THE RADIOLOGICAL ACCIDENT IN LIA, GEORGIA

IAEA
International Atomic Energy Agency

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The Agency's Statute was approved on 23 October 1956 by the Conference on the Statute of the IAEA held at United Nations Headquarters, New York; it entered into force on 29 July 1957. The Headquarters of the Agency are situated in Vienna. Its principal objective is "to accelerate and enlarge the contribution of atomic energy to peace, health and prosperity throughout the world''.

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FOREWORD

The use of radioactive material offers a wide range of benefits to medicine, research and industry throughout the world. Precautions are necessary, however, to limit the exposure of people to the radiation emitted. Where the amount of radioactive material is substantial, as in the case of radiotherapy or industrial radiography sources, great care is required to prevent accidents which could have severe consequences. Nevertheless, in spite of the precautions taken, serious accidents involving radiation sources continue to occur, albeit infrequently. The IAEA conducts follow-up reviews of such serious accidents to provide an account of their circumstances and consequences, from which organizations with responsibilities for radiation protection, safety of sources and emergency preparedness and response may learn.

A serious radiological accident occurred in Georgia on 2 December 2001, when three inhabitants of the village of Lia found two metal objects in the forest while collecting firewood. These objects were ^{90}Sr sources with an activity of 1295 TBq. The three inhabitants used the objects as heaters when spending the night in the forest. The major cause of the accident was the improper and unauthorized abandonment of radiation sources in Georgia and the absence of clear labels or radiation signs on the sources warning of the potential radiation hazard. Under the Convention on Assistance in the Case of a Nuclear Accident or Radiological Emergency (Assistance Convention), the Georgian authorities requested assistance from the IAEA to advise on the dose assessment, source recovery and medical management of those involved in the accident.

For their support provided under the Assistance Convention, the IAEA wishes to express its thanks to France and its Institute for Radiological Protection and Nuclear Safety, the Burn Treatment Centre of the Percy Military Training Hospital, in Paris, and the Russian Federation and its Burnasyan Federal Medical Biophysical Center

The IAEA is grateful to the Government of Georgia for the opportunity to report on this accident to disseminate the valuable lessons learned. In particular, the IAEA wishes to express its gratitude to the Nuclear and Radiation Safety Service of the Ministry of Environment Protection of Georgia, for their assistance in preparing this publication. The IAEA officer responsible for the preparation of this publication was P. Zombori of the Incident and Emergency Centre, Department of Nuclear Safety and Security.

CONTENTS

1. INTRODUCTION

1.1. BACKGROUND

On 2 December 2001, an accidental overexposure to radiation of three people occurred in a forest approximately 50 km east of Lia, a village in Georgia. The event resulted from the inadvertent use of two hot objects found as personal heaters, which were later found to be two ^{90}Sr radioisotope sources with an activity of 1295 TBq. Some 3–3.5 h after their first contact with the sources, the three individuals complained of nausea, headaches, dizziness and vomiting.

One to two weeks later, two of the individuals developed a burning sensation on their backs and one developed the same sensation on his right hand. Their families reported the symptoms to the local police, who advised that they proceed to the local hospital and request medical help. The three individuals were hospitalized on that same day, 22 December 2001, in the city of Zugdidi (the administrative centre of the region). Based on the anamnesis and clinical picture of the three patients, acute radiation syndrome (ARS) was diagnosed, and the case was reported to the Emergency Medical Center in T'bilisi, the capital of Georgia. A request to transfer the patients to the Institute of Hematology and Transfusiology (IHT) in T'bilisi was issued. At the IHT, general treatment was provided to all three patients, which included, among other things, medication for antibacteriological therapy and immunostimulators.

On 4 January 2002, the Government of Georgia requested IAEA assistance under the Convention on Assistance in the Case of a Nuclear Accident or Radiological Emergency (Assistance Convention). Following this request, the IAEA assembled and dispatched two field teams. The first was on 5 January 2002 to discover what had happened (fact finding) and to undertake a preliminary medical evaluation for the prognosis and treatment of the overexposed individuals. The second was on 27 January 2002 to assist in the training of the recovery team, searching and locating the radioactive sources, implementing the recovery operation, characterizing the radioactive sources, conducting a radiological survey of the accident site and facilitating medical assistance to the overexposed people.

With the help of the IAEA, two of the three patients were later transferred to specialized hospitals abroad. One patient was treated at the Burn Treatment Centre of the Percy Military Training Hospital, in Paris, France, and the other was treated at the Institute of Biophysics of the Burnasyan Federal Medical Biophysical Center, in Moscow, the Russian Federation.

1.2. OBJECTIVE

At the request of Member States, the IAEA has, for a number of years, provided support and assistance and conducted follow-up investigations after serious accidents involving radiation sources. Reports have been published on these investigations, which cover radiological accidents involving workers, the public and patients undergoing radiotherapy.

The objectives of this publication are to compile information on the causes and consequences of the accident, make recommendations and disseminate the information — particularly the lessons learned from the event — in order to avoid similar occurrences and to minimize the consequences.

1.3. SCOPE

This publication describes the circumstances and events surrounding the accident, its management and the medical treatment of the people exposed. It also describes the dose reconstruction calculations and biodosimetry assessments conducted. A number of uncertainties remain relating to some details of the accident. However, sufficient information is available for a publication that provides substantive conclusions and advice.

1.4. STRUCTURE

Background information on the location of the accident, details of the radioactive sources and a chronology of the events are provided in Section 2. The IAEA assistance missions are presented in Section 3, and the recovery of the radioactive sources is discussed in Section 4. Section 5 addresses the results of the biological dosimetry. The medical management of the individuals exposed as a result of the accident, including dose assessment and detailed biodosimetry data, is discussed in Sections 6–9. Section 10 provides a summary of the conclusions and presents recommendations and lessons learned.

2. BACKGROUND INFORMATION

2.1. LOCATION OF THE ACCIDENT

Georgia is a sovereign State in the Caucasus region of Eurasia. It is bound to the west by the Black Sea, to the north by the Russian Federation, to the south by Turkey and Armenia, and to the east by Azerbaijan. The National Statistics Office of Georgia reports a population of 4 483 800 as of 1 January 2013. The village of Lia is located in the district of Tsalenjhikha and is approximately 320 km north-west of T'bilisi, the capital of Georgia (see Fig. 1).

2.2. RADIOISOTOPE THERMOELECTRIC GENERATORS

In the former Union of Soviet Socialist Republics, various types of generator were designed on the basis of different radioisotopes [1]:

— Cerium-144 (with an activity of 740 TBq);
— Caesium-137 (with an activity of 1850–5550 TBq);
— Strontium-90 (with an activity of up to 3700 TBq).

These radioactive sources were used as sources of heat in thermoelectric energy transformers [2]. The typical power range of nuclear thermoelectric generators is between 1 and 1000 W, and their working life is between 10 and 20 years.

Beta 1, Beta 2, Beta 3, Beta C and Beta M are different types of generator designed for use with radioisotopes ^{144}Ce and ^{90}Sr. These generators were used as sources of electric power for radiometric devices and navigational systems.

By comparing the data provided by Georgia with the information provided in Refs [1, 2], it is possible to conclude that the radioactive sources involved in the accident belonged to the category of radioisotope thermoelectric generators (RTGs) of the Beta M type, with an activity of 1295–1480 TBq.

Following the accident, it was determined that eight RTGs of the Beta M type had been brought into Georgia in the early 1980s to serve the radio relay system between the Engury hydroelectric station and Hudoni hydroelectric station, which was under construction at the time. These generators were placed in pairs at four substations located in areas where there were no other means of electrical power supply. In these generators, the heat generating elements were ^{90}Sr radioisotope sources with an activity of 1480 TBq and a heat power of 250 W.

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FIG. 1 . Map of Georgia.

The bremsstrahlung gamma radiation dose rate at 1 m was 1 Sv/h. Figure 2 shows the vertical cross-section of this type of generator, with a corresponding description of its parts.

1. Heat dissipater
2. Thermobattery
3. Inner radiation protection (tungsten)
4. Radionuclide heat source
5. Heat isolation
6. Framework
7. Outer radiation protection
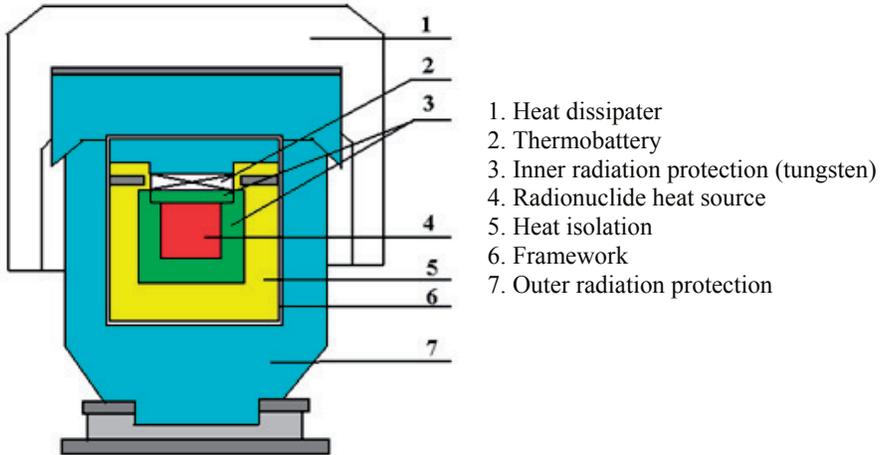
FIG. 2. Radioisotope thermoelectric generator, Beta M type.

After the construction of the Hudoni hydroelectric station was stopped, the radio relay system lost its function, and the generators were left without supervision and control. By the end of the 1990s, the generators were disassembled, with the radioactive sources exposed and removed from their original location. Of the eight ^{90}Sr radioactive sources, only six have so far been found.

The first pair of radioactive sources was found in the Svaneti region, near the village of Idiani, in 1998. They were removed and stored the same year. A second pair was found in the same region, near the village of Laburtskhila, in 1999. They were also removed and stored in May 1999. No one who came into contact with the radioactive sources received a high irradiation dose or sought help, and routine medical examinations did not reveal any abnormalities.

A third pair of ^{90}Sr sources were found by three inhabitants of the village of Lia in December 2001. This publication describes the accident.

2.3. CHRONOLOGY OF THE ACCIDENT

On a cold day of 2 December 2001, three inhabitants of Lia (later designated as Patients 1-DN, 2-MG and 3-MB) drove their truck approximately 45–50 km east of Lia to collect firewood. At around 18:00, they found two containers — metallic, cylindrical objects — lying on a forest path. Around them, the snow had curiously thawed within a radius of approximately 1 m, and the wet soil was steaming. All three individuals stated that the two, rather heavy, cylindrical objects (8–10 kg, 10 cm × 15 cm) were found by chance while carrying out their usual task of collecting firewood.

One of the three men (Patient 3-MB) picked up one of the cylindrical objects and, finding that it was hot, dropped it immediately. They planned to place the gathered wood in their truck the next morning, and because it was getting dark, they decided to spend the night in the forest, using the hot objects they had discovered as personal heaters.

Patient 3-MB used a strong wire to lift one of the hot objects, hooking it into the holes of its frame and carrying it for approximately 1 min, to a place 2–3 m from the forest path, just behind a large rock nearby. Patients 1-DN and 2-MG lit a fire to prepare dinner and for their overnight stay in the open air. As the second object's frame did not have any holes, Patient 3-MB lifted the object from the ground while Patient 2-MG curved a strong wire around it. This procedure took approximately 2 min. Patient 3-MB then moved the object to the rock (carrying it on a wire 0.5 m long) and placed it near the other source of heat.

The three individuals warmed themselves during the night using the open fire on one side, sitting and lying around it, and not far from the hot cylindrical objects, which they placed at a distance of up to 1 m behind their backs. Patients 1-DN and 2-MG lay next to these objects for 1–1.5 h each during the night, coming into very close proximity to them: the distance between the cylindrical objects and the upper and middle sections of their backs was around 10 cm. It is important to note that since none of the three individuals concerned owned a watch, all times and intervals are approximate. After dinner, they consumed some alcohol (vodka). However, they felt unusually sick after only a small amount (about 100 mL) and could not sleep.

Approximately 3–3.5 h after their first contact with the radioactive sources, they began to suffer from nausea, headaches, dizziness and vomiting. Patient 1-DN vomited a few minutes after drinking some vodka, Patient 2-MG vomited 30 min later and Patient 3-MB began vomiting around 1 h later. The vomiting was very intensive and lasted throughout the night. In the morning, they loaded only half of the gathered wood into the truck, as they were exhausted and felt weak from a lack of sleep. They arrived back at their homes, in Lia, at approximately 17:00 on 3 December 2001.

Apart from the first night, there were no further episodes of vomiting. According to an interview, Patients 1-DN and 2-MG had carried one of the two sources on their backs, tied to the top of a wooden rod, for several hours. However, some uncertainties remain concerning the exact scenario of the accident (see Tables 1 and 2).

TABLE 1. CHRONOLOGY OF MEDICAL SYMPTOMS AND MANAGEMENT OF THE THREE PATIENTS

Date	Days after exposure	Event
2 Dec. 2001	0	Approximately 3–3.5 h since first contact with the radioactive sources, Patients 1-DN, 2-MG and 3-MB vomit several times during the night. They also complain of nausea, headaches and dizziness.
3 Dec. 2001	1	Patient 2-MG experiences repeated diarrhoea and develops a skin reaction type urticaria. Itching maculae cover the whole surface of his body.
4 Dec. 2001	2	Patient 2-MG goes to the village outpatient medical department but does not mention his contact with the "heating device". The local doctor suspects intoxication and treats him with an infusion of saline and Haemodes to eliminate toxic metabolites via renal clearance and an intramuscular injection of Suprastin to treat a possible allergic reaction. Following this treatment, his symptoms disappear in a day.
10 Dec. 2001	8	Patient 3-MB develops erythema, a burning sensation and oedema on the right hand, and cannot close his fingers. The skin is flattened.
13–14 Dec. 2001	11–12	Dry desquamation appears on the right hand of Patient 3-MB.
15 Dec. 2001	13	Patients 1-DN and 2-MG feel a burning sensation and itching on their backs.
17 Dec. 2001	15	Patient 1-DN experiences pain in his throat and loses his voice. Patient 2-MG develops the same type of allergic reaction as on day 1 after exposure and dry desquamation on his back.

TABLE 1. CHRONOLOGY OF MEDICAL SYMPTOMS AND MANAGEMENT
OF THE THREE PATIENTS (cont.)

Date	Days after exposure	Event
22 Dec. 2001	20	All three patients are hospitalized in Zugdidi, Georgia. The three patients are diagnosed with ARS, and the case is reported to the Emergency Medical Center in T'bilisi (Ministry of Labour, Health and Social Affairs, Georgia), which requests a transfer of the patients to the IHT in T'bilisi.
23 Dec. 2001	21	All three patients are transferred to the IHT in T'bilisi.
23 Jan. 2002	52	After receiving treatment, Patient 3-MB is discharged from hospital and monitored as an outpatient.
31 Jan. 2002	60	The IAEA receives a request from the Government of Georgia for assistance on specialized medical treatment abroad for Patients 1-DN and 2-MG.
21 Feb. 2002	81	Patient 1-DN is admitted to the Institute of Biophysics of the Burnasyan Federal Medical Biophysical Center, in Moscow, the Russian Federation. Patient 2-MG is admitted to the Burn Treatment Centre of the Percy Military Training Hospital, in Paris, France, for further medical treatment.
18 Mar. 2003	471	Patient 2-MG is treated for CRS. He is discharged from hospital and returned to Georgia.
13 May 2004	893	The critical health status of Patient 1-DN and impairment to multiple organs results in his death.

Note: ARS — acute radiation syndrome; CRS — cutaneous radiation syndrome; IHT — Institute of Hematology and Transfusiology.

TABLE 2. CHRONOLOGY OF THE RECOVERY AND LOCAL POPULATION MONITORING

Date	Days after exposure	Event
23 Dec. 2001	21	An initial attempt is made by the Georgian authorities to determine the exact location of the heating devices (suspected radioactive sources). However, because of an impassable road conditions and bad weather, this attempt fails.
29 Dec. 2001	27	The second attempt to locate the suspected radioactive sources is successful. The exact location is determined, their physical condition is examined and a video recording is made.
4 Jan. 2002	33	The IAEA receives a request from the Government of Georgia for assistance in recovering the radioactive sources.
5 Jan. 2002	34	The Georgian medical team conduct medical examinations on approximately 20 residents of Lia.
6–7 Jan. 2002	34–37	A team of Georgian specialists from the NRSS of the Ministry of Environment Protection and Natural Resources of Georgia[a], the DESCD and the Institute of Physics, accompanied by IAEA experts, attempt to travel to the location of the radioactive sources to recover them. Unfortunately, due to extreme weather conditions, the team is not able to reach the location, and the recovery attempt fails.
2 Feb. 2002	62	A team of Georgian specialists from the NRSS, DESCD and the Institute of Physics, accompanied by IAEA experts reach the location and recover the radioactive sources safely.

Note: DESCD — Department of Emergency Situations and Civil Defence of the Ministry of Internal Affairs; NRSS — Nuclear and Radiation Safety Service.

[a] The Ministry of Environment Protection and Natural Resources of Georgia became the Ministry of Environment Protection of Georgia in 2011.

3. IAEA MISSIONS

3.1. MISSION OBJECTIVES

The IAEA conducted two expert missions to Georgia. The first took place from 5 to 11 January 2002 and was undertaken with the following objectives:

(1) To evaluate the order of magnitude of the doses incurred by people, among other things, by analysing the information available and from physical measurements;
(2) To undertake a preliminary medical evaluation for the prognosis and treatment of the overexposed individuals;
(3) To identify issues for which the IAEA could offer to provide and coordinate assistance to minimize the radiological consequences;
(4) To recommend any additional assistance the IAEA could provide to Georgia.

The second mission took place from 27 January to 9 February 2002 and was undertaken with the following objectives:

(a) To provide support and advice during the preparatory and implementation phases of the operation to recover the two orphan ^{90}Sr radioactive sources from a mountainous and remote area of the Tsalenjika region of western Georgia;
(b) To hold an IAEA technical meeting on orphan sources in Georgia.

3.2. MISSION RESULTS

3.2.1. Results of the first IAEA mission

The IAEA team participated in meetings with the Minister of Environment Protection and Natural Resources of Georgia and the representatives of the Department of Emergency Situations and Civil Defence of the Ministry of Internal Affairs (DESCD). The situation regarding the radiological emergency was presented and discussed on the basis of a short video that had been recorded by the Georgian authorities on 29 December 2001, which contained images of the radioactive sources and their location. The main concerns at this stage were:

(a) Production of shielding containers for each radioactive source;

(b) Organization and planning of the recovery operation based on the radiological and weather conditions in the area;

(c) Risk of losing the radioactive sources due to worsening weather conditions;

(d) Addressing the concern of the local population about their safety and well being.

The IAEA team were consulted on the status of the three hospitalized patients at the IHT in T'bilisi. It was concluded that the diagnosis and treatment of the patients was appropriate and could continue in T'bilisi. None of the patients was in a life threatening condition, and all of them were in a stable phase of haematological remission. Patients 1-DN and 2-MG had moderately severe extended superficial radiation burns to the back, which were in a phase of spontaneous recovery. It was agreed that Patient 3-MB had a mild radiation injury. He could be discharged from the hospital within ten days and have a follow-up appointment in the outpatient clinic of his home village, Lia.

The IAEA team contributed to an assessment of the health status of the local population, which had been performed by a medical team from the Ministry of Labour, Health and Social Affairs on 8 January 2002. The 18 medical doctors who performed the screening were briefed twice on the possible early and late health consequences of exposure to radiation, the types of injury observed in recent severe radiation accidents and their management. Members of the local population with potential radiation exposure were consulted, examined and relieved of their anxiety following a discussion of the negative findings. No radiation induced health effects were found among the 300 screened inhabitants.

The responsibilities of the Georgian authorities were presented by the IAEA team at the final debriefing of the first mission and were specified as:

(1) To urgently secure the location of the radioactive sources.

(2) To initiate planning of the recovery, with the participation of several organizations for logistical support, including aspects such as:

(i) Transportation;

(ii) Security;

(iii) Preparation of the shielding containers;

(iv) Selection of the equipment for the survey and personnel monitoring;

(v) Selection and training of the staff involved;

(vi) Training at a location simulating the real recovery (mock-up);

(vii) Transportation and storage of the sources;

(viii) To provide medical assistance for the three patients.

3.2.2. Results of the second IAEA mission

3.2.2.1. The patients

The IAEA team strongly supported the local doctors' opinion that it was essential for the well being of the two most severely injured patients — Patients 1-DN and 2-MG — to be transferred to a specialized hospital for the treatment of ARS. It was also recommended that the IAEA facilitate the specialized treatment to be received abroad.

3.2.2.2. The recovery operation

The recovery plan developed by the experts from the Institute of Physics together with the staff of the Ministry of Environment Protection and Natural Resources of Georgia was an excellent example of how to recover orphan radioactive sources safely with limited financial and technological resources. This comprehensive plan included:

— Building a special lead transport and storage container (27 cm thick, 90 cm high and weighing 5.5 t) to shield the two radioactive sources;
— Manufacturing special steel remote handling tools and tongs to collect the radioactive sources;
— Adapting an old army truck to transport the container;
— Training DESCD personnel (26 soldiers) to recover the radioactive sources, while keeping their individual doses well below limits set by international standards.

In addition, the plan addressed the logistics, which included, among other things:
— Food supplies for two days;
— Fuel for 12 vehicles (seven cars, three trucks, one bus and one bulldozer);
— Field accommodation for approximately 50 people.

The IAEA provided personal thermoluminescent dosimeters (TLDs) and ensured that the preparation and recovery operations were consistent with international radiation safety standards and good practice.

Local and international media exhibited a great deal of interest in this event. The IAEA participated in dealing with media enquiries. Despite a lack of experience with such a complex event, the Georgian authorities (Ministry of Environment Protection and Natural Resources of Georgia, and Ministry of the Interior) managed the public and media interest in a professional manner.

As requested by both Ministries, the IAEA team leader participated in several events with the media, with the purpose of assisting the Georgian authorities in providing information on the event to the local population. The IAEA team assisting in Georgia and IAEA staff located at the IAEA in Vienna, Austria, were found to be invaluable in addressing international media inquiries.

4. RECOVERY OF THE RADIOACTIVE SOURCES

4.1. INITIAL ASSESSMENT

The radioactive sources were located in a barren, unpopulated region, on a dirt track road 28 km from Lia. Photskhoetseri is the nearest village and residential area to the location of the radioactive sources. Situated beneath the high altitude dam of the Enguri hydroelectric station, the village's location from the radioactive sources is 18 km along the dirt track road, but only 4–5 km in a straight line. Photskhoetseri is separated from the location of the radioactive sources by a mountain ridge, the high altitude dam and a reservoir.

The dirt track leading to the radioactive sources was primarily used by local inhabitants and woodcutters. Driving on the dirt track road only seemed possible by very experienced drivers familiar with the track, such as woodcutters that owned high powered, three axle cross-country vehicles. The final 400 m to the location of the radioactive sources was found to be completely impassable, as it was blocked by rocks from a landslide.

The first attempt to determine the exact location of the radioactive sources and to examine their condition failed because of the near impassable road and poor meteorological conditions. The second attempt on 29 December 2001 was successful. A team consisting of specialists from the Institute of Physics, the DESCD and the NRSS arrived at the area and identified the exact location of the radioactive sources. The team verified the condition of the radioactive sources, made all the necessary measurements, took photographs and recorded a video.

It is worth noting that the radioactive sources were located just off the dirt track road in a hollow and were isolated by a heap of rocks and earth (see Fig. 3). Due to these factors, the radiation on the side of the dirt track road was partially shielded, and the dose rate measured from the dirt track road, even in close proximity to the radioactive sources, was not very high. Close to the radioactive sources, on the other side of the shielded dirt track road and around 5 m from the sources, the dose rate was 1.3 mSv/h. For unshielded radioactive sources, this value would be approximately 80 mSv/h.

FIG. 3. Initial location of the radioactive sources under a large stone.

The additional shielding provided by the heaps of rock and earth was very important, as it allowed the recovery team additional time to conduct their preparatory work (repair the road, park the vehicle loaded with the container and arrange for recovery devices to be placed in convenient locations) under conditions of relatively low radiation doses.

In addition, the fact that the nearest inhabited areas were quite far from the radioactive sources meant that the radioactive sources posed no danger to the local population. Furthermore, these types of radioactive source are specially manufactured using super resistant ceramics that are hermetically sealed in double capsules made of fireproof stainless steel. This steel is resistant to any aggressive medium and practically excludes the danger of radioactive or toxic contamination of the environment. Thus, there was no urgent need for prompt removal of the radioactive sources to limit potential exposure to the public. If the areas of high dose rate near the radioactive sources had been marked and the local population had been warned, it would have been quite possible to delay the operation until spring or summer. However, one significant development was taken into account for the expedited recovery of the radioactive sources: the public concern and fear among the inhabitants of the Tsalenjhikha region had

gradually been increasing. For this reason, the Government of Georgia decided to execute the recovery operation of the radioactive sources as soon as possible, despite the impassability of the road and poor meteorological conditions.

4.2. RECOVERY OPERATION PLAN

4.2.1. Organizations responsible for the recovery operation

According to Georgian legislation, the main organizations responsible for conducting the recovery operations are the DESCD and the NRSS. They were responsible for formulating the recovery plan, establishing and training the recovery team, and conducting the safe transportation of the container (in which the radioactive sources had been placed) to the storage facility. The NRSS was responsible for constructing the shielding container, distributing special devices (manipulators), safe storage of the container, and individual dose and dose monitoring during the recovery operation. The NRSS was also responsible for conducting a medical survey of the recovery team members (together with the Ministry of Labour, Health and Social Affairs) before and after the operation, issuing special agreements with the recovery team members, accounting of expenditures and providing information to other governmental and non-governmental institutions and the public.

The DESCD and the NRSS were responsible for selecting the training location and providing transport, selecting the means of road transport for transferring the container with its cargo of radioactive sources to the storage facility and the selection of people to participate in the recovery operation. The representative of the Georgian President in the Mengrelia-High Svaneti region was responsible for repairing the road from the Enguri dam to the location of the radioactive sources. Funds from the Georgian State budget provided financial support for the operation under a programme of the Ministry of Environment Protection and Natural Resources of Georgia entitled Protection of the Georgian Population from Harmful Effects of Ionizing Radiation.

4.2.2. Recovery operation strategy and tactics

The area in which the radioactive sources were located was characterized by poor meteorological conditions and high dose rate measurements, which made the conduct of operations particularly difficult. Taking into account the potential for high radiation exposure (the dose rate from each radioactive source at 1 m was in the order of 1 Sv/h), it was decided that each recovery team member would not be allowed to work with the radioactive sources for more than 2 min. It should

also be noted that team members were allowed to remain for several minutes in the vicinity of the radioactive sources (at 20 m). It was therefore necessary to create a recovery team of 20–25 people. The maximum dose received during the operation was limited to 20 mSv. In accordance to the as low as reasonably achievable (ALARA) optimization principle, every member of the team was required to work as far away as possible from the radioactive sources for the minimum time period, on which the team members were briefed during their training.

4.2.3. Preparatory actions

It was necessary to conduct the following preparatory actions before initiating the recovery operations:

(1) A special shielding container was constructed that could hold both radioactive sources (see Fig. 4). One of the radioactive sources had a mushroom like cap, possibly containing a tungsten protective plate, and the second had a metal outer shell cut into two pieces, in which it is believed a tungsten protective cup was originally placed. The maximum dimension of the latter radioactive source was presumed to be approximately 30 cm. Therefore, the diameter of the inner cylinder of the container was required to be greater than 30 cm. The container was also required to have protection that ensured the dose rate on its surface was lower than the maximum dose rate allowed for the transportation of the container. Thus, a container was constructed with a protective layer of lead 25 cm thick. The mass of the container was around 5.5 t.
(2) Special manipulating devices and tools (manipulators) were designed, manufactured and tested (see Fig. 5). A vessel with handles on opposite sides was required to ensure ease of movement when loading the radioactive sources into the container and to prevent the user being closer than 2 m (see Fig. 6).
(3) A medical survey of the recovery team members was conducted.
(4) Training for the recovery team was conducted in conditions similar to those they would experience during the operation.
(5) Arrangements were made to provide individual dose monitoring for the recovery team during the recovery operation.
(6) A detailed plan of the recovery team's activities was prepared to determine the timing, length of stay and positions for the members of the rescue team at different distances away from the radioactive sources. Based on Georgian regulations at the time of the emergency, the dose limit for occupational workers (20 mSv that can be received at one time for emergency situations
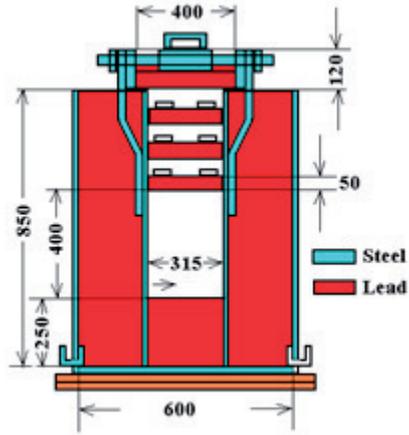
FIG. 4. *Shielding container for the radioactive sources.*
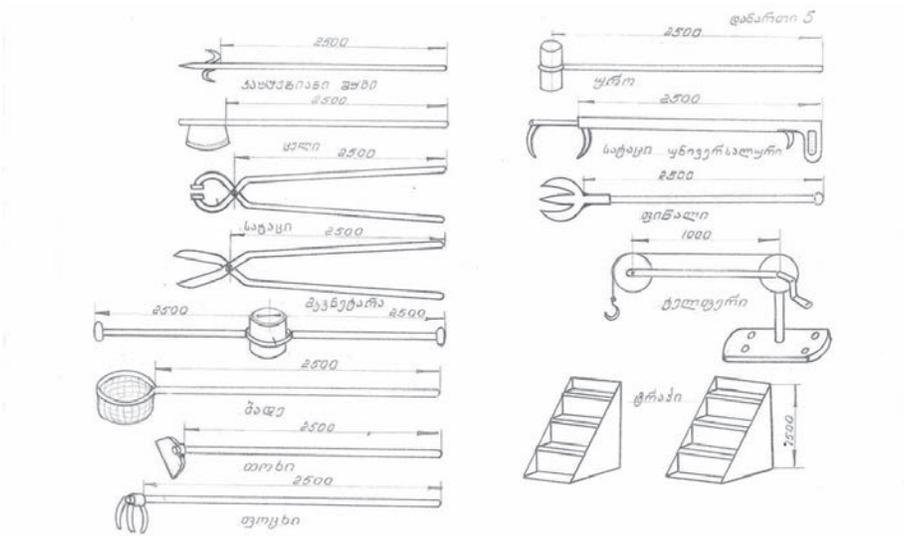
FIG. 5. *Sketch of the manipulating devices used in the recovery operation.*

FIG. 6. *Special manipulator used for carrying the radioactive sources during the recovery operation.*

and during the process of liquidation) was used as a basis for establishing the maximum doses allowed for the members of the rescue team. With due caution and to ensure that the doses to workers remained below the dose limit, it was decided to plan the work in such a way that the maximum dose received by any individual would not exceed 10 mSv. For the calculations used for determining the working time in the radiation area, see Appendix I.

(7) Preparations were made to conduct radiation monitoring of the area where the radioactive sources were located after the recovery operation to confirm the operation had been completed successfully.

(8) The road leading to the radioactive sources was repaired so that it would be possible for the vehicle, loaded with the container, to be positioned at a maximum distance of 40–50 m away from the radioactive sources.

(9) A special means of transport was provided for the container prepared for the radioactive sources. A three axle cross-country vehicle was selected, and the container was secured in such a way that it could withstand any level of impact and sudden movements encountered when travelling on the road from the village of Photskhoetseri to the radioactive sources. Figure 7 shows the three axle cross-country vehicle with the container at the recovery location.

FIG. 7. Vehicle with the container after the recovery operation.

(10) Arrangements were made to provide one day's accommodation for the recovery team during the recovery operation.

(11) Arrangements were made to provide a special traffic escort for the safe transfer of the radioactive sources to the storage facility.

4.2.4. Transporting the recovered radioactive sources

The following requirements were drawn up to ensure the safe transportation of the recovered radioactive sources:

(1) Radioactive sources were to be placed into a specially designed shielding container that is fixed securely to the vehicle.

(2) Throughout the entire transportation period, the vehicle with the container was to be escorted by police cars under secure conditions.

(3) Maximum speed of the vehicle with the containers was to be 50 km/h (without the radioactive sources) and 30 km/h (with the radioactive sources).

(4) Special attention was to be paid to the mountain road, where tractors and other specialized machinery was to be used to clear the road immediately before the vehicle with the container passes.

The DESCD and the NRSS were responsible for the safe transportation of the radioactive sources to the storage facility. The DESCD was responsible for choosing the means of transport and its technical arrangement. The head of the DESCD was personally responsible for arranging the training of the recovery team members.

4.2.5. Recovery team

The realization of the recovery operation required team members with sufficient qualifications and skills. It was decided to assign 24 people to the recovery operation. Each member of the team was responsible for a clearly defined activity. It was also decided to prepare a reserve team in case reinforcements were required. Altogether, 41 people were trained for the recovery operation. The purposes of training were:

(a) To strengthen the skills of the recovery team;

(b) To ensure harmonization of the activities undertaken among the recovery team;

(c) To train the recovery team on the effective use of the manipulating devices;

(d) To obtain feedback that would allow for improving the effectiveness of the recovery operation and to make necessary changes in the plan, as appropriate.

The core of the recovery team consisted of members of the NRSS who had previous experience in conducting recovery operations. The head of the NRSS was assigned as leader of the recovery team. The head of the NRSS Emergency Situation Department was responsible for constructing the shielding container and all manipulating devices. The deputy heads of the NRSS and the DESCD were responsible for conducting the training. The head of the NRSS Department for Inventory, Control and Regulation of Nuclear and Radiation Activity supervised radiation monitoring and obtaining individual consents from the members of the recovery team. Negotiation of the agreements with the recovery team was the responsibility of the principal accountant of the Ministry of Environment Protection and Natural Resources of Georgia and the accountant of the NRSS.

The head of the Radiation Safety Unit of the Institute of Physics and the head of the Dosimetric Assessment Unit of the National Oncology Centre were responsible for individual dose monitoring. The deputy director of the Institute of Physics, the head of its Applied Research Centre and the head of its Radiation Safety Unit were assigned as consultants in the implementation of the recovery operation.

4.2.6. Recovery operation schedule

The period of time for conducting the recovery operation depended on the following factors:

— Road and meteorological conditions;
— Preparation of technical equipment;
— Modes of transport.

4.2.7. Deployment of teams and resources for conducting the recovery operation

The day before the recovery operation, the recovery team was deployed in Zugdidi. All modes of transport were prepared in Djvari. A detailed description of the operation activities was attached to the recovery operation plan.

4.3. RECOVERY OPERATION

The recovery of the radioactive sources was executed on 2–3 February 2002. All preparatory actions had been completed, and a series of training sessions had been held in preparation for the operation.

The operation was conducted under poor road and meteorological conditions. It took 3.5 h to travel 18 km from the village of Photskhoetseri to the location of the radioactive sources. The majority of the road was covered with recently fallen snow, and travel was only possible using a towing tractor provided by the local authorities (see Figs 8 and 9).

After arriving at the site, the preparatory work and preliminary measurements took 30 min. The recovery work (moving the radioactive sources to the road and loading them into the container) was completed within 20 min. The preparation for returning to the village of Photskhoetseri took 30 min, and the travel time was 3.5 h.

The NRSS, the DESCD and the Institute of Physics were commissioned to carry out the recovery of the radioactive sources and to transport them to their place of storage, with the help of the Institute of Radiology, the Georgian Academy of Agricultural Sciences and other relevant departments.

FIG. 8. The middle section of the road leading to the radioactive sources.

FIG. 9. The final section of the road leading to the radioactive sources.

During the recovery operations, the following steps were taken:

(1) The vehicle and container were positioned so the rear of the vehicle was close to the radioactive sources.
(2) Two members of the recovery team installed stairs on the vehicle.

(3) The recovery team was divided into two groups. The first was positioned in an area located 20 m from the radioactive sources. The second remained beyond that area at a safe distance from the location of the radioactive sources.

(4) Two members of the recovery team placed the manipulating devices near the location of the radioactive sources.

(5) One member of the recovery team cleared the surrounding area of the radioactive sources.

(6) One member of the recovery team collected one of the radioactive sources and placed it into a special vessel.

(7) Two members of the recovery team transferred the radioactive source in the special vessel to the vehicle.

(8) Two members of the recovery team standing on the vehicle received the radioactive source and placed it into the container.

(9) In the event that a recovery team member became unable to complete their activity (e.g. due to the dose received), a substitute person was ready and available.

(10) The second half of the recovery team conducted the same actions for the second radioactive source.

(11) One person conducted individual dosimetry control for all members of the recovery team and recorded the doses.

(12) Two members of the recovery team conducted dose rate monitoring.

(13) All actions were led by a team member assigned to give commands to start or to stop, according to the plan. A signal to stop was given to every worker after 40 s from the beginning of each activity, indicating replacement by the next worker.

The IAEA used TLDs and the NRSS used two electronic dosimeters as personal dosimeters. The data gathered is provided in Table 3, which shows the equivalent doses received by the personnel involved in the recovery operation. The estimation of the activity of the radioactive sources was performed on the basis of measurements taken at their location.

TABLE 3. EQUIVALENT DOSES RECEIVED BY THE PERSONNEL INVOLVED IN THE RECOVERY OPERATION

| Worker no. | Equivalent dose (µSv) | |
	IAEA data	NRSS data (DOSICARD)[a]
1	80	30
2	380	302
3	250	—[b]
4	250	—[b]
5	1160	876
6	170	—[b]
7	950	952
8	60	16
9	110	550
10	290	219
11	50	11
12	450	296
13	60	11
14	590	532
15	260	203
16	290	195
17	340	304
18	70	—[b]

TABLE 3. EQUIVALENT DOSES RECEIVED BY THE PERSONNEL INVOLVED IN THE RECOVERY OPERATION (cont.)

Worker no.	Equivalent dose (µSv)	
	IAEA data	NRSS data (DOSICARD)[a]
19	90	58
20	100	32
21	290	205
22	620	878
23	—[b]	18
24	—[b]	334

[a] Every electronic dosimeter was set for two levels of alarm for the received dose.

[b] —: data not available.

The radioactive sources were situated several centimetres from each other. The total dose rate was measured at a distance of 2 m. The measurement was made with a Radiagem dose rate meter. The distance was measured with a calibrated stiff stick, fixed at the end of the telescope probe of the dosimeter. The distance was measured from the midpoint between the radioactive sources. The measurements showed that the mean value of the dose rate at a distance of 2 m was 300 mSv/h. According to the measurements taken during the first examination of the location (29 December 2001), the dose rate was 150 mSv/h at 1.5 m from the radioactive sources, which was significantly less than the results of the most recent measurements. It seems that for the first measurement, the detector was shielded by the ledge of the rock, under which the radioactive sources were located.

Denoting the dose rate (mSv/h) at distance R (m) by $d(R)$, it was found that:

$$d(2.00) \approx 300 \text{ mSv/h} \tag{1}$$

Assuming that half of this dose rate originates from one source, it is possible to estimate the dose rate for one source at a distance of 1 m (d_0):

$$d_0(1.00) \approx \frac{1}{2}d(2.00)\left(\frac{R_2}{R_1}\right)^2 = 2d(2.00) = 600 \text{ mSv/h} \tag{2}$$

This experimental value is less than the value given in the source certificate:

$$d_0(1.00) = 100 \, R/h = 1000 \text{ mSv/h} \tag{3}$$

After enclosing the radioactive sources in the container, the dose rate was measured from the top of the open container. The distance from the radioactive sources to the detector was estimated to be 50–55 cm, taking into account the container dimensions. This distance is dependent on the location of the radioactive sources inside the container. The dose rate on the top of the container was:

$$d(0.50 - 0.55) \approx 4.6 \text{ Sv/h} \tag{4}$$

Assuming again that half of this value comes from one radioactive source positioned at the average distance of 52 cm, the dose rate for one source at a distance of 1 m is estimated to be:

$$d_0(1.00) = \frac{1}{2}d(0.50 - 0.55)(0.52)^2 = 620 \text{ mSv/h} \tag{5}$$

This value is also less than the source certificate, but is very close to the value calculated from the dose rate measured at 1 m (see Eq. (2)).

The dose rates were measured at different distances from the radioactive sources after they were moved to the road, and the results are presented in Table 4. The reading was made with a Stephen 6000 dosimeter at distances of approximately 25 m, 35 m and 45 m from the source. Distances were measured approximately by the number of steps taken and the true values might differ from those in Table 4.

TABLE 4. MEASURED VALUES FOR BOTH RADIOACTIVE SOURCES

Distance from source to detector (m)	Source 1 (mSv/h)	Source 2 (mSv/h)	Dose rates calculated according to source certificate data (mSv/h)[a]
1	~670	~580	~1000
25	1.10	1.02	1.60
35	0.50	0.42	0.82
45	0.35	0.30	0.49

[a] For comparison, the dose rates calculated according to the data provided in the source certificates are given for the same distance.

It is clear that the activity of the radioactive sources is less than that of the certificate data, but the dose rates are close to the results of previous measurements (see Eqs (2, 5)).

The difference in the dose rates between the radioactive sources might be explained by the fact that the radioactive sources had a tungsten disc, which, according to the certificate, was fixed to the bottom of the cylindrical source (see Fig. 10). The dose rate depends on the orientation of the source to the detector, which could explain the difference. However, the radioactive sources did not have a tungsten disc. First, the weight of the radioactive sources according to the operators' estimation was no greater than 10 kg — with a tungsten disc, the mass of the radioactive sources would have been approximately 20 kg. Secondly, a video recording shows that the upper part of a mushroom like cap on the second radioactive source was empty. The tungsten disc had been removed, so the anisotropy of radiation can be excluded (i.e. the intensity of the radiation was almost equal in all directions).
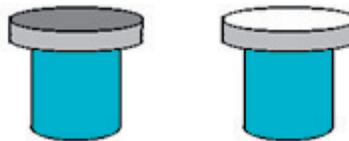
FIG. 10. Source with and without the tungsten plate.

The difference in dose rates was probably because the dose rate of the first radioactive source was measured on the road, with the second radioactive source located just behind. This may have caused the second radioactive source to have influenced the dose rates of the first. When the radioactive sources were located in their original location, the road was partially shielded by a heap of earth and stones. Therefore, on the road 40–45 m from the radioactive sources, the dose rate was around 50 µSv/h. Thus, when the dose rate of the first radioactive source was measured at a distance of 45 m after it was moved to the road, the contribution of the second radioactive source to the total dose rate would have been at least 25 mSv/h (approximately 8% of the actual measured dose rate). It should be noted that the level of shielding varied along the road. Figure 11 is a simplified drawing of the section of the road where the location of the radioactive sources and dose rates are shown at various points.
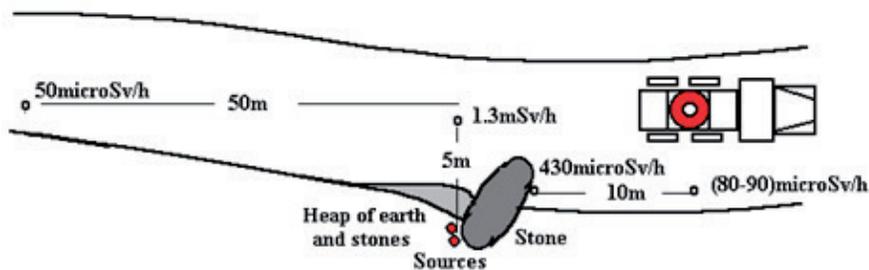
FIG. 11. Location of the vehicle and radioactive sources.

Figure 11 also shows the location of the vehicle when the radioactive sources were moved to the road and placed in the vehicle. Consequently, the dose rate of the second radioactive source was measured more precisely. This is because the first radioactive source did not influence the measurements taken, as it had been placed in the container and its radiation was almost completely shielded.

The measured activity of the radioactive sources was about 40% less than the data provided on the source certificate. This decrease in activity was caused by radioactive decay. The radioactive sources were produced in 1983, and the half-life of strontium is 28 years. After 19 years, the activity of the radioactive sources should be $0.5^{19/28}$ of the original activity. This is equal to 0.62 (i.e. the dose rate of a 19 year old source) at the distance of 1 m, which should be 0.62 Sv/h. This estimation is in good agreement with the results of the measurements taken.

The cap of the container into which the radioactive sources were placed consisted of four parts. Three of the parts were lead discs 5 cm thick, which were placed in the central cylinder of the container, and one part was a lead disc 10 cm thick, which covered the top of the container. The cover of the container was designed in four pieces due to its weight —it would have weighed over 350 kg if the cover had been constructed in one piece.

After placing the radioactive sources in the container, the dose rate on top of the open container was 4.6 Sv/h. After positioning the first cap, the dose rate at the same point decreased to 60 mSv/h. After the second cap, the dose rate decreased to 3.5 mSv/h. After positioning the third cap, it decreased to 500 µSv/h. After the final (fourth) cap had been put in place, the dose rate fell to 12–14 µSv/h, which was a permissible limit for the transportation of the containers.

The first cap reduced the dose rate more than 75 times. This indicates that in the radiation spectrum of the radioactive source, a large part belongs to the soft X radiation, the absorption coefficient of which is much higher than that of the high energy gamma quantum. The second cap decreased the dose rate 17 times, and the third and fourth 7 and 40 times, respectively.

The dose rate on the lateral surface of the container was less than 1 µSv/h and was close to the rate of background radiation. The relatively high dose rate on the top of the container was caused by the existence of gaps between the first three discs and the inner cylinder, through which the scattered radiation reached the last cap.

4.4.   LESSONS LEARNED FROM THE RECOVERY OPERATION

The structure of the container lid allowed two people to open and shut it without being too close to the open container and the radioactive sources inside. When the container was positioned on a level, horizontal surface, this was quite easy to accomplish (see (a) in Fig. 12).

However, it was not possible to place the container on a level horizontal surface at the recovery site. This caused difficulties when opening and, particularly, when closing the container. It was necessary to be located very close to the container and to alter the orientation of the lid by hand (see (b) in Fig. 12). Consequently, this caused a significant increase in the operational time and received dose.

To improve the container, it would have been better to have two eyes on the lid, as this would have made it easier to alter the angle of the lid using the rod (see (c) in Fig. 12).

| Both container and lid are horizontal. It is easy to open and close the container. | Container is positioned on uneven surface. The lid remains horizontal. It is necessary to touch the lid to alter its orientation. | Two eyes make it possible to incline the lid remotely by means of the auxiliary rod. |
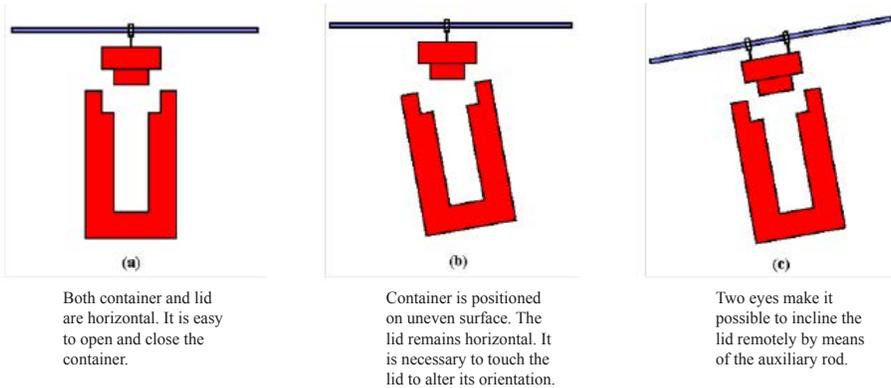
FIG. 12. Different relative orientations of the container and its lid.

In order to prevent or to reduce public concern, the vehicle with the container was covered with tarpaulin (i.e. to conceal the contents) during the journey to and from the location site. During the recovery operation, there was insufficient time to remove the tarpaulin because the weather deteriorated and it started to rain.

After placing the radioactive sources into the container, the dose rate remained high both inside and outside the vehicle. This was unexpected and was caused by the tarpaulin reflecting and scattering radiation (see Fig. 13). The process of closing the container was undertaken in conditions of increased dose rates, which could have been avoided had the tarpaulin been removed beforehand.

The individual remote tools with long handles (more than 2 m long) were very convenient and comfortable for collecting a radioactive source and pulling it along the ground. However, they were not practical for lifting the radioactive source to place it on the vehicle platform. The weight of the radioactive sources meant that it was necessary to hold the handle of the tools quite near the radioactive source (less than 1 m) in order to lift it. To lift the radioactive sources, a special tool with handles on opposite sides was used.
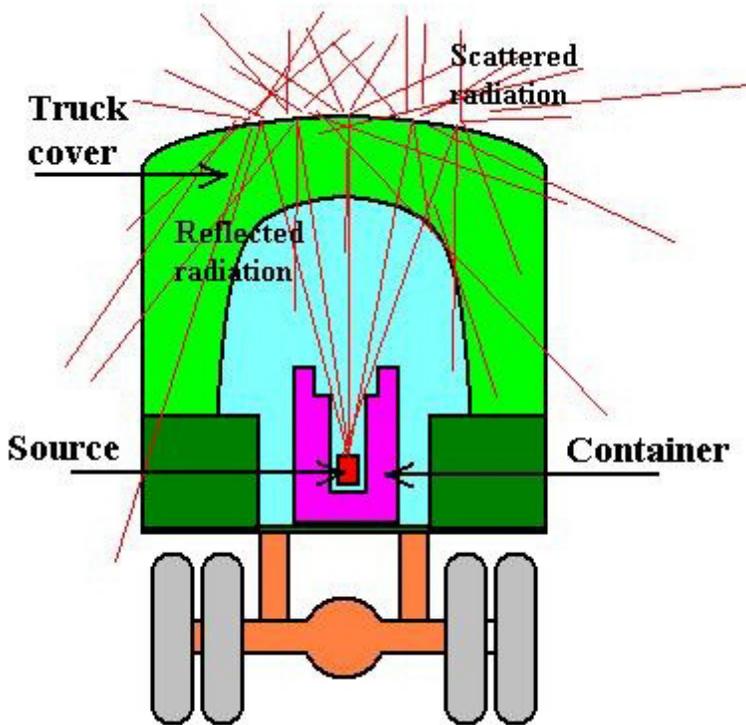
FIG. 13. The open container with the radioactive source on the vehicle.

5. BIOLOGICAL DOSIMETRY

5.1. CONVENTIONAL CYTOGENETIC ANALYSIS

Blood samples were taken from Patients 1-DN, 2-MG and 3-MB on 23 January 2002, in Georgia, for conventional cytogenetic analysis. The samples arrived at the Institute for Protection and Nuclear Safety (Institut de protection

et de sûreté nucléaire, IPSN)[1] on 24 January 2002, and cultures were set up the same day at 12:00 and harvested the following day, in accordance with the standard procedure.

5.1.1. Technical aspects

Two cytogeneticists scored unstable chromosome aberrations only in the complete metaphase of their first division. According to the quality assurance programme of the laboratory, at least two technicians checked each dicentric chromosome.

5.1.2. Results

The Poisson distribution of aberrations was tested. The Papworth extended U test based upon the mean of variance ratio of the aberration distribution quantifies the deviation from Poisson's Law. When the U test level exceeds 2, the radiation exposure may be considered heterogeneous. Applying this to the results provided in Table 5, it can be concluded that only Patient 3-MB showed a condition of homogeneous irradiation. The results also show that for Patients 1-DN and 2-MG, the irradiation was clearly heterogeneous, with probably a very strong localized dose.

TABLE 5. DOSE ESTIMATED FROM THE DICENTRIC YIELD USING IPSN GAMMA CALIBRATION CURVE (^{60}CO, 0.5 Gy/MIN DOSE RATE) AND DOSE CORRECTION CALCULATED FROM DOLPHIN AND QDR MODELS, ASSUMING A SHORT AND HETEROGENEOUS EXPOSURE

Patient	Whole body dose (Gy)	95% confidence interval (Gy)	Dose estimated by the Dolphin method (Gy)	Dose estimated by the Qdr method (Gy)
1-DN	3.1	[2.9; 3.3]	5.4	4.9
2-MG	4.4	[3.9; 4.8]	5.7	5.7
3-MB	1.3	[1.1; 1.5]	1.9	2.2

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[1] Following a merger in February 2002, the IPSN became the Institute for Radiological Protection and Nuclear Safety (Institut de radioprotection et de sûreté nucléaire, IRSN).

For the dose estimates, a dose effect relationship fitted from the chromosome aberrations scoring in blood lymphocytes irradiated in vitro by the gamma radiation of ^{60}Co was used, with a dose rate of 0.5 Gy/min. The curve coefficients are:

$$Y = 0.0008 + 0.0374D + 0.0549D^2 \tag{6}$$

where Y is the dicentric yield and D is the dose. The whole body dose estimates are also provided in Table 5.

Assuming an acute relatively heterogeneous exposure for the three patients, it was possible to check the Dolphin and Qdr models in order to improve the estimates of the initial dose received by the patients' irradiated body part.

The IPSN was able to obtain approximate data from the Georgian Cytogenetics Laboratory on the dicentric yield and the number of cells. The related doses were calculated using the Dolphin method. Table 6 shows the good agreement between the results obtained by the IPSN and those obtained by the Georgian Cytogenetics Laboratory.

TABLE 6. SUMMARY OF THE CYTOGENETICS DATA OBTAINED FROM THE GEORGIAN CYTOGENETICS LABORATORY

Patient	Georgian Cytogenetics Laboratory results		IPSN results	
	Whole body dose (Gy)	Dose estimated by Dolphin method (Gy)	Whole body dose (Gy)	Dose estimated by the Dolphin method (Gy)
1-DN	2.8	3.0	3.1	5.4
2-MG	3.3	4.3	4.4	5.7
3-MB	1.2	2.3	1.3	1.9

Note: The dose estimations were adapted on the basis of the IPSN gamma calibration curve.

5.2. TRANSLOCATIONS ANALYSIS BY FISH PAINTING

5.2.1. Technical aspects

The IPSN performed translocation analysis by fluorescence in situ hybridization (FISH) painting in the peripheral blood lymphocytes, from the same blood samples as those used for the dicentrics analyses. The cocktail of DNA probes used by the laboratory was specific to the chromosomes 2, 4 and 12, which correspond to around 20% of the whole genome.

The two dose effect relationships used by the IPSN were obtained from the total and reciprocal translocation scoring from blood samples, both of which were vitro gamma irradiated by a ^{60}Co source at a 0.5 Gy/min dose rate. All cells bearing either fluorescent complex exchanges or fluorescent unstable chromosome aberrations, which can be seen in scored lymphocytes, were excluded in order to fit these reference curves.

5.2.2. Results

The scoring of stable chromosome aberrations for the three patients is summarized in Table 7, which includes the number of cells scored, the number of complex exchanges and translocations, the related dose estimates and the 95% confidence interval of the data. Table 7 shows the very large proportion of cells bearing complex exchanges in Patients 1-DN and 2-MG (a yield of 0.09 for Patients 1-DN and 2-MG, compared with a yield of 0.003 for Patient 3-MB). The geometry of the radioactive source combined with its activity spectrum might be responsible for the presence of these highly damaged cells. However, for all three patients, the dose estimated by the reciprocal translocation yield was consistent with the dose obtained from the total translocation yield.

The dose estimated from the translocation of the least exposed individual (Patient 3-MB) is significantly higher than the dose estimated from the dicentric yield, which is in the range of 30% compared with the dose obtained based on the translocation. Such a difference could be explained by the one month delay between exposure and analysis, as lymphopenia may have developed.

However, the dose estimated from the translocation yield for the more exposed individuals (Patients 1-DN and 2-MG) seems underestimated, compared with the dose estimated from the dicentric yield. The high number of complex exchanges scored in Patients 1-DN and 2-MG could explain this underestimation. For Patient 1-DN, for whom the number of complex exchanges was higher, when the translocations that could be interpreted from the cells bearing complex exchanges are added to the total translocations yield, the dose estimation

TABLE 7. RESULTS OF THE SCORING OF RECIPROCAL AND TOTAL TRANSLOCATIONS FOR THE THREE PATIENTS

Patient	No. of scored cells	No. of cells with complex exchanges	No. of reciprocal translocations	No. of total translocations	Reciprocal translocation yield	Dose (Gy)	Confidence interval (Gy)	Total translocation yield	Dose (Gy)	Confidence interval (Gy)
1-DN	458	40	23	43	0.050	2.6	[2.0; 3.2]	0.094	2.5	[2.1; 2.8]
2-MG	79	7	7	10	0.089	3.3	[2.0; 4.7]	0.127	2.7	[1.9; 3.7]
3-MB	444	1	15	26	0.034	1.9	[1.4; 2.4]	0.059	1.7	[1.4; 2.1]

Note: The number of scored cells, the number of each type of translocation, the related dose and the number of cells bearing complex exchanges are given for each patient.

increases from 2.5 to 2.9 Gy. This is consistent with the 3.1 Gy estimated from the dicentric yield.

5.3. LOCAL POPULATION MONITORING

On the basis of the results of the local population monitoring undertaken by the Georgian Cytogenetic Laboratory, there was no significant increase of chromosome aberration for the 25 individuals who may have come into contact with the radioactive sources when living in settlements nearby.

5.4. CONCLUSIONS OF BIOLOGICAL DOSIMETRY

The cytogenetics data — namely, the yields of unstable and stable chromosome aberrations scored in peripheral blood lymphocytes of the three patients — indicate that the most irradiated patient was Patient 2-MG, followed by Patients 1-DN and 3-MB, respectively. In addition, the doses estimated from translocations are very close to those estimated from the dicentric yield. In this case of acute and heterogeneous exposure, the dose corrections averaged to the irradiated part of the body from the Qdr and Dolphin models are less consistent compared with the clinical data than the dose obtained from the cytogenetics data.

It is the first time it has come to the IPSN's knowledge that the involvement of complex exchanges of cells in the case of accidental overexposure can significantly modify the results obtained from translocations data. Further investigation of this finding would be useful to improve understanding on the formation mechanisms of complex exchanges and scoring of cells for other accidental overexposures.

6. OVERVIEW OF THE MEDICAL ASPECTS

Following the exposure on 2 December 2001, all three patients exhibited in the first 24 h symptoms of nausea, vomiting, asthenia (weakness), headaches and dizziness, followed by cutaneous radiation syndrome (CRS). These early clinical manifestations and anamnesis of the patients strongly indicated ARS of a haematological type for the three patients. Furthermore, Patient 1-DN developed transitory oropharyngeal syndrome.

6.1. STATUS OF CUTANEOUS RADIATION SYNDROME

It should be noted that the exact date of the initial signs of CRS could not be ascertained for all three patients. However, diagnosis was confirmed on 23 December 2001 by the IHT in T'bilisi.

6.1.1. Patient 1-DN

The localization of the radiological injuries observed on Patient 1-DN are shown in Fig. 14.
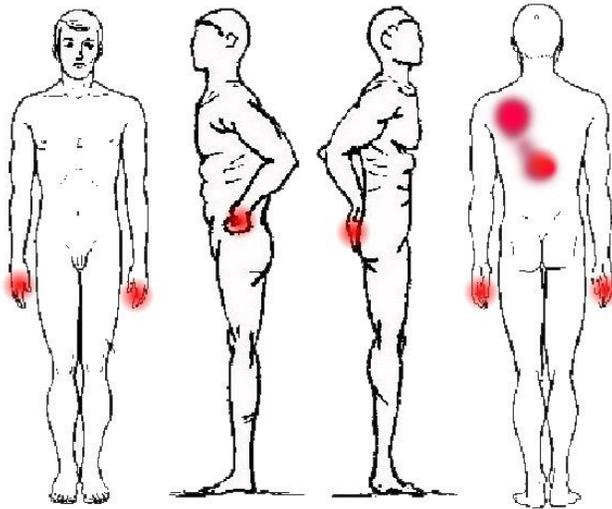
FIG. 14. Localization of the radiological injuries observed on Patient 1-DN.

As shown in Fig. 15, the location of the principal lesion was the left side of the posterior thoracic wall. This extensive lesion (approximately 40 cm × 30 cm) was almost healed on two thirds of its surface. The periphery of the lesion was surrounded by a dry desquamation and hyperpigmentation zone.

6.1.2. Patient 2-MG

The localization of the radiological injury observed on Patient 2-MG is shown in Fig. 16.

FIG. 15. Lesion on the left side of the posterior thoracic wall of Patient 1-DN, 22 January 2002 (day 51 after exposure and 36 days after the onset of the first clinical signs of CRS).
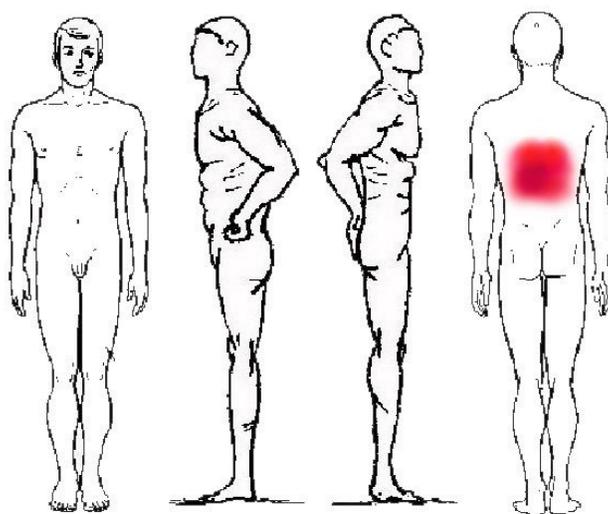
FIG. 16. Localization of the radiological injury observed on Patient 2-MG.

As shown in Fig. 17, the lesion was located on the entire posterior side of the thorax, from the waist up to the point of the scapulae. The lesion was a wide, moist epidermal denudation of around 8% of the body surface, without signs of deep necrosis.

FIG. 17. Lesion located on the entire posterior side of the thorax, from the waist to the scapulae of Patient 2-MG, 22 January 2002 (day 51 after exposure and 36 days after the onset of the first clinical signs of CRS).

6.1.3. Patient 3-MB

The localization of the radiological injuries observed on Patient 3-MB are shown in Fig. 18. The cutaneous radiological lesion was mild. It was localized on his hands, right leg and thigh, as well as both areas of the popliteal fossae (regions behind the knees). It consisted only of depigmented areas.

6.2. STATUS OF THE HAEMATOPOIETIC MANIFESTATIONS

At the time of admission to the hospital (day 20 after exposure), the blood cell counts of Patients 1-DN and 2-MG showed a severe decrease in the granulocytes, lymphocytes and thrombocytes linages. Clinical manifestations
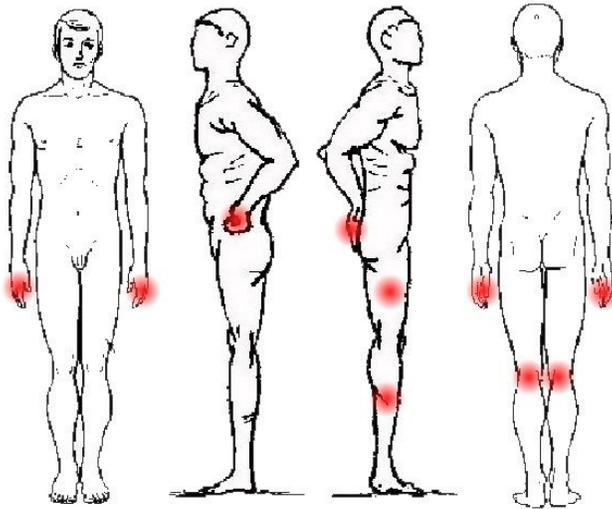
FIG. 18. Localization of the radiological injuries observed on Patient 3-MB.

were also present that were compatible with ARS of a haematological type, with radio induced aplasia. Patient 1-DN showed bleeding from the nose, tongue and gums on 27 December 2001 (day 25 after exposure).

The bone marrow impairment showed a spontaneous recovery on day 30 after exposure following treatment with a transfusion of platelets for Patients 1-DN and 2-MG and a transfusion of an erythrocyte concentrate for Patient 1-DN. The regeneration of haematopoiesis was promoted by several injections of haematopoietic growth factor granulocyte colony stimulating factor (G-CSF) (Neupogen, 300 µg/d). The fast recovery of leucocytes counts following the bone marrow stimulation by G-CSF supported assumptions of a heterogeneous exposure with areas of bone marrow relatively free from irradiation.

6.3. DECISIONS CONCERNING THE MEDICAL MANAGEMENT OF THE THREE PATIENTS

On 5 January 2002, an IAEA mission was sent to T'bilisi at the request of Georgia. The medical status of the three patients was investigated to formulate the optimal strategy for their medical treatment.

Georgian medical staff and the IAEA mission jointly decided that Patient 3-MB could remain in Georgia for treatment at the T'bilisi hospital, and

Patients 1-DN and 2-MG were to be transferred for specialized treatment to the Russian Federation and France, respectively.

— Patient 3-MB was discharged on 23 January 2002.
— Patient 2-MG was sent home on 18 April 2003.
— Patient 1-DN died on 13 May 2004.

7. MEDICAL ASSESSMENT AND MANAGEMENT OF THE PATIENTS IN GEORGIA

7.1. RESPONSE BY THE LOCAL MEDICAL SERVICE AND IDENTIFICATION OF THE ACCIDENT

7.1.1. Patient 1-DN

Patient 1-DN was reported as having been exposed during the night of 2 December 2001 for approximately 3 h in total. This included 1–1.5 h of close contact of his back to the radioactive source while warming himself, as well as a few minutes of contact to his hands when examining the radioactive source. He started vomiting around 3 h after the initial exposure. He vomited throughout the whole night, but then had no symptoms or complaints for about two weeks after. He then started to feel a painful burning sensation in his back but noticed nothing on his hands. Two days later, he felt a pain in his throat and lost his voice. Despite these pathological changes, he did not consult a doctor.

7.1.2. Patient 2-MG

Patient 2-MG was exposed during the night of 2 December 2001 for about 10–12 h in total, including about 1–1.5 h of direct contact to his back with the radioactive source while warming himself, and also for a maximum of 5 min while he curled a wire around the second source. He also vomited during the first night.

Patient 2-MG had diarrhoea repeatedly during the next night (day 1 after exposure) and also developed a skin reaction of the urticaria type, in the form of itching maculae that covered the whole surface of his body. He consulted his general physician (day 2 after exposure) but did not mention the "heating device". The general physician (a local doctor) — suspecting intoxication — treated him with an intravenous infusion of saline and Haemodes (dextran of low molecular

weight for elimination of toxic metabolites via renal clearance) and also gave him an intramuscular injection of chloropyramine (Suprastin) to treat the allergy. Following the single treatment, his symptoms disappeared in a day. He remained asymptomatic for two weeks. On day 13 after exposure, he felt a burning and itching feeling in the exposed area of his back. Two days later, a second episode of the same type allergic reactions developed and dry desquamation on the exposed area of his back appeared. Treatment with chloropyramine proved again to be very effective, and the symptoms of urticaria disappeared in a day. However, the symptoms of the radiation burn on his back (dry desquamation and severe pain) remained and forced him to seek medical advice at the local hospital in Zugdidi on 22 December 2001.

7.1.3. Patient 3-MB

Patient 3-MB's hands were exposed for about 15–20 min in total while he held the radioactive sources and moved them to the rock to observe them. His right leg and thigh, as well as both popliteal fossa (regions behind the knees) were exposed for approximately 2 h while he was sitting on the rock between 18:00 and 21:00, at around 0.5–1 m from the radioactive sources. He was the last of the three patients to begin vomiting, and only stopped vomiting early the next morning.

Erythema, a burning feeling and oedema of his right hand appeared one week later. On 8 December 2001 (day 6 after exposure), he could not close the fingers of his hand, and the skin was swollen and flattened. The terminal phalanges of all five fingers turned numb, and dry desquamation of the right hand appeared three to four days later. A feeling of severe weakness lasted for three weeks after the exposure. However, Patient 3-MB did not seek medical advice.

When he learned from Patients 1-DN and 2-MG of the skin lesions on their backs, his wife and the brother of Patient 2-MG reported the strange disease to a local police officer, who advised them to go to the local hospital and request medical help. All three were hospitalized on the same day, 22 December 2001 (day 20 after exposure) in Zugdidi, where they received their first medical aid. They were treated with an infusion of saline solution and the topical treatment of wounds, which included sterile dressing and ointments with antibiotics. Based on the anamnesis and clinical picture, all three patients were diagnosed with ARS, and the case was reported to the Emergency Medical Center in T'bilisi, which requested the transfer of the patients to the IHT in T'bilisi.

7.2. TREATMENT AT THE INSTITUTE OF HEMATOLOGY AND TRANSFUSIOLOGY, T'BILISI

7.2.1. Patient 1-DN

7.2.1.1. Dynamics of medical status and haematopoietic syndrome

Patient 1-DN was transferred to the IHT on 23 December 2001 (day 21 after exposure). Following admission, he complained of a feeling of severe weakness and a very severe pain in the throat (he was unable to eat and to swallow saliva). He had a high temperature (40°C), very low blood pressure (70/30 mmHg), a dry tongue and expressed hyperaemia (redness) of the neck, mouth and throat.

Peripheral blood counts were conducted for the first time since the exposure. The dynamics of the haematological parameters are presented in Figs 19–22. Figure 19 shows a low level in leucocytes until day 23 after exposure. The leucocyte level then began to increase following the bone marrow stimulation using Neupogen (300 µg/d) from 24 December to 30 December 2001, when the leucocytes value subsequently reached a safe level.
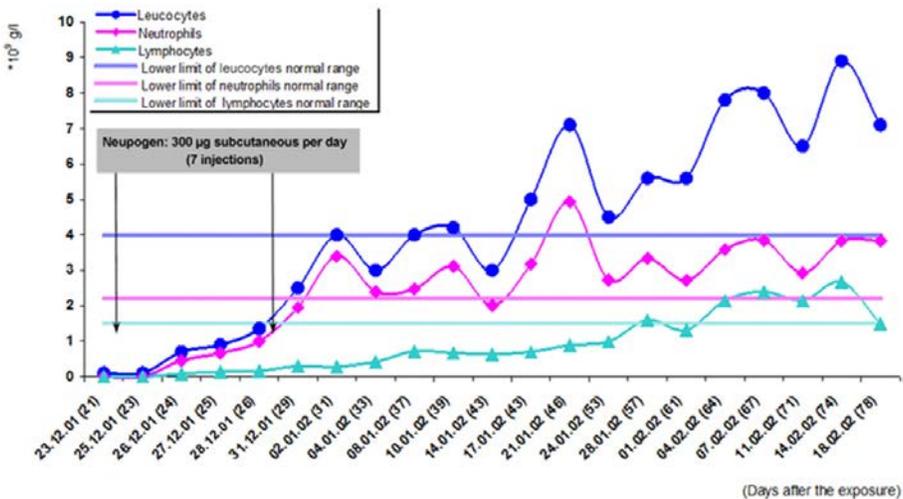
FIG. 19. Leucocyte, neutrophil and lymphocyte dynamics of Patient 1-DN.

Figure 20 shows that Patient 1-DN's lymphocytes could not be counted initially owing to severe lymphopenia. However, a slow incremental improvement was observed. The lymphocytes did not reach the lower limit of normal range in two weeks, as G-CSF stimulation led to a fast increase of granulocytes.
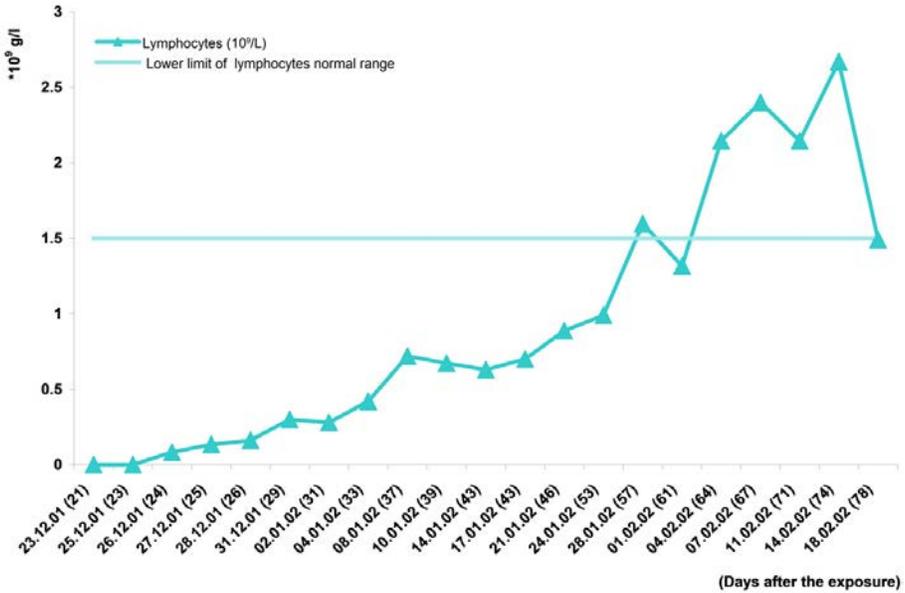
FIG. 20. Lymphocyte dynamics of Patient 1-DN.

Figure 21 shows that Patient 1-DN had severe thrombopenia, which began to improve on day 31 after exposure following the use of thrombomass, and returned to normal values on day 43 after exposure.
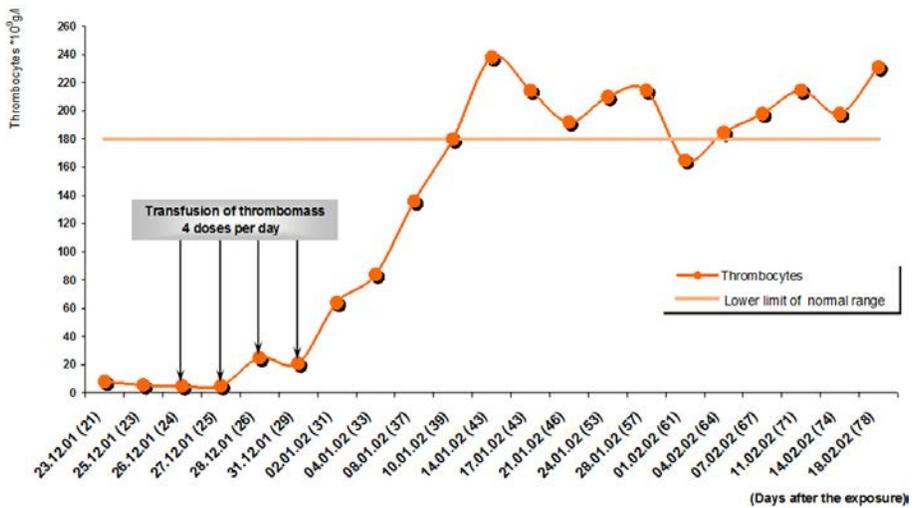
FIG. 21. Thrombocyte dynamics of Patient 1-DN.

Figure 22 shows that erythrocytes fell below the normal range (4×10^{12}/L) following day 21 after exposure. The results presented in Fig. 22 also show that following day 21 after exposure, moderate to severe radio induced anaemia evolved in Patient 1-DN, which required treatment with erythromass transfusions.
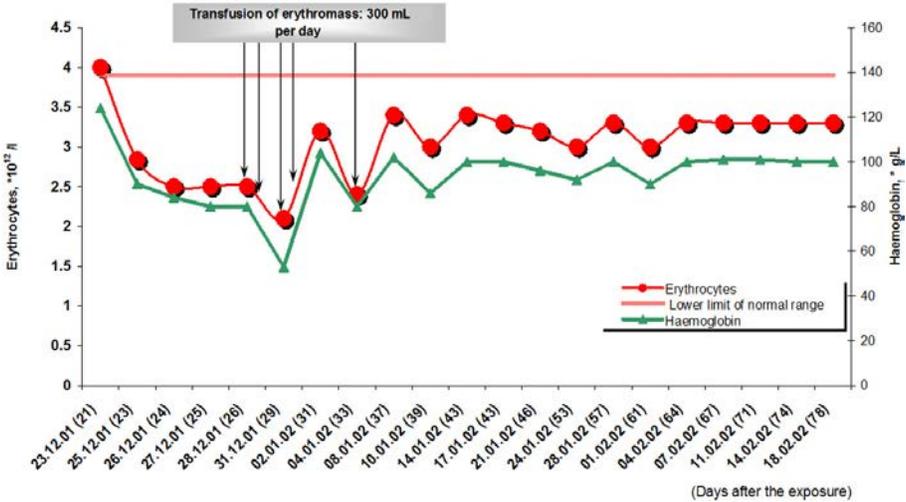
FIG. 22. Erythrocyte and haemoglobin dynamics of Patient 1-DN.

A bone marrow aspirate was taken from the sternum on 23 December 2001 (day 21 after exposure). Table 8 presents the results of the cytomorphological analysis performed on the bone marrow. The results showed very low cellularity, with only 200 cells in four smears, while the normal range is over 400 cells per smear. Table 8 shows very low cellularity, a decreased number of the immature cell forms of myeloid precursors and a higher counting of the mature forms of cells for Patient 1-DN on day 22 after exposure. Table 8 also shows the trend of returning to normal cellularity on day 66 after exposure.

To prevent severe infection and sepsis in this case of expressed agranulocytosis, Patient 1-DN was placed in a single room and a wide range of antibiotics was used in large dosages from the day of admission: ceftriaxone (Rocephin) 2.0 g twice a day and gentamicin 80 mg three times a day intravenously.

TABLE 8.   BONE   MARROW   CYTOMORPHOLOGICAL   ANALYSIS:
PATIENT 1-DN

	24 Dec. 2001	6 Feb. 2002
Days after exposure	22	66
Cell type (% of 400 cells counted)		
Myeloblasts	0.5	0.5
Neutrofils	—[a]	—[a]
Promyelocytes	1.5	3.3
Myelocytes	3.5	11.0
Metamyelocytes	2.5	12.5
Band	4.0	5.3
Segmented	6.5	5.0
Eosinophils	1.0	5.5
Basophils	0.0	0.0
Lymphocytes	50.0	2.3
Monocytes	2.5	2.0
Mitotic figures within granulopoiesis	0.5	0.8
Reticulocytes	2.0	0.0
Plasmocytes	15.5	2.3
Macrophages	1.5	0.3
Erythroblasts		
Basophil	2.5	5.0
Polichromatophil	3.5	26.5
Oxyphil	2.0	16.5
Mitotic figures within erythropoiesis	0.5	0.5
Megakaryocytes	0.0	1.0
Comments	Very low cellularity	Normal cellularity

[a]   —: data not available.

On the following day (24 December 2001), Patient 1-DN's temperature dropped significantly owing to the treatment, and by 25 December, it had returned to normal. Gentamicin was thus withdrawn. Ceftriaxone was reduced to 1.0 g/d of prophylactic dosage following a weekly treatment (30 December 2001 onwards). Saline, rheopolyglucin (dextran), Aminosol (amino acids and minerals) and HAES-steril (dextran) infusions were used from the beginning of hospitalization for parenteral nutrition.

Despite the transfusion of four units of thrombocyte concentrate on 25 December 2001, bleeding was observed on 27 December from the nose, tongue, gums and gingival area (see Fig. 23). A repeated treatment of four units of thrombocyte concentrate administered on 27 and 28 December led to a cessation of all of these types of bleeding.
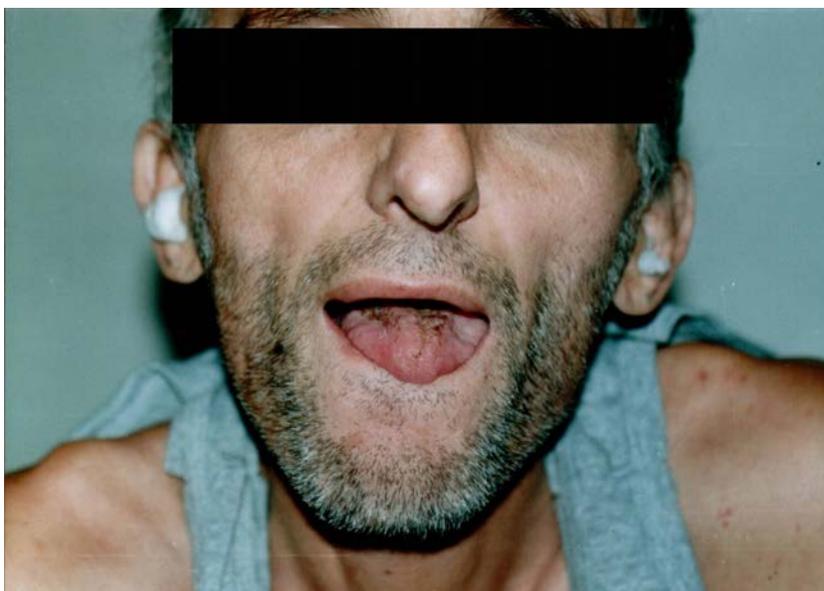
FIG. 23. Fissures and blood clots on the tongue of Patient 1-DN, 27 December 2001 (day 25 after exposure).

Moderate anaemia developed on 28 December 2001, which was immediately treated with the transfusion of an erythrocyte concentrate. However, due to radiogenic erythropenia, a lowering of the haemoglobin level was observed for three more days, despite the repeat of daily transfusions. Recovery followed the fourth transfusion of erythrocyte concentrate, on 31 December.

To prevent mycotic (fungal) infection, fluconazole (150 mg/d orally) was provided on 28 December 2001 and 4 January 2002. Neither viral, fungal infections nor general bacterial infection developed in Patient 1-DN when checked on 7 January.

7.2.1.2. Dynamics and treatment of local radiation injuries

The hands of Patient 1-DN showed signs of dry desquamation, which was more pronounced on the palm surface (see Fig. 24). There were two large areas of moist desquamation on his back, one was approximately 17 cm × 18 cm on the left shoulder and the second was a round area (14 cm in diameter) on the left side of the lower part of the thoracic wall. Both areas were covered with a yellowish fibrin layer and surrounded with a 2 cm wide hyperpigmented zone (see Fig. 25).

FIG. 24. Erythema on the palms of Patient 1-DN, 29 December 2001 (day 27 after exposure).

FIG. 25. Erythema and dry desquamation on the back of Patient 1-DN, 29 December 2001 (day 27 after exposure).

At the thoracic vertebra (T12) and upper lumbar vertebra (L1), a small depigmented area (2 cm in diameter) was observed. It resembled paper and was made of very thin, new skin that covered a small area of moist desquamation. In this small area, spontaneous epithelization had already taken place. Cultivation of a wound smear taken on 26 December 2001 revealed one week later a *Staphylococcus aureus* infection resistant to many antibiotics but sensitive to vancomycin. However, this antibiotic was not available at the IHT.

The local treatment of radiation injuries consisted of the following: cleaning with antiseptic solutions (potassium permanganate and hydrogen peroxide); and covering wounds to prevent local infection with Olasolum spray (containing antibiotic levomycetin, boric acid and anesthesin), panthenol spray (as a biostimulator) as well as Solcoseryl gel (to enhance epithelization).

On 5 January 2002 (day 34 after exposure), infiltration, hyperaemia and inflammatory oedema developed around the flat radiation ulcer located on the upper area of Patient 1-DN's back (see Fig. 26). A profuse, serous purulent discharge appeared that was light brown and odourless, and his pain increased.

FIG. 26. A flat ulcer (upper) and dry desquamation (lower) on the back of Patient 1-DN, 5 January 2002 (day 34 after exposure).

On 6 and 7 January 2002, slight dry desquamation of both palms and desquamation with erosions and slight maceration of the large lesions on the back were observed. The centres of these radiation induced lesions (17 cm and 14 cm in diameter) were coated with fibrin.

It could be concluded for Patient 1-DN's general status that the treatment provided led to a significant improvement of his condition, which was expressed in the normalization of haemodynamics and blood counts, except for the lymphocytes and slight anaemia. An urgent change of antibiotics for local treatment was required (patient was given Vancocin, active ingredient vancomycin), as well as the provision of sterile conditions for surgical treatment of the wound and for stimulation of its recovery. The prognosis for Patient 1-DN was good, providing the wound remained aseptic, and he remained under observation following surgical treatment. There was a need for reverse isolation. Therefore, a decision was made to remove relatives from the ward — except for his wife, who helped with regular medical care and full time observation.

From 12 January 2002 (day 41 after exposure), two ulcers began to merge (see Fig. 27). The area of pain increased.

FIG. 27. Two ulcers on Patient 1-DN, 12 January 2002 (day 41 after exposure).

A complex therapy for the local radiation injuries included PhagoBioDerm, panthenol and olasolum in aerosols. On 13 January 2002 (day 42 after exposure), the upper ulcer was covered with PhagoBioDerm (see Fig. 28).

During the process of wound dressing, only the gauze bandages were changed. The areas covered with the PhagoBioDerm had been irrigated with a hypertonic solution of sodium bicarbonate 2–3 times a day. The PhagoBioDerm biodegraded after ten days. The upper and lower areas of the lesion had been covered with Actosol, panthenol and olasolum (see Fig. 29).

FIG. 28. Upper ulcer on Patient 1-DN, covered with PhagoBioDerm, 13 January 2002 (day 42 after exposure).

FIG. 29. Ulcers on Patient 1-DN, covered with PhagoBioDerm and panthenol.

On 5 February 2002 (day 65 after exposure), the lower lesion spontaneously healed with small foci of superficial erosion, while the upper lesion became severely infected during February (see Fig. 30).

Figure 31 shows the lower ulcer completely closed on 10 February 2002 (day 70 after exposure). The upper ulcer reduced in diameter and was covered with a fibrin layer 2–3 mm thick. A marginal epithelization was discernible under the fibrin crust.

FIG. 30. Local radiation injury on the back of Patient 1-DN, 5 February 2002 (day 65 after exposure).

FIG. 31. Upper ulcer on Patient 1-DN, covered with fibrin layer, lower ulcer with epithelization, 10 February 2002 (day 70 after exposure).

On 21 February 2002 (day 81 after exposure), Patient 1-DN was transferred to the Institute of Biophysics of the Burnasyan Federal Medical Biophysical Center, in Moscow, the Russian Federation, for further surgical treatment.

7.2.1.3. Laboratory analysis results

The results of the laboratory analysis are presented in Tables 9–13. Table 9 presents the serum immunoglobulins of Patient 1-DN on days 22 and 68 after exposure.

TABLE 9. SERUM IMMUNOGLOBULINS: PATIENT 1-DN

	24 Dec. 2001	8 Feb. 2002	Normal range
Days after exposure	22	68	
Serum immunoglobulin (g/L)			
IgG	7.0	11.0	12
IgA	3.5	1.9	2.4
IgM	1.8	0.9	1

Table 10 presents the lymphocytes of Patient 1-DN on days 22 and 66 after exposure. It shows that on 24 December 2001 (day 22 after exposure):

— T lymphocytes were reduced to 26% (normal range 45–50%).
— T active lymphocytes were reduced to 4% (normal range 17–25%).
— T helper lymphocytes were reduced to 20% (normal range 35–40%).
— T suppressor lymphocytes were reduced to 7% (normal range 10–15%).
— B lymphocytes remained at the lower level of the normal range (normal range 11–20%).

On 6 February 2002, (day 66 after exposure), the percentile distribution showed an improvement in T active lymphocytes and normal values in the B lymphocytes (however, with no change). The other series maintained values below the normal range.

TABLE 10. LYMPHOCYTES: PATIENT 1-DN

	24 Dec. 2001	6 Feb. 2002	Normal range
Days after exposure	22	66	
Lymphocyte (%)			
T	26	30	45–50
T active	4	17	17–25
T helper	20	25	35–40
T suppressor	7	6	10–15
B	11	11	11–20

Table 11 presents the whole protein of blood and protein fractions of Patient 1-DN on days 22, 32, 45 and 66 after exposure. It shows low levels of albumins between days 22 and 66 after exposure, which is compatible with Patient 1-DN's high metabolic requirements and indicates a possible impaired nutritional status.

TABLE 11. WHOLE PROTEIN OF BLOOD AND PROTEIN FRACTIONS: PATIENT 1-DN

	24 Dec. 2001	3 Jan. 2002	16 Jan. 2002	6 Feb. 2002	Normal range
Days after exposure	22	32	45	66	
Whole protein (g/L)	99.9	65.5	65.5	72.0	67–85
Albumins (%)	44.5	48.9	42.0	42.5	50.1–59
Globulins (%)	55.5	51.1	42.5	57.5	49.9–41
α_1 (%)	5.8	5.5	57.5	6.5	2.5–5
α_2 (%)	10.5	13.3	11.5	13.4	7.2–10.5
B (%)	14.2	14.9	15.2	15.5	9.2–13.8
γ (%)	25.0	17.4	24.6	22.1	15.8–22.2
Coeff. A/G	0.8	1.0	0.7	0.7	1–1.4

Table 12 presents the kidney function tests of Patient 1-DN on days 22, 26 and 32 after exposure. It shows that the serum creatinine level was elevated on day 26 after exposure, at 250 µmol/L (normal range 61–115 µmol/L). The results suggested acute kidney failure during the first month of the his evolution. On day 32 after exposure, the values were compatible with a functional recovery process.

TABLE 12. KIDNEY FUNCTION TESTS: PATIENT 1-DN

	24 Dec. 2001	28 Dec. 2001	3 Jan. 2002	Normal range
Days after exposure	22	26	32	
Urea (µmol/L)	18.31	20.8	8.32	2.5–8.32
Creatinine (µmol/L)	212.4	250	123.9	61–115

Table 13 presents the coagulogram results of Patient 1-DN on days 22, 32 and 45 after exposure. It shows the evolution of parameters in the coagulogram. On day 45 after exposure, almost all parameters were normal, with the exception of the blood fibrinolytic activity. The prothrombin index suggested a preserved liver function during the entire period.

TABLE 13. COAGULOGRAM: PATIENT 1-DN

	24 Dec. 2001	3 Jan. 2002	16 Jan. 2002	Normal range
Days after exposure	22	32	45	
Clotting time (s)	17	8	10	5–10
Recalcification time (min)	220	115	120	90–160
Prothrombin index (%)	80	90	80	80–100
Thrombin time (min)	28	32	31	29–39
Fibrinogen concentration (g/L)	6.5	3	2.5	2–4

TABLE 13. COAGULOGRAM: PATIENT 1-DN (cont.)

	24 Dec. 2001	3 Jan. 2002	16 Jan. 2002	Normal range
B-fibrinogen	(++)	(−)	(−)	(−)
Paracoagulation tests	(+)	(−)	(−)	(−)
Blood fibrinolytic activity (%)	9	5	5	14–16

7.2.1.4. Results of further medical examinations

The liver function tests were without pathological changes, and there were no significant changes indicated from the results of the electrocardiography (ECG). A chest radiography was performed on 8 January 2002, which showed the lung to be reticular and enhanced, and the root of the right lung was deformed and dilated (see Fig. 32).

On 12 February 2002, an additional chest radiography was performed, but there was no observable improvement (see Fig. 33).
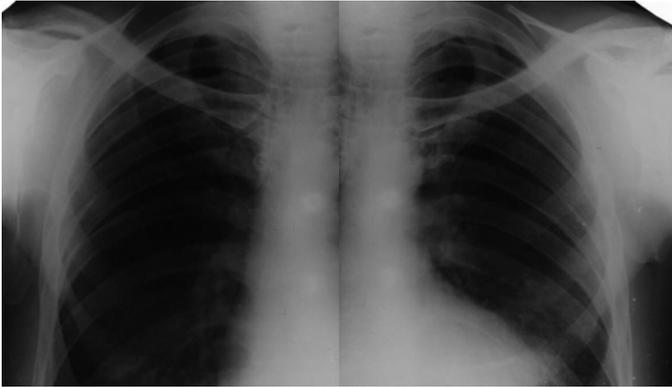
FIG. 32. Chest radiography of Patient 1-DN, 8 January 2002 (day 37 after exposure).
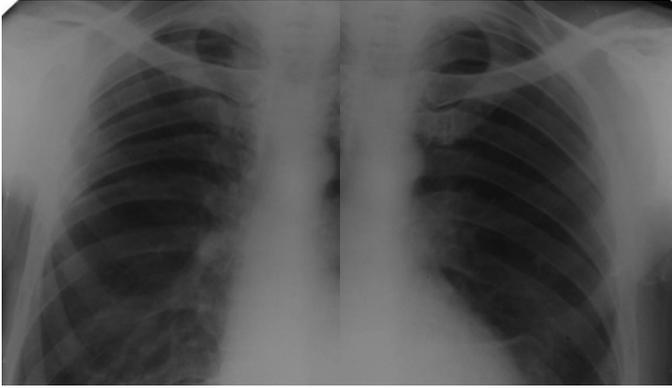
FIG. 33. Chest radiography of Patient 1-DN, 12 February 2002 (day 72 after exposure).

An ultrasound examination of the abdomen showed:

(a) Liver was enlarged at 2–3 cm below the costal margin on the medio-clavicular line:
  — Contours were sharp and regular;
  — Structure was small and granular;
  — Echogenicity was increased in a non-uniform way;
  — Vascular image was poor.
(b) No other organs showed pathological changes.

Sample swabs for bacterial analysis were taken from the ulcers on Patient 1-DN's local radiation injuries on his back. The results of this analysis are presented in Table 14.

TABLE 14. BACTERIOLOGICAL ANALYSIS OF SWABS TAKEN FROM LOCAL RADIATION INJURIES: PATIENT 1-DN

Date	Result	Sensitive to
27 Dec. 2001	*S. epidermidis*	Gentamicin Doxycycline Vancocin
10 Jan. 2002	Sterile	None
16 Jan. 2002	Sterile	None
24 Jan. 2002	Sterile	None

The IHT did not have equipment such as a computed tomography (CT) scanner, a magnetic resonance imaging (MRI) scanner, thermography tools or high frequency ultrasound devices (20 MHz) at the time of the accident, which might have been helpful for examining the three patients.

7.2.2.   Patient 2-MG

In light of the anamnesis and clinical manifestations of Patient 2-MG, a diagnosis of ARS was considered at the time of admission.

7.2.2.1. Dynamics of medical status and haematopoietic syndrome

Patient 2-MG had herpes simplex following admission on 23 December 2001, which was successfully treated with acyclovir using both oral and local ointment over a period of five days (see Fig. 34).

Patient 2-MG's haematological parameters were not as severely suppressed as Patient 1-DN following admission. Three doses of Neupogen led to the normalization of Patient 2-MG's leucocytes (see Fig. 35), which can also be associated with an improvement of lymphocytes during the same four day period (see Fig. 36).

As Patient 2-MG's temperature remained subfebrile, measuring 37.6°C on 7 January 2002, there was an urgent need to change to antibiotics that provided for a wide spectrum in effectiveness (ciprofloxacin and doxycycline, combined with vancomycin).

FIG. 34. Herpetic eruption of Patient 2-MG, 23 December 2001 (day 21 after exposure).
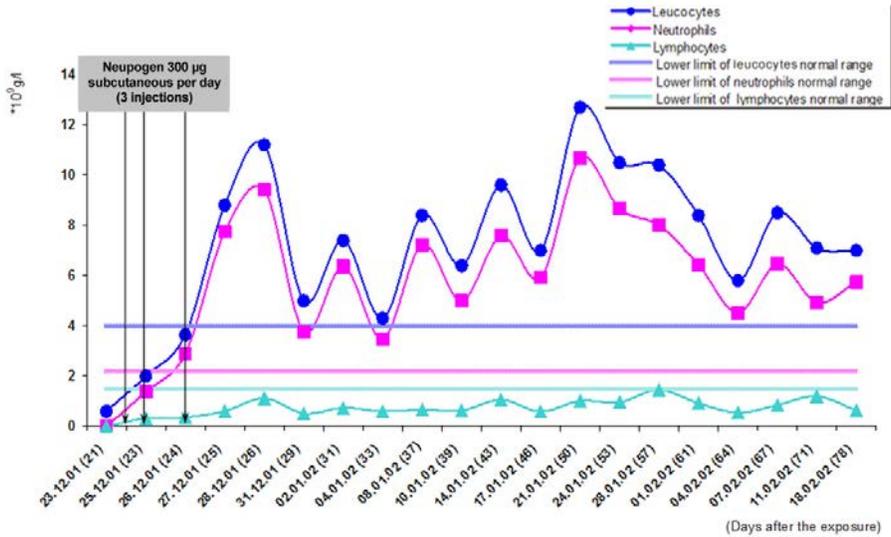
FIG. 35. Leucocyte, neutrophil and lymphocyte dynamics of Patient 2-MG.
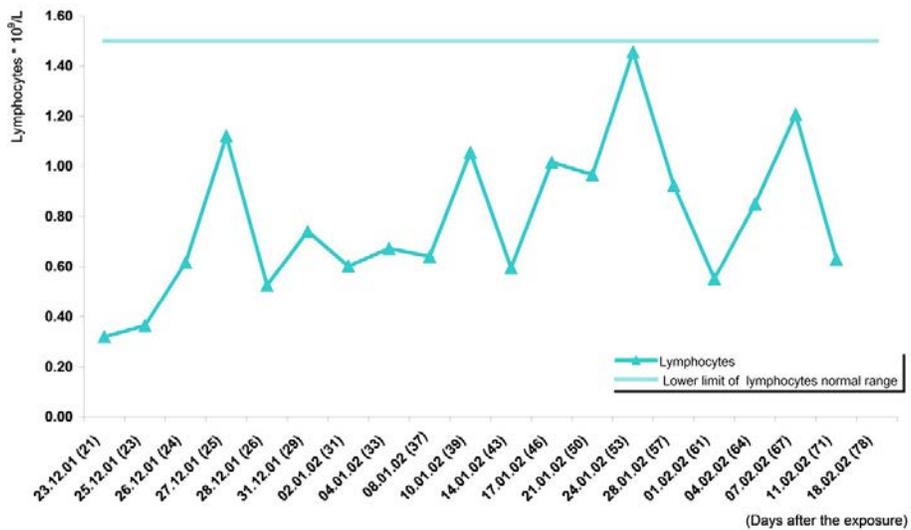
FIG. 36. Lymphocyte dynamics of Patient 2-MG.

A single transfusion of thrombocyte concentrate also allowed Patient 2-MG to recover normal platelet values (see Figs 37 and 38). The erythrocytes of Patient 2-MG remained just below the lower limit until 8 January 2002

(see Fig. 38). The low levels of lymphocytes, platelets and erythrocytes were compatible with ARS of a haematological type with impaired bone marrow function.
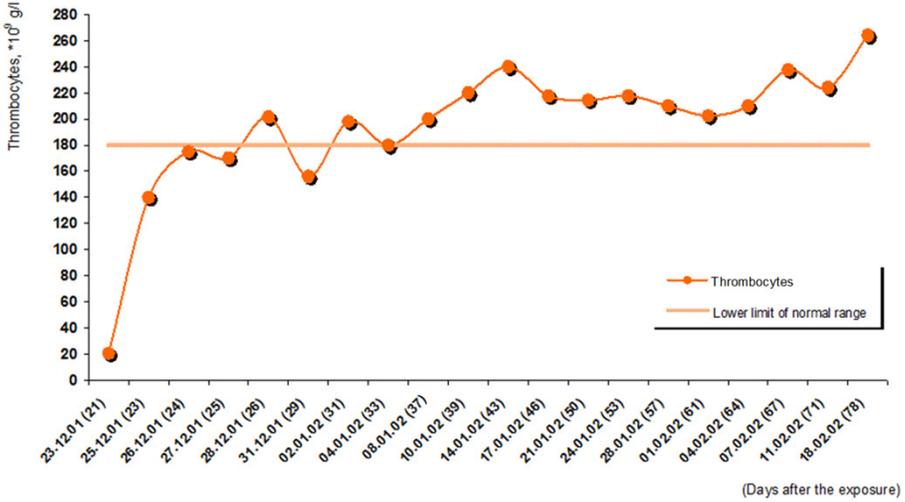
FIG. 37. *Thrombocyte dynamics of Patient 2-MG.*
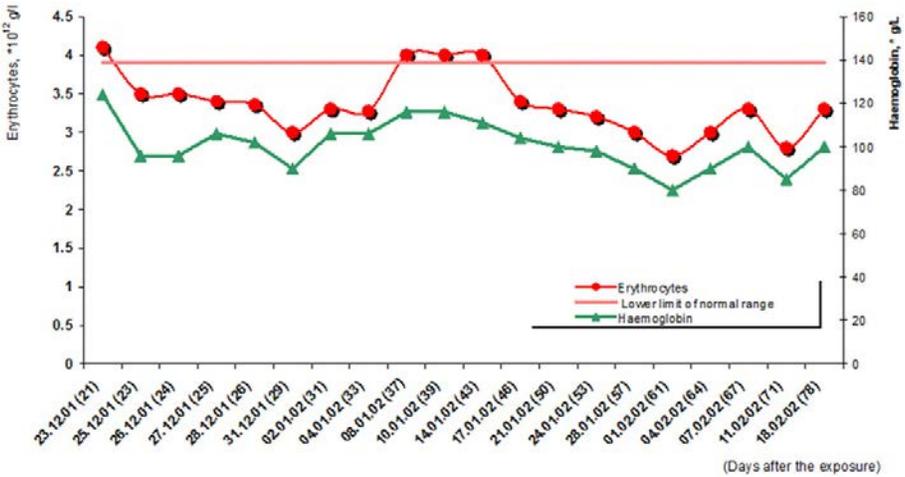
FIG. 38. *Erythrocyte and haemoglobin dynamics of Patient 2-MG.*

Table 15 presents the results of Patient 2-MG's bone marrow cytomorphological analysis. It shows the response of the bone marrow to the radiation injury. On 24 December 2001 (day 22 after exposure), an increase was observed in the plasmocytes and reticulocytes with low cellularity. On 6 February 2002 (day 66 after exposure), all the values tended to normal cellularity, with the exception of the lymphocytes, which had markedly diminished.

TABLE 15.   BONE   MARROW   CYTOMORPHOLOGICAL   ANALYSIS: PATIENT 2-MG

	24 Dec. 2001	6 Feb. 2002
Days after exposure	22	66
Cell type (% of 400 cells counted)		
Myeloblasts	3	0.5
Neutrofils	__[a]	__[a]
Promyelocytes	10	2
Myelocytes	10	8.5
Metamyelocytes	5	9.75
Band	5.75	16.5
Segmented	7	19.25
Eosinophils	1.5	5
Basophils	0	0
Lymphocytes	10	4.25
Monocytes	2	2.25
Mitotic figures within granulopoiesis	2	0.75
Reticulocytes	5	1
Plasmocytes	6.25	1.25
Macrophages	3	0.5

TABLE 15.   BONE   MARROW   CYTOMORPHOLOGICAL   ANALYSIS: PATIENT 2-MG (cont.)

	24 Dec. 2001	6 Feb. 2002
Erythroblasts		
Basophil	6.25	3
Polichromatophil	14.25	11.75
Oxyphil	7	12.5
Mitotic figures within erythropoiesis	1.5	0.5
Megakaryocytes	0.25	0.75
Comments	Low cellularity	Normal cellularity

[a]   —: data not available.

7.2.2.2. Dynamics and treatment of local radiation injuries

Patient 2-MG's clinical picture was very similar to Patient 1-DN. *S. aureus* was defined by the large superficial radiation injury on his back (38 cm × 35 cm and approximately 9% of the whole body surface). The large moist desquamation was without spots of deep ulceration or necrosis. The injury was a huge flat ulcer with infiltration, hyperaemia and inflammation of the oedema. In the left lateral and central areas, the injury was deeper with bleeding of the capillaries. A large amount of serous purulent discharge appeared that was light brown and odourless (see Fig. 39).

Patient 2-MG's infection was sensitive to many antibiotics that were used, including ceftriaxone (Rocephin). He was in permanent pain, which could only be reduced to a certain extent by narcotics. There was no significant epithelization, and there were multiple foci of erosive lesions with a superficial bleeding of the wound.

As a result of the general and local conservative treatment given in stages, the infiltration, hyperaemia and inflammatory oedema of the surrounding areas decreased, pain abated and the discharge diminished and changed characteristics — it became yellow and appeared more severe. The main part of the injury was covered with a fibrin layer. Small areas of epithelization also appeared.

The prognosis for Patient 2-MG was satisfactory, and following appropriate surgical treatment, a full recovery was feasible. However, the antiseptic and aseptic conditions of the dressings and surgical procedures needed to be observed. Reverse isolation and removal of relatives from the ward were required (except for his daughter, who helped with regular medical care and full time observation).

FIG. 39. Flat ulcer on the back of Patient 2-MG, 29 December 2001 (day 27 after exposure).

On 21 February 2002, Patient 2-MG was taken to the Percy Military Training Hospital, in Paris, France, for further medical treatment.

7.2.2.3. Laboratory analysis results

The results of the laboratory analysis are presented in Tables 16–18. Table 16 presents the serum immunoglobulins of Patient 2-MG on days 22 and 68 after exposure.

TABLE 16. SERUM IMMUNOGLOBULINS: PATIENT 2-MG

	24 Dec. 2001	8 Feb. 2002	Normal range
Days after exposure	22	68	
Serum immunoglobulin (g/L)			
IgG	12.0	8.8	12
IgA	1.7	1.8	2.4
IgM	1.0	0.6	1

Table 17 presents the lymphocytes of Patient 2-MG on days 22 and 66 after exposure. On 6 February 2002 (day 66 after exposure) the values tended to the normal values, with the exception of the T suppressor lymphocytes.

TABLE 17. LYMPHOCYTES: PATIENT 2-MG

	24 Dec. 2001	6 Feb. 2002	Normal range
Days after exposure	22	66	
Lymphocyte (%)			
T	28	47	45–50
T active	19	43	17–25
T helper	22	39	35–40
T suppressor	8	9	10–15
B	12	10	11–20

Table 18 presents the whole protein of blood and protein fractions of Patient 2-MG on days 22, 32, 45 and 66 after exposure. The table shows a tendency to low levels of albumins between days 22 and 66 after exposure, which is compatible with his high metabolic requirements and indicated a possible impaired nutritional status. The other proteins had normal values on day 66 after exposure.

7.2.2.4. Results of further medical examinations.

The liver and kidney function tests revealed no pathological changes and, following an ECG, there were also no significant changes. A chest radiography showed that the lung field was reticular and enhanced. An ultrasound examination of the abdomen showed that:

(a) Liver was enlarged at 1–2 cm below the costal margin on the medio-clavicular line:
— Contours were sharp and regular;
— Structure was small and granular;
— Echogenicity was normal;
— Vascular image was normal.
(b) Spleen was enlarged at 1–2 cm below the costal margin;
(c) No other organs showed pathological changes.

TABLE 18. WHOLE PROTEIN OF BLOOD AND PROTEIN FRACTIONS: PATIENT 2-MG

	24 Dec. 2001	3 Jan. 2002	16 Jan. 2002	6 Feb. 2002	Normal range
Days after exposure	22	32	45	66	
Whole protein (g/L)	71.2	65.1	71.6	68.0	67–85
Albumins (%)	48.3	58.0	45.3	43.5	50.1–59
Globulins (%)	51.7	42.0	54.7	56.5	49.9–41
α_1 (%)	5.2	2.0	6.5	6.3	2.5–5
α_2 (%)	12.0	6.7	13.0	14.8	7.2–10.5
β (%)	10.5	19.1	11.5	15.2	9.2–13.8
γ (%)	24.0	14.2	23.7	20.2	15.8–22.2
Coeff. A/G	0.9	1.4	0.8	0.8	1–1.4

Sample swabs for bacterial analysis were taken from the ulcers on Patient 2-MG's local radiation injuries on his back (see Table 19).

TABLE 19. BACTERIOLOGICAL ANALYSIS OF SWABS TAKEN FROM LOCAL RADIATION INJURIES: PATIENT 2-MG

Date	Result	Sensitive to	
27 Dec. 2001	S. aureus	Levomycetin Oxacillin Gentamicin Erythromycin	Claforan Doxycycline Ciprofloxacin Vancocin
10 Jan. 2002	S. aureus	Gentamicin Doxycycline Vancocin	
16 Jan. 2002	S. aureus	Gentamicin Doxycycline Vancocin	
24 Jan. 2002	Sterile	None	

7.2.3. Patient 3-MB

7.2.3.1. Dynamics of medical status and haematopoietic syndrome

The exposure of Patient 3-MB was significantly less severe than the other two patients. Consequently, his clinical status was less serious and his haematological signs were milder. He periodically felt a burning sensation in his hands and legs. Panthenol ointment was used to help mitigate this.

A decision to administer two single doses of Neupogen given on 24 and 29 December 2001 was not based on the haematological indicators shown in Fig. 40. Instead, the decision was due to other reasons: following a similar procedure for treatment used on three individuals hospitalized at the same institute and according to information on the treatment used in Germany for patients from the Lilo radiological accident, the experimental use of Neupogen proved to be effective for the stimulation of epithelium reparation. This sporadic clinical observation is also supported by data in the scientific literature [3].

Figure 40 shows two peaks of leucocytes related to the administration of Neupogen. Between 2 and 21 January 2002 (days 31–50 after exposure), the curve shows that the leucocytes values tended to be slightly lower than normal.
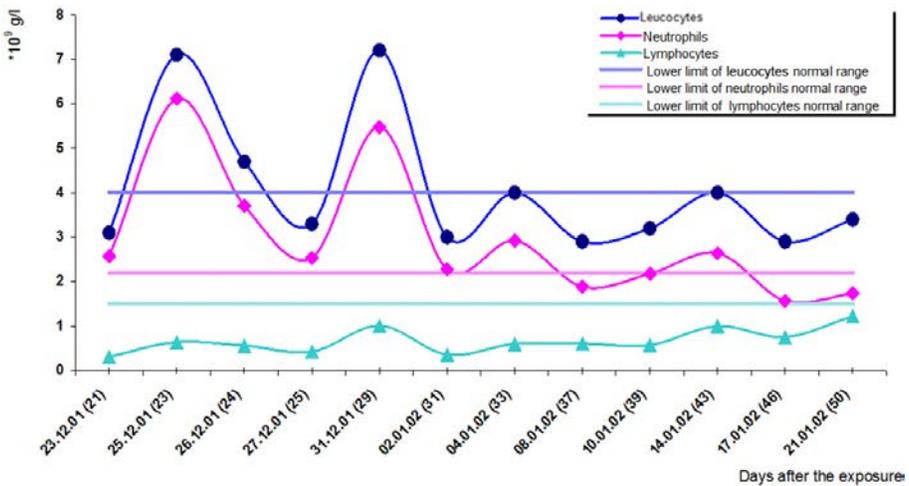
FIG. 40. Leucocyte, neutrophil and lymphocyte dynamics of Patient 3-MB.

Patient 3-MB's lymphocyte counts quickly recovered (see Fig. 41), but his platelets and red blood cells did not change significantly (see Figs 42 and 43). The lymphocyte curves shown in Fig. 41 were compatible with leucopenia during the entire period.
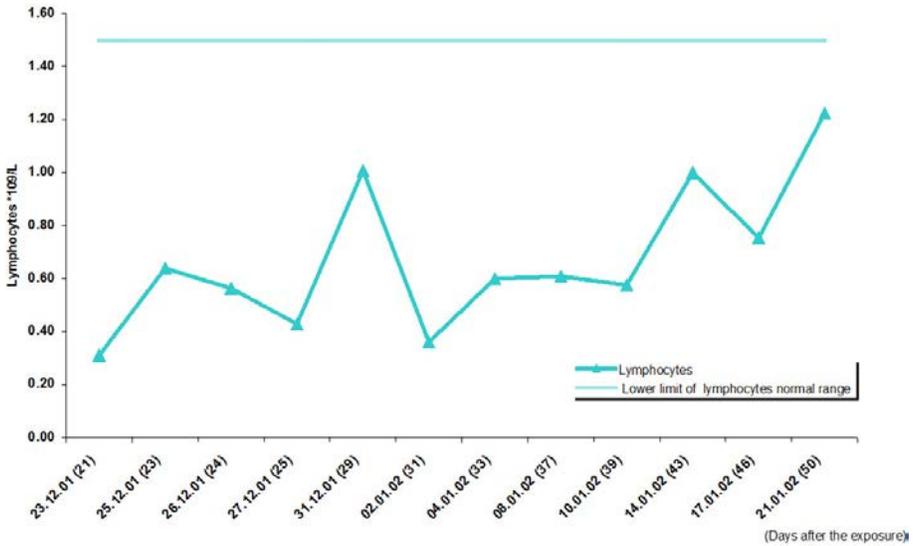
FIG. 41. Lymphocyte dynamics of Patient 3-MB.

FIG. 42. Thrombocyte dynamics of Patient 3-MB.

Figure 42 shows a normal curve of thrombocytes for Patient 3-MB from 25 December 2001 (day 23 after exposure).

Figure 43 shows the erythrocytes and haemoglobin curves for Patient 3-MB, which did not decrease as markedly as for the other two patients. This was consistent with the lower estimated absorbed dose for Patient 3-MB, since the curves remained near the lower normal limit.
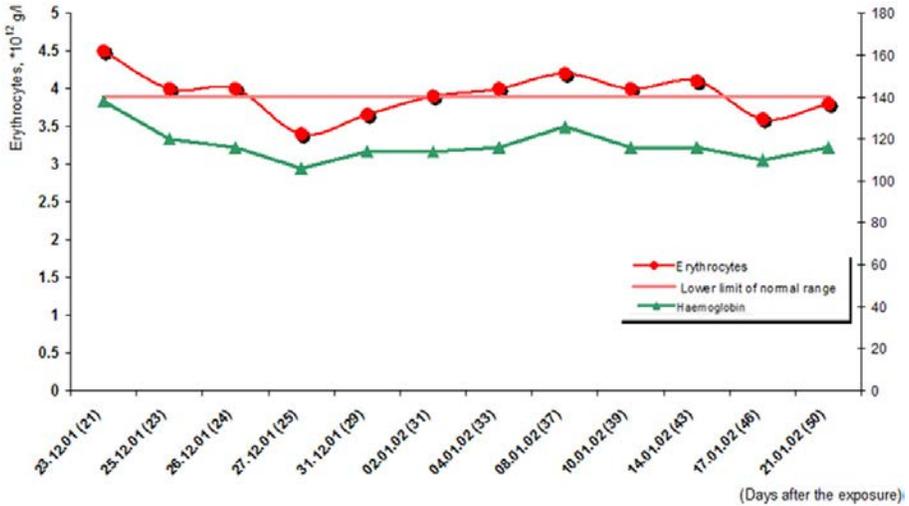
FIG. 43. *Erythrocyte and haemoglobin dynamics of Patient 3-MB.*

Table 20 presents the results of Patient 3-MB's bone marrow cytomorphological analysis. This analysis did not identify large changes, as was the case of the analyses conducted for Patients 1-DN and 2-MG. By 6 February 2002 (day 66 after exposure), most of the parameters were in the normal range for Patient 3-MB.

TABLE 20.　BONE MARROW CYTOMORPHOLOGICAL ANALYSIS:
PATIENT 3-MB

	24 Dec. 2001	6 Feb. 2002
Days after exposure	22	66
Cell type (% of 400 cells counted)		
Myeloblasts	1.00	0.25
Neutrofils	—[a]	—[a]
Promyelocytes	0.00	0.50
Myelocytes	6.25	15.00
Metamyelocytes	10.25	15.25
Band	0.50	10.50
Segmented	27.25	14.50
Eosinophils	5.00	2.75
Basophils	0.00	0.00
Lymphocytes	9.00	10.00
Monocytes	2.50	0.00
Mitotic figures within granulopoiesis	0.00	0.50
Reticulocytes	0.25	0.00
Plasmocytes	0.00	1.25
Macrophages	0.75	0.50
Erythroblasts		
Basophil	6.25	4.50
Polichromatophil	12.25	14.50
Oxyphil	0.25	8.75
Mitotic figures within erythropoiesis	0.25	0.75
Megakaryocytes	0.25	0.50
Comments	Low cellularity	Normal cellularity

[a]　—: data not available.

7.2.3.2. Dynamics and treatment of local radiation injuries

Patient 3-MB complained of discomfort in his fingers and a darkening and desquamation of his hands. On the lateral surface of the middle third of the right thigh was an erythema (3 cm in diameter, see Fig. 44). The erythema was marked also in the subpopliteal areas. The hyperaemia, oedema and dry desquamation were visible on the palms (see Fig. 45). The erythema on the thigh disappeared without additional medical treatment. As a result of the conservative local treatment using glycerine and vitamin A and E ointment, the skin of the palms normalized.

The prognosis for Patient 3-MB was very good, and recovery was expected without surgical treatment. On 23 January 2002, he was discharged from the hospital and monitored as an outpatient. His general condition remained satisfactory.

FIG. 44. Erythema on the right thigh of Patient 3-MB (date not known).

FIG. 45. Hyperaemia, oedema and dry desquamation on the palms of Patient 3-MB (date not known).

Table 21 presents the monthly laboratory results of his peripheral blood counts in dynamics over the follow-up period of ten months. The haematological indices have mainly remained within the normal or subnormal ranges. For the purpose of preventing immunodeficiency, he was periodically treated with a transfusion of Ig VENA intravenously using a complex of immunoglobulins: IgG1, IgG2, IgG3, IgG4 and IgA and multivitamins. The dynamics were positive. However, Patient 3-MB's psychological status needed particular attention. He suffered from depression, high anxiety, radiophobia (fear of radiation) and thanatophobia (fear of death or dying). For this reason, he was administered tranquilizers diazepam, carbamazepine and azaleptin, under the supervision of a psychiatrist.

7.2.3.3. Laboratory analysis results

The results of the laboratory analysis conducted for Patient 3-MB are presented in Tables 22–24. Table 22 presents the serum immunoglobulins, Table 23 presents the lymphocytes and Table 24 presents the whole protein of blood and protein fractions.

TABLE 21. DYNAMICS OF PERIPHERAL BLOOD COUNTS: PATIENT 3-MB

	Date (2002)									
	11 Feb.	2 Apr.	22 May	17 Jun.	22 Jul.	27 Aug.	19 Sep.	29 Oct.	10 Dec.
Days after exposure	71	121	171	197	232	268	291	331	373
Erythrocytes (10^{12}/L)	3.7	3.4	3.5	4.1	3.6	4.0	4.3	3.7	3.9
Haemoglobin (g/L)	114	104	109	135	116	113	137	114	116
Thrombocytes (%)	70	55	60	50	70	60	50	70	65
Thrombocytes (10^9/L)	259.0	187.0	210.0	205.0	252.0	240.0	215.0	259.0	253.5
ESR (mm/h)	10	5	6	5	20	4	5	12	2
Leucocytes (10^9/L)	7.30	3.40	4.50	2.55	4.60	2.40	4.80	3.50	3.20
Myeloblasts (%)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Myelocytes (%)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Metamyelocytes (%)	0.0	0.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Button nucleus (%)	6.0	3.0	4.0	2.0	7.0	4.0	3.0	3.5	3.5

TABLE 21. DYNAMICS OF PERIPHERAL BLOOD COUNTS: PATIENT 3-MB (cont.)

	Date (2002)								
Segmented (%)	60.0	52.0	65.0	40.0	50.0	72.0	64.5	54.0	59.0
Neutrophils (%)	66.0	55.0	69.0	42.0	57.0	76.0	67.5	57.5	62.5
Eosinophils (%)	2.0	5.0	4.0	5.0	3.0	3.0	2.0	1.5	1.0
Lymphocytes (%)	15.5	26.5	17.0	47.0	30.0	17.0	22.5	31.5	25.5
Monocytes (%)	16.5	13.0	10.0	6.0	10.0	4.0	8.0	8.5	11.0
Neutrophils (10^9/L)	4.82	1.87	3.11	1.07	2.62	1.82	3.24	2.01	2.00
Lymphocytes (10^9/L)	1.13	0.90	0.77	1.20	1.38	0.41	1.08	1.10	0.82

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TABLE 22. SERUM IMMUNOGLOBULINS: PATIENT 3-MB

	2001-12-24	2001-04-02	2002-04-22	2002-05-22	2002-06-17	2002-07-22	2002-08-27	2002-09-19	2002-10-29	Normal range
					Outpatient control					
Days after exposure	22	121	141	171	197	232	268	291	331	
Serum immunoglobulin (g/L)										
IgG	7.0	10.8	11.0	13.4	10.0	10.0	10.0	12.0	12.2	12.0
IgA	1.7	1.0	2.0	1.6	1.5	1.9	1.9	1.6	1.4	2.4
IgM	0.7	1.1	1.2	1.3	1.0	1.2	0.9	0.9	1.0	1.0

TABLE 23. LYMPHOCYTES: PATIENT 3-MB

Days after exposure	2001-12-24	2002-04-22	2002-05-02	2002-07-22	2002-08-27	2002-09-19	2002-10-29	Normal range
	22		Outpatient control					
		121	171	232	268	291	331	
Lymphocyte (%)								
T	60	36	56	48	37	21	32	45–50
T active	40	10	30	8	20	9	17	17–25
T helper	19	27	44	44	31	39	24	35–40
T suppressor	42	10	17	5	7	1	9	10–15
B	10	3	12	13	11	11	13	11–20

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TABLE 24. WHOLE PROTEIN OF BLOOD AND PROTEIN FRACTIONS: PATIENT 3-MB

	24 Dec. 2001	3 Jan. 2002	16 Jan. 2002	Normal range
Days after exposure	22	32	45	
Whole protein (g/L)	76.3	81.8	82.5	67–85
Albumins (%)	45.2	60.1	44.5	50.1–59
Globulins (%)	54.8	39.9	55.8	41–49.9
α_1 (%)	11.3	5	5.5	2.5–5
α_2 (%)	15.6	6.7	12.3	7.2–10.5
β (%)	21.4	7.7	15.8	9.2–13.8
γ (%)	21.4	20.5	22.2	15.8–22.2
Coeff. A/G	0.8	1.5	0.75	1–1.4

7.2.3.4. Results of further medical examinations

The liver and kidney function tests revealed no pathological changes in Patient 3-MB. The results of the ECG and the chest radiography showed that there were no significant changes.

The results of the ultrasound examination of the abdomen showed:

(a) Liver was enlarged at 2–3 cm below the costal margin on the medio-clavicular line:
— Contours were sharp and regular;
— Structure was normal;
— Echogenicity was normal;
— Vascular image was normal.
(b) Spleen was enlarged at 1–2 cm below the costal margin.
(c) No other organs showed pathological changes.

7.3. SUMMARY OF THE TREATMENT PROVIDED IN GEORGIA

Figure 46 presents the complex treatment that was provided to the three patients, which was based on the following principles:

— Reduction of the haematological and oropharyngeal syndromes;
— Decrease of the severity and duration of neutropenia by growth factors and antimicrobial drugs (to treat or prevent infection);
— Active infusive therapy using blood substitutes;
— Improvement of microcirculation;
— Desensitization;
— Vitamin therapy;
— Immunostimulative therapy;
— Topical treatment of local radiation injuries;
— Psychotherapy.
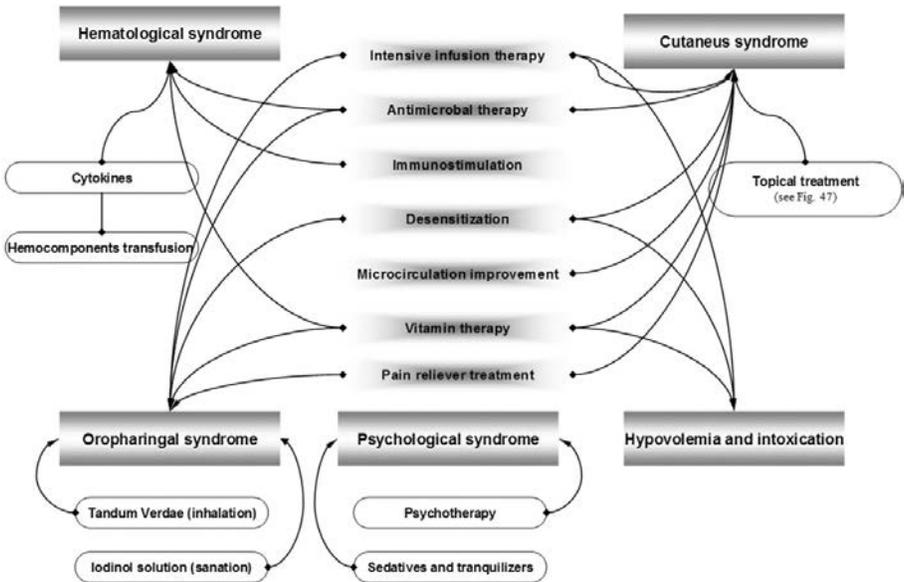
FIG. 46. Main principles underlying patient treatment.

7.3.1. Treatment for haematological syndrome

Cytokines therapy (G-CSF), Neupogen (filgrastim) and transfusions of haemocomponents were performed.

Patient 1-DN was treated with:

— Neupogen 300 µg/d (24–30 December 2001);
— Packed red blood cells 300 ml/d (five transfusions);
— Concentrates of platelets 4 doses/d (three transfusions).

Patient 2-MG was treated with:

— Neupogen 300 µg/d (24–27 December 2001).

Patient 3-MB was treated with:

— Neupogen 300 µg/d (27 December 2001). Leucopenia was not severe, but after episodic increases of white blood cells, it developed again, which is why Neupogen was used.

7.3.2. Intensive therapy

Blood substitutes were used for different purposes (anti-shock effect, parenteral nutrition, correction of albumin imbalance and improvement of microcirculation), with the following solutions:

— NaCl 0.9%;
— Ringer's lactate;
— Glucose 5%;
— Reopoliglyukin (dextran);
— HAES-steril 6%;
— Aminosol;
— Albumin 20%.

Patients 1-DN and 2-MG were treated with infusive therapy equally, whereas Patient 3-MB was treated with less intensity and for the first ten days only.

7.3.3. Treatment for infections

The treatment (or prevention) of neutropenia fever was provided using the following antimicrobial drugs:

— Ceftriaxone sodium (Rocephin) 2 g × 2 + gentamicin sulphate 80 mg × 3 (5 days);
— Ceftriaxone sodium (Rocephin) 1 g × 2 (10 days);
— Doxycycline 100 mg + ciprofloxacin 500 mg × 2 (14 days);
— Ampicillin and sulbactam (Ampicid) 1 g × 3 (15 days);
— Vancomycin (Vancocin) 1 g × 2 (10 days).

Patients 1-DN and 2-MG were generally given antibiotic therapy on the same schedule, and Patient 3-MB was injected with a prophylactic dose of Rocephin during the first week only. For the purpose of preventing fungal infection, the three patients were given Diflucan and fluconazole 150 mg a week. For the clinically expressed herpes simplex virus, Patient 2-MG was given acyclovir 1000 mg/d for five days and an ointment applied locally on the eruption.

7.3.4. Treatment for oropharyngeal syndrome

For a reduction of oropharyngeal syndrome, Patient 1-DN received together with general treatment:

— Nasal pharyngeal inhalation of Tantum Verde;
— Sanation with Iodinol solution.

7.3.5. Improvement of microcirculation for Patients 1-DN and 2-MG

Patients 1-DN and 2-MG were administered:

— Reopoliglyukin (dextran) — solution;
— Trental (pentoxifilline) 600 mg/d — tablet;
— Actovegin (produced by animal blood) 34 ml/d — solution;
— Solcoseryl (produced by animal blood) 4 ml/d — solution.

7.3.6. Desensitization therapy

Patients 1-DN and 2-MG were administered antihistaminic drugs for desensitization with alternation:

— Suprastin;
— Tavegyl;
— Promethazine hydrochloride (Pipolphen);
— Ketotifen (Zaditen).

7.3.7. Vitamin therapy

For vitamin therapy treatment, the three patients were administered:

— Group B (vitamins B1, B6 and B12);
— Vitamin C;
— Multivitamins: Centrum (in the later phase of treatment).

7.3.8. Immunostimulative therapy

For immunostimulative therapy, the three patients were administered:

— Actovegin (produced by animal blood) 34 ml/d — solution;
— Solcoseryl (produced by animal blood) 4 ml/d — solution.

7.3.9. Pain control

For the purpose of pain relief, various non-steroid anti-inflammatory, non-narcotic and narcotic analgesic drugs were used.

7.3.10. Psychological therapy

For psychological treatment, the three patients were provided with therapy consultations and sedative drugs and tranquilizers:

— Alora (natural sedative drug);
— Diazepam.

7.3.11. Topical treatment for cutaneous radiation syndrome

The topical treatment for CRS is presented in Fig. 47.

Occasional, less intrusive dressings	→	The dressings were applied once every two days, premedication with non-narcotic analgesics and topical, terminal anaesthesia with 10% lidocaine aerosol
Topical antiseptic solutions	→	Potassium permanganate solution, 3% hydrogen peroxide
Antibacterial, enzymatic and combined preparations (ointments, creams, gels, spray, dressings)	→	Ointment silvadene, ointment irucsol, solcoseryl gel and cream, panthenol spray, olasolum spray, PhagoBioDerm - biodegradable polymer impregnated with ciprofloxacin and lytic bacteriophages, corticotull (impregnated with hydrocortisone, neomycin, polymixin B and glycerine)

FIG. 47. Topical treatment for CRS.

8. DIAGNOSIS AND TREATMENT OF PATIENT 1-DN IN A SPECIALIZED HOSPITAL IN THE RUSSIAN FEDERATION

8.1. MEDICAL STATUS ON ADMISSION

On 21 February 2002 (day 81 after exposure), Patient 1-DN was admitted to the State Research Centre (SRC), Institute of Biophysics, in Moscow. The clinic cooperates with the World Health Organization European Centre in providing help to those involved in radiological accidents.

On arrival, Patient 1-DN complained of feeling weak, his temperature increased in the evening and he felt pain in the radial ulcer areas located on his back. He also felt faint owing to poor nutrition.

In addition to expressed hyperpigmentation and atrophy of the skin on the left and partially on the right side of his back, there were ulcer defects in the shape of an '8' (10 cm and 3 cm in diameter). The ulcer was covered with a thin layer of fibrin, which was difficult to remove (see Fig. 48). Following an auscultation examination, noises could be heard when he breathed. And when he breathed deeply, noises could also be heard originating from the lung area. He complained of chest pains.

FIG. 48. Radiation ulcer on the back of Patient 1-DN, 15 February 2002 (day 75 after exposure).

8.2. MEDICAL EXAMINATIONS

The X ray examinations made on 22 February and 6 March 2002 revealed lung emphysema, diffusive pneumosclerosis, metapneumatic local fibrosis and chronic bronchitis. The walls of the bronchial tubes and roots of the lungs were compact and contained calcifications. The interlobe pleura were compact on both the right and left side. The possibility of pneumoconiosis was not excluded. Figure 49 is the chest X ray examination made on 6 March, which shows infiltrative foci and calcifications in the roots of the lungs. This presented difficulties in the diagnostics of the acute phase of the lung radiation injury.

A CT scan performed on 27 February 2002 enabled the medical team to obtain an improved image of the lungs, as the vessel components and single micro focal areas (measuring 0.6 cm) could be observed. In both lungs (in the right mainly in the upper and middle lobes, in the left mainly in the lower lobe), there were subpleural and paravasal areas and zones of lung tissue compression (0.8 to 4–6 cm in diameter), which surged together and partially transformed into pleural commissures. There were single paratracheal and bifurcated lymph nodes in the mediastinum (up to 1 cm in diameter).

06/03/2002
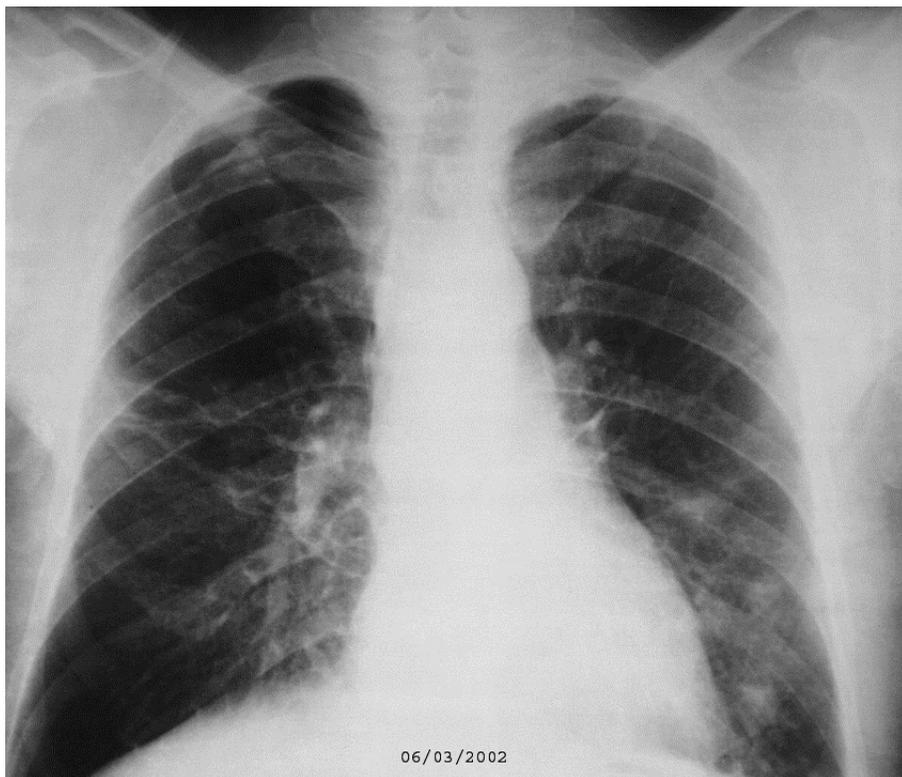
FIG. 49. Chest radiography of Patient 1-DN, 6 March 2002 (day 94 after exposure).

The fibrobronchoscopy performed on 18 March 2002 revealed a bronchial mucous membrane in the oedema, a large amount of mucous purulent phlegm and deformation of the orifice of the upper lobe bronchial tube on the right side. In the histological samples examined, a moderate lymphatic and granulated infiltration was found. A second fibrobronchoscopy revealed the effects of pus bronchitis. A broncho-alveolar lavage was performed using a pathological liquid and the luminescent microscopy of sediment showed two Koch bacilli.

The ECG showed moderate sinus tachycardia, with a heart rate of 92 bpm. The electrical heart axis was positioned normally. The echocardiography identified an insignificant dilatation of the right auricle, with tricuspidal regurgitation of 1–2 degrees. The global contractility of the left ventricle was without peculiarities.

Blood analyses were conducted, which revealed:

— Iron deficient anaemia (erythrocytes 3.45×10^{12}/L, haemoglobin 101 g/L);
— Leucocytosis (8.0–12.0×10^9/L) with a deviation of the differential count to the left (6–11%);
— Accelerated erythrocyte sedimentation rate (51 mm/h);
— Eosinophilia (11–18%);
— Hypoproteinemia, which measured up to 63–64 g/L owing to hypoalbuminemia at 34 g/L.

The cytogenetic examination of the lymphocyte blood culture showed that the total dose of the whole body was 2 Gy. Following the results of the cytogenetic examination that was conducted three months after exposure with the cultures of the chest bone and right iliac bone marrow, the lymphocyte doses of irradiation were set at 1.6 Gy and 3.3 Gy, respectively. The calculated dose of local irradiation for the left side of the back was 25–35 Gy. The bone marrow examination revealed polymorphous cellular marrow in trepanation and small focal hypoplasia at three months after exposure.

An analysis of the circumstances of Patient 1-DN's irradiation found that he picked up the radioactive source, fixed it to a wooden stick using a long metal wire and then carried it on his left shoulder. The radioactive source was very close to his back and caused him to feel it emitting heat through his leather jacket and sweater. He did not change shoulders, but held the stick once with his right hand, and then with his left. Two centres of local radial tissue affections on the left side of the back formed in the shape of an '8' (see Fig. 50).[2]

The primary symptoms of Patient 1-DN were dizziness, nausea, vomiting 2 h after first coming into contact with the radioactive source and a latent period of 10–12 days for the local radiation injury of the back tissue. The anamnesis data collected on days 22–23 after exposure showed hyperaemia, which was indicated by dry, peeling skin on the palm of the hand.

8.3. DIAGNOSIS AND TREATMENT

The diagnosis of Patient 1-DN was acute radiation sickness in severe forms from highly uniform beta–gamma irradiation. This included bone marrow syndrome of a moderate degree, acute local radial injuries on the back surface

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[2] It should be noted that there were differences between the description of the circumstances provided by the Patient 1-DN when in Georgia and when he was hospitalized in the Russian Federation.

FIG. 50. Distribution of absorbed dose, using the calculations for anthropomorphic heterogenic phantom on the back of Patient 1-DN, which indicated he was exposed for 63 min.

area of the thorax to a severe degree (III) of 5% of the total body surface and moderate degree (II) of 10% square of the total body surface and on both hands to a light degree (I) of 2% square of the total body surface.

8.3.1. Tuberculosis

Patient 1-DN was diagnosed with disseminated tuberculosis of the lungs (type mycobacterium), which was in a recovery phase. The operation on the local radiation injury was subsequently postponed owing to the diagnosis of tuberculosis. He received conservative treatment of the local radiation injury as an alternative, which consisted of absorbing, non-adhering antiseptic bandages together with an injection of pentoxifilline 200 ml/d and Actovegin 20 ml for reducing oxygen starvation in the tissue. The active anti-tuberculosis treatment consisted of:

— Maxaquin (lomefloxacin) 400 mg/d (6 months);
— Mikobutin (mycobutin) 450 mg/d (6 months);

— Pyrozinamid (pyrazinamide) 1.5 g intravenously (3 months);

— Isoniazid 600 mg/d (3 months).

After one year, the course was repeated over one month with the administration of isoniazid 600 mg/d and Maxaquin (lomefloxacin) 400 mg/d.

X ray, CT and spirography examinations were performed for a dynamic evaluation of the functioning of the lungs and bronchial tubes. Following two and a half months of complex anti-tuberculosis therapy, positive dynamics appeared owing to the regression of the foci in the lungs (see Fig. 51). In addition, intoxication symptoms decreased and Patient 1-DN gained weight. The results of blood analyses found improvements in both the anaemia and infection.
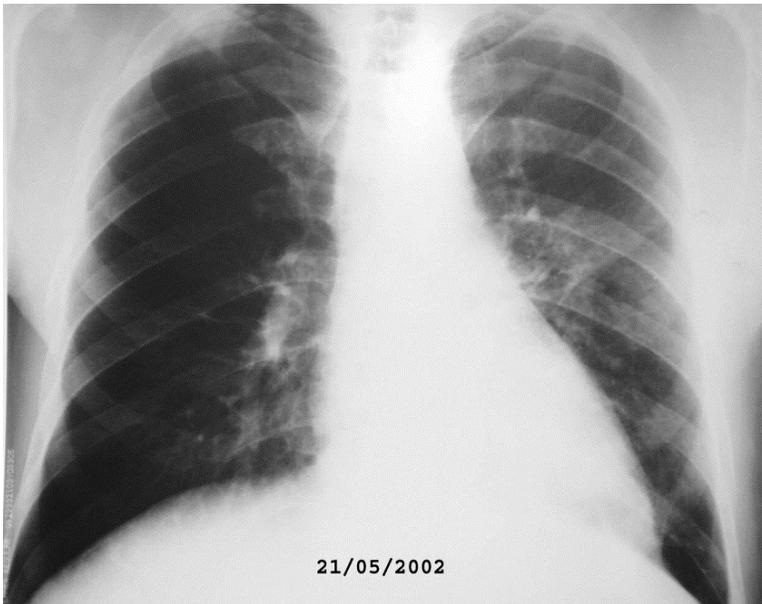
FIG. 51. Chest X ray of Patient 1-DN showing regression of the foci in the lungs after anti-tuberculosis treatment, 21 May 2002 (day 170 after exposure).

The epicentre of the local radiation injury was focused on the lower lobe of the left lung, which strongly indicated that this portion of lung tissue was subject to a maximum dose of 10 Gy.

One year after exposure, a scar fibrosis formed in the lower lobe of the left lung, which was located in the epicentre of the area in which the maximal

dose was absorbed. The scar fibrosis formed while a metatuberculosis change in other parts of the lungs took place (see Figs 52 and 53). The dynamic changes in the lung–bronchial system corresponded quite well to the functional status of the lungs.

Following admission to the clinic (three months after exposure), Patient 1-DN complained of moderate tightening in the lungs. This could have been conditioned by an active progression of tuberculosis and the local alveoli oedema, which was a result of the radiation injury to the lungs and which was characterized by the lung volume capability (LVC) diminishing (60%). In April 2002, after complex anti-tuberculosis therapy, the LVC level practically returned to normal (87%).
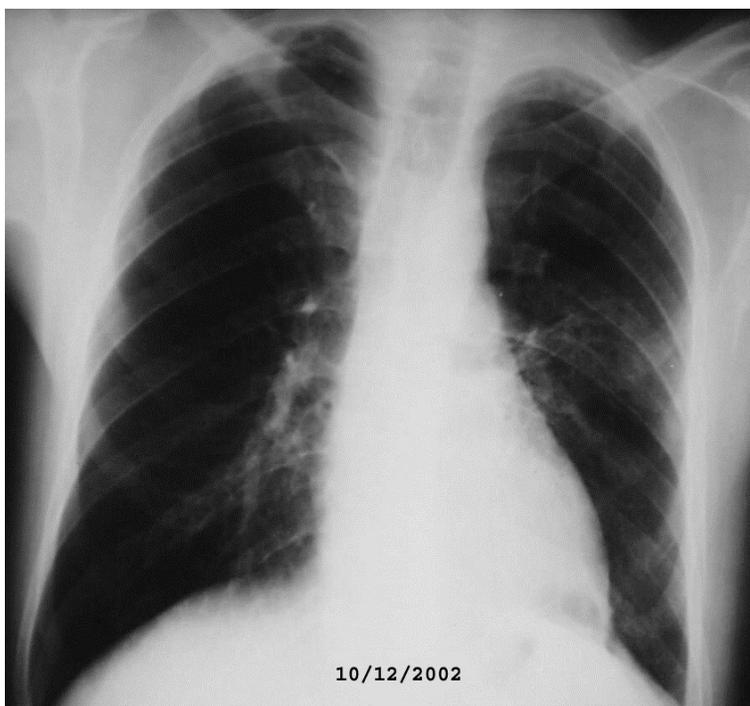
FIG. 52. Chest X ray of Patient 1-DN after treatment of tuberculosis over a period of nine months, 10 December 2002 (day 373 after exposure).

FIG. 53. Chest X ray of Patient 1-DN showing the scar fibrosis that had formed in the lower part of the left lung, 14 July 2003 (day 589 after exposure).

8.3.2. Local radiation injury

On 29 May 2002, an operation was performed which consisted of a necrectomy of the radial ulcers and the application of a split dermatome autograft that was taken from the front surface of the left hip. However, during the post-operative period, the skin grafts failed to acclimatize (see Fig. 54).

The bottom of the wound developed partially necrotized tissue. Single hearths of weak granulations were found in the muscles that had stitches positioned at angles in the upper and lower part of the wound. This caused the skin grafts to spontaneously detach and increased the amount of separated skin.

FIG. 54. Late radiation ulcer on the back of Patient 1-DN, 13 June 2002 (day 193 after exposure).

Pathogenic *Staphylococcus* appeared, causing the wound to widen to 16–20 cm. Considering the sickliness of the wound and indications of drug dependency, it was decided to continue surgical wound cleansing under anaesthesia using vacuum bandages and antibiotics, which took into consideration the sensitivity of the *Staphylococcus*. However, the application of the vacuum bandages and the bottom of the wound became covered with fibrin very fast, as shown in Figs 55 and 56, causing Patient 1-DN's condition to deteriorate.

Five necrectomies were performed consecutively. By day 300 after exposure, vacuum bandages were applied more tightly in the upper medial and lateral edges of the wound, causing granulations to appear more flourishingly (see Fig. 57).

A second necrectomy of the wound and a skin transplantation of the granulated wound areas were performed on 6 September 2002 (see Fig. 58).

After the fibrin was removed from the wound, it reduced in depth. Practically 70% of the surface epithelized, except the central part and the lower medial edge of the wound (see Figs 59–61).

FIG. 55. Late radiation ulcer on the back of Patient 1-DN, 24 June 2002 (day 204 after exposure).

FIG. 56. Late radiation ulcer on the back of Patient 1-DN, 2 July 2002 (day 212 after exposure).

FIG. 57. Late radiation ulcer on the back of Patient 1-DN, 4 September 2002 (day 276 after exposure).

FIG. 58. Repeated necrectomy on Patient 1-DN, 6 September 2002 (day 278 after exposure).

FIG. 59. Late radiation ulcer on Patient 1-DN, 9 October 2002 (day 311 after exposure).

FIG. 60. Late radiation ulcer on Patient 1-DN, 15 October 2002 (day 317 after exposure).

FIG. 61. Late radiation ulcer on Patient 1-DN, 25 October 2002 (day 327 after exposure).

On 2 December 2002, the necrectomy of the non-epithelized wound areas and plastic surgery of two split grafts were performed (see Fig. 62). The grafts were taken from the right hip and were placed on the central part of the wound between the angle of the left shoulder blade and the lower edge of the wound.

FIG. 62. Late radiation ulcer on Patient 1-DN, 2 December 2002 (day 365 after exposure).

Considering that the wound in the area of the shoulder blade angle did not heal and there were erosions in the lower-medial departments of the left side of the back under the dry crusted areas (see Figs 63–65), a decision was made to stretch the skin from part of the right shoulder blade and the left side of the chest in order to harvest a skin transplantation from a larger area.

FIG. 63. Late radiation ulcer on Patient 1-DN, 13 January 2003 (day 407 after exposure).

FIG. 64. Late radiation ulcer on Patient 1-DN, 25 February 2003 (day 450 after exposure).

FIG. 65. Late radiation ulcer on Patient 1-DN, 25 February 2003 (day 450 after exposure).

On 15 April 2003, two expanders (700 ml each) were attached to the right half of the back and a third expander was attached on the left side surface of the chest (see Fig. 66).

FIG. 66. Late radiation ulcer on Patient 1-DN, 15 April 2003 (day 499 after exposure).

Two and a half months after the expanders were attached, the stitches healed and the square of skin from the autotransplantation gradually increased in size. On 5 June 2003, the fibrosis perforated tissue was removed. A resection of periosteum was performed on the shoulder blade and the fifth rib. A major plastic surgical operation was performed for the simultaneous transfer of the right side of the shoulder blade skin sized 28–30 cm, and a section of the skin from the left side of the chest into the middle of the radial affection. An autodermoplastic operation of three skin sections taken from the side surfaces of both hips was performed on the area of the body where the skin was transplanted (see Fig. 67).

FIG. 67. Autografting on Patient 1-DN, 5 June 2003 (day 550 after exposure).

On day 10 after the operation, despite vigorous antibacterial and vessel therapy, Patient 1-DN appeared to have necrosis at the edges of the skin grafts. Most of the area covered by the three skin segments failed to acclimatize.

Following a histological examination, scars appeared on the incised tissue, along with fibrosis and an infection. The infection was purulent and appeared in deep layers of the derma. A skin necrobiosis of the skin grafts also developed (see Fig. 68).

By the middle of July 2003 (one year and seven months after exposure), the general condition of Patient 1-DN deteriorated after removing the necroses: his temperature increased to 38.0–39.0°C, he was shivering and suffered from intense pains that developed in the left shoulder blade area. The mobility of the sixth, seventh and eighth ribs was examined after the bandaging was removed

(see Figs 69–72). It was suspected that osteomyelitis had developed, and there were pathological fractures to the sixth, seventh and eighth ribs. He was submitted for an X ray and CT examination. New bandages were applied practically every day that had non-adhering nets and were made from bees' wax with antibiotic additives that were sensitive to the flora microorganisms (see Fig. 72).

FIG. 68. Status of wound on Patient 1-DN, 19 June 2003, (14 days after autografting).

FIG. 69. Status of post-operative surface of Patient 1-DN, 30 July 2003 (55 days after autografting).

FIG. 70. Infected wound on Patient 1-DN (one year and nine months after exposure).

FIG. 71. Infected wound on Patient 1-DN (one year and ten months after exposure).

FIG. 72. Non-adhering net bandages covering the wound on Patient 1-DN (one year and ten months after exposure).

An operation was performed on 8 September 2003, which removed part of the fifth, sixth seventh and eighth ribs and also treated the infected area of the left shoulder blade. In addition, a simultaneous autoplastics procedure using a movable skin graft from the hip on the right side of the wound area was performed during the operation (see Fig. 73).

Following a histological examination, the soft tissue and bones showed fibrosis and a chronic infection, with a fibrotic necrotic component. The examination also revealed segments of dead bone. The impact of infection was limited to a local radial area. An operation was performed on 11 September 2003 to conduct an autotransplantation of skin grafts from Patient 1-DN's hip onto the right and lower part of the wound area.

A digital paramagnetic resonance (DPR) examination of the bone fragments of the ribs and shoulder blade that had been removed during the operation showed that the absorbed dose was in the range of 21–37 Gy (see Table 25). The DPR results were higher than expected, which also indicated that the skin had received an even higher dose than had previously been estimated. This provides a compelling explanation of the ineffectiveness of the autotransplantation of the skin grafts, despite the use of movable, blood supplied grafts. The reason was that the pathological fracture had been complicated by the development of osteomyelitis, in addition to the radial osteoporosis that had already developed.

FIG. 73. Part of the infected wound on Patient 1-DN, 8 September 2003 (day 645 after exposure).

TABLE 25.   DIGITAL   PARAMAGNETIC   RESONANCE   RESULTS (PRELIMINARY) FROM BONE FRAGMENTS OF PATIENT 1-DN

Bone fragment	Dose (Gy)
Shoulder blade	$\approx 21 \pm 4$
V rib	$\approx 23 \pm 4$
VI rib	$\approx 37 \pm 6$
VII rib	$\approx 27 \pm 5$

Two additional issues also need to be considered to explain the failure of the skin graft to acclimatize:

(1)   Several traumatic operations had to be performed.
(2)   Several local infections were also present on the wound area.

An autotransplant operation of the omentum to cover the injury using movable skin grafts had been planned for the future but was not performed.

8.3.3. Treatment during and after operations

One year after exposure, obstructive changes in the bronchial tubes relating to Patient 1-DN's chronic bronchitis intensified owing to the metatuberculosis and radial fibrosis. Pneumosclerosis in the lower lobe of the left lung developed with his LVC measuring 30%. The significant reduction in LVC can also be explained because of the large, enduring injury and the repeated reconstructive plastic operations that were performed.

The ECG detected dynamics in the sinus rhythm, the heart electric axe was found to be normal and the heart contraction frequency was 85 bpm. In the acute infection periods of the injury, the sinus tachycardia measured up to 109 bpm and deterioration of the left ventricle myocardium status was observed.

An echocardiography was performed which showed insignificant dilatation of the right auricle and global contraction of the left ventricle, without any peculiarities detected during the total observation period. In January 2003, indirect signs of transitory lung hypertension and insignificant degenerative changes of the aorta valve folds were detected. In October 2003, the heart chamber dimensions appeared to be normal.

The results of the blood sample analyses for Patient 1-DN are presented in Table 26. Analyses of the dynamic blood samples identified frequent relapses of iron deficiency anaemia, which was particularly noticeable after the operations had been performed. This was despite a transfusion of erythromass during and after the operations. Normal levels of erythrocyte numbers in the blood were only sustainable by the constant provision of iron supplements.

Preventive measures and the treatment of infections of the injury were performed throughout the duration of his treatment. Antibiotics were used in a controlled environment and so were flora sensitivity tests (including gentamicin, lincomycin, meropenem, Tienam, Maxaquin, rifampicin, nystatin and Nizoral).

Following indications of significant intoxication and considering the complications owing to the infection of the injury (e.g. osteomyelitis in the post-operative period), detoxification therapy and substitution therapy (fresh frozen plasma, albumins, vitamins and glucose) were performed. The status of the wound on 10 October 2003 (day 677 after exposure) is presented in Fig. 74.

TABLE 26. BLOOD SAMPLE ANALYSES: PATIENT 1-DN

Date of analysis	RBC[a] (10^12/L)	Haemoglobin (g/L)	Reticulocytes (%)	Platelets (10^9/L)	ESR[b] (mm/h)	WBC[c] (10^9/L)	Basophiles (%)	Eosinophils (%)	Myelocytes (%)	Band Neutr. Granulocytes (%)	Segm. Neutr. Granulocytes (%)	Lymphocytes (%)	Monocytes (%)
22 Feb. 2002	3.5	101	24	348	51	8.6	—[d]	15	—[d]	5	35	55	5
4 Mar. 2002	3.6	108	10	355	45	8.1	—[d]	5	—[d]	2	63	20	10
6 Mar. 2002	3.6	110	—[d]	209	65	7.7	1	11	—[d]	3	60	20	5
11 Mar. 2002	4	122	—[d]	276	62	8.5	—[d]	5	—[d]	6	46	28	15
13 Mar. 2002	3.7	114	—[d]	206	58	7.3	—[d]	4	—[d]	2	70	22	2
15 Mar. 2002	3.7	114	5	211	51	7.1	—[d]	18	—[d]	6	34	35	7
18 Mar. 2002	3.4	104	—[d]	186	48	5.8	—[d]	2	—[d]	6	54	26	11
26 Mar. 2002	3.5	107	—[d]	218	60	7.5	5	1	—[d]	3	5	27	9
25 Apr. 2002	3.7	108	10	197	22	9.3	—[d]	1	—[d]	7	69	16	7
14 May 2002	4.1	122	—[d]	238	65	10.7	1	4	—[d]	6	55	24	10
4 Jun. 2002	2.1	61	22	286	80	11	—[d]	1	—[d]	23	60	12	4
11 Jun. 2002	4.1	110	—[d]	281	65	13.6	—[d]	1	—[d]	7	71	15	6
24 Jun. 2002	4.4	132	11	238	55	11.8	—[d]	4	—[d]	5	61	21	9
27 Jun. 2002	4.4	133	—[d]	258	47	13.6	—[d]	4	—[d]	9	61	20	6
3 Jul. 2002	4.2	111	—[d]	161	65	13.2	1	4	—[d]	6	59	24	6
30 Jul. 2002	3.3	100	11	344	59	11.3	—[d]	1	—[d]	30	58	9	2

TABLE 26. BLOOD SAMPLE ANALYSES: PATIENT 1-DN (cont.)

Date of analysis	RBC[a] (10^12/L)	Haemoglobin (g/L)	Reticulocytes (%)	Platelets (10^9/L)	ESR[b] (mm/h)	WBC[c] (10^9/L)	Basophiles (%)	Eosinophils (%)	Myelocytes (%)	Band Neutr. Granulocytes (%)	Segm. Neutr. Granulocytes (%)	Lymphocytes (%)	Monocytes (%)
16 Aug. 2002	3.3	90	13	360	54	8.7	—d	3	—d	6	75	14	2
30 Aug. 2002	3.5	100	7	374	15	11.4	—d	1	1	8	57	24	9
16 Sep. 2002	2.8	85	15	344	35	9.2	—d	3	—d	3	66	24	4
27 Sep. 2002	5	150	10	278	6	6.2	—d	3	—d	1	59	28	9
14 Oct. 2002	4.2	125	7	352	25	9.8	—d	5	—d	3	64	23	5
29 Oct. 2002	3.5	109	15	286	19	8.5	—d	4	—d	3	62	26	5
16 Dec. 2002	3.7	109	—d	288	48	7.9	—d	4	—d	4	66	19	7
25 Dec. 2002	4	117	18	239	24	10.3	1	3	—d	4	59	27	6
15 Jan. 2003	4.3	129	14	244	32	9.3	—d	3	—d	5	57	28	7
29 Jan. 2003	3.8	119	12	237	30	6.8	—d	7	—d	4	52	28	9
17 Feb. 2003	3.8	115	15	232	41	7.8	—d	7	—d	2	53	31	7
17 Mar. 2003	3.7	110	17	200	7	8.6	—d	1	—d	4	65	23	7
1 Apr. 2003	4.1	118	16	274	28	8.9	—d	2	—d	3	61	28	6
30 Apr. 2003	4.1	119	19	273	13	18.4	—d	1	—d	17	60	14	8
12 May 2003	2.8	86	15	264	10	17.9	—d	4	—d	16	65	11	4
28 May 2003	3.1	87	15	464	50	9.4	1	9	—d	8	50	24	8

TABLE 26. BLOOD SAMPLE ANALYSES: PATIENT 1-DN (cont.)

Date of analysis	RBC[a] (10^{12}/L)	Haemoglobin (g/L)	Reticulocytes (%)	Platelets (10^9/L)	ESR[b] (mm/h)	WBC[c] (10^9/L)	Basophiles (%)	Eosinophils (%)	Myelocytes (%)	Band Neutr. Granulocytes (%)	Segm. Neutr. Granulocytes (%)	Lymphocytes (%)	Monocytes (%)
30 May 2003	3.5	97	26	430	26	9.5	2	9	—[d]	10	46	27	6
5 Jun. 2003	4.2	114	22	393	30	12.4	1	12	—[d]	6	50	23	8
16 Jun. 2003	3.3	88	58	441	18	9.4	—[d]	6	—[d]	7	66	18	3
7 Jul. 2003	3.3	91	—[d]	409	26	—[d]	—[d]	8	—[d]	10	52	28	2
24 Jul. 2003	3.3	90	—[d]	250	37	17.7	—[d]	4	—[d]	20	53	18	5
15 Aug. 2003	3.2	86	—[d]	218	50	10.3	—[d]	2	—[d]	7	66	20	5
25 Aug. 2003	3.3	89	7	305	37	7.7	—[d]	5	—[d]	7	65	19	4
8 Sep. 2003	3.7	100	16	332	30	7.2	2	8	—[d]	7	52	24	7
22 Sep. 2003	3.8	107	6	279	45	8.1	—[d]	5	—[d]	9	45	23	18

[a] Red blood cells.
[b] Erythrocyte sedimentation rate.
[c] White blood cells.
[d] —: data not available.

FIG. 74. Wound on the back of Patient 1-DN, 10 October 2003 (day 677 after exposure).

Patient 1-DN's health deteriorated in April 2004. On the surface of the open wound, there was a large amount of pus secretion, and a secondary necrosis of the muscles, ribs, shoulder bones and vertebrae increased in depth. Repeated samples taken from the wound identified poly-resistant microbes, the largest quantity of which was the blue pus bacillus. Blood samples taken from him remained sterile until 27 April 2004.

On 23 April 2004, Patient 1-DN's condition deteriorated dramatically. He exhibited a high fever, signs of respiratory insufficiency (with an inspiratory rate of 80 per min), an expressed intoxication and an arterial hypotension. X ray examinations were performed that revealed pneumonic locus near the right root of the lung. Despite a large amount of antibiotic therapy, multi-organ dysfunction (respiratory, kidney hepatic, cardiovascular and wound exhaustion) and intoxication ensued. On 12 May 2004, his temperature increased to 39°C. On 13 May 2004, arterial pressure decreased to 40/20 mmHg due to septic shock. He was treated with massive antibacterial agents, infusion and vasopressors. He also suffered acute renal failure. The death of Patient 1-DN was due to fibrillation of the ventricles in a cardiac arrest, and it occurred at 22:55, 13 May 2004 (day 893 after exposure).

8.4. CONCLUSION OF PATIENT 1-DN'S MEDICAL TREATMENT

The extensive and deep local radiation injuries located in anatomic areas that could not be amputated, combined with damage to the underlying bone structures and vital internal organs, proved problematic in the administration of Patient 1-DN's treatment. In addition, his severe somatic pathology debilitated the multilayer graft operations with axial blood supply, which were performed to close the wound and to restore atrophy of the exposed tissue. Covering the wound using Patient 1-DN's own tissue was not possible, owing to the inability to prepare an autograft for the size of the area required. Furthermore, infection was able to enter through the areas of the skin not completely covering the wound. The further spread of the infection resulted in his death.

The use of various collagen films or imitation leather that can mechanically close the skin completely could have been a solution in this case. However, it was impossible to restore the atrophy in the area of the exposed tissue, which left Patient 1-DN with a decreased chance of recovery.

In addition, the dose received by Patient 1-DN on his back was the largest among all three exposed patients. Patient 1-DN's heart area was also irradiated as a consequence of the exposure to the left side of his back. It should be noted that he had tuberculosis and had previously suffered from narcotism.

9. DIAGNOSIS AND TREATMENT OF PATIENT 2-MG IN A SPECIALIZED HOSPITAL IN FRANCE

On 21 February 2002, Patient 2-MG was admitted to the Percy Military Training Hospital, in Paris, France, for the treatment of severe CRS [4]. Technical support for the medical management was provided by the IPSN.

9.1. MEDICAL STATUS ON ADMISSION

Prior to the accident, Patient 2-MG had been in relatively good general health. At the IHT in T'bilisi, he had exhibited a marked haematopoietic syndrome followed by a spontaneous recovery. However, there was no sign of aplasia in the peripheral blood cells at the time of admission to the Percy Military Training Hospital. The blood samples taken from Patient 2-MG showed leucocytes levels at 6.7×10^9/L, lymphocytes at 0.99×10^9/L, platelets at 228×10^9/L and erythrocytes at 3.41×10^{12}/L. Following admission, he complained of

tiredness and he was in pain. He was apyretic and his blood pressure measured 140/90 mmHg.

The location of the cutaneous radiological lesion covered the whole posterior side of the thorax from the waist up to the scapulae. The lesion was a wide, moist, epidermal denudation (approximately 30 cm × 20 cm), which covered more than 8% of the total body surface of the body, but without any signs of deep necrosis. A yellow fibrin layer completely covered the lesion. It was surrounded by a distinct contour, an inflamed halo (approximately 3 cm) and dyschromia of the skin (see Fig. 75).

FIG. 75. Lesion on Patient 2-MG, 21 February 2002 (day 81 after exposure).

After seven days of local treatment with sulfadiazine and removal of the yellow fibrin layer, the central lesion was non-haemorrhagic with a granulation bud that exhibited yellow hypovascularized areas (see Fig. 76). The radiological burn was superinfected with methicillin resistant *S. aureus*, which was treated prophylactically with the antibiotics piperacillin and amikacin. The first

FIG. 76. Lesion on Patient 2-MG, 28 February 2002 (day 88 after exposure).

therapeutic strategy was to perform a large resection of the wound covered by an artificial skin graft and, three weeks later, a meshed skin autograft.

9.2. DOSIMETRIC DATA

The prognosis and treatment of severe CRS require data on Patient 2-MG's clinical development in addition to the dosimetric data. A lack of accurate information on the exposure scenario causes difficulties in deriving a dose reconstruction for radiological overexposures by numerical methods. The absorbed dose can only be determined if both the position of the radioactive source and the exposure times are known. For Patient 2-MG's exposure scenario, there were two main geometries: localized irradiation was superimposed onto whole body irradiation, thereby presenting an additional challenge in the dose reconstruction. An initial dose estimation was performed using the Monte Carlo radiation transport simulation, which was based on the description provided by Patient 2-MG (that indicated the period of exposure), the clinical signs of the lesion and the biological dosimetry [5].

A spectrometry and adjustment of the Monte Carlo radiation transport simulation was conducted by combining a new cytogenetic analysis on the skin with three bone biopsy analyses performed by electron paramagnetic resonance (EPR). This increased the accuracy of the absorbed dose estimation and the estimation of the respective contributions in the dose distribution of the localized

and whole body irradiation. The whole body dose obtained from the second study is closer to the dose assessed by cytogenetic assay [6].

9.2.1. Skin biological dosimetry

9.2.1.1. Material and methods

Conventional biological dosimetry relies on the determination of the frequency of chromosomal aberrations such as dicentrics in the circulating lymphocytes. This approach is satisfactory and reliable when the dose is distributed uniformly over the whole body, but is limited in the case of localized irradiations, where only a small fraction of the circulating lymphocytes are irradiated.

The skin is the first organ targeted in all instances of localized overexposure, and the victim suffers from more or less severe burns. In most cases, surgery has to be performed to remove damaged tissue, thereby making a skin sample available for dose reconstruction. The determination of chromosome changes in lymphocytes is well established as a biological indicator of the dose in the case of whole body irradiation. For this reason, a cytogenetic technique was proposed for application on the skin fibroblast [7]. This approach is based on the excess chromosome segments determined by the PCC-FISH technique, which was used on the fibroblasts isolated from a skin biopsy. Skin biopsies were removed from Patient 2-MG's damaged tissue (see A of Fig. 77) for the cytogenetic technique and the fibroblasts isolated and grown over several days. After this period, the cells underwent PCC-FISH painting of the whole chromosome 4 (see B of Fig. 77), and the number of excess chromosome segments per metaphase were determined. An ex vivo reference curve correlating the number of excess chromosome segments per metaphase to the radiation dose (0–10 Gy) was established [7].

On day 88 after exposure, the damaged skin was removed and the fibroblasts were isolated. The removed skin was rectangular in shape (approximately 40 cm × 20 cm). The skin sample was divided into 41 separate squares of 2–4 cm^2, and 18 pieces were used for the PCC-FISH analysis. Two weeks after the neodermis graft, two additional 0.2 cm^2 skin biopsies were removed. The first biopsy was performed on the left inguinal area and the second on the back of the left ear. Fibroblasts from the two additional biopsies were then isolated and grown in 20 separate pieces, according to the methods described above.

The excess chromosome segments per metaphase were measured by isolating and growing fibroblasts that were removed from the damaged skin, and a subsequent conversion to the radiation doses was performed according to the IPSN published reference curve (see C of Fig. 77). The dose map was obtained using the skin biological dosimetry technique (see D of Fig. 77).
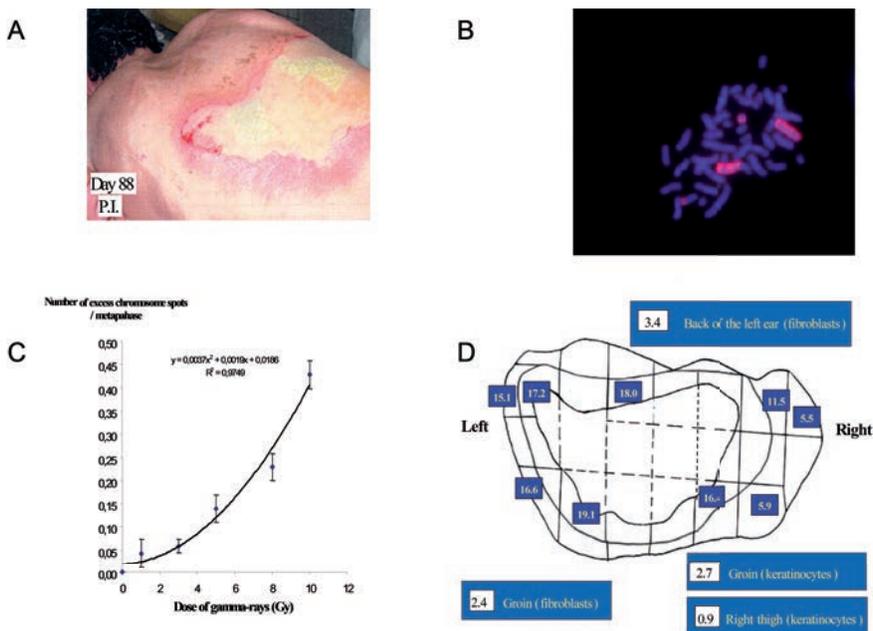
FIG. 77. Skin biological dosimetry performed by the IPSN (reproduced from Ref. [7] with permission courtesy of the Radiation Research Society, United States of America).

9.2.1.2. Results of the skin biological dosimetry

The number of fibroblasts collected in the moist central area of the removed tissue was in the range of $(0.03–0.36) \times 10^6$ cells/cm² of skin. The values in the inflammatory part of the skin were found to be slightly higher and was in the range of $(0.11–0.52) \times 10^6$ fibroblasts/cm² of skin. In the peripheral area of the removed tissue, the density was in the range of $(0.12–0.34) \times 10^6$ fibroblasts/cm², whereas on the back it increased to 1.2×10^6 and 1.5×10^6 fibroblasts/cm² for the left ear and left inguinal area sectors, respectively. The time taken to reach 50% confluence in the cell culture for applying the PCC-FISH assay was dependent on the area under study. Experiments could be performed on day 5 or 6 after the removal of the fibroblasts that had been isolated from sectors 1, 3, 9 of the left ear and the left inguinal area. However, fibroblasts isolated from domains 27 and 29 were analysed on day 12. Analysis could not be performed for some sectors because the cells did not grow.

The number of metaphases analysed was in the range of 21–209. The number of excess chromosome segments per metaphase ranged from 1 to a maximum of 5. For the majority of sectors, as indicated by U-test values, the

distribution of excess chromosome segments per metaphase did not differ significantly from a Poisson distribution. The highest number of excess chromosome segments formatted was determined in metaphase spreads obtained from sectors of the left bottom part of the exeresis, with yields between 0.86 and 1.35 excess chromosome segments per metaphase. The yield of excess chromosome segments per metaphase in the peripheral area decreased to values between 0.13 and 1.08, and dropped to 0.04 and 0.0 for the left inguinal site and the back of the left ear, respectively. Conversion of the numbers of excess chromosome segments per metaphase into radiation doses was conducted using the ex vivo calibration curve pre-established in the experiments described above (see C of Fig. 77).

On the basis of the number of excess chromosome segments per metaphase analysed, the sectors could be divided into three areas:

(1)   In less exposed areas, such as the left inguinal area and the back of the left ear, doses were found to be below or equal to 3.4 Gy.
(2)   In mid-range areas found on the side of the body, doses were around 5 and 6.5 Gy.
(3)   Doses located on the back of the body that were found to be higher than 11.6 Gy, and in some areas, they were up to 21 Gy.

The dose distribution followed an isodose curve that was compatible with the clinical features of the lesion.

9.2.1.3. Conclusion

The radiation dose map obtained using the skin biological dosimetry technique (see D of Fig. 77) was found to be in accordance with the clinical data and physical dosimetry, as well as with the conventional biodosimetry. Patient 2-MG's biological doses were in the range of 11.5–19.1 Gy in the immediate area of the lesion and decreased rapidly to 5.5–5.9 Gy a few centimetres from where the lesion began [7].

9.2.2.   Electron paramagnetic resonance dosimetry

9.2.2.1. Material and methods

The EPR spectrometry technique provides an estimate of the absorbed dose in irradiated inert materials by detecting paramagnetic centres, such as free radicals or point defects, which are specifically generated by ionizing radiation. The number of paramagnetic centres, induced by the interaction of ionizing

radiation in materials, is proportional to the absorbed dose. In most materials, the paramagnetic centres generated recombine very quickly, making their detection unlikely. In some cases of dosimetry, particularly retrospective dosimetry, the paramagnetic centres are stable with time or at least have a lifetime of the order of (or greater than) one year, which is the case for bone and dental enamel.

EPR spectrometry is a physical method of observing the resonance created when the paramagnetic centre in a material absorbs a microwave when placed in a magnetic field. The intensity of the magnetic field and the resonance frequency are characteristic for a given paramagnetic centre and enable material analysis in the same way as, for example, measuring the infrared absorption spectrum. The measurement of the EPR signal amplitude of the specific paramagnetic centre caused by irradiation in bone or dental enamel can therefore be used to estimate the dose received. The EPR measurements were performed on three samples taken from Patient 2-MG's bones (see Fig. 78).
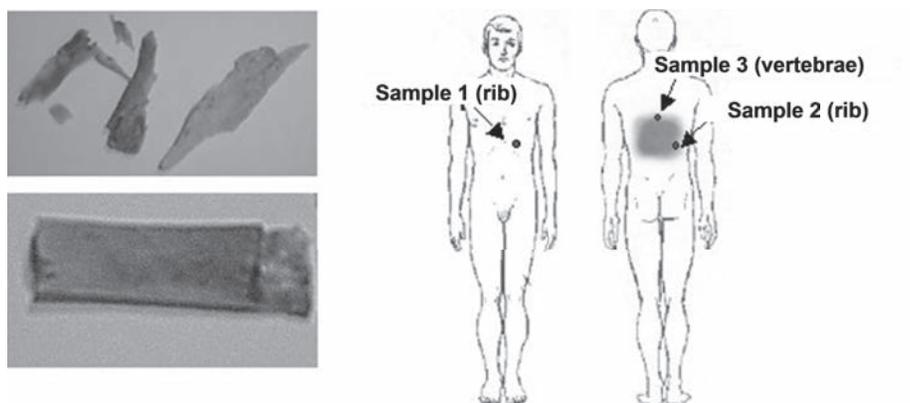

FIG. 78. Bone samples from Patient 2-MG measured using the EPR spectrometry technique for dose reconstruction (left) and localization of the three bone samples (right) (reproduced from Ref. [6] with permission courtesy of Oxford University Press).

Bone is mainly composed of hydroxyapatite crystals $Ca_{10}(PO_4)_6(OH)_2$ bound by an organic matrix consisting mainly of collagen. The paramagnetic centres responsible for the EPR signal induced by irradiation occur almost entirely in carbonated apatites (i.e. in hydroxyapatite crystals where some of the OH^- or PO_4^{3-} have been replaced by CO_3^{2-}). Bone tissue can contain up to 8% of these carbonated apatites. The paramagnetic centre created by the irradiation at room temperature are mainly CO_2^- ions and to a lesser extent CO_3^{2-} ions.

Two bone samples used in the EPR spectrometry technique were from Patient 2-MG's eleventh rib: one from the front (sample 1); and one from the back at the location of the radiological burns (sample 2). A third bone sample were pieces of vertebrae (sample 3) taken from the upper area of the back at the location of the radiological burns (1 cm deep).

The dose additive method was used to establish a calibration curve and to determine the absorbed dose in each biopsy. This method consists of post-irradiation of the bone to produce a calibration curve for the sample itself. Three different doses were successively applied (10, 20 and 40 Gy) in terms of air kerma with a ^{60}Co source, in order to determine the relationship between the EPR signal amplitude and the absorbed dose.

The relationship is linear for bone and passes through the abscissa at the initial dose, provided there is no signal saturation. This method has the advantage of overcoming the variability between samples, since it is always the same material that is irradiated and measured. Conversion factors from dose in air to dose in bone for this case were estimated, taking into account calculated energy spectra at each location of the bone samples and the energy response of the bone EPR signal. The EPR spectra of bone samples were recorded with an X-band spectrometer (of the type Bruker EMX) equipped with a high Q resonator. The spectra were recorded according to IPSN protocol with a modulation frequency of 100 kHz, modulation amplitude of 0.3 mT and a microwave power of 2 mW.

9.2.2.2. Results of EPR dosimetry

A full report of the doses measured by EPR spectrometry on the bone samples are provided in Ref. [5], and Table 27 presents a summary of the results. The results are of a wide range (from 4.5 Gy to almost 50 Gy), which confirms the high heterogeneity of the irradiation and the hypothesis assumed for the exposure scenario.

TABLE 27. TOTAL DOSE ON BONE SAMPLES BY THE EPR TECHNIQUE

Sample	Total dose (Gy)
1 (front rib)	4.5 ± 1.1
2 (back rib)	48.4 ± 1.8
3 (vertebrae)	12.5 ± 1.0

9.2.3. Dose reconstruction by numerical simulation

The dose reconstruction by numerical simulation, based on Monte Carlo calculations, first required the determination of the absorbed dose rate in free air at different distances from the source. Using this information, an assessment of the dose received by Patient 2-MG in terms of dose gradient in the tissue, and in terms of dose to the skin, organs and whole body, was then performed.

9.2.3.1. Material and methods

The calculations were carried out using the Monte Carlo radiation transport simulation code, MCNP4C2 (Monte Carlo N-Particle), developed at Los Alamos National Laboratory [8] with a general purpose Monte Carlo code for neutron, photon and electron transport. The geometry of MCNP4C2 treats an arbitrary 3-D configuration of user defined materials in geometric cells bounded by first degree and second degree surfaces and fourth degree elliptical tori. The cells are defined by intersections, unions and complements of the regions bounded by surfaces. The cells can be filled with materials of arbitrary composition and density.

The geometry of the radioactive source was defined in MCNP4C2 using two concentric cylinders with the dimensions indicated in Fig. 79. The inner cylinder of the radioactive source was filled with strontium titanate, which has a density of 5.12 g/cm^3. The casing (outer cylinder) of the radioactive source was made of iron, with a density of 7.87 g/cm^3. The emission spectrums of ^{90}Sr and ^{90}Y were taken into account in the calculations. Strontium is in a secular
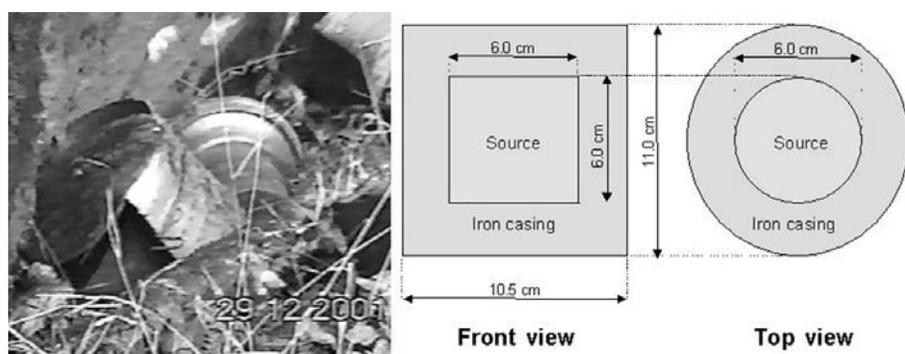

FIG. 79. Radioactive sources in the recovery location (left) and front and top view of the radioactive sources (right) (reproduced from Ref. [6] with permission courtesy of Oxford University Press).

equilibrium with its daughter ^{90}Y, which ensured the electrons emitted by ^{90}Y were also taken into account in the calculations. The activities of the radioactive sources were assumed to be equal to 1.3×10^{15} Bq for both ^{90}Sr and [90]Y.

Strontium-90 and ^{90}Y are beta emitters with a mean energy equal to 196 keV and 934 keV, respectively. A simplified graphical representation of the beta spectrum of each element is shown in Fig. 80.
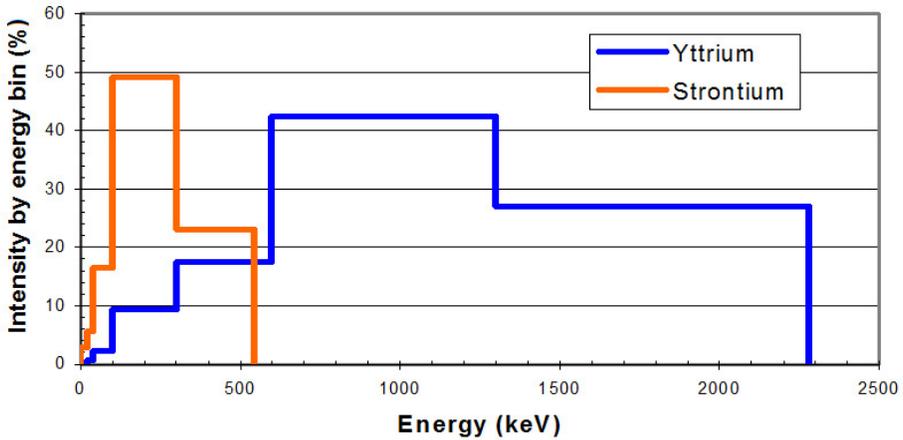

FIG. 80. Beta spectra of ^{90}Sr and [90]Y.

Within the material that comprises the RTG, the electrons emitted by ^{90}Sr and ^{90}Y produce X rays by bremsstrahlung, with energy that ranges from 0 to the maximum energy of the electrons (i.e. 2.28 MeV). The mean path of electrons of 2.28 MeV in iron is 0.2 cm. Owing to the thickness of the iron source casing (2 cm), all electrons are consequently contained inside the radioactive source. The only particles escaping from the radioactive source are X rays. The depth dose of X rays with an energy range of 10 keV to 1 MeV in soft tissue is shown in Fig. 81. The curves are normalized to 1 at the entrance. The data were calculated using mass energy absorption coefficients μ_{en}/ρ [9].

The Cristy numerical anthropomorphic phantom [10] was used as the MCNP4C2 input to simulate Patient 2-MG (see Fig. 82). This phantom, developed at Oak Ridge National Laboratory, represents a standard adult male and includes the main tissue and organs. Three tissue compositions and densities are distinguished: soft tissue (1.04 g/cm^3), lung tissue (0.296 g/cm^3) and skeleton tissue (1.4 g/cm^3). The phantom was surrounded by air (0.001 g/cm^3) in the MCNP4C2 calculations.
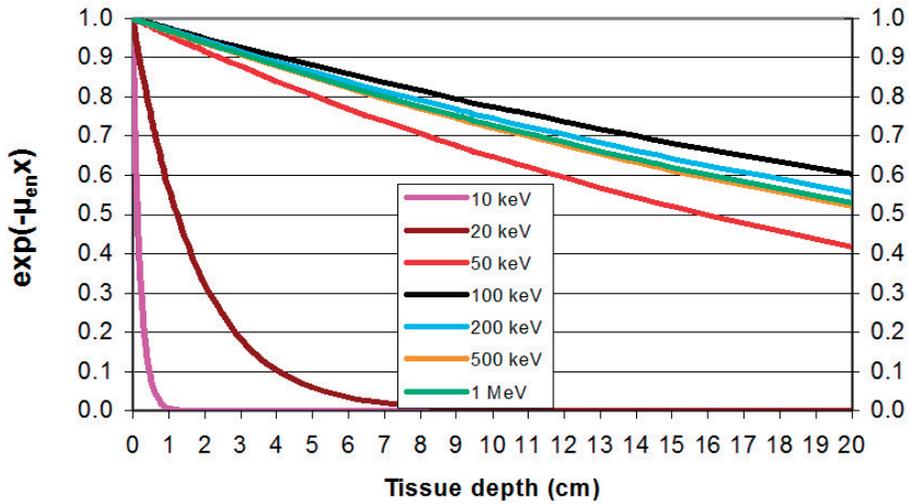
FIG. 81. *Depth dose of X rays with an energy range of 10 keV to 1 MeV in soft tissue.*
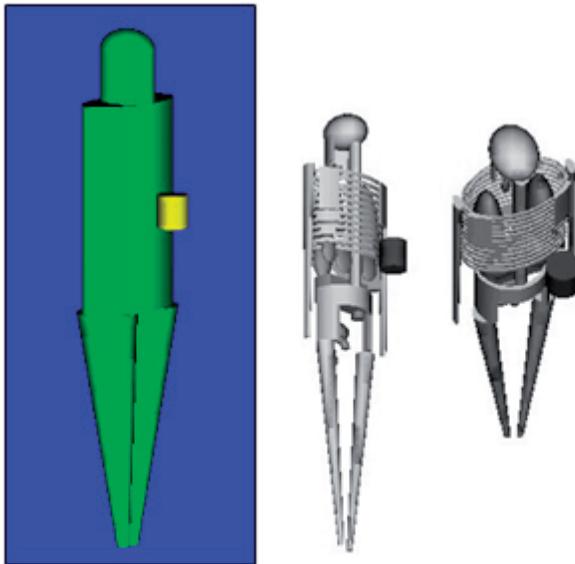

FIG. 82. *Modelling of numerical phantom and radioactive source for MCNP4C2 calculations (left image reproduced with permission courtesy of IRSN, France; right image reproduced from Ref. [6] with permission courtesy of Oxford University Press).*

The dose rate in free air was calculated at contact with the radioactive source and at distances of 0.25 m, 0.5 m and 1 m from its surface. The mean energy was determined as an average over both the fluence spectrum and the dose spectrum.

According to Patient 2-MG's clinical signs, the radioactive source was located on the back of the phantom at 2 cm from the skin. However, without knowledge of the exposure time, the calculations can only provide a dose distribution per unit of time.

9.2.3.2. Results of the simulation

The absorbed dose rates in free air (Gy/h) on contact with the radioactive source and at distances of 0.25 m, 0.5 m and 1 m from its surface are given in Table 28 and Fig. 83. For comparison, Table 28 includes the dose rate at contact with the radioactive source taken from the technical specification and measurements obtained on site at 1 m. The mean energy averaged over the fluence spectrum and the mean energy averaged over the dose spectrum for each distance are also given in Table 28.

TABLE 28. DOSE RATE IN FREE AIR, FLUENCE AVERAGED MEAN ENERGY AND DOSE AVERAGED MEAN ENERGY AT DIFFERENT DISTANCES FROM THE SURFACE OF THE SOURCE

Distance from the surface of the source (m)	X ray dose rate (Gy/h)	Measurements (Gy/h)	Mean energy (fluence) (keV)	Mean energy (dose) (keV)
0 (contact)	235	230[a]	374	549
0.25	7	—[b]	392	568
0.50	2	—[b]	394	571
1	0.6	1[c]	395	572

[a] Non-validated data (from source technical notice): 24 000 R/h.
[b] —: data not available.
[c] On site measurements: 100 R/h (at this energy range, $1\ R = 9.6\ 10^{-3}$ Gy).
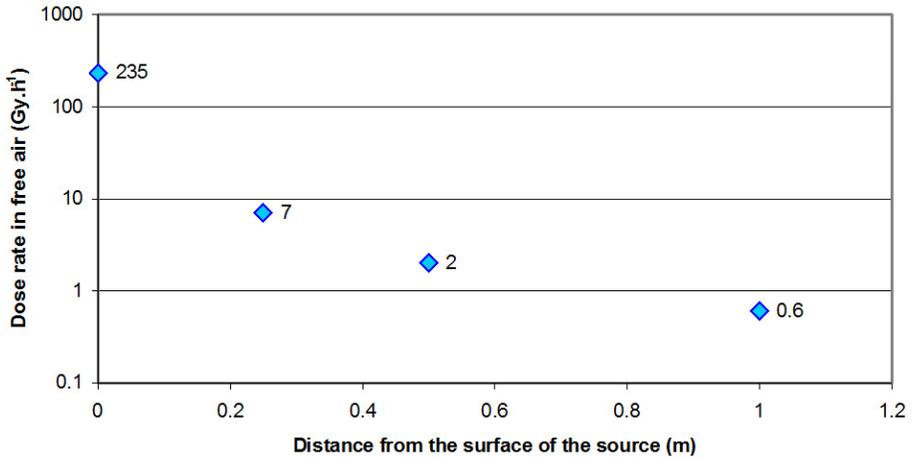
FIG. 83. Calculated dose rate in free air (Gy/h) on contact with the radioactive source and at distances of 0.25 m, 0.5 m and 1 m from its surface.

The fluence spectrum and dose spectrum provided in Table 28 at 0 m (contact) and at 1 m from the surface of the radioactive source are shown in Figs 84 and 85, respectively.
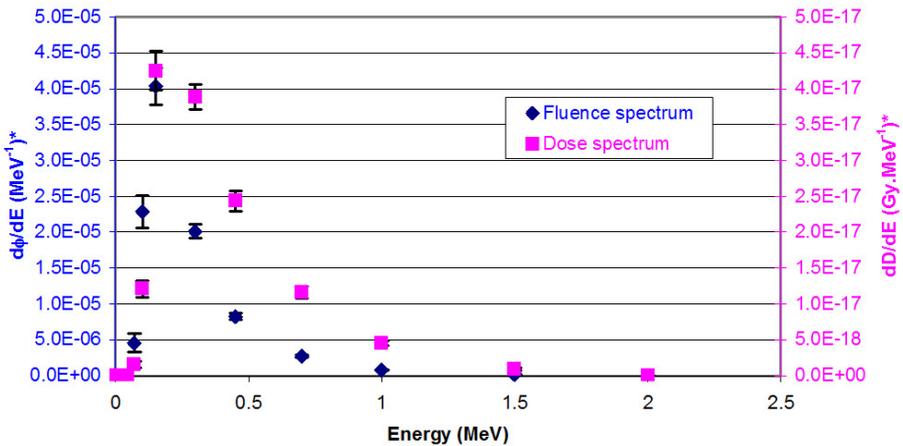

FIG. 84. Calculated fluence and dose spectra at 0 m (contact) with the radioactive source in free air.
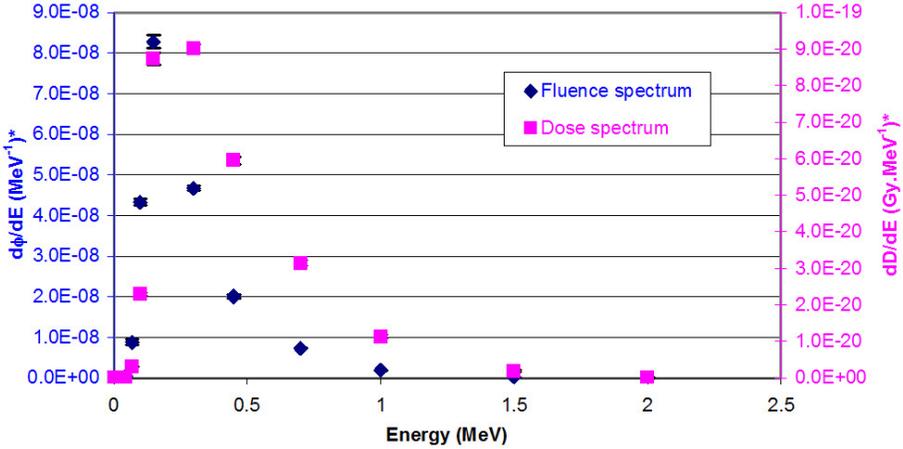
FIG. 85. *Calculated fluence and dose spectra at 1 m from the surface of the radioactive source in free air.*

9.2.3.3. Conclusion

The absorbed dose rate in free air is very high at contact with the radioactive source, which was calculated to be more than 200 Gy/h, and decreases roughly with respect to the inverse square law for distances greater than a few tens of centimetres from its surface. These results are consistent with the measurements performed at contact with the radioactive source and at a distance of 1 m, as shown in the third column of Table 28.

9.2.4. Assessment of the exposure time and determination of the total dose

According to the hypothesis of the exposure scenario, the dose measured by EPR spectrometry in each sample corresponds to a total dose composed of the dose due to local irradiation plus a dose due to a homogeneous irradiation of the whole body. For the local irradiation, the doses at the location in which the bone samples were taken are linked by a proportionality factor determined by the simulations. This problem can be solved by a system of three equations (see Eqs (7–9)) [6]:

$$
\begin{cases}
EPR\_D1 = LOCAL\_D1 + HOM\_D \\
EPR\_D2 = LOCAL\_D2 + HOM\_D \\
EPR\_D3 = LOCAL\_D3 + HOM\_D
\end{cases}
\tag{7}
$$

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where

*EPR_D*1/2/3   is the total dose calculated using the EPR measurement technique on bone samples 1/2/3;

*LOCAL_D*1/2/3   is the dose to bone samples 1/2/3 owing to the local irradiation;

and *HOM_D* is the dose due to the whole body irradiation.

*LOCAL_D*1, *LOCAL_D*2 and *LOCAL_D*3 are linked by a proportionality factor given by the dose rate distribution, which is given as:

$$\begin{cases} LOCAL\_D1\_RATE = k_{12} \times LOCAL\_D2\_RATE \\ LOCAL\_D1\_RATE = k_{13} \times LOCAL\_D3\_RATE \\ LOCAL\_D2\_RATE = k_{23} \times LOCAL\_D3\_RATE \end{cases} \tag{8}$$

where

*LOCAL_D*1/2/3_*RATE* is the local dose rate for the location of bone samples 1/2/3 owing to the local irradiation as determined by calculations, and $k_{12/13/23}$ are constants estimated by the Monte Carlo calculations.

From Eq. (8):

$$\begin{cases} LOCAL\_D1 = k_{12} \times LOCAL\_D2 \\ LOCAL\_D1 = k_{13} \times LOCAL\_D3 \\ LOCAL\_D2 = k_{23} \times LOCAL\_D3 \end{cases} \tag{9}$$

Therefore, the deduced data are then:

(a)   The local dose at the location of the bone samples:

$$\begin{cases} LOCAL\_D2 = (EPR\_D1 - EPR\_D2)/[(k_{12}) - 1] \\ LOCAL\_D1 = k_{12} \times LOCAL\_D2 \\ LOCAL\_D3 = LOCAL\_D2/k_{23} = LOCAL\_D1/k_{13} \end{cases} \tag{10}$$

(b)   The dose due to the homogeneous irradiation:

$$\begin{cases} HOM\_D = EPR\_D1 - LOCAL\_D1 \\ HOM\_D = EPR\_D2 - LOCAL\_D2 \\ HOM\_D = EPR\_D3 - LOCAL\_D3 \end{cases} \tag{11}$$

(c)   The exposure time:

$$\begin{cases} t = LOCAL\_D1/LOCAL\_D1\_RATE \\ t = LOCAL\_D2/LOCAL\_D2\_RATE \\ t = LOCAL\_D3/LOCAL\_D3\_RATE \end{cases} \tag{12}$$

where t is the exposure time for local irradiation. The dose rate that was calculated for the local dose at the location of the bone samples was deduced by the exposure time.

For the chosen geometric configuration, the dose rates of bone samples 1, 2 and 3 are 2 Gy/h, 109 Gy/h and 22 Gy/h respectively. Using Eqs (10–12), the doses owing to the local irradiation at the location of the bone samples are then calculated (i.e. 1 Gy, 45 Gy and 9 Gy for samples 1, 2 and 3, respectively). The exposure time of the local irradiation was deduced to be approximately 30 min and the additional homogeneous dose was calculated to be 3.5 Gy.

9.2.5.   Organ doses

The mean absorbed dose owing to the local irradiation for an exposure time equal to 30 min and the total mean absorbed dose owing to the local and homogenous irradiations for different organs and regions of the body are given in Fig. 86. The mean total dose to the organs ranged from 3.5 Gy to more than 18 Gy. Figure 86 shows that in the case of local irradiation, the kidneys received a high mean absorbed dose, as they were located very close to the radioactive source. The mean dose to the whole body is approximately 5 Gy, which is consistent with the value of 4.4 Gy obtained by the biological dosimetry using the cytogenetic technique performed by the IPSN.
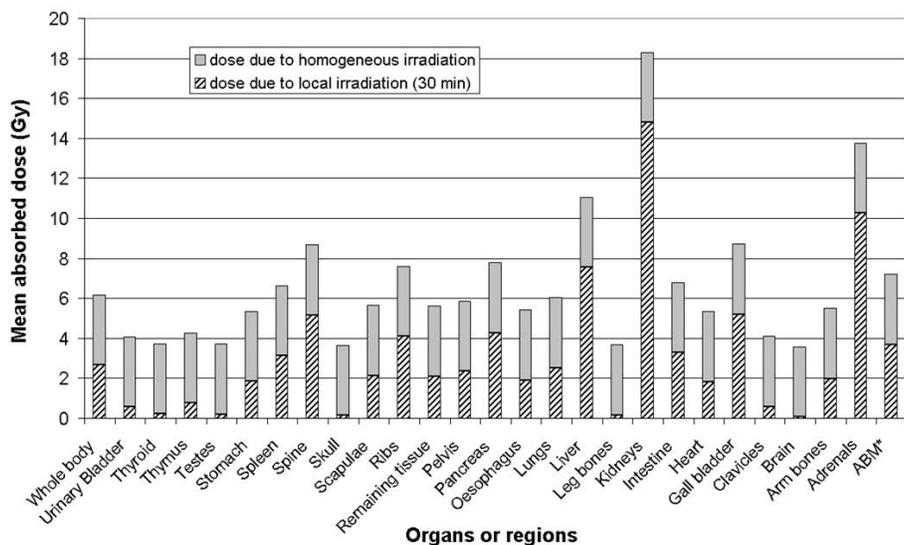
ABM: active bone marrow.

FIG. 86. Mean absorbed dose for local irradiation for an exposure time equal to 30 min and the mean absorbed dose for homogenous irradiation for different organs and regions of Patient 2-MG's body.

The EPR measurements provided very accurate and objective points of normalization for the numerical simulations when the scenarios were not well known, which is usually the case for accidental exposures. However, the ex vivo EPR technique is limited by its invasiveness and can only be used for specific situations.

9.2.6. Conclusion of Patient 2-MG's dosimetry

The physical dose reconstruction was performed by the IPSN for Patient 2-MG using classical biological dosimetry, skin biological dosimetry, EPR measurements on bone samples and Monte Carlo calculations. The dosimetric results showed that the mean dose to the organs was extremely heterogeneous, ranging from several Gy to more than 20–25 Gy. The combination of the Monte Carlo calculations and the classical biological dosimetry, skin biological dosimetry and EPR technique were successfully used to estimate the dose distribution in the tissue with reasonable accuracy and helped the development of the treatment strategy. Patient 2-MG received a total body irradiation estimated at 6 Gy, and the time of the localized exposure was estimated to be 30 min.

9.3. DIAGNOSIS AND TREATMENT

The clinical development of the lesion and the dose reconstruction indicated CRS. The lesion was severe and covered more than 8% of the total body surface, which had received more than 20–25 Gy.

Despite the high doses received locally to the thoracic area, Patient 2-MG did not develop radio-induced pneumonitis or a major pulmonary fibrosis. The general pulmonary function was normal. However, the CT scans revealed a much localized fibrosis at the right apex (see Fig. 87) and a pleural effusion predominant on the right side (see Fig. 88) on day 109 after exposure.

The principle clinical symptom of the lesion was the pain felt by Patient 2-MG. Therefore, the systemic treatment was focused on alleviating this pain. High doses of morphine sulphate (over 100 mg/d) were required to achieve this, and the amounts administered were quickly reduced after each surgical procedure. The morphine he was provided on request was accompanied with a neuroleptic (levomepromazine) and an anxiolytic.

FIG. 87. CT scan of Patient 2-MG showing localized fibrosis at the right apex, 21 March 2002 (day 109 after exposure).

FIG. 88. CT scan of Patient 2-MG showing a pleural effusion predominant on the right side, 21 March 2002 (day 109 after exposure).

9.4. DESCRIPTION OF THE SURGICAL PROCEDURES

9.4.1. Artificial skin graft on day 88 after exposure

The first excision of the lesion (see Fig. 89) was 8–10 cm wide, which included the inflammatory area of the healthy cutaneous zone, and a deep excision was made to the aponeurosis of the paravertebral muscles.

The resection area was covered with a synthetic dermal matrix (Integra) (see Fig. 90). The matrix was composed of a double layer with a sheet of collagen, which was treated to increase the colonization of cells from the viable tissue underneath. The upper surface of the matrix was made of a silicone layer. This layer was completely transparent, which enabled examination of the lesion below.

Figure 91 presents the histological changes of the skin of Patient 2-MG following exposure to ionizing radiation. A photo of his lesion is given in A of Fig. 91, B is a graphic illustration of the lesion and the position of the biopsies (G2 to G34), and C shows the results of the haematoxylin–eosin staining (HES) (x40), Ki67 immunostaining (x40), Sirius red staining (collagen) (x10) and Bax (x40) immunostaining of the skin biopsies as a function of the position in the skin lesion (G2 to G34).

*FIG. 89. First excision on Patient 2-MG, 28 February 2002 (day 88 after exposure).*

FIG. 90. Artificial derma (Integra) on Patient 2-MG, 28 February 2002 (day 88 after exposure).
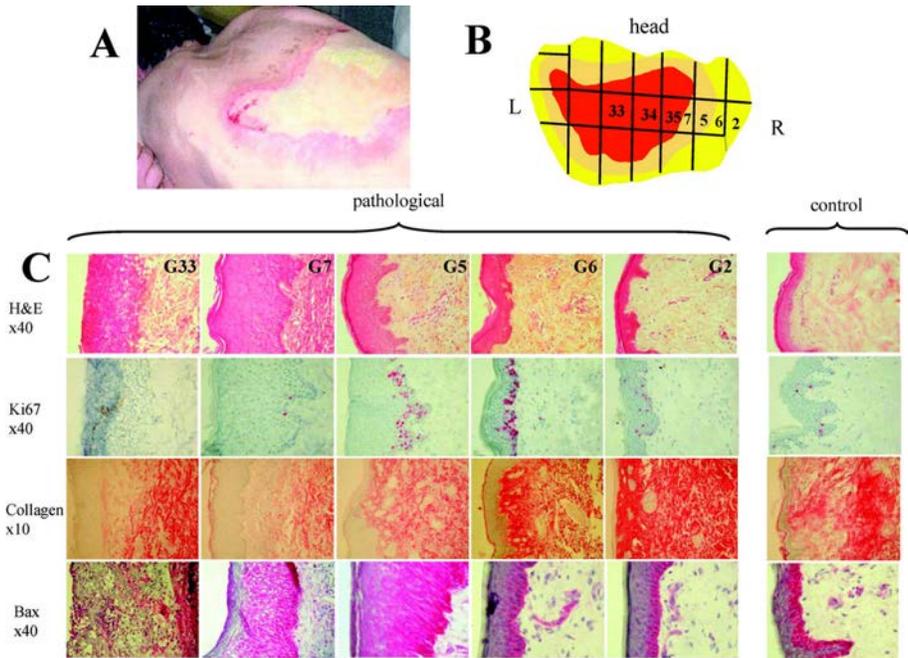
FIG. 91. Histological changes of Patient 2-MG's skin following exposure to ionizing radiation (reproduced from Ref. [11] with permission courtesy of Radiation Research Society, United States of America).

The examination of HES sections revealed common histological features of moist desquamation. A marked epidermolysis associated with a loss of epidermis adhesiveness to the basal layer and a microvascular destruction was observed at different locations within the lesion. The absence of dermal necrosis was confirmed using Bax immuno-nistochemical staining (C of Fig. 91). The epidermal hyperproliferative response Ki67, the perivascular inflammatory cell infiltration and the extracellular matrix protein deposition (i.e. collagen) revealed a healing process surrounding the lesion (C of Fig. 91) [11].

9.4.2. First skin autograft

Figure 92 shows the artificial derma covering the lesion after 22 days of development. The artificial skin appeared normal and exhibited a predominantly fawn colour, which was typical for this type of autograft.

FIG. 92. Artificial derma covering the lesion on Patient 2-MG after 22 days of development, 22 March 2002 (day 110 after exposure).

Despite the normal appearance of the Integra areas, the artificial skin graft was found not to have been colonized by fibroblasts and endothelial cells in large areas. This was particularly the case in the middle section of the lesion, which meant the silicon sheet had to be removed (see Fig. 93).

The wound was covered with a thin skin graft measuring 0.3 mm, which had been harvested from the thigh and meshed threefold (see Fig. 94).

9.4.3. Second skin autograft

The development on 50% of the surface of the graft was unfavourable and was characterized by large devascularisation areas with an irregular shape (yellow area), which were observed on day 27 after the skin autograft (see Fig. 95).

A second skin autograft was performed after the removal of the yellow devascularized zones (see Fig. 96). The dermo-epidermic graft (measuring 0.3 mm), which was meshed twofold, had been taken from the posterior part of the right thigh and was placed on the paravertebral and left subscapular areas.

9.4.4. Third skin autograft

On day 43 after the second skin autograft, its development showed a recovery of approximately 50% on the surface (see Fig. 97).

FIG. 93. Silicon sheet removed from Patient 2-MG, 22 March 2002 (day 110 after exposure).

FIG. 94. First autograft on Patient 2-MG, 22 March 2002 (day 110 after exposure).

FIG. 95. Development of the first autograft on Patient 2-MG, 18 April 2002 (day 137 after exposure).
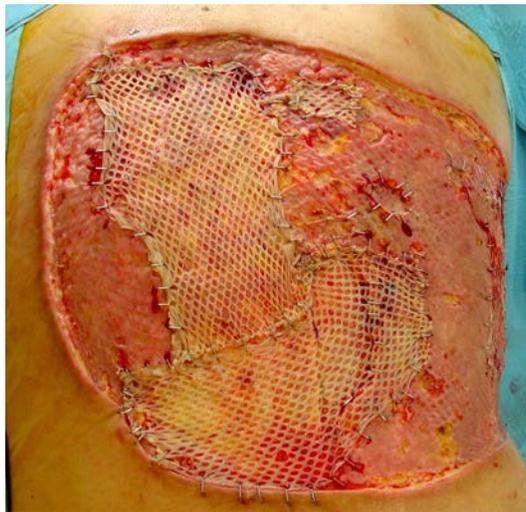
FIG. 96. Devascularized zones removed and second autograft performed on Patient 2-MG, 18 April 2002 (day 137 after exposure).

FIG. 97. Development after the second skin autograft on Patient 2-MG, 31 May 2002 (day 180 after exposure).

The devascularized tissue extended below to include muscle, which was mainly observed in the left and right paravertebral areas. The atonic tissue, the 'fish flesh coloured' muscle fibres and a dorsal spine vertebra were removed (see Fig. 98).
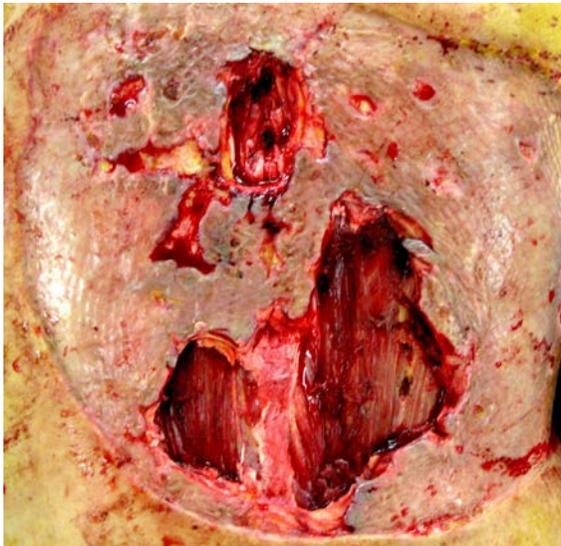

FIG. 98. Excision on Patient 2-MG, 31 May 2002 (day 180 after exposure).

The dorsal spine vertebra bone sample that was removed was used for further dose assessment using the EPR technique. The dose was calculated to be 12.5 ± 1.0 Gy. A thin skin graft (measuring 0.3 mm), which was meshed twofold and had been taken from the posterolateral part of the left thigh, was grafted in the three excised areas (see Fig. 99).
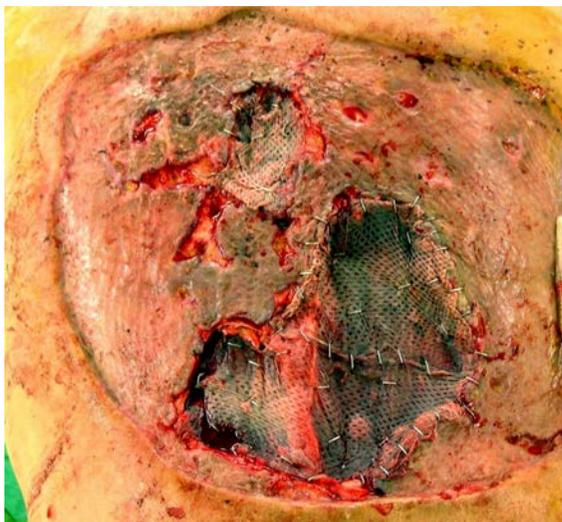

FIG. 99. Third skin autograft on Patient 2-MG, 31 May 2002 (day 180 after exposure).

Over several months, the development of Patient 2-MG's health was characterized by a stable condition. An increase in surface recovery of the lesion was not observed, despite three successive excisions of the necrotic tissue, which were conducted on days 264, 290 and 306 after exposure. These surgical excisions were combined with local treatment using the vacuum assisted closer technique, which theoretically promotes the neoangiogenesis and the budding of the wound. Figure 100 shows the extension of the superinfected tissue with a necrotic part after the third skin autograft.

9.4.5. Fourth skin autograft

A surgical excision of the lesion down to the bone was performed, which displayed several dorsal spine vertebrae and the posterior eleventh rib (see Fig. 101).

FIG. 100. Development after the third skin autograft on Patient 2-MG, 23 August 2002 (day 264 after exposure).

FIG. 101. Evolution of the third skin autograft on Patient 2-MG, 8 November 2002 (day 341 after exposure).

A fourth skin autograft, meshed twofold, which had been harvested from the posterior part of the left thigh, was applied (see Fig. 102).

FIG. 102. Fourth autograft harvested from the posterior part of the left thigh of Patient 2-MG, 8 November 2002 (day 341 after exposure).

Patient 2-MG's health continued to develop unfavourably. Ninety-nine days after the fourth skin autograft, the open lesion that was not cured by successive grafting procedures remained uncovered down to the bone (see Fig. 103). Consequently, a new therapeutic strategy was taken to cover this area with a vascularized flap. The localization of the radiological lesion at the thoracic level enabled the use of an omentum flap.

9.4.6. Omentum flap and fifth skin autograft

The omentum is a double fold of peritoneum attached to the stomach by a certain amount of the abdominal viscera. The omentum flap was removed from the peritoneal cavity in order to keep its vascular pedicle connected with the left gastro-epiploic artery. The lesion area was widely abraded, and all tissue with a fragile cicatrization were removed in a large circular area (around 30 cm in diameter). The dorsal spine vertebrae were resected from the eleventh thoracic to the third lumbar vertebra. A fragment of the exposed eleventh rib was also excised. The omentum flap was transferred from the peritoneal cavity to the level

of the lesion on the back through a subcutaneous tunnel excavated after resection
of the lateral arc of the tenth left rib (see Fig. 104).

FIG. 103. Evolution of the fourth autograft on Patient 2-MG, 24 February 2003 (day 449 after exposure).

FIG. 104. Transfer of the omentum flap from the peritoneal cavity to the level of the lesion on the back of Patient 2-MG, through a subcutaneous tunnel excavated after resection of the lateral arc of the tenth left rib, 24 February 2003 (day 449 after exposure).

The vascularized omentum flap was positioned onto the abraded area and attached at the peripheral level (see Fig. 105).

A fifth skin autograph (measuring 0.4 mm), which had been taken from the external and anterior part of the left thigh and meshed 1.5-fold, was performed on the surface of the omentum flap (see Fig. 106).

FIG. 105. Vascularized omentum flap positioned onto the abraded area of the lesion of Patient 2-MG and attached at the peripheral level, 24 February 2003 (day 449 after exposure).

FIG. 106. Fifth skin autograph performed on Patient 2-MG, 24 February 2003 (day 449 after exposure).

Following the fifth skin autograph, Patient 2-MG's development and recovery were favourable. The lesion healed on day 490 after exposure (see Fig. 107).

FIG. 107. The lesion on Patient 2-MG, 6 April 2003 (day 490 after exposure).

9.5. CONCLUSION OF PATIENT 2-MG'S MEDICAL TREATMENT

The general therapeutic strategy used for the treatment of severe CRS is the iteration of comprehensive excisions and autografts until the healing of the lesion or halting of its extension. In this case, however, as the lesion could not be cured by autografts because of the hypovascularization, a vascularized flap was used for the final covering.

The treatment of Patient 2-MG over approximately 16 months can be divided into three successive phases:

(1) Excision and covering with an artificial skin graft followed by autograft;
(2) Iterative excisions and autografts alternately with vacuum assisted closure dressings;

(3)   Final covering with a vascularized omentum flap, which was selected due to the thoracic localization of the lesion.

Patient 2-MG was sent home on 18 April 2003 (day 502 after exposure), when functional recovery to normal life was complete. He was in a generally good condition, and the covering of the lesion was found to be stable. A complete epidermization and non-morphinic antalgic was used to control the residual pain. Since his return to Georgia, no medical information has been obtained.

10. CONCLUSIONS

The review of radiological accidents is a mechanism for feeding back operational experience to reduce the likelihood of similar accidents in the future and to mitigate their consequences if they occur. Such reviews add to the body of technical and medical knowledge and illustrate principles and criteria used, or which could have been considered, in policy and decision making. A number of lessons are not unique to this accident but are worth reiterating in this publication, and the IAEA has collected lessons learned from other radiological accidents [12–15].

The medical management of the victims and the source recovery operation were adequate with the support of the relevant national, regional and local organizations, and with international assistance that combined professional experience in, and knowledge of, radiation protection.

Experience from this accident demonstrates a need for nationwide dissemination of information to general practitioners on basic radiation biology, associated clinical symptoms and the medical management of people overexposed to ionizing radiation. This can be accomplished in the form of national training workshops. A roster of doctors specializing in radiation induced injuries can be kept by general practitioners and regulatory authorities for reference. These specializations would include treatment of CRS, ARS and comparable radiation injuries.

As in the case of this accident, the IAEA provides assistance, upon request, under the Assistance Convention to Member States in response to radiation emergencies. In the framework of the Assistance Convention, the IAEA established an Emergency Response Network (ERNET) in 2000, which was subsequently renamed Response and Assistance Network (RANET) in 2010. The IAEA RANET is a mechanism that provides for an integrated system through which States, their competent authorities, international organizations, technical experts and the IAEA Secretariat can effectively coordinate the provision of

assistance for response to incidents or emergencies within the framework of the Assistance Convention.

The major cause of the accident was the improper and unauthorized abandonment of eight ^{90}Sr radioactive sources in Georgia of which only six have so far been found. In addition, there were no clear labels or radiation signs on the sources that conveyed the potential radiation hazard. It is necessary for the labelling and warnings on radioactive sources to be regulated to a unified standard and to be in harmony with international standards such as ISO 361:1975 of the International Organization for Standardization [16].

Appendix I

CALCULATIONS USED FOR ESTIMATIONS
OF THE WORKING TIME NEAR
THE RADIOACTIVE SOURCES DURING THE RECOVERY

At the recovery location, the radioactive sources were isolated from the roads with a heap of earth or stones, which served as shielding. This was convenient for performing preparatory work (e.g. parking the container vehicles for the radioactive sources and arranging the auxiliary instruments). However, the removal of the radioactive sources from their original location and positioning them in open areas caused the protective shielding to be lost and consequently exposed the operating personnel to increased dose rates.

It was assumed that someone starting from distance L_S approached the radioactive source, where the dose rate $d(r)$ in sieverts per hour at a distance of r metres is described by the following expression:

$$d(r) = \frac{A_0}{r^2} \tag{13}$$

where A_0 is the gamma ray dose constant ($Sv \cdot m^2 \cdot h^{-1}$).

The minimum distance from the radioactive source that needed to be reached is equal to L_W, and the constant velocity of the person's motion is equal to V. The dose received by the person during motion will be equal to:

$$D_0 = A_0 \int_0^t \frac{dt}{r(t)^2} = -\frac{A_0}{V} \int_{L_S}^{L_W} \frac{dr}{r^2} = d(L_W) \frac{L_W}{V} \left(1 - \frac{L_W}{L_S}\right) \tag{14}$$

where

D_0 is the dose received by the worker approaching the source (Sv);
t is the time integration variable (s);
r is the distance integration variable (m);
V is the velocity of the worker approaching the source (m/h);
L_W is the minimum distance of the worker from the source (m);
L_S is the initial distance of the worker from the source (m);

and $d(L_W)$ is the dose rate at the minimum distance of L_W (Sv/h).

If $L_S >> L_W$ (note that this is always the case for operations performed in the close vicinity of a high activity radioactive source), then the dose is calculated as:

$$D_0 = d(L_W)\frac{L_W}{V} \qquad (15)$$

This result is not dependent on the starting distance L_S. Therefore, the dose that can be received by a person approaching the radioactive source and then returning back to the safe distance L_S without remaining near the radioactive source, will be twice Eq. (15):

$$D = d(L_W)\frac{2L_W}{V} \qquad (16)$$

where D is the total dose received by the worker approaching and leaving the source position (Sv).

Equation (16) shows that if there is no suitable shielding available, it is better to locate the operating personnel as far away from the radioactive source as possible. However, L_S does not have to be very large in order to cover the distance $2(L_S - L_W) \approx 2L_S$ with a high velocity.

For the case of the radioactive sources being recovered, the minimum working distance was assumed to be $L_W = 1$ m. The dose rate at this distance was $d(L_W = 1) = 0.6$ Sv/h. The operating personnel were young and healthy, so it can be stated that $V = 10$ km/h. According to the data, the dose (Eq. 16) is of the order of $D = 0.12$ mSv and is 160 times less than the maximum planned dose $D_{\text{Max}} = 20$ mSv.

If the time allowed for a person to remain working near the radioactive source at the distance L_W (the working distance, i.e. the distance at which the work has to be performed) is τ_W, then the total dose received per person can be expressed as:

$$D_{\text{Tot}} = d(L_W)\left(\frac{2L_W}{V} + \tau_W\right) \qquad (17)$$

If the planned maximum dose is determined, $D_{\mathrm{Tot}}\left(\tau_W^{\mathrm{Max}}\right) = D_{\mathrm{Max}}$, from Eq. (17) for the maximum time τ_W^{Max}, the following equation can be applied:

$$\tau_W^{\mathrm{Max}} = \frac{D_{\mathrm{Max}}}{d(L_W)} - \frac{2L_W}{V} \tag{18}$$

For this particular case under consideration, the second term in Eq. (18) is negligibly small and for the maximum working time it can be written as:

$$\tau_W^{\mathrm{Max}} \approx \frac{D_{\mathrm{Max}}}{d(L_W = 1)} \approx 120 \text{ s} \tag{19}$$

Appendix II

CALCULATIONS USED TO ESTIMATE
THE EQUIVALENT DOSE RECEIVED BY PATIENTS 1-DN AND 2-MG

Since the radioactive sources under consideration are cylindrical, having almost equal height and diameter ($h \approx 2R \approx 0.1$ m), it is possible to consider them as spherical, for approximate estimations. Consequently, the following equation to calculate the dose rate can be used:

$$D(r) = \frac{A_0}{r^2} \qquad (20)$$

where $r > R$ is the distance from the centre of the radioactive source, and $A_0 = 0.6$ Svm^2/h and is a coefficient that has been well documented by measurements taken at large distances (where the above approximation is correct).

For the calculation of the local dose rate across the surface of the radioactive source at distance x (see Fig. 108), it was assumed the centre of the radioactive source is located at L_0 and that the radioactive source was located above point **O** on a flat surface.
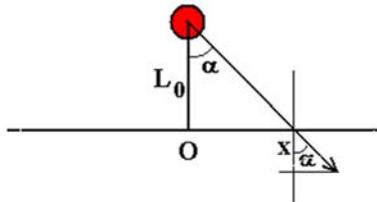
FIG. 108. *Determining the local dose rate across the surface of the radioactive source at distance x.*

Taking into account that gamma rays are emitted in a radial direction from the radioactive source, the dose rate at point x can be expressed as:

$$d(x) = \frac{A_0}{r^2} \cos \alpha = \frac{A_0 L_0}{r^3} = \frac{A_0}{L_0^2} \frac{1}{\left(1 + \left(x^2/L_0^2\right)\right)^{3/2}} \qquad (21)$$

The dose rate, averaged across the area of a circle x_0 radius, according to Eq. (21) is equal to:

$$\bar{d}(x_0) = \frac{1}{\pi x_0^2} \int_0^{x_0} d(x) 2\pi x \, dx = D(L_0) \frac{2L_0^2}{x_0^2} \left[1 - \frac{1}{\left(1 + x_0^2/L_0^2\right)^{1/2}} \right] \tag{22}$$

For the calculation, it was assumed that the centre of the radioactive source was at a distance of $L_0 = 0.1$ m from the individual's back (0.05 m from the radius of the radioactive source, plus 0.05 m from the thickness of the winter clothing). The radius of the overexposed area is equal to $x_0 = 0.25$ m, which is approximately half of the width of the individual's back. The formula can therefore be expressed as:

$$\bar{d}(x_0 = 0.25) = D(L_0) \frac{2}{2.5^2} \left[1 - \frac{1}{\left(1 + 2.5^2\right)^{1/2}} \right] \approx 0.2D(L_0) \tag{23}$$

Since $D(L_0)$ is the dose rate at the distance $L_0 = 0.1$ m from the centre of the radioactive source:

$$D(L_0) = \frac{A_0}{L_0^2} = 60 \text{ Sv/h} \tag{24}$$

for $\bar{d}(x_0 = 0.25)$, the following was applied:

$$\bar{d}(x_0 = 0.25) \approx 60 \times 0.2 \approx 12 \text{ Sv/h} \tag{25}$$

For a 2 h exposure (based on the event narrative that the two patients carried the radioactive source for a period of around 2 h each), this gives the dose as $D = 24$ Sv, which is in good agreement with the estimations obtained from Patient 2-MG's dosimetry ($D = 20$–25 Gy, see Section 9.2.6).

It is important to note that the position of the radioactive source was not fixed and moved randomly along the carrier's back during motion, which would have caused the dose distribution on the back to be quite heterogeneous.

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ABBREVIATIONS

ARS	acute radiation syndrome
Assistance Convention	Convention on Assistance in the Case of a Nuclear Accident or Radiological Emergency
CRS	cutaneous radiation syndrome
CT	computed tomography
DESCD	Department of Emergency Situations and Civil Defence of the Ministry of Internal Affairs, Georgia
DPR	digital paramagnetic resonance
ECG	electrocardiography
EPR	electron paramagnetic resonance
FISH	fluorescence in situ hybridization
G-CSF	granulocyte colony stimulating factor
HES	haematoxylin–eosin staining
IHT	Institute of Hematology and Transfusiology, T'bilisi, Georgia
IPSN	Institute for Protection and Nuclear Safety (Institut de protection et de sûreté nucléaire)
IRSN	Institute for Radiological Protection and Nuclear Safety (Institut de radioprotection et de sûreté nucléaire)
LVC	lung volume capability
NRSS	Nuclear and Radiation Safety Service, Ministry of Environment Protection of Georgia
RTG	radioisotope thermoelectric generator
TLD	thermoluminescent dosimeter

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