have a greater likelihood of back disorder and a higher rate of intervertebral disk degeneration. Mechanical forces and particularly torsional stresses seems to be most detrimental and increase the onset of disk degeneration.

Spondylolysthesis

Spondylolysthesis refers to a defect in the pars interarticularis with forward displacement with respect to a subadjacent vertebra, usually the fift lumbar on the sacrum. Limited operational evidence exists pointing to the fact that high G manoeuvering may aggravate the defect, resulting in acute back pain.

Scheuerman's disease

Scheuerman's disease (Epiphysitis juvenilis) is defined as a rigid kyphotic deformity involving the lower tharacic spinal column. A lateral X-ray shows :

1. an increased dorsal curvature
2. an anterior wedging of the vertebral bodies in the lower dorsal region
3. a blurring, irregularity and mottling in the cartilaginous end plate of the intervertebral disk and in the apophyseal ring of the vertebral body, especially anteriorily.
4. an herniation of nuclear material into the vertebral bodies (Schmorl's nodule).

To determine the extend and the evolutivity of Scheuerman's disease, an RX full spine (including pelvis) and a profile of the lumbar and thoracal spine have to be performed.

The "Rissersign" is looked up. We apply the term "risser" when the crest of the iliac bone is not entirely ossified.

Interpretation of this sign : according to the degree of development of the ossification nucleus, a score between 0 and 5 is given : this represents the "risser-test".

Quotation 1 to 4 in the risser test means an insufficient ossification of the iliac bone's crest ; quotation 5 means a complete ossification.

The relationship between Scheuerman's disease and risser score 1 to 4 implies that the illness may still be in evolution ; risser test 5 implies stabilisation of the process. The evolutive Scheuerman's disease is disqualifying. The stabilised scheuerman's disease, with overt clinical and serious radiological symptoms, such as major kyphosis with wedge-shaped lesions of the spinal bodies (Schmorll's nodule) is also disqualifying.

Presently we perform in our center the following investigations :

Routine X-ray examinations :

- full spine, anterior-posterior
- X-ray thoracic spine : lateral

- X-ray lumbar spine : lateral
- X-ray cervical spine will shortly be added to this group.

In case of abnormalities the next policy is applied :

(A) applicant-pilots :

Since they all apply for the F-16 aircraft, the criteria are ; unfit for flying duties if :

1) Scoliosis, lumbar or thoracic (measured with the Cobb method) : exceeds the tolerance threshold of 15°.
2) other injuries :
   a. extensive signs of epiphysistis juvenilis of Scheuerman (nodules of Schmörll and wedging of vertebrae)
   b. uni-or bilateral spondylolysis
   c. spondylolysthesis
   d. pronounced, sequelae of previous fractures.

(B) For F-16 candidates who are already rated fighter-pilots, less stringent tolerance limits and also waivers are allowed.

Concerning the cervical spine :

- Systematic X-raying of the cervical spine is not at the present carried out.
- The frequency of complaints about cervical ache is quite high.

1) A training scheme for the strengthening of the neck muscles is being performed and, to the opinion of the pilots, exerts a favourable influence on the complaints.
2) Untill now there has occurred one serious case of subluxation of a cervical vertebra with longduration unfitness to fly, but this case recuperated fully with anti-inflammatory and kinetic therapy.

D. The vision-problem

Undeniably, excellent visual capacities are of the highest importance.

At the present we do not accept any insufficiencies and the use of spectacles is disqualifying for high sustained +Gz missions until more information, in order to eventually permit contaclenses and/or correction-glasses, will be available. If correction glasses or contact lenses are used, one should take into account :

- the compatibility with other items of personal equipment
- the weight of the glasses
- the discomfort
- the potential image distortion
- the limitation of visual field
- the glare

The problem of visual acuity raises another question : in how far is the visual acuity different in various contrast-situation ?

The common acuity tests are performed only under high contrast conditions. Contrast sensitivity has proven to be more comprehensive than standard acuity, since it determines how people see large and small targets in both high contrast (sunny), and low contrast (fog, rain, snow, twilight) conditions. The modern vision contrast test systems define visual capability differences in a normal population that relate to visual task performance, but also quantifies the acuity losses.

V. Conclusion

In conclusion one might state that the present criteria need to be further tested, and I hope that on one of our next meetings this very important item will be discussed in depth.

The systematic application of new technologics (Spiroergometrie, Echocardiogram, Holter monitoring, RX full spine, RX cervical spine) and the vision problem raises the question, of where the tolerance limits of normality are to be settled, in order to avoid inappropriate or too severe decisions about the physical fitness.

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DISCUSSION

Question

1. Mild coronary after-disease is difficult to detect; arteriography is the most reliable method. Yet it is a reason for rejection, you say. Do you have age criteria for F16 pilots?
2. You have also said that peptic ulcer leads to rejection. What is your policy after resection?

Reply

1. We have no official age limits; in practice the maximum age of F16 pilots is 45, 46.
2. An ulcer patient with conservative treatment (cimetidine) we ground for a period of 4—6 months. We do not waiver for F16 nor do we waiver for F16 after resection. We consider other planes after resection therapy.

Question

Do you perform a coronary arteriogram also when there is only a suspicion?

Reply

When we suspect coronary artery disease the diagnostic sequence is: E.K.G. then effort E.K.G. If the findings are negative or inconclusive we make a myocard scan; if again we cannot make the diagnosis and the suspicion is still there, we make an arteriogram.

Question

1. Do you exclude, pilots with spondylolysis without listhesis?
2. Is the echocardiogram a routine investigation?

Reply

1. Spondylolysis makes the candidate unfit for military duty. Furthermore we fear negative effects as a result of the backstrain.
2. Echocardiagram is routine for F16 pilots

(Dr Clement added that spondylolysis without listhesis is a controversial matter, but in Belgium by law applicants are declared unfit for military duty. The law however, will probably be changed. F16 pilots remain on flying status when the lysis is discovered later.)

G-INDUCED LOSS OF CONSCIOUSNESS (GLC)

by

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The topic of G-induced loss of consciousness (GLC) is being discussed frequently by countries flying the F-16. Although to my knowledge, only the United States has lost an aircraft to GLC, unless the measures we discuss this morning are adopted, or maybe even with them, it is only a matter of time before other countries also experience similar losses Allow me to read from two recent accident reports:

The young F-16 pilot was maneuvering defensively during a training sortie. When he realized his attacker was at six o'clock, he made a hard slice-back turn. After approximately six to seven seconds, the aircraft rolled wings level and continued in a controlled, 20° dive for approximately fifteen seconds until it impacted the ground. There were no radio transmissions and no attempt to eject.

The F-16 pilot was determined to do better on the next bomb run. He made a perfect approach, dropped his bomb near the bull and pulled right. The aircraft gained altitude while turning tightly for 5-8 seconds. The wings then rolled level, the nose dropped, and the aircraft continued a low angle descent until it impacted the ground. There were neither radio transmissions nor an ejection attempt made.

Our first thought upon hearing these scenarios is pilot incapacitation.....and we would be correct. In times past, we would have hypothesized a cardiac event or seizure as the probable cause. Today, however, with the arrival of aircraft into the inventory with high thrust to weight ratios, low wing loading, and the capability of rapid G onset rates and of sustaining these high G levels, a new addition to the differential diagnosis is necessary.

G-induced loss of consciousness (GLC) is merely a matter of blood flow, and hence hypoxia, in relation to accelerative forces. The hydrostatic column of blood from heart to eye level is approximately 30 cm and weighs approximately 22 mm Hg. With each +Gz, this weight is increased by 22 mm Hg. When the ability of the heart to pump blood at least to 20 mm Hg at eye level is surpassed, visual symptoms occur. If blood flow diminishes to a point where oxygen delivery to the brain effectively ceases, then after a period of approximately 5-6 seconds during which oxygen reserves are utilized, unconsciousness ensues.

History

GLC is not limited to third generation fighter aircraft. It has been described frequently in aircraft capable of generating 4-6 G's for several seconds and without provision for an anti-G garment. It has been associated with loss of one T-37 and suspected as cause in another T-37, F-105D, A7D, and two F4D mishaps. The Canadian and British have also reported instances of GLC. Prior to the new generation of fighters, however, either the absence or the inadvertent disconnection of the anti-G garment was usually a factor in the majority of GLC reported.

To date, the USAF has lost three F-16 aircraft to GLC. This is, however, only the tip of the iceberg. An anonymous survey of 1680 fighter pilots revealed 201 incidents for a 12% rate! Another survey revealed that 20% of polled pilots had experienced at least one episode of GLC. This is particularly noteworthy since there is usually amnesia for the event, so that most certainly many incidents are being missed. GLC is occurring predominately in the 5-7 G region, and at least six cases have occurred since June 1983, after a strong pilot education program on the topic had been completed.

Associated Factors

The same surveys and selected mishap investigations have identified factors commonly associated with GLC.

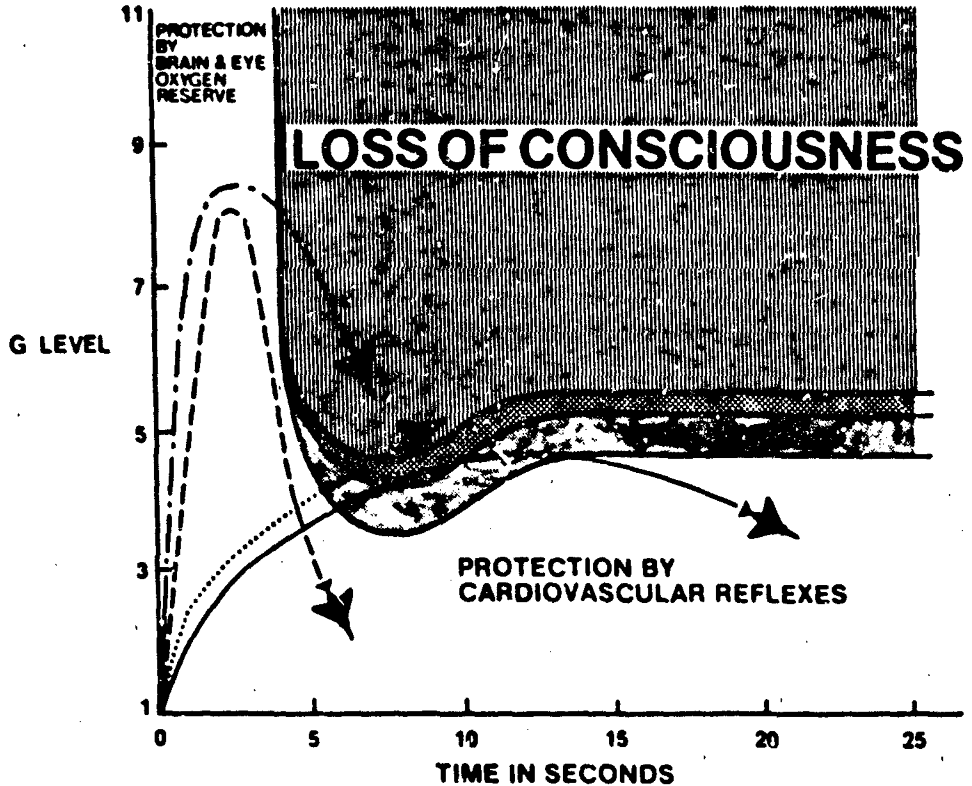
- Rapid G onset
- Fatigue
- Improper diet - dehydration
- Crewmember not flying aircraft
- Crewmember mentally unprepared for G onset
- Lack of physical conditioning program
- Lack of recent exposure to G-forces

Additionally, centrifuge data has characterized a typical episode of GLC.

1. Often no warning symptoms
2. Average incapacitation probably about 15 seconds +
3. Retrograde amnesia (several seconds)
4. Clonic movements.

Physiology

Figure 1 can help us better understand the concept of GLC. The area below the curve is the area of no symptoms. We can see that pilots are able to go to very high G levels without symptoms of GLC if the total time from onset to unloading is less than five seconds. This is due to the protection afforded by an oxygen reserve in the brain and eyes. The "bump" in the curve is the physiological protection afforded by the cardiovascular reflexes, i.e., baroreceptor reflex.



The usual strategy of the fighter pilot however, is to load G until he experiences visual symptoms (noted by the hatched area). He then either performs his anti-G straining manuever which raises this entire curve upwards, or he unloads the airplane enough to put him in the area below the curve. With gradual or moderate onset rates, visual symptoms will usually be experienced before loss of consciousness (above the curve) results. As noted previously, rapid excursions to high G will result in no symptoms because of oxygen reserve in the brain. In the two scenarios mentioned at the beginning of this briefing, however, we have rapid onset and sustained G bringing us into the arena of loss of consciousness without the warning of visual symptoms. The pilot does not know he is about to lose consciousness and can only prevent its occurrence by performing a proper anti-G straining maneuver in conjunction with an anti-G garment. A proper straining manuever involves muscle tensing of the legs and arms and straining against a closed or partially closed glottis. Inhalation must be quick and occur approximately every three seconds. Longer straining will impede venous return to the heart, reducing cardiac output and predisposing to GLC. Longer inhalation will drop intra-thoracic pressure, and with it, brain level blood pressure.

Prevention

With the F-16 30° tilt back, feet up position, we have effectively reduced the hydrostatic column and aided venous return making for better brain perfusion at any given G level. The anti-G garment affords a 1 1/2 to 2 G protection. A mechanical approach to improving G tolerance is the new high flow ready pressure (HFRP) valve. This valve is capable of more rapid response to G onset and, by having the G suit partially inflated at all times, the lag time is prevented. This valve is currently undergoing testing.

By far, the most effective means of protecting the pilot from GLC is a properly performed anti-G straining manuever, and the strength and endurance to maintain it. Surprisingly, centrifuge testing has revealed that many pilots do not know the proper technique. In fact, well over 50% of some classes were performing the manuever incorrectly. As noted previously, our G-time tolerance curve is significantly elevated by the anti-G straining manuever. Dr. Van dem Biggelaar's briefing addresses centrifuge training as a means to teach pilots the correct technique.

Gradual reintroduction into the high G environment after a lay off from G's is being viewed as critical, since losses of G tolerance are seen after as little as one week without flying. Reattaining previous levels of tolerance may very well take several sorties.

The anti-G straining manuever is, of course, very fatiguing and physical conditioning, especially weight training, has been shown to increase G tolerance. Dr. Jessen's briefing deals with physical training and its relation to G tolerance.

Lastly, aircrews must be taught that maintaining themselves in top condition with regard to nutrition and rest may very well be the deciding factor in the unforgiving high G environment.

Summary

Although not a new phenomenon, GLC has recently been implicated more frequently as the primary cause for aircraft mishaps. New generation aircraft with the ability of rapid onset and sustainability of high accelerative forces is certainly the major reason for this. Pilot surveys have revealed GLC is more common than previously thought. Prevention of GLC is totally dependent on education of the aircrews: education on the timely performance of a proper anti-G straining manuever, the physiology of GLC, and the need to maintain the body in optimal condition for flying.

PHYSICAL TRAINING AND G TOLERANCE

by

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High performance aircraft impose extreme physiological stress to the pilots. In particular is the G tolerance of the pilots crucial as exposure to sustained and repeated acceleration forces acting in the head-to-foot direction - +Gz - induces increased demands [illegible] cardiovascular and pulmonary functions.

[illegible] use of backward tilting of the seat and of anti-G-suits will, however, in combi[illegible] with straining manoeuvres help tolerance of high G forces.

[illegible] effect of the straining on G tolerance will depend on the capacity of the cardi[illegible] system and of the oxidative metabolic capacity of the exercising muscles (in [illegible] abdominal and leg muscles). Physical training could consequently be one pos[illegible] way to improve G tolerance.

Cooper and Leverett (1966)(1), however, failed to show any relationship between ae[illegible] power, i.e. the capacity for endurance exercise and relaxed G tolerance where no straining manoeuvres are involved. By comparision a study carried out by Epperson, Burton, and Bernauer (1977)(2) in the centrifuge of the United States Air Force School of Aero[illegible] Medicine indicated that 12 weeks of resistance exercise with weights enhanced +Gz tolerance. This result has later and recently been confirmed by Tesch, Hjort, and Balldin (1983)(3) from the Swedish Air Force as 11 weeks of muscle strenght training of 11 figh[illegible] pilots improved the G tolerance assessed in a centrifuge by 39 per cent on the ave[illegible]

In order to offer the pilots of the Royal Danish Air Force the optimal means of phy[illegible] training as a supplement to flying the Danish Defence Physical Training School was [illegible] to develop a socalled PILOT CIRCLE. This was done in collaboration with the August [illegible] Institute of Physiology at the University of Copenhagen.

[illegible] principles for this program are based on the nature of the under G-load applied [illegible] manoeuvres. The muscular contraction used during the straining is of isometric [illegible] and the effect of the contraction depends on the strength attainable - and on the [illegible].

[illegible] muscle groups involved are primarily those of the trunc and the hip and knee [illegible] and extensors. Further is the training of the neck muscles considered very impor[illegible] the protection of the cervical spine.

Consequently the weight training mentioned should be a muscle strenght and endurance [illegible] system developped with special regard to the pilots working environment - the [illegible].

Various previous investigations indicate that isokinetic training is most effectful [illegible] improvement in isometric muscle strength and endurance compared to training sy[illegible] based on isotonic or isometric contractions.

[illegible] isokinetic method will further to a high degree make it possible to simulate the [illegible] pattern in the pilots seat in a cockpit. Some advantages compared to other methods [illegible]dition to its superiority in strenght and endurance efficiency are:

[illegible] time necessary for adequate training is reduced as a warming-up period of time [illegible] be excluded.

[illegible] isokinetic training is not accompanied by a significant increase in muscle mass.

[illegible] training of the body muscles can include not only the big muscle groups of impor[illegible] for the G tolerance but also the neck muscles which are especially strained du[illegible] flying high performance fighters.

[illegible] pain and fatigue due to the training is minimal why flying consequently can be [illegible] out almost immediately after a training period.

[illegible] system consists of eight stations for the different muscle groups but together [illegible] a circle. Much attention has been paid to the principle that all exercises should [illegible]tional and task-related as possible. Some instruments are consequently modified [illegible] as much as possible to the pilots position in the cockpit of the F-16.

[illegible] heart of all the stations is a regulator - Mini Gym 500x, see figure 1. Isokine[illegible] contraction is a contraction under constant velocity which can be fast or slow [illegible] on the regulator. The Mini Gym responds to any force applied to the apparatus [illegible] exactly the same resistance to be overcome by the trainee under constant, [illegible] velocity.

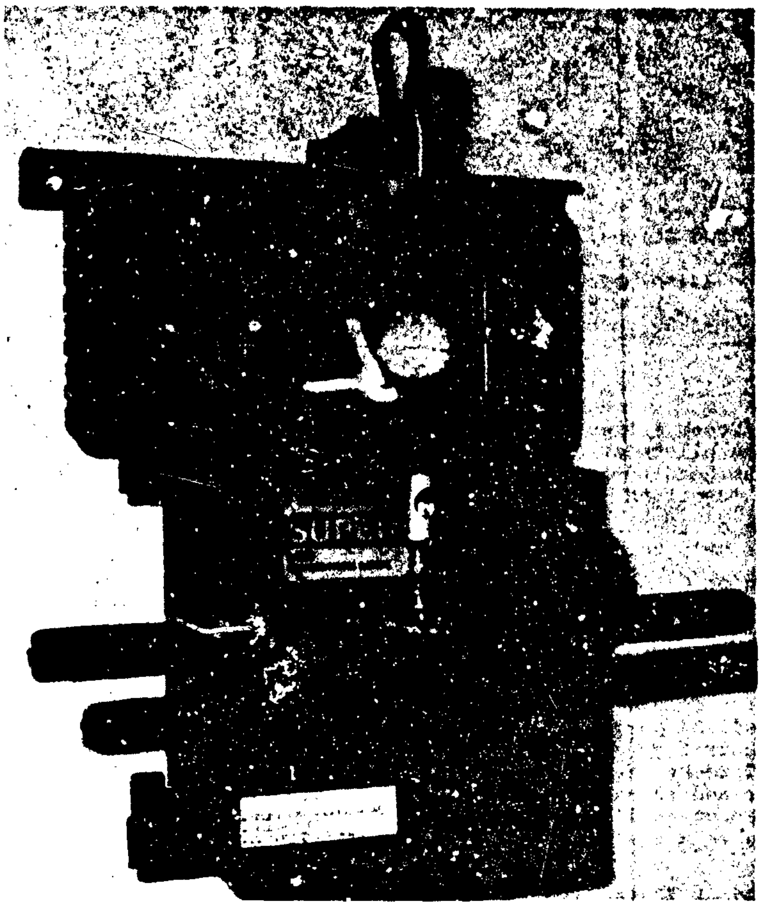

Figure 1: Mini Gym 500x, the regulator of most stations:

it responds to any force applied by producing exactly the same resistance to be overcome under constant but preselected velocity.

The Mini Gym regulator is implemented in the different combinations as demonstrated in

figures 2 and 3, where the socalled knee machine is modified to simulate the situation in the F-16 Aces II seat and training abdominal and leg muscles,

figure 4, where arm extensor and shoulder muscles are activated,

figure 5, where the hip muscles are trained,

figure 6, where the neck extensor muscles are trained, and

figure 7, where the neck flexor muscles are trained.

In addition to the eight stations the entire circle will include a moderate circulatory conditioning program in order to counteract the anaerobic metabolism which occurs at the sustained isometric muscular contractions during the straining manoeuvres. This condition should remain moderate as too low heart rate at rest as a result of (over-)training may embarrass the circulatory function at high G load. (See figures 8 and 9).

The mode of utilization differs from station to station as some muscle groups should be trained by approximately 15 contractions in a serie, repeated one or two times at a high velocity, whereas other groups should be trained up to 8 times in a serie at low or medium velocity (see legend to figures).

It is recommended that the full program is carried out three times a week the first three months in order to achieve the desirable muscle strength and endurance level and then maintained by two training periods every week.

The total program - in Denmark entitled 'The F-16 Circle' - will demand 45-60 minutes of training time, but every station can be used separately allowing the pilots to utilize smaller breaks in the flying program. The training can then be done in flying suits.

The nature of isokinetic muscle training is so that smaller periods of training time not normally is followed by muscular fatigue why pilots can fly almost immediately after training, and the construction of the stations minimizes the risk of damages to muscles and joints due to training.

To make the most of these advantages the stations - which are not very space consuming - should be placed in locations in every squadron, close to the briefing room.

It should be noticed that the effect of the training is difficult to control without a special gauge mounted on the apparatus since the Mini Gym as mentioned responds with the same resistance as the force applied to it. This means that it may look as if a trainee is working almost with optimal contraction force - and though only applying a few per cent of his maximal capability.

It should also be noticed that although this system is very effective and task-specific it is not very stimulating to the pilots if they use it as the only means of training. It is boring.

Therefore, all attempts of getting pilots into sporting games should be strongly recommended as a supplement to the developped isokinetic system. All sorts of games which stimulate a quick muscular reaction time will be of value: squash and tennis are examples on ball-games; skiing - and in particular slalom - is beneficial for those pilots who have access to snow. But all muscle exercises which do not impose a too high risk could be used - especially if they have a moment of competition which is known to stimulate fighter pilots very much.

Further is might be of value to educate and train all pilots as instructors in muscle training. The Swedish Air Force (Hjort, personal communication) has a program where they train pilots one week every year for three years at centralized courses. The aim is to get all pilots trained in this way in order to give them the more sincere understanding of muscular training and its effect on G tolerance in addition to their knowledge of flying.

In conclusion, lessons learned so far seem to suggest that initial motivation, supervision, and control is necessary for a satisfactory result, whereas subsequent and maintenance training could be entrusted to the individual since the system developped and described is very suitable for self-training - if it is combined with some competitive sporting games.

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Figure 2:

The Knee Machine with adjustable back support (modified to simulate the F-16 Aces II seat).
The torso of the pilot works via a shoulder harness against a Mini Gym placed on the wall.

<u>Mode:</u> Slow velocity, 8 contractions of 5-6 sec. each in every serie of training (simulating the straining manoeuvre).

Figure 3:

Knee extension and flexion training.

<u>Mode:</u> Fast velocity, 15 contractions in every serie of training.

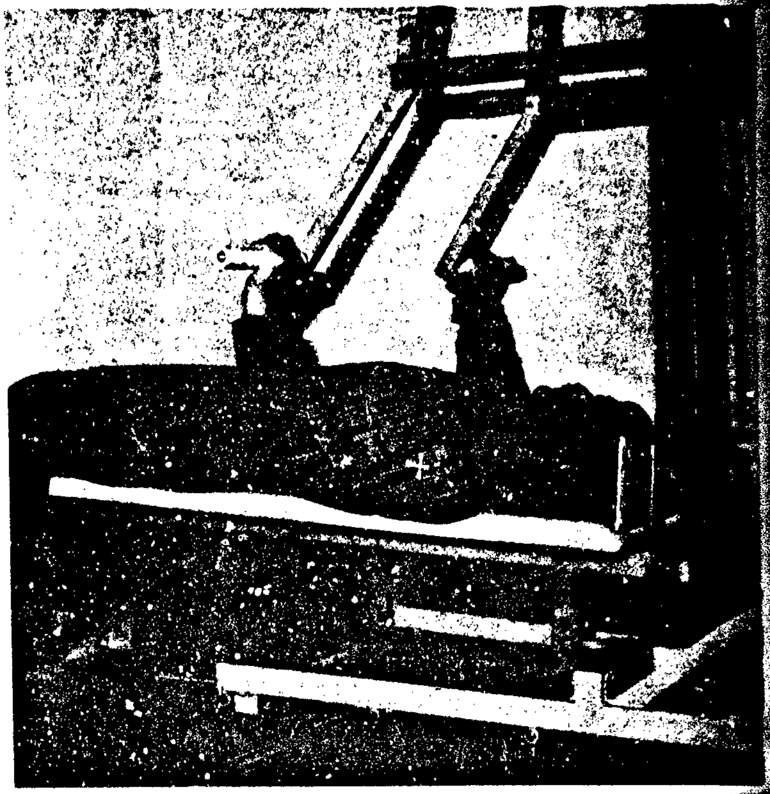

Figure 4:

Arm extension and shoulder muscles.

Mode: Medium velocity, 15 contractions in every serie of training.

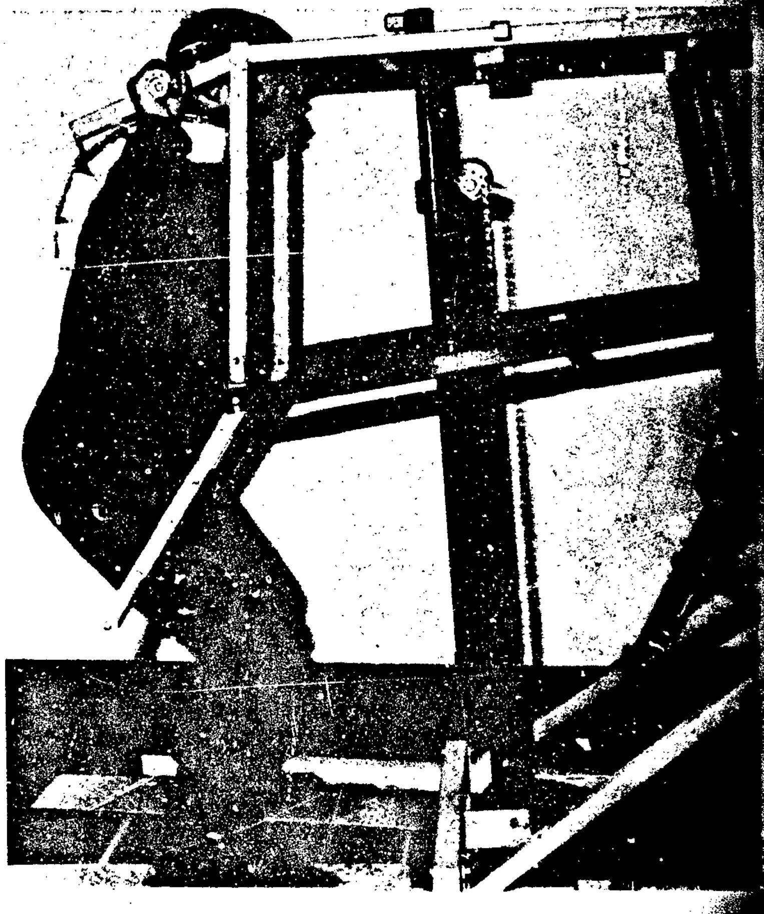

Figure 5:

Knee and hip muscles.

Mode: Medium velocity, 15 contractions in every serie of training.

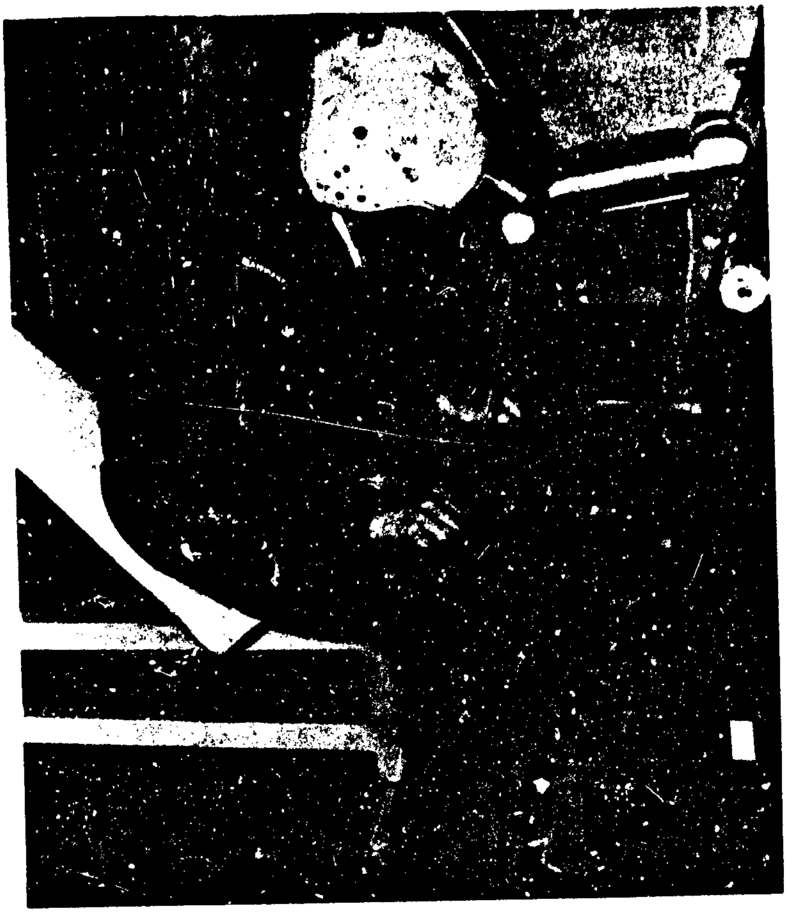

Figure 6:

Neck extensor muscles.

Mode: Medium to fast velocity, 15 contractions in every serie of training.

Figure 7:

Neck flexor muscles.

Mode: Medium velocity, 15 contractions in every serie of training.

Figure 8:

Jogging belt for moderate circulatory conditioning training.

Figure 9:

Ergonometric bicycle for moderate circulatory conditioning training.

DISCUSSION

Question

Can you incorporate the exercise program? Is there not too much sweating in the uniform?

Reply

The temperature in Denmark is much lower than in Turkey. Isokinetic exercises are not so heat producing. One can easily incorporate one or two stations of the pilot circle in the daily program. The sweat produced thereby is incomparable to the production during a 90 minute mission.

CENTRIFUGE OPERATIONS AND TRAINING IN THE ROYAL NETHERLANDS AIR FORCE

by

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I - INTRODUCTION

1. With the introduction of a new generation fighter aircraft many allied nations are confronted with the "High Sustained G" (HSG) phenomenon. This phenomenon may result in a sudden unexpected loss of consciousness (GLC) which has proven to cause fatalities, as already has been explained by Dr. Landry.

2. Many publications from the USAF School of Aerospace Medicine during the last ten years make clear that three requirements must be met by the pilot of a HSG fighter in order to be able to master his man-machine system, without losing his consciousness:

a. Good understanding of the "anti-G straining techniques".

b. Excellent physical condition.

c. A well fitting anti-G suit.

II - DESCRIPTION OF SYSTEM AND CREW

3. The Royal Netherlands Airforce uses a Human Centrifuge as training aid for the G-training of the F-16 pilot population. This centrifuge is located in the National Aerospace Medical Center in the town of Soesterberg, close to Soesterberg airbase.

4. The centrifuge operates on the "free swing" principle and is powered by an electric engine. Maximum attainable +Gz is 23.5; maximum onset-rate exceeds 3.5G/sec. The centrifuge is controlled by a digital computer.

5. The gondola is situated at the end of a four meter balanced arm. It is fitted with a simulated "ACES II" type seat which is adjustable in seat back angle. A close television-circuit is installed, connected to a video-recording system, in order to enable the operating crew to have a continuous visual picture of the face of the pilot. A two way communications system is installed and can be routed through the flying helmet. An air bottle is situated on the vertical axis of the centrifuge and through a standard G-valve air is supplied to the pilots anti-G suit. The right hand panel houses a F-16 type side stick control with a trim switch and a trigger. On the left console a "throttle" shaped handle is fitted with a "dead mans knob". In front of the pilot, mounted in the central panel, a television screen is located. On this screen a computed image of the "outside world", horizon and sky is superimposed by a "gunsight cross" and a moving target. By keeping the cross on the target the pilot is executing the computer programmed G-pattern. A horizontal "Light Bar" fitted with one red light in the centerand two green lights at the 10.30 and 13.30 hrs clock position is located on top of the television screen. This light bar is used for G-tolerance measurements.

6. Operation can be performed in three modes:

a. Automatic through the computer.

b. By manual means form the control panel.

c. By the pilot form the gondola, through side stick control (closed loop circuit).

7. Medical monitoring of EKG, EEG, Heartrate and Breathing Frequency is possible by routing the essential electrical signals from the gondola to the instructor and monitoring panels through a set of golden "slip rings" mounted in the vertical axis of the centrifuge.

8. The centrifuge is operated by RNLAF specialists of the Physiological Training Branch: technical assistance is provided by the NAMC. The centrifuge control team consist of six men:

a. A team supervisor (TS). This is the officer in command of the centrifuge operations. He must be a qualified Physiological Training Officer.

b. A qualified RNLAF Flight Surgeon (FS) with experience in centrifuge operations, including stress EKG monitoring and Cardiac Resuscitation.

c. A physiological Training Assistant (PTA). This specialist programs the centrifuge runs and operates the control switches.

d. Three PTA's who are stationed respectively near the gondola, in the dressing room and at the signal-registration desk.

III - THE "ANTI-G STRAINING MANEUVER"

9. The most effective way of combatting high G-loads is a correct executed straining maneuver. It is a combination of three specific simultanious efforts:

a. Pulling the head down between the shoulders in order to shorten the vertical heart-head distance.

b. Tensing of the peripheral skeletal and abdominal muscles as much as possible in order to support the diaphragm and heart, reduce venous volume and increase vascular resistance thereby lessening blood pooling.

c. Increasing the intrathoracic pressure by forcefull attemps to exhale against a closed or partially closed glottis. After 3 seconds a quick exhalation-inhalation gasp must be performed. Arterial blood pressure at head level can be raised significantly during the build-up of pressure but falls to approximately zero during the inspiratory phase.

10. The straining maneuver should be performed at medium and high G-levels and at the onset of a rapid build-up to HSG. The combination of this maneuver together with a well fitting G-suit may improve G-tolerance as much as 4.5G. However, when executed properly the straining maneuver is extremely fatiqueing and when performed for more than ten seconds or during successive periods, complete exhaustion may well occur when the subject is not in excellent physical condition.

IV - MEDICAL MONITORING

11. Medical monitoring of the centrifuge subject is necessary. The attending FS is tasked for this duty. His desk is instrumentated with a Cathode Ray Tube (CTR) which displays the EKG signal. Heartrate is displayed also. He can observe the pilots face on video, on which the following digital readings are projected in the four corners: date, time in hours, minutes and seconds, present G-value and heartrate. At a seperate desk located behind the FS, the same data are recorded on an automatic recorder.

12. In close proximity to the stopping position of the gondola, emergency medical equipment is located, i.e. a cardiac defibrillator and a cardiac resuscitation kit.

13. Medical indications for discontinuing a specific centrifuge run are:

a. Heartrate > 200 BPM.

b. Frequent PVC's (5 or more per run).

c. Paired PVC's.

d. Multiform PVC's.

e. ST-T depression/elevation > 2mm.

f. Ventricular tachycardia or fibrillation.

g. Supraventricular tachycardia.

h. Stress induced bradycardia.

i. GLC.

j. Any unusual pain.

k. Severe disturbance in well-being.

V - TYPICAL TRAINING DAY SCHEDULE

14. A total of six pilots can be accepted for each training day. All pilots must hold a valid aeromedical qualification. The Dutch pilots must have passed a Stress-EKG test and Spinal X-rays must have been taken. Subjects wear their personal helmets and G-suits.

15. Day schedule.

08.30 - 09.45	Briefing on HSG and GLC. Briefing on centrifuge training procedures. Pre-training questionnaire.
10.00 - 12.30	Centrifuge training, three subjects.
12.30 - 13.15	Lunch break.
13.15 - 15.30	Centrifuge training, three subjects.
15.45 - 16.30	Debriefing of the individual runs with the use of the recorded videotape. Post-training questionnaire.

VI - MISSION PROFILES (F-16 PILOTS, SEATBACK ANGLE 30 DEGREES)

16. Each centrifuge subject must complete four seperate runs. After each run he is debriefed by the TS.

a. GOR* Demonstration Profile; onset rate 1G/10 sec.; relaxed to peripheral light loss (PLL) followed by straining up to max. attainable G; break-off G: 9.0.

b. ROR* Training Profile; 6G for 30 sec.

c. ROR HSG Standard Profile; 8G for 15 sec.

d. ROR ACM* Profile; varying successive G-loads with an onset rate of 3.5G/sec., a 20 sec. top of 8.5G and a 10 sec. top of 9G.

*GOR: Gradual Onset Rate
*ROR: Rapid Onset Rate > 1G/sec.
*ACM: Air Combat Maneuvring

17. Centrifuge training for F-15 pilots (USAFE) is carried out with the seatback angle in the 13 degrees position. The top G-values are lowered by one G as tilting the seat to 30 degrees increases the average G-tolerance with 1Gz.

VII - RESULTS

18. Since regular training has started in April of this year, approximately 75 pilots took part in the program. Of this total number 24 subjects were USAFE pilots, flying F-15 and F-16 fighter aircraft. The United States Air Force, realizing the urgent need for training of fighter pilots, participates in the Dutch centrifuge program since August of this year for aircrew stationed in Europe.

19. Although the total group still is relatively small some interesting facts and preliminary conclusions came out of the training as well as the anonymous questionnaires:

a. Approximately 15% of the participating pilots had ever experienced a GLC in flight.

b. More than 90% of the pilots admitted the training had been profitable to them.

c. Over 80% of the trainees showed an inadequate straining maneuver at the onset rate of training.

d. An equal percentage wore an improperly fitted G-suit.

20. During the centrifuge training 10% of the subjects experience a GLC. This is generally due to improper straining maneuvers, fatigue or early relaxation. The centrifuge cannot be slowed down fast due to the extreme tumbling sensations that will occur. Although well briefed on this item, some individuals either start talking or stop the straining maneuver which consequently results in a GLC.

VIII - MEDICAL REMARKS

21. During the various centrifuge sessions no medical emergencies were encountered. Some Dutch pilots did show isolated PVC's and other pilots who had isolated PVC's in the 1G environment did show these during HSG. On two Dutch pilots we observed a Nodal Escape rhythm during a few beats. All variations of normal beats and rhythm did occur at +7Gz or more.

22. Some of the pilots complained of a heavy tumbling sensation during starting and stopping of the centrifuge. This phenomenon is caused by the relatively short arm of the centrifuge and is only annoying during the first two runs.

23. Many pilots, especially those who had not been flying in a high G-environment recently show the typical petechiae on the lower side of the fore-arm and back.

24. A few pilots did have a rather high heartrate toward the high G-values, approaching 190 BPM. With the resting pulse not being restored two minutes after the run has terminated one can assume the physical condition not being optimal.

XI - CONCLUSIONS

25.

a. We strongly feel that centrifuge training improves the pilots ability to operate in a high G-environment. Nearly all pilots who went through the centrifuge training course recommend this training for HSG-fighter pilots. They report that after the training they can often achieve a higher G-level for a longer time, which results in a greater combat effectiveness and a greater safety during ACM.

b. GLC can be prevented when a pilot is briefed on the G-problem and trained in a simulated combat situation trying to master actual high G-conditions.

c. Although centrifuge training is definitely not a medical or physical evaluation of the pilot or his personal equipment, valuable information can be gathered to improve his condition and equipment.

DISCUSSION

Question

1. How often do you think the centrifuge training has to take place?
2. Is there an age limit for the training?

Reply

1. We do not know yet. We give priority to all F16 (and also USAFE F-15) pilots who have not trained at all. We feel that the pilot after a full training day can go for quite a while, especially when he keeps up high performance flying bringing his acquired techniques regularly into practice. Perhaps once every three years.
2. We have not set an age limit. We have had trainees of over 45.

Question

Do you have figures on increase of G tolerance after training? Is there a big difference after training in handling the G force?

Reply

I do not have figures. Most pilots state in the anonymous questionnaire that they benefited tremendously from the training. One example: We have trained a flight surgeon with only six hours flying experience; he was able to control 9 G's after the one training day.

Question

1. How long does it take to stop the centrifuge from 9 to 1 G?
2. How many subjects suffer so much from unpleasant sensations that they have to stop?
3. How many are reluctant to train in the centrifuge?

Reply

1. We have two stopping modes. From the console it takes three seconds to come to full emergency stop, however we prefer the pilot to do it himself by means of a switch on the sidestick it then takes four seconds because the deceleration decreases during the last 2 G's.
2. Tumbling sensations are experienced, no nausea or vomiting until now. We have not stopped for that reason.
3. The reluctant ones have to participate anyway; afterwards they are enthusiastic.

HYDRAZINE AND THE F-16

by

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The introduction of the F-16 into many of the world's air forces has also introduced a rocket fuel to many areas previously unfamiliar with the propellant. The F-16, unlike other conventional aircraft, has no mechanical connections between the cockpit and the flight control surfaces. In the event of the single engine failure or any interruption of hydraulic or electrical power, a high energy, quick response (three seconds) source of emergency power is available in the Emergency Power Unit (E.P.U.) which is fueled by hydrazine. The hydrazine is in the form of H_{70} (70% N_2H_4 and 30% H_2O) and 6.8 US gallons make a full tank. The EPU operates in three modes:

1. Using 13th stage engine bleed air.

2. Using both 13th stage engine bleed air and hydrazine decomposition gases.

3. Using hydrazine decomposition gases.

These decomposition gases are H_2, N_2, NH_3, and H_2O and may reach temperatures of 1600° F. The hydrazine is ignited by passing it over an Iridium catalyst bed which causes oxidation into the decomposition gases. The gases turn a turbine which in turn drives a generator and a hydraulic pump.

Toxicology

Hydrazine is a colorless liquid with a fish-like odor. Many describe the odor as slightly ammonia-like. The odor threshold is approximately 3 - 5 parts per million (ppm), over twenty times the permissible exposure limit of 0.13 mg/m^3 (0.10 ppm). Excursions to 0.39 mg/m^3 are allowed as long as the eight-hour time weighted average (TWA) is not exceeded.

Hydrazine is a strong convulsant at high doses and a CNS depressant at lower doses. Carcinogenicity has been seen in rats, but despite a 100 year history of industrial use and US military experience, this has never been observed in humans. In humans the toxicological effects are reported in the liver where hydrazine detoxification occurs. High acute exposures have also caused kidney and hematopoietic pathologic changes. Acute exposure may also cause eye, lung, skin, and mucus membrane irritation. An important point to note is hydrazine can be absorbed through intact skin.

Hydrazine Safety

Given this information, certain tasks associated with the F-16 must be considered potentially hazardous. These tasks are primarily those dealing with the servicing, purging, and filling of the EPU. These tasks must be accomplished only with protective equipment and specific safety precautions.

All personnel with a reasonable risk of exposure to hydrazine should be entered into a medical surveillance program. The program should consist of:

1. Preplacement examination

   a. To include history with special reference to the CNS, eye, lung, liver, kidney, hematopoietic, and skin systems.

   b. A physical examination with emphasis on the systems mentioned.

   c. Laboratory studies including a hemogram, urinalysis, liver function tests, serum creatinine and BUN, baseline chest x-ray, and pulmonary function tests.

2. Accidental exposure examination which should include the same as 1) above. This should be accomplished at the time of exposure and 24 hours after. Any subsequent testing will be determined by any abnormalities found.

3. Termination examination - which should be the same as 1) above.

Several conditions should contra-indicate assignment to a position with possible hydrazine exposure. All disorders of CNS, eye, lung, liver, kidney, hematopoietic system, skin, and use of some maintenance medicine should be thoroughly investigated to determine if possible hydrazine toxicity will be detectable in view of the disorder. Additionally, the consideration that certain conditions may cause increased susceptibility to the toxic effects of hydrazine must be made.

Emergency treatment of exposed personnel should consist of immediate removal from the site, removal of clothing, flushing of contaminated areas with large amounts of water, and in the case of skin - soap and water. Education in all the emergency procedures and potential toxic effects of hydrazine is critical for a successful program.

Hydrazine spills must be handled with a prescribed, safety-conscious, protocol involving neutralization with chlorine solution and water and an approved disposal system.

Summary

Hydrazine fuel has made the F-16 a safer airplane to fly for pilots. With an easily implemented program, those who service the F-16 can also be afforded, even in the presence of hydrazine, a safe working environment. The program is indeed conservative, however, only when adequate data exist which allow us to relax some of these standards, will we consider doing so. To date, our safety record with regard to the F-16 is essentially flawless and our goal is to maintain this record.

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14. Abstract

Thirteen invited scientific papers resulting from recent French-Soviet Salyut 7, Shuttle and NASA/ESA Spacelab-1 missions were presented at the Aerospace Medical Panel's 41st Symposium on "Results of Space Experiments in Physiology and Medicine" held in Istanbul, Turkey 25—26 September 1984. An introductory paper reporting on the experience of a science astronaut on the Spacelab-1 mission was followed by five reports on vestibular and sensori-motor responses to microgravity, four papers on cardiovascular responses, and three papers covering sleep, immunological and radiobiological responses.

A one-half day informal briefing session was held at the same site on 27 September 1984 covering selection procedures, centrifuge operations and training, physical training and G tolerance, and several aeromedical problems associated with F-16 fighter aircraft operations.

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