Monitoring in Medical Practice

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Basic Medical Skills

Textbook for medical students

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Introduction

Motto: "*Your goal is not to foresee the future, it is to enable it.*"
(Antoine de Saint-Exupéry, Le Petit Prince)

The "Basic Medical Skills" course at the Institute of Surgical Research is designed to teach monitoring skills. By definition, monitoring is the continuous or repeated, regular observation of a chosen characteristic of an object at constant sites by standardized methods. In medicine, monitoring may be defined as the interpretation of all collected and available clinical data in order to help with the recognition of present or future mishaps or unfavorable system conditions in time. In this sense, a cross-section of vital data should be obtained and analyzed in each case; accordingly the technique and methodology (the "skills") of the analyzer are critical.

Further important goals of the course are to foster skills-based knowledge and to broaden the correlation of physiology and anatomy to cover acute clinical care. In line with this, we utilize a student-oriented teaching methodology which is strongly based on self-education. Emphasis is placed on procedures, critical thinking and assessment of skills to support a career choice in those medical specialties in which decision-making or "problem-solving" is critical.

The themes of the course are organized into modules. These curricular structures are used to summarize the background knowledge and to provide practical expertise on current monitoring possibilities relating to separate, well-defined organ systems. In this scheme, new scientific and medical findings relevant to medical practice can easily be inserted and thus the borders of the individual blocks can be simply expanded and updated. The goals for a successful module are efficient student learning (at the same time covering a deeper content) and efficient faculty effort (no increase in work load resulting from use of the new instructional materials).

The topics, principles and practice of monitoring are taught in the skills laboratory and in the students' operating theater at the Institute of Surgical Research in a simulated, life-like environment with best-practice medical technology, where the basic monitoring techniques and advanced interventions targeting the main organ systems can be practised in a secure surrounding.

The chapters of this book have been compiled by the staff and Ph.D. students of the Institute of Surgical Research (Dr. Ágnes Adamicza, Dr. Mihály Boros, Dr. Tamás Jánossy, Dr. József Kaszaki, Dr. Andrea Szabó, Dr. Csilla Torday, Gabriella Varga, Dr. Gábor Erős and Dr. Miklós Czóbel), together with Dr. László Szalay (Department of Ophthalmology), Dr. Attila Paszt and Dr. Károly Szentpáli (Department of Surgery), Zsolt Bella (Department of Oto-Rhino-Laryngology) and Dr. Zoltán Bajory (Department of Urology) from the University of Szeged, and Dr. András Thoman (Department of Urology, Semmelweis University, Budapest); Dr. Zsolt Bodnár (Department of Surgery, Kenézy Gyula Hospital, Debrecen). The editor wishes to acknowledge the creative illustrations by Drs Miklós Czóbel and László Szalay and Mrs. Kálmánné Csíkszentimrei. The activities of Dr. Miklós Czóbel have made it possible to maintain a highly effective website (http://web.szote.u-szeged.hu/expsur) where the main parts of this book can be found.

The project ROP-3.3.1-2005-02-0001/34 has led to an infrastructure for skills training where specific monitoring techniques can be safely practised and mastered. We hope that the new skills laboratory at the Institute of Surgical Research, this handbook and the website (http://web.szote.u-szeged.hu/expsur/rop/index.htm) will stand the test of time, and that many medical students will benefit from them.

Mihály Boros
Editor

February 2007

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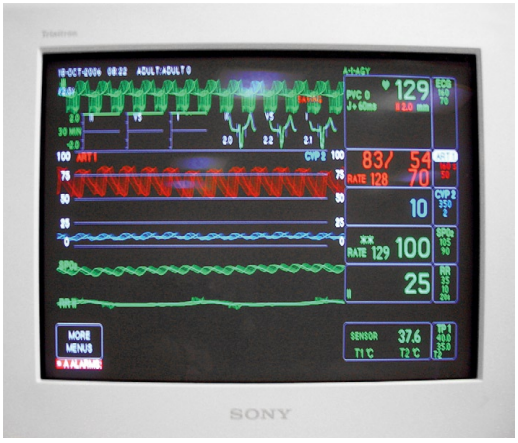
I. Monitoring

"I would like to see the day when somebody would be appointed surgeon somewhere who had no hands, for the operative part is the least part of the work"
(Harvey Cushing, 1911)

Harvey Cushing (1869–1939), professor of neurosurgery at Harvard Medical School, is considered to be the father of monitoring. He invented and popularized the anesthetic chart, continuously measured and registered the blood pressure and heart rate of his patients during operations, and emphasized the relationships between the vital signs and the neurosurgical events (these observations led him to recognize that increasing intracranial pressure results in hypertension and bradycardia).

Monitoring in today's medicine involves things to observe (e.g. the pupils and the color of the skin), things to measure (e.g. determination of such physiological variables as the blood pressure or the heart rate) and inferring diagnoses (if hypotension is present, it is a diagnostic question to assess the shock-related circulatory reaction). The type, quality and quantity of the collected data during the process are important (sometimes vitally important) questions.

The ideal clinical monitor is cheap, reliable, can be applied without complication, and has demonstrated clinical utility (it tells us something important). If any of these criteria is not met, use of the monitor may decline in the some way as ballistocardiography, vector cardiography, systolic interval measurement, classical EEG or the video-stethoscope.



For health monitoring, some instruments have a number of functions integrated into one device. Many of these instruments can be used outside hospitals (e.g. in homecare), the data obtained can be transferred, and an interface can signal an alarm for the doctor and the relatives if necessary. In addition to the possibility of continuous recording, these monitors provide the feeling of safety and allow an earlier and more accurate diagnosis (e.g. in cardiovascular diseases).

In the process of the monitoring of different organ functions, there are both low-tech options (e.g. the manual measurement of blood pressure, examination of the pulse rate, or listening to lung and heart sounds) and high-tech possibilities. The latter usually require sophisticated equipment (e.g. Swan-Ganz catheterization, transesophageal echocardiography, or the monitoring of intracranial pressure or evoked potentials). These monitors are normally available in parallel.

Another classification is based on the degree of invasiveness, as vital parameters and organ functions can be observed by both invasive and noninvasive methods (e.g. the oxygen saturation of the blood, heart rate, blood pressure, etc.).

The basis of each developed monitoring technique is the conversion of changes into electric signals. The method is usually based on the following steps: detection of the change → its conversion into an electric signal → enhancement and filtration → data output (analog or digital) → data processing (alarm) → data storage.

Attention must be paid to the software. All modern monitors use software, and trivial software failures sometimes lead to completely unexpected (and sometimes deadly) side-effects. Such system failures can be avoided if the staff are familiar with the system.

At the end of this section, it is important to define and distinguish the terms (vital) "signs" and "symptoms". A sign is an objective parameter which is characteristic of the actual state of the patient. It can be observed and measured by an examiner; in other words, it is detectable by an independent observer. A symptom is a subjective parameter. It can not be confirmed by an independent observer, but is felt and reported by the patient. As examples, bleeding is a sign, whereas vertigo or dizziness is a symptom.

1. Monitoring in the present

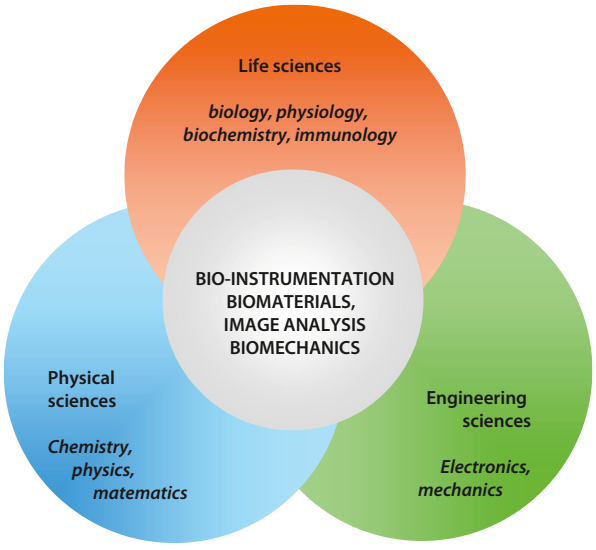
Guidelines relating to contain the rules of monitoring for most of the specialties are currently set by medical associations (a medical association is "*an organization of practitioners who judge one another as professionally competent and who have banded together to perform social functions which they cannot perform in their separate capacities as individuals*"). The Hungarian Society of Anesthesiology and Intensive Care laid down the conditions of minimal monitoring requirements for anesthesiology and intensive care in 1994. Continuous ECG registration, measurement of blood pressure, pulse-oxymetry and capnography are obligatory when

an operation is performed under general anesthesia. The minimally required equipment for a bed in an intensive care unit has likewise been specified; legislation on the principles was passed in 2004. The European Society of Intensive Care Medicine published the European standards concerning monitoring in intensive care under the title "Recommendations on Optimal Requirements for Intensive Care Departments" (see *Intensive Care Med 23:226–32, 1997*). The ASA (American Association of Anesthesiologists) guidelines state that all surgical interventions require the possibility of the invasive or noninvasive measurement of blood pressure, ECG, capnography (if an endotracheal tube or a laryngeal mask is applied) pulse-oxymetry, appropriate lighting to visualize an exposed portion of the patient, and an apparatus with which to measure temperature.

- The use of integrated monitors and other patient-guarding equipment is becoming more frequent (these monitors check pressure, temperature, etc. in parallel).
- Many special-purpose monitors are available (e.g. gastrointestinal tonometers).
- There are many problems with existing monitors (e.g. cost, complexity, reliability and artifacts), but in fact many disorders (e.g. hypoxia, air emboli, complications during surgery or drug overdoses) are not readily detectable without high-tech monitors.

2. Bio-instrumentation and monitoring

Bio-instrumentation is an interdisciplinary science (partially overlapped by bioengineering), which applies engineering methods and techniques to solve problems in biology and medicine; in other words, it is the application of the engineering principles of measurement, modeling or control which impacts on health-care delivery. The main goal is to obtain objective information on the living body. It involves a merging of different disciplines, medical and engineering methods, and it is highly practical because it must solve medical problems effectively.



2.1. Medical devices

Devices used in medicine can be broadly classified as therapeutic or monitoring (measuring) clinical devices. The definition of a medical device according to the regulations of the Hungarian Ministry of Health (47/1999. X. 6.) is as follows:

- An instrument, apparatus, implement, machine, software, contrivance, *in vitro* reagent, or other similar or related article, which is designed for application in humans. The aims are:
  - to prevent, diagnose, assess, or treat diseases or to alleviate the symptoms of a disease
  - to diagnose, assess, or treat injuries or handicaps or to alleviate their symptoms
  - to examine, substitute, or modify the anatomic structure or the physiological processes
  - contraception
  - The primary effect of medical devices is not pharmacological, immunological or metabolic; however, their function can be enhanced in these ways

The classification of therapeutic devices is as follows:

- Circulation (electrotherapy, defibrillators and pacemakers)
- Respiration (respirators)
- CNS (anesthesia)
- Invasive (surgical) devices (aspiration, vacuum, hand tools, sterilizers and operating tables)
- General vital functions (incubators)

The areas of application of the main groups of monitoring clinical devices are:

- Circulation, hemodynamics (pressure, action potential—ECG, heart rate, frequency, cardiac and circulatory sounds)
- Respiration
- Intensive care monitoring systems
- Thermometry

Another classification of medical devices concerns primarily the level of risk to the users/patients according to risk analysis:

Class I (low risk)
Minimal potential for harm to the user and often simpler in design than other devices. Examples: enema kits and elastic bandages. 47% of medical devices fall in this

category, and 95% (e.g. bed pans or radioactive seed needle guides) of them are exempt from the regulatory process.

Class II:
A high proportion of medical devices (43% in the USA) are considered Class II devices and subject to performance standards. Examples: diagnostic ultrasound equipment, pregnancy test kits, etc.

Class IIa *(low to medium risk):*
ECG, EEG, MRI, diagnostic US machines, invasive surgical tools (needles, single-use knives, gloves and sponges), etc.

Class IIb *(medium to high risk):*
potentially dangerous active diagnostic and therapeutic tools (e.g. monitor systems, blood-gas analyzers, traditional X-ray machines, infusion pumps, diathermy units, respirators, etc.).

Class III *(high risk):*
these usually sustain or support life, are implanted, or present a potential unreasonable risk of illness or injury; examples are: implantable pacemakers or breast implants. 10% of medical devices fall in this category.

3. Basic metrology, classification of measurements

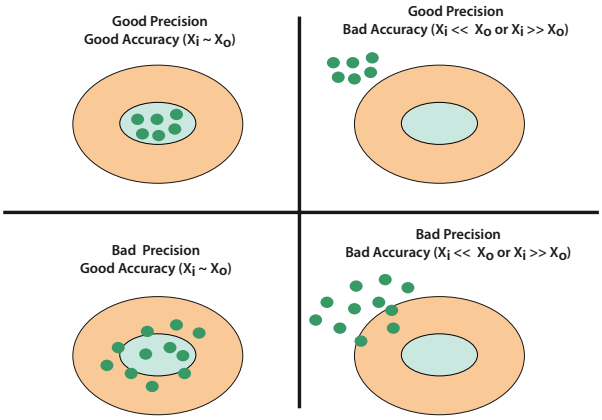
Measurement is a method performed in order to determine a quantity; numerals are assigned to represent physical properties. A measurement can be qualitative, non-numerical or verbally descriptive. This type has two main classes: nominal measurement (there is no order or rank, e.g. a list) and ordinal measurement (this allows ranking, but differences between the data are meaningless, e.g. an alphabetical list).

Quantitative measurement denotes numerical ranking. In cases of intervals, comparison is meaningless (e.g. calendars), while in cases of ratios, the measurement is based on a fixed or natural zero point (e.g. the measurement of weight or pressure).

Direct measurement means comparison with a calibrated standard (e.g. the determination of body height with a scale). Indirect measurement can be applied only in comparison with a direct measurement. Indirect measurement can be chosen if the direct collection of data is difficult or dangerous (e.g. the invasive measurement of blood pressure with a transducer *vs* Korotkoff sounds; or the direct measurement of the electric activity of the brain with transplanted electrodes *vs* MRI). When a null-measurement is performed, an unknown parameter is determined in a calibrated reference system; the properties of the system are changed until the difference disappears (e.g. the electric potentiometer in a Wheatstone bridge).

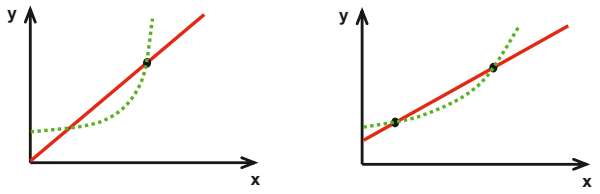
3.1. Definitions in metrology

Accuracy is defined as how close a measurement is to a standard.
Repeatability: receiving the same value in response to the same stimulus.
Reproducibility: the correlation of the data obtained if the measurement is repeated in different trials.
The *error* is the difference between the measured value and the real value. This is the normal random variation and not a mistake (it is usually caused by the limitations of the machine). If we have a non-changing parameter and measure it repeatedly, the measurements will not always be precisely the same, but will cluster around a mean (*Xo*). The deviation around *Xo* is the error, but in this term we can assume that the measurement result is *Xo* as long as the deviation is small.
Validity is a statement as to how well the instrument measures what it is supposed to measure.



3.2. Tactics to decrease error in measurements

- If possible, each measurement should be repeated (e.g. the measurement of central venous pressure).
- Successive measurements should be made on different parts of instruments (different parts of a ruler, Bürker's chamber, an image analyzer, etc.).
- The measurement should be repeated on another instrument.
- The calibration (and the number of calibration measurements) is crucial.



Calibration of one point does not allow the recognition of a nonlinear correlation. Even the correlation of two points makes such recognition difficult.

3.3. The most frequent units

System	Distance	Force	Mass	Time	Pressure
SI (in Hungary since 1980) *	m	newton	kg	s	N/m^2 = pascal (Pa)
CGS **	cm	dyne	g	s	$dyne/cm^2$
British ***	inch	pound	slug	sec	PSI (pound per squareinch)

* SI = Système International d'Unités, according to the 11th General Conference on Weights and Measures (1960). MKS (metric) system = meter, kilogram, second.

** CGS system = centimeter, gram, second.

*** For further information, see the website of the British Weights and Measures Association (http://www.footrule.org/): "*Welcome to the world of real measurement*" (!). The inch is "the length of three barleycorns placed end to end"; the world pound comes from the Latin word "*pondus*" (weight); its abbreviation is lb (from the Latin "*libra*" –a unit of weight, which comes from the word "*librare*"—to measure something); 1 slug = (1 pound of force) / (1 foot/s^2 of acceleration).

II. Noninvasive cardiovascular monitoring

"You may examine the color of the skin
or the characteristics of the urine,
or you may observe the harmony of the pulsation—
but you should realize that they may strive to
deceive and mislead their enemy, the physician!"
(Erasmus Roterodamus:
The Laudation of Medicine, 1518).

Noninvasive monitoring methods do not involve breaching of the mucosa or the skin. Noninvasive monitoring of the circulatory system is indicated in all pathological conditions and in various physiological, but not conventional conditions of life (e.g. delivery and sport). There are practically no contraindications.

1. Basic (low-tech) monitoring

The advantages of these procedures are that they do not require sophisticated equipment, and do not cause major complications. They have the limitations that in severe conditions the reliability of the data is questionable (e.g. pulse-oxymetry and noninvasive blood pressure measurement), and sophisticated data (e.g. cardiac output) usually cannot be collected with these methods.

1.1. Clinical observations

- An altered general condition
- An alteration of the mental state (indicating hypoperfusion of the brain)
- Alterations in the rate and type of respiration
- Observations of capillary refill and other signs of the peripheral circulation

1.2. Pulse examination

This has been used for thousands of years by medical practitioners; for a long time, it was the only objective medical diagnostic aid. It does not require instruments and it can be used in all patients. The pulse (heart rate) can be monitored:

- by palpation on the radial artery
- by palpation on the carotid artery
- by palpation on the temporal artery
- by palpation on the dorsal artery of the foot
- with an ECG monitor (see later)
- from the arterial pressure curve (see later)
- by finger photoplethysmography (this method is based on the fact that light can pass through the capillary network. The pulsation of the arteries modifies the volume of the tissues, and this influences the absorption, reflection and scattering properties of light. Its advantages are that it is simple and clearly demonstrates the heart frequency. It has the disadvantages that it is sensitive to the patient's movement, and the heat of the light source can cause vasodilation, which influences the measurements (see in detail later).

The limitations include the nonspecificity, the considerable inter- and intraobserver variations, and the fact that great clinical practice is needed for the correct interpretation of the results. Its present role in the diagnostic repertoire includes its place in the case-history of the patients, the initial assessment of the condition, the diagnostics of peripheral vascular diseases, and control examinations following vascular surgery.

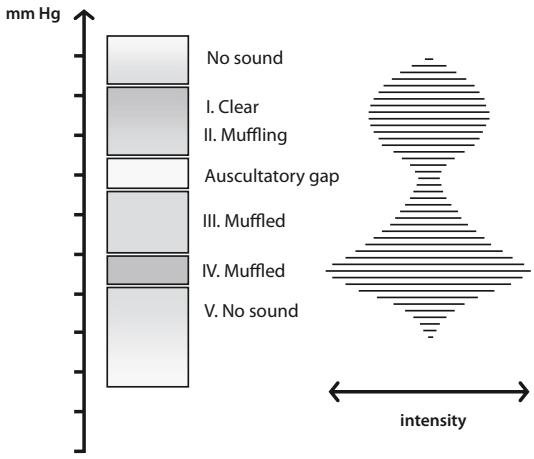
1.3. Nonivasive measurement of blood pressure

Measurement of blood pressure is one of the prerequisites for an understanding of the condition of the circulation. It can be carried out in either direct (invasive) or indirect (noninvasive) ways.

1.3.1. Historical background

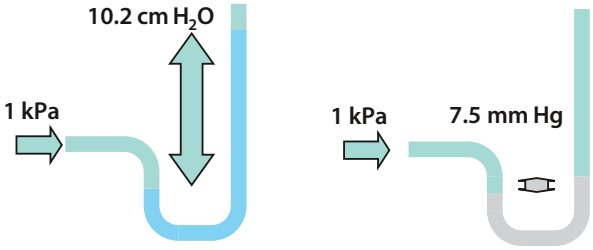
1896 Scipione Riva-Rocci (1863–1937), an Italian physician (the abbreviation RR originates from Riva-Rocci), applied a mercury sphygmomanometer which was able to register systolic pressure only when the brachial artery was palpated (the value observed at the disappearance of the pulse corresponded to the pressure of the totally compressed artery).

1905 Nikolai S. Korotkov (1874–1920), a Russian army surgeon, first described the characteristic sounds emitted after the opening of the occluded artery, observing that the sounds caused by the disturbed arterial blood flow are associated with the systolic and the diastolic pressure (i.e. the diastolic pressure could also be measured); the indirect blood pressure measurement could be applied in its present form.



The profile of Korotkov (Korotkoff) sounds

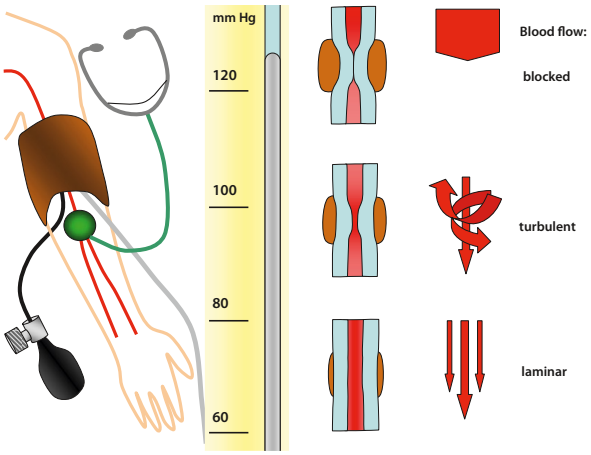
1.3.2. Measurement techniques



Physical basis of blood pressure measurement with the mercury manometer

The standard techniques of indirect measurement are manual mercury or aneroid pressure measurement and oscillotonometry ('electronic' blood pressure measurement). The ultrasound measurement method should also be mentioned.

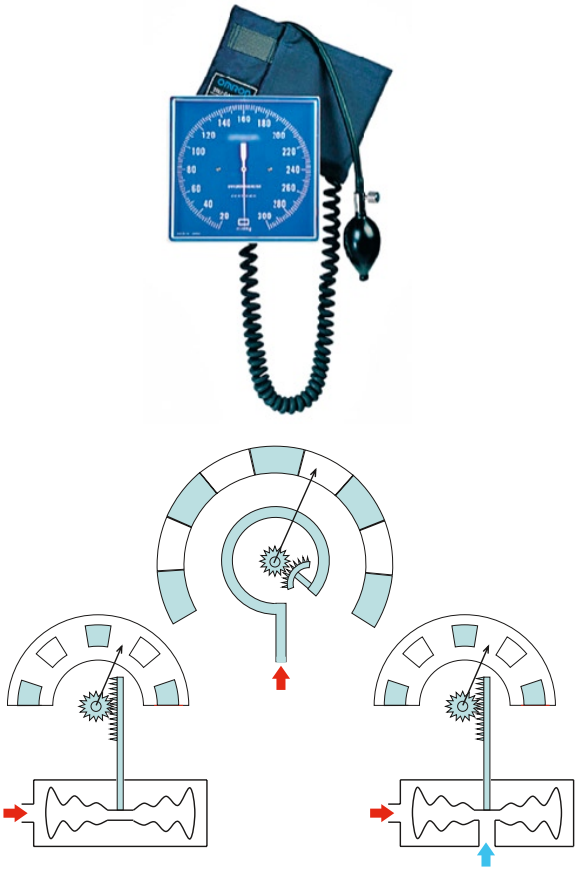
1.3.2.1. Mercury manometry



The principle of mercuromanometry

1.3.2.2. Bourdon aneroid manometry

The aneroid technique is mainly applied in the USA and the UK. To an extent proportional to the pressure changes in the cuff, the inner metal bellows is compressed or expanded, and this movement is made visible by a needle and a dial. The accuracy of the measurement is uncertain, even when the needle is positioned at 0 (zero) and the cuff is deflated. The instrument should be regularly calibrated by using a Y connector and an accurate mercury manometer.

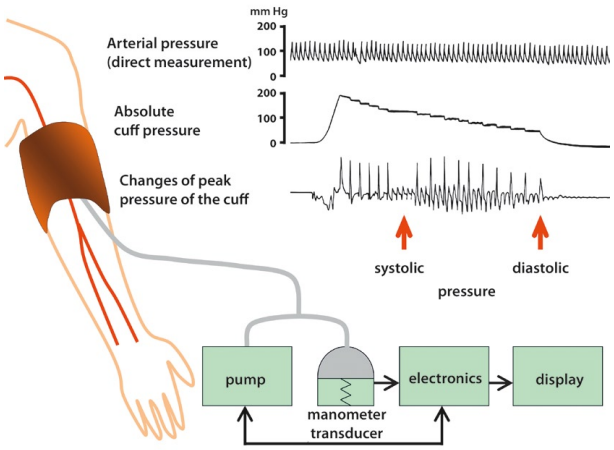


The Bourdon manometer [invented by a French engineer, Eugéne Bourdon (1808–1884)]

1.3.2.3. Oscillotonometry

The mean arterial pressure obtained by oscillotonometry correlates best with the values measured by other methods of blood pressure monitoring (this is the most reproducible parameter). The use of this method can cause petechias and hematomas under the cuff. This procedure is inaccurate and unreliable in peripheral circulatory disorders (e.g. in shock patients, the low blood pressure is overestimated) and arrhythmias (the algorithm of the measurement assumes a regular pulse, and

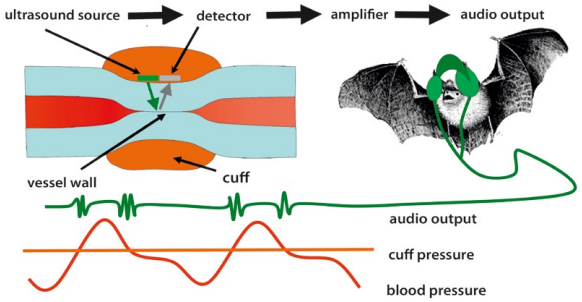
the reading is therefore unreliable in patients with an irregular heart frequency).



The principle of oscillotonometry

1.3.2.4. Ultrasound blood pressure measurement

The instrument applies sensors which detect the movements of the vessel wall. The transmitter and receiver crystals are placed on the skin over the vessel, and the inflatable cuff is then put on the two crystals. The ultrasound wave is focused on the vessel wall and the blood. Since the vessel wall is moving, the frequency of the detected ultrasound is shifted relative to that of the emitted ultrasound. The extent of the frequency shift is proportional to the speed of movement of the vessel wall and the velocity of the blood flow. If the pressure in the cuff is higher than the diastolic pressure and lower than the systolic pressure, then during a heart cycle the artery is closed and then opened. The closing and opening are detected via the sign of the measured ultrasound.



As the pressure in the cuff is further increased, the signs of closing and opening come closer and closer to each other, until they meet. In this case, the pressure in the cuff corresponds to the systolic pressure. Similarly, if the pressure in the cuff is decreased, the opening of the vessel and the closing in the next heart cycle approach each other until they meet. In this case, the pressure in the cuff is equal to the diastolic pressure. The advantages of this technique are that it can be used in infants and in patients with low blood pressure, or in a very noisy environment, and the wave picture of the total arterial pulsation can be produced. The blood pressure measurement can also be performed synchronized to the ECG. A disadvantage is the fact that movement during measurement changes the direction of propagation of the ultrasound between the detector and the vessel, and thus a false value can be obtained.

1.4. Manual blood pressure measurement in practice

For measurements of diastolic pressure, use of the Korotkoff IV sound is recommended, since the interobserver variation is smaller, and its application is easier for most physicians. (The Korotkoff IV sound is on average 8 mm Hg, while the Korotkoff V sound is on average 2 mm Hg above the invasively measured diastolic blood pressure.)

1.4.1. Factors significantly influencing the results

1. Coffee drinking (caffeine) within 1 hour before measurement
2. Smoking (nicotine) in the preceding 15–30 min
3. Use of adrenergic stimulants (e.g. phenylephrine or nasal or ophthalmic decongestant drops)
4. Bladder and bowel tension
5. The temperature of the environment
6. Tight clothing on the arm or forearm where the measurement is made
7. Acute anxiety, stress or pain
8. Speaking prior to or during the procedure

1.4.2. Standardized technique of blood pressure measurement

- Mercury, calibrated aneroid or validated electronic manometers can be used. The aneroid instruments must be calibrated every 6–12 months. The reliability of oscillotonometry (an automatic electronic method) is still questionable.
- If possible, an always identical, sitting position should be used. The patient should be calmly seat-

ed on a backed chair for at least 5 minutes. His or her feet should reach the floor and the legs should not be crossed. The blood pressure measured in the standing position is used to test the orthostatic hypotension (after standing for 1–5 min, in patients older than 65 years, subjects treated with antihypertensives, diabetics, or when the patient's complaints suggest hypotension). Standing blood pressure measurement is essential when syncopes are examined.

- The arm must be supported, and the cuff should be at the level of the heart (the pressure is related to height: $\Delta p = \rho g \Delta h$). The manometer must be placed horizontally, with its scale at the level of the observer's eye.
- The stethoscope is placed over the brachial artery. To exclude the possibility of an "auscultatory gap", the cuff pressure should be increased rapidly to 20–30 mm Hg above the level of disappearance of the pulse of the radial artery.
- The pressure should be decreased by 2 mm Hg/s. The level of appearance of sound I (Korotkoff phase I) is equal to the systolic pressure.
- The further pressure drop is 2 mm Hg/beat. Disappearance of the sound (Korotkoff phase V) indicates the diastolic pressure. The values should be recorded, and repeated measurement 1 min later is recommended.

At the initial reading, the blood pressure must be measured in both arms, and it should subsequently be measured in the arm with the higher reading. The accuracy of the reading can be increased if two measurements are made on the side where the blood pressure was higher.

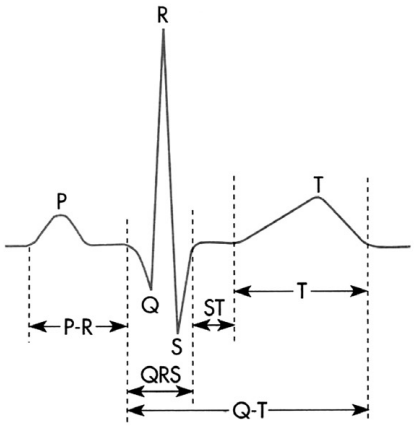
Parallel to the blood pressure measurement, the heart frequency should always be determined, and the data should be recorded.

The pulse pressure is the difference of the systolic and diastolic pressures (the amplitude of the pulse pressure wave). Since the 1980s, it has been known that there is a direct correlation between the diastolic pressure and the risk of cardiovascular diseases. For an assessment of the severity of hypertonia (diseases related to blood pressure), the diagnostic role of the diastolic pressure is emphasized in all text books, but the diastolic pressure can be interpreted correctly only in association with the pulse pressure, i.e. a higher pulse pressure indicates a higher risk of cardiovascular diseases. The size of the cuff influences the results significantly.

Arm circumference (cm)	Size of cuff (cm)
18 – 26	9 × 18 (child)
26 – 33	12 × 23 (standard adult)
33 – 41	15 × 33 (large, obese)
> 41	18 × 36 (extra large)

1.5. Electrocardiography (ECG)

The limited extent of this book does not permit a detailed description of this key method. Its major *indications* are: 1. the diagnosis of heart dysfunctions: rhythm disorders, pathological changes of the myocardium (e.g. hypertrophy, hypoxia or myocardial necrosis); and 2. the diagnosis of alterations not directly related to the myocardium (e.g. electrolyte disturbances, and the effects of drugs on the heart). Limitations of the method: 1. single-lead ECG does not always reveal myocardial ischemia (wrong lead placement is common); and 2. electric (electromyography and alternating current) artifacts are common (see in detail in pathophysiology, internal medicine and cardiology).



2. High-tech monitoring

2.1. Pulse-oxymetry

Pulse-oxymetry is based on the combined application of the principles of conventional optical oxymetry and plethysmography. It is a continuous, noninvasive method that records the arterial oxygen saturation and heart frequency, and analyzes the absorption of infrared light by the examined circulatory area.

Plethysmography is a method for measuring volumes (rather volume changes are important, since from these it is possible to draw conclusions on the degree of blood flow. The most frequent indications of pulse-oxymetry: continuous monitoring of oxygenation in critical periods, e.g. during operations and in the postoperative period, in intensive therapy, during delivery, in premature infants, etc. Its aim is to indicate hypoxia early and to prevent the development of severe hypoxia. In monitors involving the use of sound signals, good oxygen saturation is accompanied by a higher sound synchronized with the pulse, while decreasing saturation is indicated by a gradually deepening sound.

2.1.1. Historical background

1935 Development of the first instrument, though its sensor was not of appropriate quality (*Mathes: Arch Exp Pathol Pharmacol 179: 1935*). The development was made in the interest of the safety of the crew of bombers flying at high altitudes (*Rev Sci Instrum 1942*).

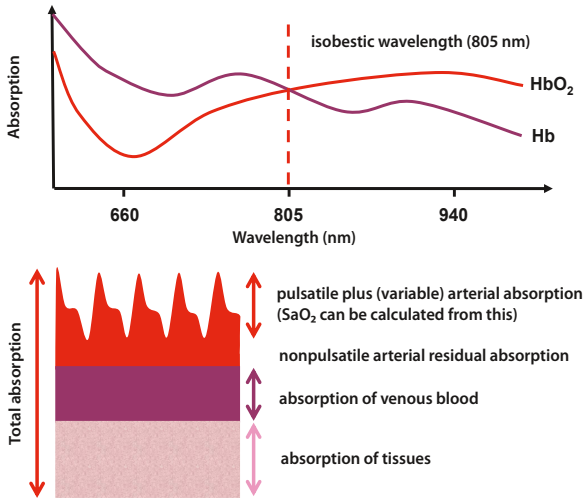
1974 The first noninvasive oxymeter (recognition of the significance of the extra information given by the arterial pulsation) (*Aoyagi et al.*).

2.1.2. Oxygen saturation of the blood

The level of saturation of the blood with oxygen can be calculated via a formula, from the ratio of the amount of oxygenated hemoglobin and the total amount of hemoglobin (SpO_2 = percentage of hemoglobin saturated by oxygen):

$$SpO_2 = \left(\frac{HbO_2}{HbO_2 + Hb} \right)$$

In this formula, SpO_2 is the level of oxygen saturation of the blood, HbO_2 is the concentration of oxygenated hemoglobin, and Hb is the concentration of deoxygenated Hb.



2.1.3. The principle of operation of pulse-oxymetry

The most important advantage of the method (and the cause of its success in clinical practice) is the measurement of arterial oxygen saturation throughout the whole pulsatile cycle.

The light absorption spectrum of hemoglobin depends on the degree of oxygenation (arterial and venous blood have different colors). If blood is illuminated with light of a given wavelength, the oxygen concentration can be concluded from the intensity of the reflected (transmitted) light.

Due to the influencing factors, light of different wavelengths (at least two) is used. It can be deduced that the ratio of the detected amplitudes is related to the arterial oxygen saturation.

In the event of the red or infrared detection of oxy- and deoxyhemoglobin, the light source can be a LED (light-emitting diode) or a laser, the light of which is in the wavelength range 650–1000 nm. The most frequent LED wavelengths are 660 nm (red) and 940 nm (infrared). The use of several light sources yields greater accuracy, and laser light is more advantageous, because its spectrum is narrow (1–2 nm), which allows more precise measurements.

After reflection, only a part of the light reaches the detector, and only a small fraction of it (the pulsating part) carries the information. Since this pulsation is characteristic only of the arterial blood, the plus (variable) absorption due to the pulse-added volume of arterial blood is used to calculate the level of arterial oxygen saturation (other factors can be filtered out).

The intensity measured at the isobestic wavelength is characteristic of the amount of blood and not its oxygen content.

The arterial oxygen saturation of healthy people is constant (97–99%), while the saturation of venous blood is on average 75%. Hospital oxymeters usually signal an alarm at an arterial level of 95% (but a heavy smoker is able to lead a "normal" life even at SpO_2=93%).

2.1.4. Limitations of the method

If measurements are made through the skin, the lower limit is given by the nontransparency of the skin (<650 nm), while the upper limit is governed by the light absorbance of water (>1000 nm); accordingly, oxygen measurements are effective between 650 and 1000 nm. At values between 60 and 100%, other factors cause at most 1% variance:

- Movement of the patient
- Wrong placement
- Ambient light
- Circulating dyes
- Nail polish
- Pigmented skin
- Peripheral circulatory dysfunction (by definition, the method can be used only if the pulse (the heart rhythm) is regular. In the event of low cardiac output and vasoconstriction, it is difficult to distinguish the real signal from the background noise.

- Carbon monoxide poisoning. The red and infrared absorbance of carboxyhemoglobin is identical to that of hemoglobin. For this reason, in heavy smokers the actual SpO_2 is 2–4% lower, while in cases of carbon monoxide poisoning it is 20–40% lower than the measured normal values (it is 95–96% for spontaneous breathing in fresh air and 99–100% for mechanical ventilation).
- The presence of other compounds, e.g. hemoglobin (which is increased in malaria and liver diseases).
- This method is extremely sensitive to artifacts (the most frequent cause of false alarm in intensive care units).

2.2. Noninvasive monitoring of organ perfusion

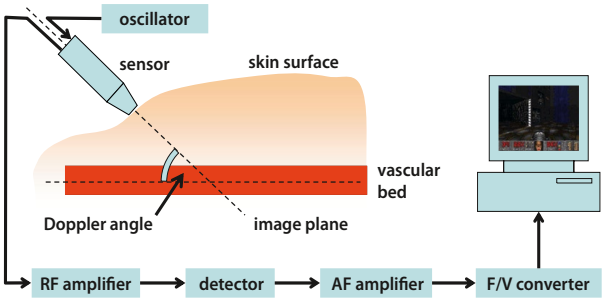
Mainly indirect methods are available in this field, but in certain cases (e.g. intravital videomicroscopy and the OPS technique—see later), direct examination of the blood flow is also possible.

- Morphological-anatomical methods for evaluation of the perfusion of the greater vessels (e.g. duplex ultrasound, magnetic resonance angiography and angiography with computer tomography; blood flow characteristics and blood flow volume measurements (see radiological techniques)
- Functional-tissue (e.g. mucosa) perfusion measurements
- Ultrasound flowmetry with the Doppler technique
- Laser Doppler flowmetry
- Endoluminal pulse-oxymetry (see above)
- Endoscopy with an intravital microscope (see later)
- Near-infrared spectroscopy (see later)

2.2.1. Ultrasound Doppler flowmetry

This method is based on the observation in 1842 by Christian Doppler (1803–1853), an Austrian physicist, that a moving object reflects a sound of known frequency with a frequency shift, the extent of which is proportional to the speed of the object. In accordance with this, the frequency of a sound emitted by a sound source with frequency f_0 is detected at a frequency higher than f_0 by a detector which is moving in the direction of the sound source at speed v. If the detector is moving away from the source with similar velocity, the frequency of the detected oscillation is lower than f_0.

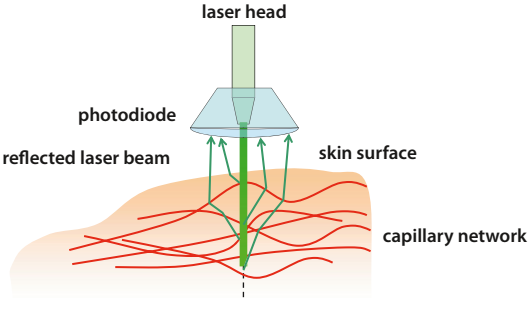
Ultrasound flowmetry involves the use of ultrasound waves emitted by the oscillator; a sensor detects the waves reflected from the cells. The RF (radiofrequency) amplifier amplifies the received signal and the carrier frequency, and the AF (audiofrequency) signal is then produced by a detector.



In measurements of blood flow, a crystal working in the ultrasound wave band serves as a sound source, with the red blood cells as sensors, which, according to the above principle, "detect" the signal frequency at higher or lower than f_0 depending on their speed vector. As elemental sound emitters, their oscillation frequency depends on this (red blood cells start to oscillate because they are much smaller than the wavelength of the detected ultrasound wave). On detection of the emitted frequency of red blood cells differing from f_0 by another (fixed) crystal of the scanning head, a further frequency shift takes place, but in this case the frequency of the moving elemental oscillator is detected by the standing sensor crystal with a frequency shift according to the Doppler principle. The relative position of the transmitter and sensor crystal is important, since the magnitude of the detected signal depends on this (the Doppler frequency is proportional to the scalar product of the difference of the vectors of the reflected and the incident waves and the flow vector of the blood). Positioning of the transmitter and receiver crystals near to one another results in a large, measurable signal, i.e. it is worthwhile to place the two crystals at the same height on the same or the opposite sides of the vessel wall.

2.2.2. Laser Doppler flowmetry

This is a noninvasive method based on the Doppler effect which can mainly be used for the assessment of peripheral microcirculatory alterations. Its main *indications*: tumor angiogenesis, the microcirculation of pulmonary lobes, peripheral vascular diseases, complications of diabetes, the monitoring of wound healing and dermatological diseases. The frequency of the laser light most frequently applied in clinical practice is



between 633 and 810 nm, which enters the tissues 1–1.5 mm deep over an area of approximately 1 mm². The flow in nutritive capillaries or thermoregulatory shunts in the skin can be examined at this depth.

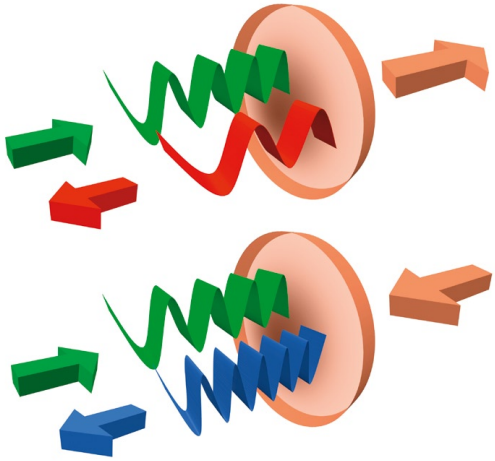
In the instruments, a helium-neon or argon laser (10 mW – 20 W power) is used, and the emitted monochromatic laser light beam is partly absorbed and partly reflected in the examined tissues. The frequency of light reflected from the red blood cells changes, and this change is proportional to the number and mean speed of the cells moving in the examined structure. The reflected light is detected by a detector (photodiode), and the apparatus calculates the capillary flow of the examined tissue volume, which is proportional to the frequency shift. *Limitations* of the method:

- The measured data are only approximate values, because the penetration of light is influenced by a number of factors (skin thickness, pigmentation, wavelength, edema, etc.).
- The measured data do not express the tissue flow in absolute values (for this, the instrument should always be calibrated to the examined tissue; it is not possible in living tissues); these are not real, but merely relative flow values (the measured unit of flux is the perfusion unit).
- Due to the great variability of the baseline values, the changes are of diagnostic significance only in certain groups of patients.

2.2.3. Echocardiography, transesophageal echocardiography

The esophageal Doppler method was first used to measure the velocity of blood flow in the 1960s, but the ultrasound apparatus has been applied to measure cardiac output widely only since the 1990s. In the examination, the reflection of 2–10 MHz sound waves from the border of different tissues is used for imaging (this is achieved with a computer software from the amplitude of the reflected sound and the reflection time). Depending on the mode of visualization of the echo, the images can differ: the motion (M) mode shows the movement of the interfaces as a function of time (e.g. a pulse wave passing through a vessel section is shown by converging and diverging wavelines of the vessel walls). The B mode visualizes the intensity of individual echoes with light points of different intensity and produces a two-dimensional picture.

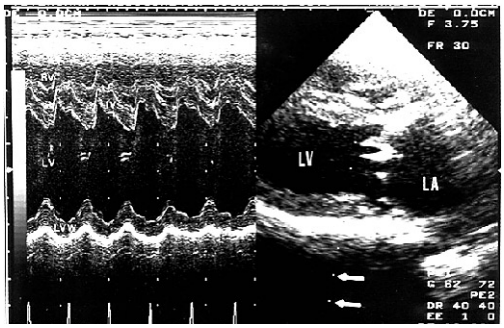
Echocardiography applies both M- and B-mode imaging. On use of the Doppler technique, the direction and velocity of flow can also be visualized in a color-coded mode (the flow in the cranial direction is indicated in red, and that in the opposite direction in blue).



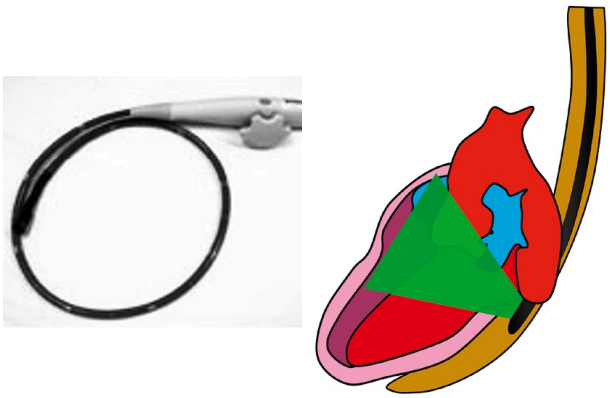
The operation principle of Doppler echocardiography

Principle of operation of Doppler echocardiography

- Pulsating ultrasound waves are directed parallel to the direction of the blood flow, e.g. suprasternally downward to the ascending aorta. The wavelength of the sound changes when it is reflected from the moving red blood cells.
- The change in peak height indicates the velocity of the red blood cells.
- Determination of the diameter of the aorta gives the cross-section of the vessel, and hence the blood flow, and then the cardiac output can be calculated.



M mode and B mode in the echocardiography



The transesophageal examining device and the position of the probe in the esophagus

- Pseudo-coloring is applied to visualize turbulence.

A special form of echocardiography is the transesophageal technique. In this case, a small examining head is introduced into the esophagus, which allows the heart and mediastinum to be examined more effectively than by simple echocardiography.

By the use of transesophageal echocardiography, the movements of the ventricular wall, changes in volume of the cardiac cavities and morphological changes of the heart can be investigated. *Indications*:

- Ischemic conditions (indicated by movement disorders of the heart wall)
- Measurement of the ejection fraction
- Examination of the heart (especially mitral) valves
- Recognition of intracardiac thrombi, tumors and air
- Intra- and postoperative control investigations
- Endocarditis (endocardial vegetation)

Transesophageal echocardiography is contraindicated in severe esophageal diseases (stricture, tumor or varix) and in severe coagulopathy. Like all semiinvasive interventions, this procedure involves risks of *complications:*

- Esophagus perforation
- Gastrointestinal bleeding
- Esophageal burn
- Transient vocal cord edema

III. Invasive cardio-vascular monitoring

"Then laying bare the left Carotid Artery, I fixed to it towards the Heart the Brass Pipe, and to that the Wind-Pipe of a Goose; to the other End ofwhich a Glass Tube was fixed, which was twelve Feet nine Inches long. The Blood rose in the Tube till it reached to nine Feet six Inches Height"
(Steven Hales, 1733).

1. Historical background

1733 The invasive monitoring of blood pressure began with the experiment by Steven Hales (1677–1761), an English physiologist, who inserted a metal cannula into a neck artery of a horse, connected it to a tube 340 cm long, and then measured the height of the blood column (it was 290 cm). The experiment demonstrated that the heart exerts pressure in order to pump blood.

1847 Carl F.W. Ludwig (1816–1895), a German physiologist, first measured human blood pressure in a similar manner with his kymograph.

2. Pressure measurements

Exact pressure measurement is a prerequisite of circulatory diagnostics. Under *in vivo* circumstances, the constantly changing blood pressure can be measured by invasive and noninvasive methods.

2.1. Principles of invasive pressure measurements

The basic tool is a hollow tube (cannula or catheter) introduced into the lumen of the vessel (e.g. an artery) and connected to an electrical strain gauge that converts pressure into force, which is sensed electrically. In the case of an arterial cannula (intravascular), only a permanent pressurized rinse is safe. A slow flow of heparinized saline (3 mℓ/h) does not influence the result of the pressure measurement. If blood or air bubbles enter the catheter, they must be removed, since they can influence the pressure measurement significantly. In contrast with a fluid, air can be compressed, and the pressure curve will therefore be blunted.

The technique is accurate, but invasive. The zero level of the system must be defined at the beginning of every setting, and subsequently repeated.

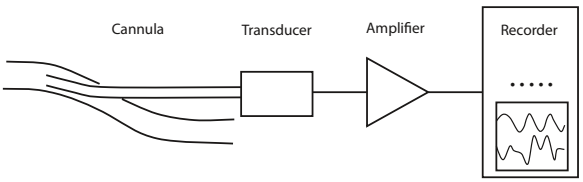
Characteristic features of the measuring system are the resonant frequency and the damping coefficient β (0.6–0.7). Banging the system at its resonant frequency leads to an overshoot, and thus it has to surpass the frequency of the arterial pulse (16–24 Hz), while the latter leads to the removal of energy from a resonant system and therefore foreruns the reflected waves caused by resonance.

2.2. Possibilities of direct pressure measurement

Cannulas introduced into certain parts of the circulation mediate venous or arterial pressure as a mechanical energy signal through a flexible, but relatively rigid-walled tube to a mechanical–electronic signal converter (transducer).

2.2.1. Extravascular sensor

The fluid column (e.g. saline) in the cannula is in direct contact with the flowing blood in the vessel (according to the Pascal law, the pressure propagates constantly, without weakening in the nonflowing fluid column). In this way, the blood pressure signal is transmitted to the sensor membrane mediated by the fluid column inside the cannula. The sensor is positioned outside the body and transforms the mechanical signal to an electric one.



A sensor/transducer is a device that converts energy from some other form (e.g. heat, light, sound, pressure, motion or flow) into electrical energy. The basis of the conversion is that some semiconductors change their resistance to movement, which is then quantified

by a Wheatstone bridge. The characteristics of a transducer are:

- The sensitivity is the minimum input parameter that creates a detectable output change.
- The range is the difference between the maximum and minimum values of the applied parameter that can be measured.
- The precision is the degree of reproducibility of the measurements.
- The resolution is the smallest detectable incremental input parameter that can be detected in the output signal.

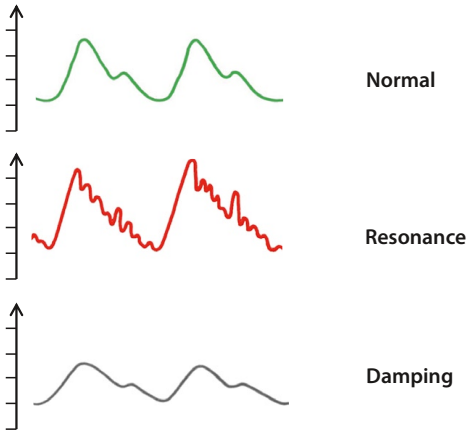
The output of the transducer is an electric signal which can be amplified and stored. This signal is led through a cable to the monitor. The useful frequency range of a fluid-filled pressure measuring system is commonly lower than 20 Hz, as the resonant frequency is very low.

2.2.2. Intravascular sensor

In intravascular sensors, the cannula contains an optical cable. At the end which is positioned in the vessel lumen, a membrane is situated in a variable-volume unit (0.5 × 0.5 × 1–5 mm), while at the other end a LED and a photodiode are localized. Half of the fiberglasses mediate the light signal from the LED toward the membrane, while the other half of the cables do so in the opposite direction, to the photodiode. The LED-generated light passes to the membrane at the end of the catheter, where it is reflected, and a part enters into the fiberglass leading to the photodiode. The membrane of the miniature box positioned in the vessel lumen changes its form in response to the external pressure change and this modulates the reflected light. Thus, the light quanta sensed by the photodiode are proportional to the blood pressure. Indication areas include very precise or accurate *in vivo* monitoring (arterial, intrauterine, intracranial or intraocular pressures). One advantage is that very small high-frequency pressure changes are detectable. A disadvantage is that the transfer characteristic is completely nonlinear (there is a nonlinear connection between the blood pressure and the reflected light quantum). Sediment blood on the surface of the membrane distorts the modulation of light.

2.3. Problems of invasive pressure measurements

1. Resonance limits the use of physical devices; because of mass, the movement of the saline column and the spring of the system (the elastance of the tubing and transducer diaphragm), the system at its resonant frequency leads to an overshoot. The resonant frequency is proportional to the radius of the cannula and inversely proportional to the square root of the fluid consistency and the length of the cannula. The larger the resonant frequency, the better the measurement is, and thus a thick and short catheter should be the best to use. However, in this case it would be difficult to cannulate and only a shorter vessel segment could be catheterized. In practice, a compromise must be made.
2. Damping is the removal of energy from a resonant system. If an air bubble in the cannula mediates the mechanical energy (pressure) of the blood to the transducer, the compression of the bubble takes up energy from every pulse wave, so that the pressure wave arriving at the transducer will be damped.



3. Blood flow

3.1. Principles

We can determine several important parameters via pressure and flow values, but an overview of some fundamental physical laws is needed.

According to the Bernoulli equation, when blood flows through an artery, the total energy of the fluid at any point is assumed to be constant. The sum of the energy stored in pressure, energy provided by flow and potential energy due to the height of the blood above a reference point is constant (e.g. an increase in blood flow velocity results in a decrease in pressure) (energy = $[V^2/2g] + [P/r] + H$ = constant, where V = flow velocity, P = pressure, and H = potential energy, i.e. the difference in height). It follows that, in an arterial stenosis, the increase in velocity causes a fall in pressure in the stenosis.

The Poiseuille equation describes the relationship of the pressure, flow and resistance:

$$Q = \frac{\Delta p \pi R^4}{8 \mu L}$$

Hence, the flow (Q) depends on the pressure drop across a length of vessel (Δp), on the radius of the vessel (r), and on the length of the vessel (L). For a given pressure, there is a greater flow when the blood vessel is short and wide and when the blood is thin.

Since the blood pressure is usually constant under physiological circumstances, the blood flow is controlled by the small changes in r (the vessel radius), which is the most important feature of the arterioles.

It is well known that human blood flow is pulsatile. In clinical practice, the circulation is mostly simplified and defined as nonpulsatile flow, and accordingly we determine the ohmic resistance. The resistance (R) could be calculated from the quotient of the pressure difference of the inflow and outflow fluid columns and the flow concerning a given area. Resistance is measured in Wood units. As an example, in the pulmonary circulation, resistance could be calculated from the difference between the mean pulmonary artery (PA) pressure and the left atrium (LA) pressure and the cardiac output (CO) as (PA pressure—BP pressure)/CO (e.g. 14 mm Hg – 7 mm Hg/5 ℓ/min results in 1.4 Wood units).

In the event of laminar flow, the blood flow velocity is below a critical limit and the flow is orderly and streamlined (this is the usual pattern of flow in the vascular system.), whereas turbulent flow is disorderly and noisy with vortices (this area is still relatively uncharted; according to Richard Feynman: *"turbulence is the last great unsolved problem of class ical physics"*). In the vascular system, high-flow velocities at the heart valve and sites of narrowing places cause turbulent flow and produce sound. The murmur heard when blood flows through a narrowed heart valve is due to turbulent flow. To determine whether flow is laminar or turbulent, the Reynolds number (R, a dimensionless number) should be calculated:

$$R = \frac{\rho V D}{\mu}$$

The value depends on the velocity (V), diameter (D), density (ρ) and viscosity (μ). Values below 2000 are defined as laminar flow.

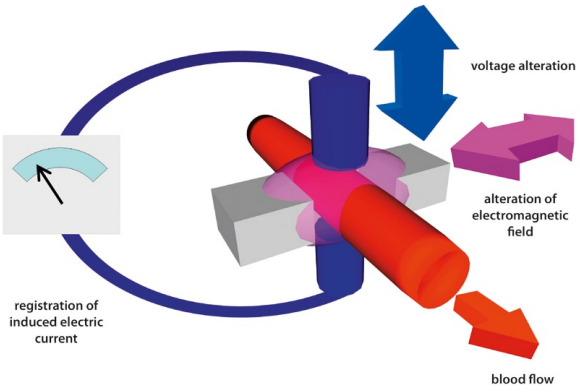
3.2. Measurement of blood flow

The aim of the measurement is to determine the amount of blood flowing through a cross-section of a vessel during a time unit (invasive and noninvasive methods are both applicable).

3.2.1. Electromagnetic blood flow measurement

The principle of electromagnetic flowmetry is based on the Faraday induction law (fluid flowing through a magnetic field induces electric current). An electromagnetic field is created inside an electric coil. Through rhythmical alteration of this electromagnetic field (sinus or square signals), small-scale fluctuations are caused by the fluid moving and the created electric current can be amplified. This flow velocity-proportional voltage signal is converted to a digital signal by an A/D (analog-digital) converter. The precision of the measurement can be improved by application of an alternating magnetic field so that the alternating component of voltage is measurable.

In clinical practice, several problems can occur, the most important being that the magnetic probe has to fit closely around the vessel without shift or vessel deformation (the magnetic field must be homogenous during measurements). This method is rarely used (e.g. in aorta or coronary bypass surgery to measure the circulation of grafts) because of the technical problems.

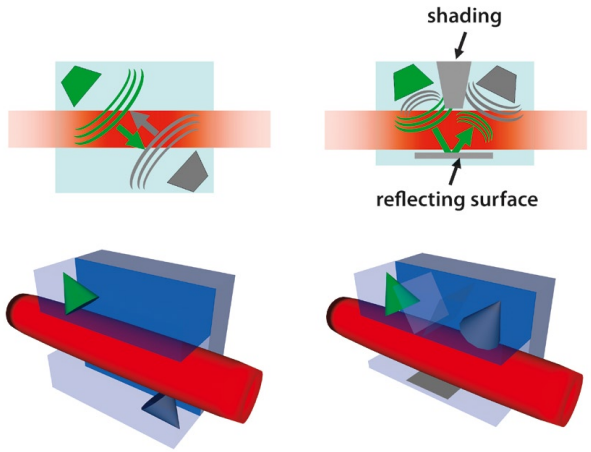


3.2.2. Ultrasound flow measurement

Ultrasound flowmetry can be direct or indirect, and the flowmeters can be invasive or noninvasive devices. The technique is based either on the measurement of the transit time or on the Doppler technique. The invasive method is useful in surgery and research, while the noninvasive technique has more practical significance in dermatology, cardiology, neurosurgery and vascular surgery.

Direct ultrasound flow measurements apply ultrasound waves and the transit time is determined by probes placed around the vessel. The ultrasound head and receiver are localized opposite each other (usually at 30–45°), or side by side (the double-beam method, when there is a reflecting surface on the other side of

the vessel), and both heads transmit ultrasound waves to the other. One of the signals runs in the direction of the blood flow, while the other runs in the direction opposite to the flow. When the first beam arrives, the other beam starts moving oppositely to the flow. The transit time of the ultrasound waves differs for the flow-direction and the against the flow-direction movement (similarly to somebody who wants to swim against a water flow).

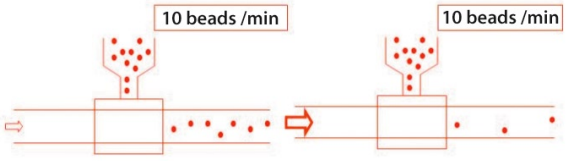


The basis of the measurement is the difference in transit times, or rather the establishment of transit time differences by computer software.

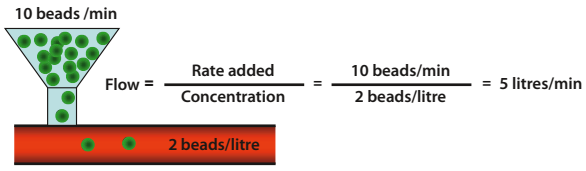
The advantage of this method is that flow probes positioned perivascularly do not deform the vascular wall and there is no interference with the blood flow of the target area.

3.2.3. Blood flow measurements

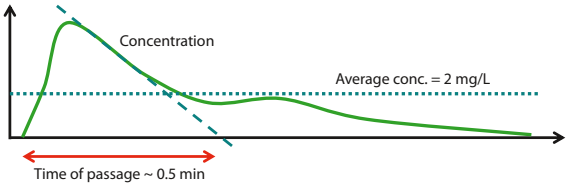
In clinical practice, the Fick method is usually used to determine blood flow. The concept was proposed by Adolf Eugene Fick (1829–1901) in 1870, but it was not applied in clinical practice until the 1950s. The very accurate method was the gold standard for cardiac output measurements, but it is invasive and discontinuous.



If the quantity of indicator particles injected into the circulation and their concentration in a sample taken from the circulation are known, the amount of blood flowing in that particular vessel part can be calculated.



Fick applied this principle to determine the amount of blood flowing through the lung, using the oxygen content of the blood as an indicator. According to the original description a catheter is positioned in the pulmonary artery, and blood samples are withdrawn simultaneously from a peripheral artery and the pulmonary artery as room air is inspired. The volume of expired air is measured, the inspired volume is calculated, and the difference between the oxygen content of the inspired air and that measured in the expired air can then be used to calculate the oxygen uptake per minute at the lungs. The amount of blood flowing through the lung during 1 min is equal to the amount of blood ejected by the right and left hearts, i.e. the cardiac output.



Amount of dye added = 5 mg
Average dye concentration = 2 mg/l
Therefore the volume that diluted the dye = $\frac{5\text{ mg}}{2\text{ mg/l}}$ = 2,5 l
Time it took to go past ~ 0.5 min

Flow rate = $\frac{2{,}5\text{ l}}{0{,}5\text{ min}}$ = 5 l/min

General equation: Flow rate = $\frac{\text{mass of dye (Q g)}}{\text{average dye conc (X g/L) x time of passage (}\Delta\text{t min)}}$

For determination, a representative arterial blood sample (e.g. from the femoral or brachial artery) is taken. This is relatively easy, whereas it is difficult to obtain representative venous samples from the mixed venous blood. For this purpose, a blood sample should be taken from the right ventricle or the pulmonary artery, since in other circulatory areas the venous oxygen content may differ significantly (e.g. the oxygen content of the renal venous blood is ~ 170 mℓ O_2/ℓ, while in the coronary venous blood it is ~ 70 mℓ O_2/ℓ).

3.2.3.1. Indicator dilution method

The basis of the Stewart method is that a known concentration of indicator dye is injected into the venous system (into the right ventricle if possible) at a high rate (mixing of the dye is ensured and its concentra-

tion from this site to the site of sampling will be constant). The dye concentration is determined in a blood sample taken on the arterial side and the concentration is plotted against time to obtain the dilution curve of the dye. Extrapolation of the descending part of the curve to the abscissa yields the time until the total injected amount of dye passes across to the arterial side (see Figure). In reality, the dilution curve does not reach the baseline because of the recirculation, i.e. blood containing the indicator again reaches the site of sampling. Important criteria are that the applied dye must be nontoxic and not immediately absorbed (e.g. indocyanine green). An example of this investigation is the clinical determination of the blood flow of the splanchnic system by the steady-state indocyanine green method (similarly to the Fick method, the process is invasive and discontinuous):

- The continuous infusion of indocyanine green is started through the arterial catheter (this dye is metabolized only by the liver, the extent depending on the rate of flow).
- The splanchnic perfusion can be calculated from the rate of infusion and the arterio-hepato-venous gradient (for the evaluation of splanchnic perfusion, additional data may be obtained from the stomach mucosal pCO_2 determination and calculation of the pCO_2 gradient; see later).

3.2.3.2. Thermodilution blood flow measurement

This is based on the same principle but, instead of dye, heat (i.e. cold saline) is used and the thermodilution curve characterizes the blood flow (or cardiac output) measurements. Its advantage is that toxic effects can be excluded and the degree of measurement noise caused by recirculation is lower. The cold saline is injected at the border of the vena cava and the right atrium, and the change in thermodilution is measured with a thermistor catheter on the arterial side (or at the pulmonary artery with a Swan-Ganz catheter; see later).

$$CO = \frac{|Q|}{\rho_b c_b \int_0^{t_1} |\Delta T_b(t)|\, dt} \ (m^3/s)$$

Q = heat injected, in joules
ρb = density of the blood, in kg/m³
cb = specific heat of the blood, in J/(kg·K)
ΔTb = temperature gradient function

The cardiac output (CO) is calculated on the basis of the thermodilution curve.

3.2.4. Flow measurement with a video-microscope

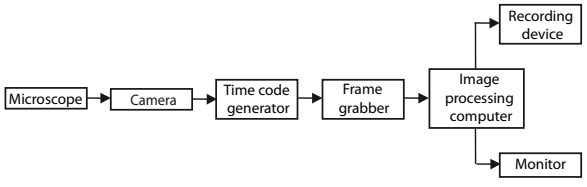
This involves a dynamic intravital observation, i.e. *in vivo* examination of the microcirculation in the deep layers of a tissue. The method is as old as the history of the microscope.

1833 F. Kiernan published surprisingly exact data on the microcirculation of the liver (in *"The anatomy and physiology of the liver". Philos. Trans. R. Soc. Lond. 1833*).

1917 Light from an external light source is led to the opened abdominal cavity via the inner refraction of glass rods (*Basler A: Pflüger's Archiv. 1917*).

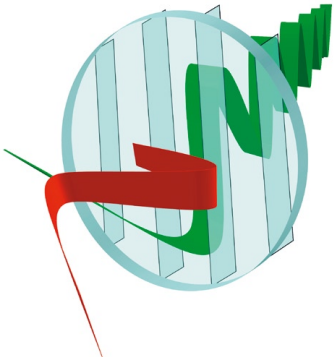
1934 M. Knisely improved this method and described one of the typical consequences of the slowed-down microcirculation, the sludging of red blood cells (*Proc. Soc. Exper. Biol. Med. 1934*).

With an intravital fluorescent video-microscope cellular reactions, the microvascular diameter, the flow velocity and the capillary permeability can be visualized perfectly by the *ex vivo* or *in vivo* staining of cellular blood components or the plasma. The changes are recorded continuously by a CCD (charge-coupled device) video camera; the evaluation is performed off-line by the computer analysis of video frames.

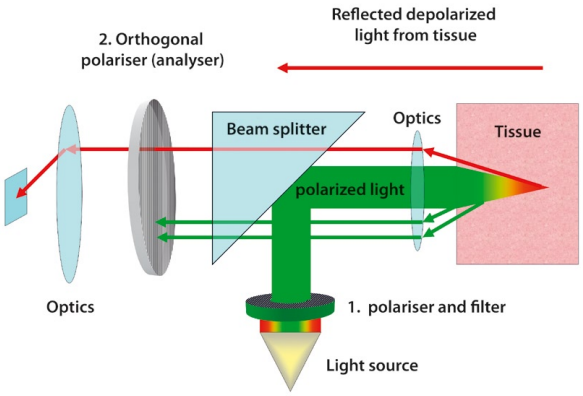


Intravital fluorescent video-microscopic images allow perfect observation of the microcirculation under experimental conditions, though clinical adaptation is rather limited to the observation of surface tissues such as those of the skin, the eye or the oral cavity. Capillaroscopy is used among others in dermatology and for the diagnosis of peripheral vascular disorders. Difficulties in the direct observation of the microcirculation of deeper layers are mainly due to the need for transillu-

mination, the fluorescent dyes applied for contrast amplification and the size of the instruments. An intravital system without contrast enhancement (nonfluorescent method) is the orthogonal polarization spectral (OPS) imaging technique involving the use of polarized light.

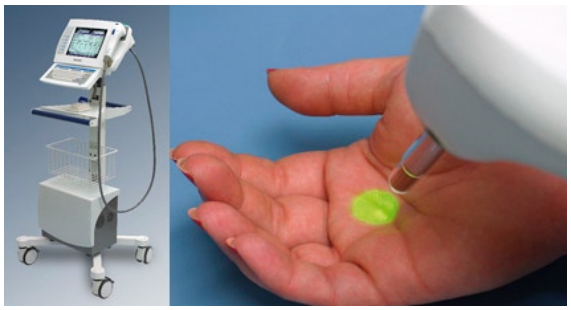


A natural light beam is the result of spontaneous, disordered wave emission of many atoms, in which there are vectors oscillating in every direction. The polarizator allows oscillation in only one direction.



In an OPS technique, the examined object is illuminated with linearly polarized light. The image formation is based on the phenomenon that light scattered in the tissues will be depolarized, and partially reflected. The light which originates from the inside of the tissues therefore back-illuminates the structures. After the first polarizator, a perpendicular, second polarizator (analyzator) is used. Depolarized light arriving from the deep layers of the object is sufficient to illuminate structures under the surface of the object. For an OPS image, 548 nm light is applied (in this range hemoglobin and oxyhemoglobin display equal rates of absorbance), and thus every object which contains hemoglobin can be visualized. The blood flow velocity and changes in capillary diameter can be determined through the mucosal layer of the oral cavity or in the sublingual area. A computer program on-line determines the hematocrit or hemoglobin content too.

The *indications* include noninvasive hematocrit and hemoglobin determinations in neonates, infants and infectious patients, the monitoring of different forms of

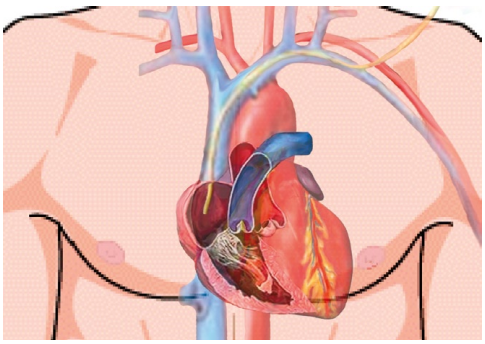


circulatory shock, sepsis, transplantation, ischemia-reperfusion and surgical interventions, e.g. the intraoperative examination of anastomoses, the follow-up of vasoactive therapy, and the observation of the microcirculation of tumors and wound healing.

4. Devices of invasive cardiovascular monitoring

4.1. Central venous catheter

The possibilities of central venous catheter insertion are **1.** venasection, i.e. catheterization of a vein, usually the median cubital vein or the external jugular vein, by venous cutdown (a surgical intervention which is indicated if insertion of a percutaneous central venous catheter is impossible; today it is outdated), and **2.** percutaneous puncture of a central vein. A peripherally inserted central catheter is usually inserted via percutaneous puncture into the superior vena cava through an arm vein (antecubital or basilic, cephalic vein), the internal jugular vein or the subclavian vein.



The internal jugular vein can be localized lateral to the pulsating carotid artery; the subclavian vein is at the border of the internal, medial third of the clavicule.

4.1.1. Needle-cannula combinations

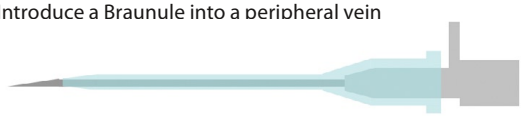
For cannula application, two catheter-needle combination methods have been developed.

1. In the "catheter on needle" variation, a thicker plastic catheter is pulled on to the hypodermic needle. After the puncture and the removal of the needle, the catheter remains in the lumen of the vein. This method is used to puncture superficial vessels, e.g. peripheral veins or the radial artery.
2. In the "catheter in needle" variation, the puncture is performed with a thicker needle and the catheter is led into the lumen. Following catheter positioning, the needle is pulled back from it. A disadvantage of the method is that the cone of the cannula has to be removed. This is out-of-date methodology and should to be avoided, because bleeding and drug-induced extravasations may occur along the cannula after the needle is pulled back.

4.1.2. Seldinger technique

The Seldinger technique for central venous catheterization involves the insertion of a flexible guide-wire into the lumen of the catheter on a needle following the puncture. After removal of the needle/catheter, a guide-wire remains dwelling in the central vein; the central venous catheter is drawn onto the wire and then positioned in the lumen. Today this is the most widespread process for catheterizations of deep vessels such central veins or the femoral artery.

1. Introduce a Braunule into a peripheral vein



2. Remove the needle

3. Insert a flexible guide-wire into the central vein through the lumen of Braunule

4. Remove the Braunule cannula (the guide-wire stays in the lumen of vein)

5. Insert—then remove the dilator cannula

6. Insert the central venous cannula through the guide-wire

7. Remove the guide-wire and fix the cannula

4.1.3. Indications of central venous catheterization

- The injection of compounds damaging the endothelial layer of the veins.
- Longer (3–5 days) volume therapy
- Parenteral nutrition
- Circulatory shock
- Measurement of central venous pressure
- Pacemaker implantation
- If there is no peripheral venous access, but venous access is indicated

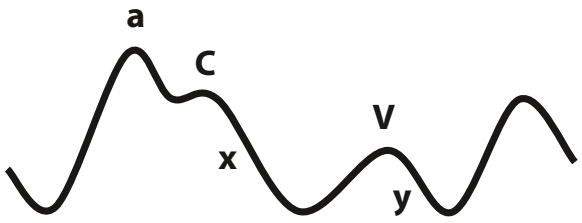
4.1.4. Contraindications of central venous catheter

The introduction of a central venous catheter is forbidden when there are signs of thrombosis, thrombophlebitis, or bacterial vegetation on the tricuspidal valve. Anticoagulant therapy or carotid artery stenosis on the same side could mean a relative contraindication.
Important complications of catheterization are:

- thrombosis, thrombophlebitis
- a catheter embolus
- sepsis
- pneumothorax
- local inflammatory infiltration
- bleeding

4.1.5. Central venous pressure (CVP)

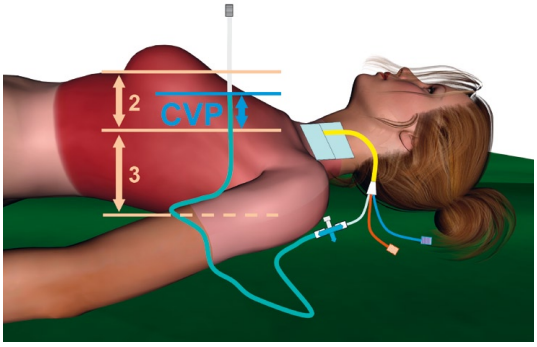
The CVP indicates the right ventricular preload (the rate of venous inflow, a sign of preload), but it does not gives information about the left ventricular work. The CVP is influenced by several factors, and in critically ill patients its predictive value in giving a measure of the filling of the intravascular space is limited. In extreme situations, it demonstrates the severity of hypo- or hypervolemia.



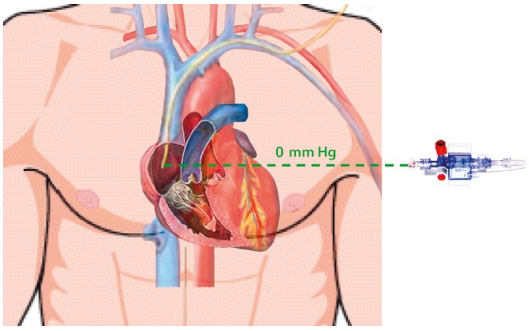
The parts of the CVP curve are the *a* wave (due to atrial contraction and tricuspidal opening; it is absent in atrial fibrillation, and enlarged in tricuspid stenosis, pulmonary stenosis and pulmonary hypertension); the *c* wave (due to bulging of the tricuspid valve into the

right atrium or possibly transmitted pulsations from the carotid artery); the *x* descent wave (due to atrial relaxation); the *v* wave (due to the rise in atrial pressure before the tricuspid valve opens; it is enlarged in tricuspid regurgitation); and the *y* descent wave (due to atrial emptying as blood enters the ventricle).

Traditionally, the CVP is measured by water column manometry; it is expressed in cm H_2O. The normal value above a point level with the right atrium in a patient lying flat is 0–8 cm H_2O.



Modern methods include measurements with an electromanometer. The measurement of pressure is performed continuously in a closed system with a mechanical-electronic energy transducer. Serial readings (the trend of the CVP values) are more informative than single readings.



The CVP is elevated in cases of:
- increased intrathoracic pressure, at ventilation with positive pressure
- an impaired cardiac function (heart failure, pericardial tamponade); this is informative only on the right side of the heart
- hypervolemia (overfilling)
- superior vena cava obstruction

Decreased CVP:
- reduced intrathoracic pressure (e.g. inspiration)
- in cases of obvious hypovolemia (if a volume challenge of 250–500 mℓ of crystalloid causes an increase in CVP that is not sustained for more than 10 min, this is suggestive of (relative) hypovolemia)

4.2. Arterial catheter

4.2.1. Principles

- An arterial line means catheterization of the axillary, brachial, femoral or radial arteries in clinical practice. It provides a direct measurement of blood pressure, blood gas measurement and continuous hemodynamic information.
- The peripheral blood pressure is the afterload of the heart in a hemodynamic sense.
- Maintenance of a sufficient average arterial blood pressure level is of significance as concerns maintaining an adequate organ perfusion. From the pulsating pressure signal, the systolic, diastolic and mean pressure values and the number of pulse waves per minute (i.e. the heart rate) can be determined. The pulse pressure (the difference between the systolic and diastolic pressures) indicates the volume state; a high pulse pressure points to vasodilation-hypervolemia, an aortic valve insufficiency or older age-caused vascular calcification, while a low pulse pressure points to vasoconstriction-hypovolemia and a low stroke volume. A pulse pressure lower than 25% of the systolic pressure indicates a decreased cardiac pump function.
- Although the most accurate technique is arterial pressure measurement, the accuracy depends on the set-up (correct tubing and tight connections), bubble-free tips, zero calibration and the level of the transducer.

There may be serious complications after arterial catheterization:
- Bleeding—blood loss due to disconnection
- Arterial thrombosis
- Infection
- Hematoma formation
- True and false aneurysm formation
- Distal and central embolization

4.2.2. Indications of arterial catheterization

Patient factors:
- Severe sepsis or shock
- Cardiac diseases such as unstable angina, a recent acute myocardial infarct, current congestive heart failure or cardiac arrhythmias or indications for a pacemaker

Surgical considerations:
- Cardiac surgery (major surgery on the aorta or carotid artery)

- Neurosurgery such as craniotomy or aneurysm clipping
- Major surgery with expected significant blood loss of a volume shift (if the blood loss is > 2–3 U)

Anesthesiology and intensive care considerations:
- Intensive care in serious, life-threatening states
- Controlled hypotensive techniques
- Inability to measure blood pressure noninvasively
- Frequent arterial blood sampling required during and after the operation and/or the postoperative period (e.g. blood gas control)

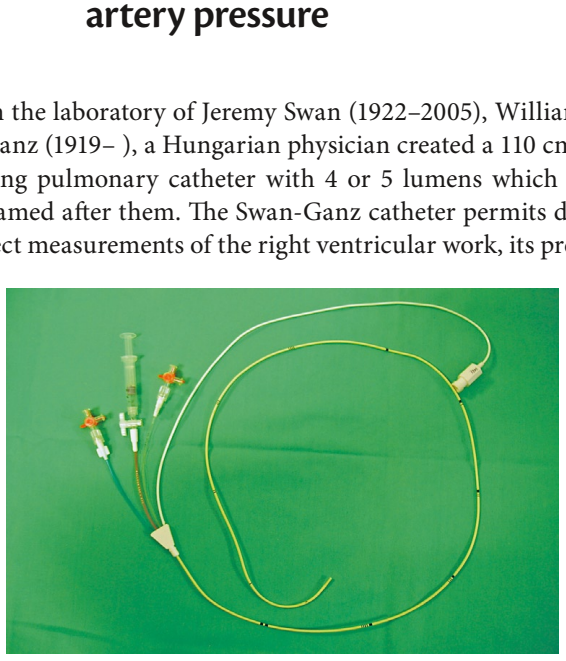
4.2.3. Setting up an arterial pressure measurement line

Needed: a collapsible 0.9% 500 mℓ sterile normal saline bag (with 1–2 mℓ of heparin), a pressure-applying cuff and a manometer, an infusion set and a pressure transducer with proper connectors and arterial cannula. The steps are as follows:

1. setting up of the pressure measurement system with the pressurized bag to 300 mm Hg
2. catheterization of an artery
3. connection to the pressure measurement system (it must be bubble-free)
4. secure fixation of the cannula
5. zeroing of the transducer
6. fixation of the transducer at the heart level
7. start of the measurement

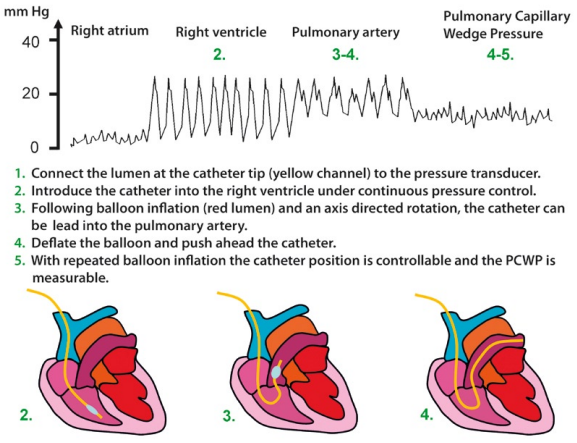
4.2.4. Measurement of pulmonary artery pressure

In the laboratory of Jeremy Swan (1922–2005), William Ganz (1919–), a Hungarian physician created a 110 cm-long pulmonary catheter with 4 or 5 lumens which is named after them. The Swan-Ganz catheter permits direct measurements of the right ventricular work, its preload and the pulmonary pressures. It is possible to measure the cardiac output directly (by a thermodilution method) and a mixed venous blood sample can be taken from it.



The catheter has 4 or 5 lumens, which are designated in different colors:
- **Yellow** is the channel for pulmonary pressure.
- **Blue** is a CVP port, and thermodilution test solution can be passed through it; the hole is at 29 cm from the end of the catheter.
- White is the thermistor cable (thermistors are temperature-measuring devices; (see later) positioned at the end of the catheter.
- The **red** channel provides a means of inflating and deflating the balloon located near the tip of the catheter. The inflated balloon permits the catheter tip to be driven into the pulmonary artery.
- The fifth channel (in the event of a 5-lumen catheter) is a reference thermistor cable for measuring the temperature of injected saline.

The catheter is usually introduced through the femoral vein or jugular vein, under continuous pressure control. When the pressure signal of the right ventricle has been obtained, following balloon inflation (red lumen) the thermistor catheter tip can be led into the pulmonary artery. In the event of successful introduction, a 10–25 mm Hg pressure signal can be seen on the monitor. Following deflation of the balloon, the catheter is pushed ahead until collision. With repeated balloon inflation, the pulmonary capillary wedge pressure distally from the catheter tip can be measured; this is equal to the pressure in the returning branch of the pulmonary circulation (left atrium).



The position of the Swan-Ganz catheter on the right heart side. The site of the catheter tip can be determined by observing the pressure curves of the pulmonary artery and the wedge pressure, (now known as the pulmonary artery occlusive pressure).

4.2.4.1. What can be measured with the Swan-Ganz catheter?

- Central venous pressure
- Pulmonary artery systolic and diastolic pressures
- Pulmonary capillary wedge pressure
- Cardiac output (thermodilution methods)
- Mixed venous oxygen saturation (SvO_2)
- Blood temperature
- Derived hemodynamic data such as the stroke volume, cardiac index, and systemic and pulmonary vascular resistance

4.2.4.2. Indications

- Ischemic heart disease with recent myocardial infarction
- Symptomatic valvular heart disease
- Serious cardiomyopathy
- Congestive heart failure and low ejection fraction
- Shock (septic or hypovolemic)
- Pulmonary hypertension
- Cardiac surgery or severely loading surgery with a poor ventricular function

4.2.4.3. Complications

In general, these are similar to those for CVP catheterization. Specific complications are:

- Arrhythmias
- Thrombosis and embolization
- Pulmonary infarct or bleeding
- Endocarditis
- Atrial and ventricular perforations
- Intracardial node

4.3. Thermodilution cardiac output determination in clinical practice

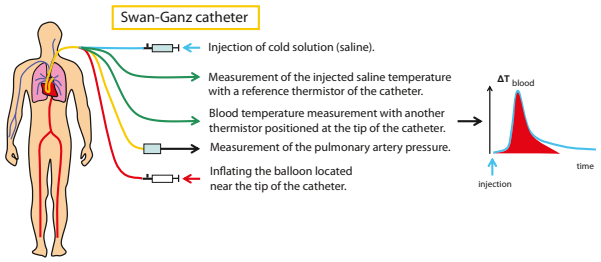
Cardiac output changes depend on several factors:

- The heart rate
- The preload = CVP; right ventricular end-diastolic volume
- The heart contractility
- The afterload = total peripheral resistance

It is worth mentioning that the change in cardiac output is rather small in healthy humans, because of the inverse relationship between the heart rate (relatively variable in a wide range between 40 and 180/min) and the stroke volume.

4.3.1. Pulmonary thermodilution measurements with a Swan-Ganz catheter

This process permits measurements of the right ventricular and pulmonary artery pressures from a central venous approach. It can give the value of the left atrium pressure if the catheter tip is pushed ahead until it reaches a relatively narrow pulmonary branch, and the balloon at the catheter tip is then inflated, and thereby occluding the artery. Since the lumen of the catheter tip is open after the balloon, the occlusion of the anterograde flow permits measurement of the left atrium pressure in a retrograde manner (it is assumed that there are no pathological changes in the pulmonary circulation, e.g. embolism). In the event of determination of the cardiac output by pulmonary thermodilution, a standard volume (2.5–5–10–20 mℓ) of cold (at least 10 °C lower than the blood temperature) solution is injected through the blue branch into the right atrium, as quickly as possible.

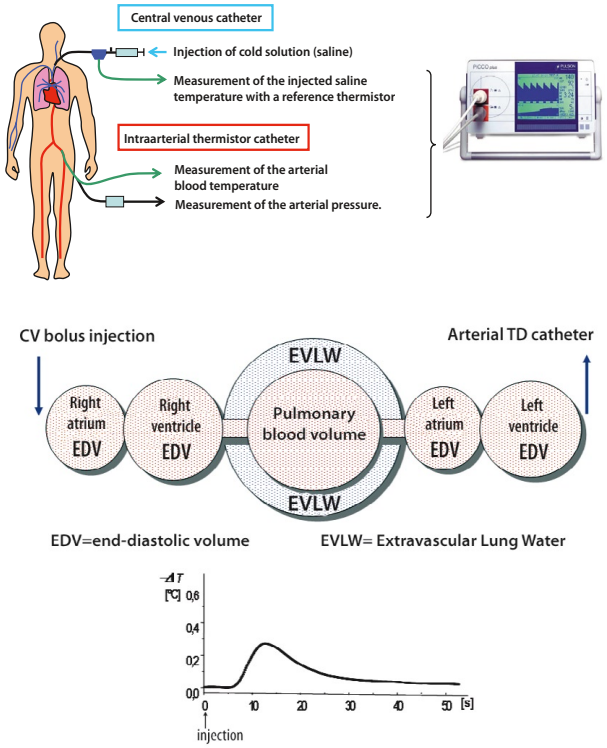


The exact temperature of the injected saline is measured with a reference thermistor of the catheter, while the moving cold blood bolus is registered by another thermistor positioned at the tip of the pulmonary catheter, at about 30 cm from the injecting point. The computer software produces a thermodilution curve from the transient change in temperature of the blood. The cardiac output is calculated by integration of the curve area. For the measured and calculated parameters, patient and catheter-dependent data should be given before the measurement.

4.3.2. Transpulmonary thermodilution technique

The effect of the thermal bolus injected into the central vein is registered by a thermistor catheter positioned in the femoral artery. For pulmonary thermodilution, the arterial side of the pulmonary circulation is considered representative of the total circulation, while transpulmonary thermodilution extrapolates data from a lon-

ger compartment, from the total pulmonary circulation and part of the arterial side of the circulation. This extended (both in time and in space) sample-taking decreases the effect of breathing, and another algorithm (based on the same Stewart-Hamilton principle) is used to determine the cardiac output from integration of the bolus-effect curve. From the extrapolated curve, via the equation $Q = V/t$ several representative volume data are obtained which characterize different parts of the circulation (volumes of heart cavities, pulmonary volume, etc.). These, together with the pressures (CVP and arterial pressure) permit an exact characterization of the circulation. The most important volume parameter is the global end-diastolic volume, i.e. the sum of the end-diastole volumes in all four cavities of the heart, which is a tool for the volumetric preload determination.



Advantages of the transpulmonary thermodilution method:

- Fewer risks and complications
- Determination of hemodynamic and volumetric preload parameters (but no information on the pulmonary circulation pressures)

4.3.3. Parameters derived from cardiac output

- The cardiac index (CI) is the ratio of CO to the body surface area (ℓ/min/m²). An advantage of the CI relative to the CO is that it is independent of the body size, and thus individual patient data are comparable. For an individual patient, however, following the trend or changes in CO or CI is more important than the actual values. The normal range is 2.5–3.5 ℓ/min/m².
- Stroke volume = CO/heart rate (mℓ). This relates to the efficacy of the heart function. Its low values show well that the heart beats emptily, but values above the normal range do not mean the optimal capacity of the Frank-Starling mechanism. The normal range is 60–90 mℓ.
- The systemic vascular resistance (SVR) is the difference between the mean arterial pressure and CVP / CO. It indicates the tone of systemic circulation. It is the main component of the afterload on the left heart side. A high SVR denotes vasoconstriction (a low cardiac output, and effects of catecholamines), while a low SVR denotes vasodilatation (sepsis and anaphylaxis). The normal range is 800~1200 dyne/s/cm^{-5}.
- Oxygen delivery (DO_2) is the amount of oxygen delivered by the circulation. Its components are 1. the oxygen content (depending on the hemoglobin concentration and the saturation (SO_2), 1 g of completely saturated hemoglobin delivers 1.34 mℓ of oxygen; and 2. the CO (or CI): DO_2 [mℓ/min] = CO × [(1.34 × Hg × SaO_2) + (0.003 × paO_2)]. Normal range: 15–20 mℓ/min/bw kg or 500–600 mℓ/min/m² (see later).
- The consumption or VO_2 is the relationship between the difference between the arterial and venous oxygen contents and the blood flow: VO_2 (mℓ/min) = (CaO_2 – CvO_2) × CO. If Hg, CO and A/V saturation are known, VO_2 can be calculated without a knowledge of pO_2 (the dissolved oxygen is lower than 0.3 vol% of the total oxygen content): VO_2 (mℓ/min) = Hg × 1.34 × [(SaO_2 – SvO_2) / 100] × CO (see later).

4.4. Heart contractility

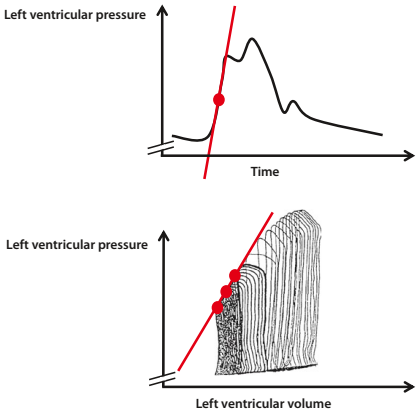
The role of the left ventricle is to move the diastolic volume (i.e. the blood) toward the systemic circulation. Factors influencing the ventricular work:

- Preload
- Afterload
- Heart rate
- Oxygen and energy supply
- Neurohumoral state
- Contractility

The heart contractility in human practice is determined together with the monitoring of the systolic phases of the normal heart cycles. The method is based on the *dP/dt max* values of the isometric contraction or on the end systolic pressure-volume relation (ESVR).

1. The *dP/dt max* value of the arterial pressure curve represents the rate of pressure increase in the left ventricle, and is thus a parameter of the myocardial contractility.

2. ESPVR evaluation requires the simultaneous measurement of one parameter related to the pump function (*dP/dt*, ventricular pressure) and another one related to the preload (end-diastolic-volume), these two parameters producing pressure-volume loops. The slope of a straight line fitted to the end-systolic points of the pressure-volume loops is the elastance, which is an accepted value for heart contractility. In practice this evaluation is possible only by means of a special catheter introduced into the cavity of the left ventricle, which simultaneously measures the signals of pressure and volume. It is important that *dP/dt* max is a load-dependent parameter, in contrast with ESPVR.



Above: determination of *dP/dt max* value of arterial pressure curve. *Below:* estimation of ESPVR; on the y axis, ventricular pressure as the pump function-related parameter, and on the x axis, end-diastolic volume as a preload-related parameter.

IV. Respiratory system monitoring

"Genius is one per cent inspiration, ninety-nine per cent perspiration"
Thomas Alva Edison (1847–1931)

Monitoring of the respiratory system is of particular importance in internal and pulmonary medicine, in anesthesia practice and in intensive therapy (e.g. pulmonary function tests, ventilation, control of oxygenation, monitoring of the mechanical ventilation parameters, etc.). Endotracheal intubation is sometimes necessary for monitoring. Intubation is the most general and secure way to provide open airways and it allows continuous monitoring of the composition of inhaled or exhaled gases. This technique must be known for all practising doctors.

Basic (low-tech) monitoring includes auscultation and observation of the characteristics of breathing (rhythm, frequency, depth, etc.).

1. Respiratory frequency monitoring

- Thermistor (see later): in the nostril of a spontaneously breathing patient
- Measurement of the changes in thoracic impedance
- Pressure changes in the airways
- Capnometry

2. Measurement of efficiency of ventilation

During capnometry, the gas concentration is determined through the measurement of changes in light intensity at the absorption wavelength of CO_2. The capnogram well demonstrates the breathing or the mechanically ventilated parameters (frequency, volume, inspiration/expiration ratio, alveolar inhomogeneities, and pulmonary perfusion parameters).

During blood gas analysis, samples are taken from an artery or arterialized capillaries (see below).

Pulse-oxymetry is based upon the principle of the difference in light absorption between hemoglobin and oxyhemoglobin. Red and infrared (the absorption maxima of the two types of hemoglobin at these wavelengths) light is transmitted through the capillaries and the amount of oxyhemoglobin is determined from the light absorption ratio. Sensor sites are fingers, the earlobes, the bridge of the nose, the toes, foot or the feet of the palms (in neonates). The device can measure the oxygen saturation of hemoglobin and the heart rate, and a finger plethysmogram can also be displayed (see above).

Transcutaneous oxy- and capnometry: the partial pressures of gases diffusing through the skin are determined with an electrochemical method. Accurate values can be measured only during sufficient perfusion (see below).

3. Monitoring of respiratory gases

The measurement of arterial CO_2 concentration is a very accurate method, but it is invasive and does not allow continuous data monitoring. Measurement of the concentrations or partial pressures of gases, e.g. CO_2, exhaled from the lung is a noninvasive method, and may be performed intermittently or continuously. The main possibilities:

- Colorimetric devices
- Infrared absorption photometry
- Mass spectrophotometry
- Raman spectra

3.1. Colorimetry

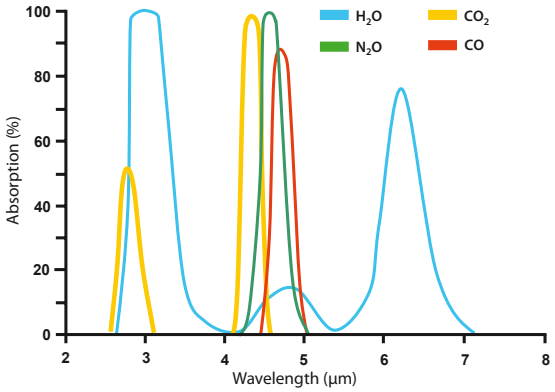
The principle of this portable, lightweight method is that a pH-sensitive dye undergoes a color change in the presence of CO_2. The dye is usually metacresol (purple), which changes to yellow in the presence of CO_2.

False-positive results are rare (acidic solutions, e.g. atropine or lidocaine, immediately change the color), but false-negative ones are more common.

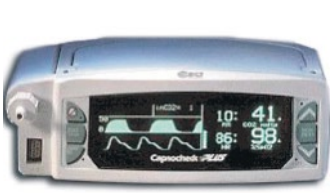
3.2. Infrared absorption photometry. Capnography and capnometry

The principle of measurement was described in 1859; and it is based upon the Beer-Lambert law, similarly to pulse-oxymetry. (This law demonstrates a linear rela-

tionship between the light absorption and the absorbing material; in the case of capnography, the higher the CO_2 concentration, the higher the light absorption will be at a definite infrared wavelength. The absorption maximum of CO_2 is at 4250 nm, but N_2O, H_2O and CO can also absorb at this wavelength).



It is important to distinguish capnography from capnometry: in capnography, the CO_2 content of a gas sample (e.g. taken from the endotracheal tube) is measured continuously and the capnogram (the pressure waveform of the exhaled CO_2; see Figure below) is displayed. Capnometry measures the end-tidal CO_2 concentration (there is no waveform in this case), and the device is called a capnometer.



3.2.1. Basic types of capnographs

There are two main types of devices, with sidestream and mainstream measurements.

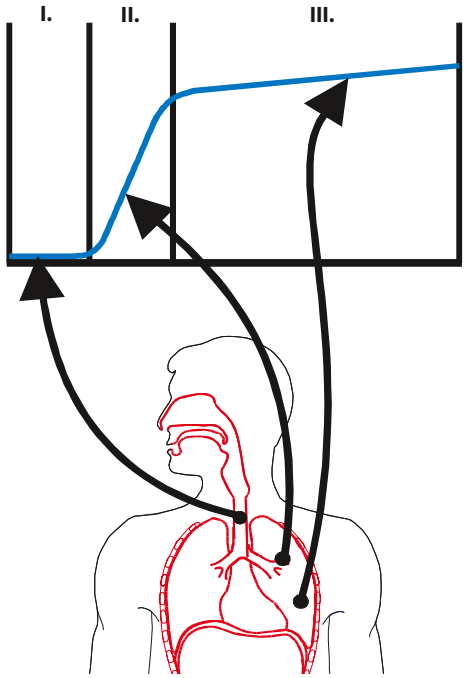
The characteristics of sidestream measurements
The gas sample is taken through a small tube, and analyzed in a separate chamber. The results are very reliable (less accurate at higher respiratory frequency); the time delay is 1–60 s (necessity). Difficulties are water, mucus and ambient air leaks.

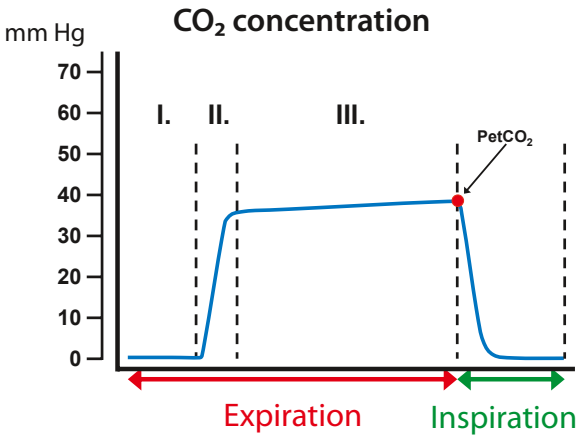
The characteristics of mainstream measurements
Here the tube is larger (smaller tubes can be obturated), which adds dead space to the airways (the sensor is in the airways). The reaction time is only 40 ms, and the technique is very accurate. Calibration is difficult without taking the equipment to pieces, and "rebreathing" detection is too difficult. Moisture and steam influence the measurements, with a greater chance of damage.

3.2.3. $SBCO_2$ waveform

Via the analysis of a single exhalation, three main phases can be distinguished in the normal capnogram (the single-breath CO_2, i.e. $SBCO_2$ waveform).

Phase I is characteristic of the airways, phase II indicates transitional gas, while phase III demonstrates the changes in the alveolar gas.





- Exhalation, characteristic mostly of the anatomic dead space, begins in phase I.
- In phase II, the alveolar gas begins to mix with the dead space gas, and hence the CO_2 concentration rapidly rises. The anatomic dead space can be calculated from phases I and II on the basis of the equation VD = VDanat + VDalv. A significant increase in the alveolar dead space indicates a marked V/Q mismatch (shunt circulation).
- Phase III corresponds to the elimination of CO_2 from the alveoli. Normally, it is only slightly increased, but in disease states, during the sequential exhaustion of the alveoli, it becomes definitely elevated, which indicates inhomogeneous exhaustion ("slow alveoli" have a low V/Q ratio, and therefore an elevated CO_2 concentration); additionally diffusion of CO_2 is faster during expiration.
- The end-tidal CO_2 ($ETCO_2$) concentration is equal to the maximum in phase III. $ETCO_2$ is usually approximately 0.4 kPa lower than $paCO_2$.
- Phase IV indicates inspiration.

Causes of increased $ETCO_2$
- Alveolar hypoventilation
- CO_2 rebreathing
- Increased CO_2 exhalation caused by:
- alveolar hypoventilation (most frequent and important)
- CO_2 rebreathing
- increased metabolism and CO_2 production (e.g. malignant hyperpyrexia or hyperthyroidism)
- compensation of metabolic alkalosis (during spontaneous breathing)
- release of tourniquet on the limbs
- administration of exogenous CO_2 (e.g. during laparoscopy, see "Surgical Techniques") or for some minutes after HCO_3^- administration

Causes of decreased $ETCO_2$
- Alveolar hyperventilation (continuously decreasing $ETCO_2$)
- Decreased CO_2 production caused by:
  - hypothermia
  - deep anesthesia or neuromuscular blockade
  - compensation of metabolic acidosis during spontaneous breathing

Other capnogram abnormalities

Increased phase III: obstructive pulmonary disease (increased $ETCO_2$)

The capnogram waveform is considerably depressed (a horizontally elongated phase III):
- pulmonary emboli
- decreasing CO
- hypovolemia

A sudden decrease in $ETCO_2$ to 0:
- a dislodged endotracheal tube
- cessation of breathing
- cessation of circulation
- an airway obstruction
- a system fault or leakage

A sudden decrease in $ETCO_2$:
- partial obstruction
- an air leak during mechanical ventilation

An exponential decrease in $ETCO_2$:
- severe hyperventilation
- pulmonary embolism
- a cardiopulmonary event

3.3. Uses

General uses
- Confirmation of endotracheal tube placement (intubation)
- Monitoring breathing and mechanical ventilation, demonstration of respiratory disorders (e.g. bronchospasm) and effectiveness of therapy
- Monitoring of circulatory insufficiency.
- Monitoring of the effectiveness of reanimation
- Demonstration of hypermetabolic states

"Special use" for the diagnosis of air embolism

The etiology of passive air embolism includes opened veins, venous sinuses, e.g. neurosurgical interventions performed in a sitting position, spinal operations, and the introduction of a central venous catheter.

The etiology of active air embolism: rapid transfusion under pressure, during laparoscopy (carbon monoxide pneumoperitoneum; see there), operations in the femoral region, and the use of gas-cooled laser techniques.

Symptoms
- Sudden collapse, hypoxia and decreasing $ETCO_2$
- Low cardiac output and bradycardia

Diagnosis
- Capnography
- Doppler ultrasound
- Esophageal stethoscope ("mill-wheel noise")
- Decreasing arterial oxygen saturation

Prevention
- Care with fluid infusors, precaution during infusion, and removal of air from the infusion set (motto: "*Even if blood doesn't come out, air can still go in*")
- Careful placement of the patient (maintenance of the site of surgery below the heart level where possible)
- Caution during the use of central venous catheters

(e.g. the minimum number of connections to the pressure transducers, and change of the connections below the heart level)
- Removal of catheters and lines with the patient in a head-down position in expiration (during mechanical ventilation, this is done during inspiration)

Treatment
- Application of 100% oxygen
- Stop whatever caused it (surgeon, equipment or position)
- Removal of air (e.g. with a central venous catheter) *in situ*
- Rinsing and flooding of the entry point of air with physiological saline
- Preparedness for reanimation

4. Endotracheal intubation

Definition: Introduction of a tube through the mouth or nose into the trachea to provide open airways. The principle of the technique is to introduce a plastic or rubber tube of appropriate size into the respiratory system so that its end is situated in the trachea or one of the main bronchi to separate the two lungs. This procedure can be performed in some situations in a conscious state or under local anesthesia, but more frequently it is carried out under general anesthesia or with muscle relaxation. When the endotracheal tube is no longer required, it can be removed (extubation).

4.1. Securing the open airways

During surgery, securing of the open airways is one of the most important tasks of the anesthesiologist. It can be performed with an extratracheal method, by tilting the patient's head backward to prevent the tongue from sliding back. To provide open airways, oro- or nasopharyngeal tubes (of different sizes, made from different materials) or laryngeal masks can be used. Endotracheal intubation is the most reliable method of securing the airways during anesthesia and surgery (and in emergency situations, or in accidents).

4.2. Advantages of endotracheal intubation *vs* extratracheal methods

- The anatomic dead space can be decreased to 50–60%, and the alveolar ventilation can be improved, mainly in high-risk surgical patients.
- It allows positive pressure ventilation; the ventilated air or anesthetic gas mixture circulated manually or with a respirator can only reach the lungs instead of the stomach.
- Airway aspiration can be avoided during vomiting or regurgitation.
- Mucus can easily be suctioned out from almost all parts of the bronchial system.
- Micro- and macroatelectasis can be eliminated with an appropriate mechanical ventilation technique.
- The position of the patient (e.g. the prone position) does not affect ventilation.
- Different drugs may be given to the patients, if needed.

4.3. Equipment required for safe endotracheal intubation

- Oxygen supply, dosing apparatus for anesthetic gas
- Face mask, pharyngeal tubes, tubes with cuff or simple endotracheal tubes
- Laryngoscopes, mouth retractors of different sizes and types
- Syringes to inflate the cuff and an instrument to clamp the duct above the balloon
- Instrument for introducing the tube (Magill)
- Medication
- Suction apparatus, suction catheters (to remove mucus; a "bronchus toilette")

4.4. The technique of intubation

Intubation can usually be performed under direct visualization with the help of a laryngoscope (direct laryngoscopy). Introduction of an endotracheal tube into the larynx through the mouth or nose can be done under narcosis and muscle relaxation, or in deep unconsciousness, or in a state of clinical death. The most widely used intubation technique is as follows:

1. The required equipment, tools and drugs are first prepared on the table next to the patient and checked consecutively:
   - A Ruben balloon with valve and mask, or an anesthesia machine with manual ventilation
   - A suction pump with a suction catheter
   - A laryngoscope
   - Endotracheal tubes
   - Tube adaptors
   - A syringe for inflation of the cuff
   - A Péan for clamping the duct of the cuff
   - A bite block (a Guedel tube or a 10 × 5 cm gauze strip)
   - Tape or a Köpper band for fixing the tube

- If the patient is apnoic or has insufficient breathing, ventilation through a mask must be applied until the tools are prepared.

2. The patient is laid in a supine position, with the head toward the person performing the procedure.

3. General anesthesia (or local anesthesia and sedation) is applied.

4. Oxygen is delivered via a face mask for at least 3 min. If intubation fails for a short time (not more than 1 min) in a nonbreathing patient, ventilation is applied through a mask. Intubation should be attempted again only in a well-oxygenated patient.

5. The patient's head is placed in a proper position. The pillow is removed from under the shoulder. The Jackson position (see below) makes exploration of the larynx easy. In adults, the narrowest part of the airways is the glottis (the subglottis in children). In the supine position, there is an obtuse angle between the oral and pharyngeal axes. Two positions have been developed for alignment of the two axes and easier passage of the endotracheal tube:

5.1. In the classic Jackson position, the patient is laid in a supine position without a pillow, and the head is tilted backward at the atlanto-occipital joint, with the doctor's palm placed on the patient's forehead, so that the cervical spine is also turned backward (retroflected). In most cases, this position is effective. The oral and pharyngeal axes are near each other, so the glottis can be seen easily with the illuminating blade of the laryngoscope.

5.2. In the modified Jackson position, a pillow (10 to 15 cm thick) is placed under the patient's nape, and the head is tilted so that the mouth can be opened (like the sniffing position: a slight bending forward to sniff something). The oral, pharyngeal and laryngeal axes approach each other. The glottis can be seen with the laryngoscope underneath, under the epiglottis.

6. Using muscle relaxation, the patient is paralyzed after oxygenation and anesthesia, and the effect is awaited while the patient is ventilated continuously.

7. After the completion of muscle relaxation, the doctor stands behind the patient in the Jackson position, grasps the handle of the Macintosh laryngoscope in the left hand and pushes the tongue to the left with the curved blade. Then blade is then pushed 1 to 2 cm forward along the right side of the tongue while the handle is lifted. During intubation, attention must be paid to the teeth: pressure must not be exerted against the upper teeth and the handle of the laryngoscope must not be tilted toward the teeth (teeth injuries!). The end of the blade is between the base of the tongue and the epiglottis, in the plica glossoepiglottica. If the base of the tongue is lifted the epiglottis can also be raised (due to the lig. hypoepiglotticum spreading between the corpus ossis hyoidis and the cartilago epiglottidis) and the triangular glottis with its peak upward can also be elevated. If the epiglottis and the front of the trachea cannot be seen, the assistant should press down the base of the thyroid cartilage and the cricoid cartilage (Sellick maneuver). Accordingly, the endotracheal tube in the right hand should be inserted from the right side of the mouth into the glottis, and then into the trachea. The tube is then pushed 4 or 5 cm forward until the cuff disappears in the glottis.

Care must be taken not to damage the soft tissues with the blade of the laryngoscope, not to reach the epiglottis, and not to force the tube into the narrow glottis. The laryngoscope must not be turned, but lifted up for better visualization, and not pushed against the upper front teeth. The tongue is held so as not to be in the way of the field of vision.

8. The depth of intubation is indicated by the sign on the tube. The distance of the tracheal bifurcation from the front teeth is approximately 23 and 27 cm in women and men, respectively. For the appropriate oxygenation of the two lungs, the end of the tube has to be 1–3 cm above the bifurcation.

The cuff is then inflated and, if it has no valve, the control balloon is closed. In order to avoid pressure damage, the balloon must not be overinflated (a "low-pressure cuff" is used). A special manometer can also be used to avoid overinflation.

The cuff inhibits the trickling of saliva, blood or gastric content into the lung, and escape of the inspired air, and it allows suctioning of the deeper airways. The tension of the control balloon reflects the inflated condition of the cuff.

9. Verification of the success of intubation

The breathing sounds are checked at both medio-axillary lines above the lungs and the proper position of the tube is ensured. If the end of the tube is in the trachea above the bifurcation, the breathing noises over the two sides are similar. If the tube is advanced over the bifurcation, it is usually in the right main bronchus. Therefore, the breathing sounds on the left side will be much weaker or inaudible. A tube located very deeply must be pulled back until the breathing sounds become similar on both sides.

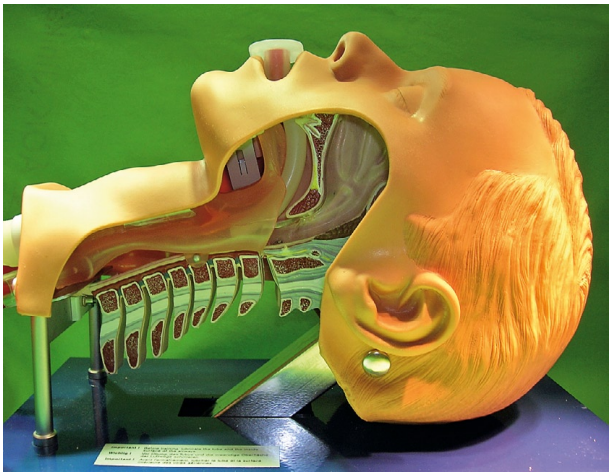
The simplest method of checking the position of the tube is to jog the upper part of the thorax, when the air outflow from the tube is heard.

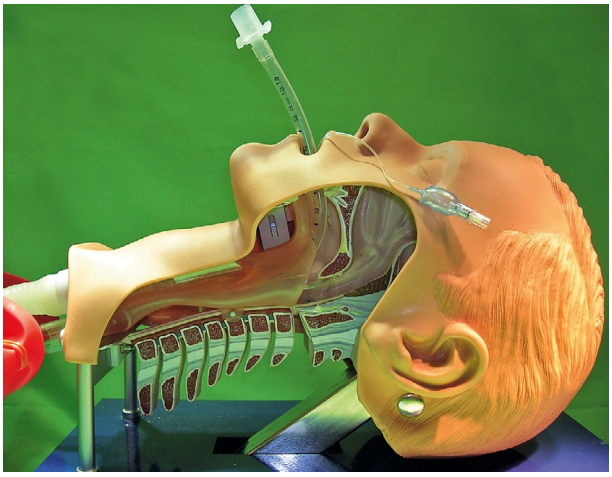
If air is blown into the tube, first the elevation and then the depression of the thorax may be observed at the level of the chest, and the free airflow in the tube indicates the correct position of the tube in the trachea.

On use of a capnograph, the CO_2 waveform imme-

diately indicates the correct position of the tube (if the tube is in the esophagus, the $ETCO_2$ value will be 0).

Biting of the tube may be prevented by the use of a bite-protector (a Guedel tube or a wet bandage). The tube attached to the bite protector can be secured to the patient's face with an approximately 30 cm long piece of adhesive plaster forming an X-shaped bandage.





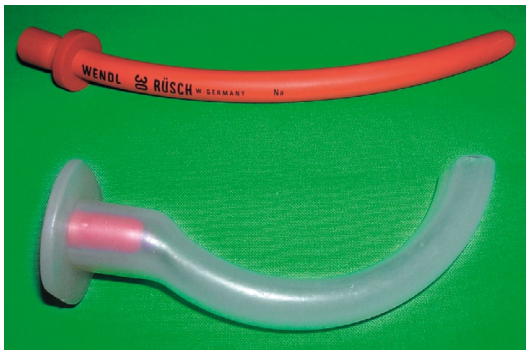
4.5. Tubes

The endotracheal tube is approximately 30 cm long and slightly curved. At the end there is an inflatable cuff; a thin tube is used for inflation and the cuff has a control balloon. The tubes are made in different sizes; the outer diameter is given in Charriére units or mm (1 Ch=1/3 mm). Recently, the inner diameter in mm, and the "oral" or "nasal" type are also indicated (see below). The ideal size is 36–38 Ch (an internal diameter of 8 to 9 mm) for adult men, and 34–36 Ch (an internal diameter of 6.5 to 8 mm) for adult women; these can easily be introduced into the glottis. A scale (underlined numbers) is also given at the opposite end of the tube, showing the distance from the end.

The tubes are made of rubber, plastic or latex, and may have metal wiring reinforcement (e.g. the Woodbridge tube). Their forms may be conventional, curved or preformed, with or without a cuff. There are tubes with or without a side-hole at the end of the tube for oral or nasal introduction. The cuffs may also differ in size (normal or longer), low-pressure, and with X-ray-capturing black marks at the end.

The special pediatric tubes (e.g. the Cole tube) are made from plastic or latex without a cuff (for under 6 years of age), or they may be of spiral type. Some of them have an end with X-ray-capturing signs.

Tracheostomy patients are intubated with special, short tubes (e.g. Tracheoflex) of different sizes, with a special guide and cuff. The latex tubes are produced with a yellow cuff which have a sign warning against sliding out.



4.6. Nasotracheal intubation

Nasotracheal intubation differs from the orotracheal method in several steps. First, a nose tube with appropriate diameter must be used (in some cases of septum deviations, only one is appropriate). Then, a vasoconstrictor nose drop or nose strip must be applied to decrease the mucosal blood supply. After the choice of an appropriate nasotracheal tube, the other preparations are the same as the steps of the previous method. The tube is carefully introduced until the oropharynx, and

then inserted through the laryngeal gate with laryngoscopic exploration. In the event of difficulty in intubation (e.g. lockjaw), a fiberoscope can be used. The tube must be pulled onto the fiberoscope and pushed through the glottis and into the trachea.

4.7. Awake intubation

This is indicated if:

- anesthesia is difficult to perform and the intubation is possibly accompanied by difficulties
- the danger of airway aspiration is high
- there is acute respiratory insufficiency with demanding positive-pressure ventilation
- the patient is hypersensitive to muscle relaxants and anesthetics, and hence quick intubation is needed

If the alternative possibilities are considered, the nasal method should rather be chosen because, while the tube is being placed, the patients are able to breathe spontaneously. The appropriate nostril is chosen and the mucosa must be anesthetized. The superficial anesthesia is made in the sequence the nostril, the base of the tongue, the oropharynx, the fossa pyriformis, the vocal cords and the pharynx, and finally the upper part of the trachea. In adult women, a 7.00 mm tube with a soft cuff may be chosen, and in adult men an 8.00 mm nasal tube. The intubation is easier when the patient's head is tilted slightly forward. After exploration, the tube is introduced through the glottis during inspiration. The above instructions then follow.

Awake intubation is reasonable when general anesthesia is not safe due to the patient's condition or the intubation difficulties (it would be dangerous to keep the airways free). Substantial local anesthesia (nose, pharynx, hypopharynx and larynx) and sedation must be applied before a tube is introduced which is frequently achieved nasally (blind or with the help of a laryngoscope).

4.8. Blind nasotracheal intubation

This is primarily indicated in cases of lockjaw (e.g. maxillofacial injuries, inflammation or tumors). The tube is introduced with listening to the breath sounds. The method is contraindicated in cases of basal skull fractures, epipharynx tumors or a blocked nose.

4.9. Suction

In an intubated patient, the lower portion of the trachea can be suctioned. The suction catheter of appropriate size should be introduced without application of any suction, but it should be pulled out under continuous suction. When the lower airways are suctioned sterility is particularly important. The suction process should not be longer than 10 to 15 s, after which the patient should be ventilated. Under hypoxia, the patient should be ventilated with oxygen-rich air. Prior to extubation, the pharynx should always be suctioned first (the area above the cuff) and only after this should the cuff be deflated and the tube removed, during which continuous suction should be applied with the help of an inserted sterile cannula (above the cuff, mucus can accumulate).

4.10. Difficulties

The most frequent causes of intubation difficulties are a limitation of mouth opening (e.g. inflammatory, tumorous, callous, ankylotic, etc. lockjaw), difficulties in the laryngoscopic exploration (e.g. a short and thick neck, mandible and maxilla abnormalities, macroglossia, cervical spondylosis, etc.), or difficulties in tube introduction (e.g. a larynx tumor, a tracheal stricture or dislocation).

Apart from deficiencies and instrument failures, the laying of the patient causes further difficulties. When relaxation with medicines is impossible, the lack of muscle relaxation may cause further technical problems.

If there is a risk of aspiration, quick reactions are required: after a powerful oxygenation, respiration through a mask should be avoided, and the mucus or the regurgitated gastric content should be suctioned continuously, if needed. Compression of the cricoid cartilage with three fingers (the Sellick maneuver) can reduce the risk of gastric regurgitation. The circular plate of a seal-ring-shaped cricoid cartilage, facing posteriorly, compresses the underlying esophagus against the cervical vertebra and closes it. During intubation, this procedure is performed by the assistant.

During emergencies (a sudden emergency, or a risk of asphyxia), the fastest way to provide open airways is to dissect the ligamentum crycothyreoideum (with intubation via the larynx) or to puncture it (with "jet-ventilation").

4.11. Complications

- Injuries to the mouth, the teeth, the mucosa of the pharynx and larynx, the vocal cords, and bleeding in the pharynx.
- The tubes themselves can also cause complications. A too thin tube (mainly in children) increases the airway resistance. The tube can become obstructed when it faults, or bitten by the patient; it can be narrowed or closed by excretion, foreign material, blood, or the overinflated balloon. The end of the

tube may be an improper position: it can cause a fatal injury if it is in the esophagus instead of the trachea; it can slip out the trachea or it may be in a too deep position, in the bronchi. Ventilatory difficulties may result from the patient's coughing, tensing or extruding, which all cause airway spasms.

- Rare severe complications are recurrent nerve and vocal cord lesions, jugular subcutaneous and mediastinal emphysema, and fibrotic tracheal stricture or rupture. An overinflated balloon can cause partial occlusion of the lumen of the tube or can lead to damage from the increased pressure.

4.12. Intubation of infants

There are difficulties because of the different anatomical characteristics:

- the epiglottis is located higher than in adults
- the glottis aperture is at the level of the third vertebra
- the epiglottis is longer and steeper than in adults
- the bifurcation is also located proportionally higher (a risk of endobronchial intubation)
- the narrowest part of the upper airways is the internal part of the tapered-lumened crycoid cartilage and not the vocal split

Therefore, tubes without a cuff (e.g. a Cole tube) may be needed for the intubation of babies. In the event of intubation difficulties, insufficient equipment, or a lack of experience, conicotomy may be recommended.

V. Monitoring of the oxigenization

"Anoxaemia not only stops the machine, but wrecks the machinery."
John Scott Haldane (1860–1936)

Oxygenization is the most important factor in the life of tissues and cells. It is determined by the triad of the arterial oxygen content, the perfusion pressure and the possibility of free blood flow. The evaluation of the oxygenization level is always based on the actual clinical state of the patient and the data obtained by monitoring.

1. Historical background

1774 Joseph Priestley (1733–1803) and Carl Wilhelm Scheele (1742–1786) discovered oxygen independently from each other.

1779 Antoine Laurent de Lavoisier (1743–1794) established its role in burning and described this component of air as 'oxygen'.

2. General principles

Oxygen is a constituent of all living tissues (in the free or combined state) and maintains life. The atmosphere, the sea water, the fresh water, the Earth's crust, and the human body contain 21 v/v% (23.15 w/v %), 85.8 w/v %, 88.8 w/v%, 46.7 w/v%, 60 w/v % oxygen, respectively.

Air is a mixture of oxygen, carbon dioxide, nitrogen and water vapor, and according to Dalton's law the total pressure of a gas mixture is equal to the sum of the independent, partial pressures of each constituent gas. At sea level the normal barometric pressure (pATM = 760 mm Hg) is the sum of the partial pressures $pN_2 + pO_2 + pCO_2 + pH_2O$.

The oxygen gas pressure is measured in mm Hg or Torr. Given a normal barometric pressure of 760 mm Hg at sea level and at 0% relative humidity, the oxygen partial pressure is 159 Torr [(760) × (20.95 / 100)].

Industrially, oxygen is produced by the fractional distillation of liquid air. Under the critical pressure it is gaseous, whereas above it a pale-blue liquid with a garlic smell. It can be stored in containers (e.g. Dewar vacuum flasks) constructed on the principle of the ordinary thermos flask or in high-pressure gas cylinders containing 20–30 kg.

A clinically important datum is the fraction of oxygen in the inspired gas mixture, FiO_2. The inspired oxygen is heated up, its relative humidity becomes 100% (see below), and thus the oxygen pressure falls to 149 Torr. The ~ 40 mm Hg pCO_2 in the alveoli further reduces the oxygen pressure. Then, oxygen at a pressure of about 109 Torr is forced into the capillary blood through the alveolo-capillary membranes.

The absolute humidity is the mass of water relative to the amount of gas (mg/ℓ). The relative humidity (RH) is the ratio of the absolute humidity to the maximal capacity (%). At normal body temperature (37 °C), the maximum water-carrying capacity is 44 mg/ℓ, and an absolute humidity of 33 mg/ℓ at body temperature therefore yields an RH of 75% (if the RH is 75 %, the absolute humidity is 33 mg/ℓ).

If droplets of water are dispersed in air bacterial contamination is excluded at 0.01 micron particle size (i.e. at this size pathogens are not transported). With vaporizers or nebulizers (*nebula* = cloud), water droplets can be suspended in air and, because of the larger particle size, the transport of bacteria is possible.

Oxygen is carried in the blood in two forms: dissolved (~2–3% of the total content) and bound to carrier molecules (~97–98% of the total content). The total oxygen content of the blood (CaO_2) is calculated from the dissolved amount that bound to hemoglobin (Hb). PaO_2 is partial pressure of oxygen in the arterial blood, while $PaCO_2$ is the partial pressure of CO_2 in the arterial blood.

The oxygen-carrying capacity of blood is directly proportional to the concentration of Hb present in the blood. The oxygen saturation (SpO_2, SaO_2, $SatO_2$) is the ratio of oxygenated and deoxygenated/reduced Hb. The oxygen-carrying capacity of 1 g of Hg is ~ 1.34 mℓ O_2. The physiological SpO_2 is 95–98% (a perfusion disturbance can be presumed if SpO_2 is less than 95%, a severe functional disturbance of the cells is indicated if SpO_2 is lower than 90%. In clinical practice, the parameters are generally continuously monitored by pulse-oxymetry in a noninvasive way.

PaO_2 is an indicator of the oxygen dissolved in the plasma. The physiological PaO_2 range is 80–100 mm Hg (when air of normal pressure is inspired), which corresponds to 95–100% SpO_2 (depending on the Hb concentration, 60 mm Hg PaO_2 corresponds to 90% SpO_2, and 40 mm Hg PaO_2 to 75% SpO_2). Invasive monitoring of PaO_2 is possible in the clinical practice by analyzing the arterial blood sample (see acid-base balance below).

3. Hypoxemia

Hypoxemia is defined as a decreased (abnormally low) amount of oxygen in the arterial blood. It is caused by a low Hg concentration, oxygen saturation ($SpO_2 < 90\%$) or a partial pressure of oxygen (PaO_2) less than 60 mm Hg (see later).

The characteristics are a decreased cellular oxygenation and anaerobic metabolism, i.e. the loss of cellular energy production.

Settings where hypoxemia is common are emergency wards, intensive care units (adult and pediatric), long-term care facilities, postoperative wards, pulmonary rehabilitation, bronchoscopy suites, geriatrics, emergency transport, hospices and home care.

The main signs and symptoms are changes in the mental state (ranging from agitation to somnolence), tachycardia, changes in heart rate, tachypnea, decreasing pulse-oxymetry values and cyanosis. (It should be noted that cyanosis is a late sign of hypoxia, because its appearance depends on the reduced Hb content of the blood; and it appears late in anemic patients too.) An acute oxygen deficiency requires urgent intervention, whereas in its chronic forms (e.g. Chronic Obstructive Pulmonary Disease (COPD) patients) very low values are sometimes well tolerated.

Recognition is not always easy. It is diagnosed by only half of the observers only if the arterial oxygen saturation falls under 80%; and one-third of them can not recognize it even if SaO_2 is 75% (see Comroe JH and Bothello S. *The unreliability of cyanosis in the recognition of arterial anoxaemia. Am J Med Sci 1947*).

3.1. Etiology of hypoxia

- Inadequate external respiration (decreased oxygen level in the pulmonary capillaries)
- Inadequate oxygen transport (decreased oxygen-carrying capacity)
- Inadequate internal respiration (decreased off-loading of oxygen at cellular capillaries)

3.1.1. Disturbance of external respiration

The cause may be the low oxygen content or pressure of the inspired gas, inadequate ventilation, or a disturbance in the exchange of gases between the alveoli and the pulmonary capillaries. Oxygen always diffuses from an area of higher partial pressure to an area of lower partial pressure, thus, it should be constantly available and should continuously diffuse across membranes. When the oxygen molecule reaches the circulation it should be able to saturate the transport molecule (Hb). The main causes of inadequate external respiration are:

1. **A decrease in the level of available oxygen in the environment**

- A low oxygen content of the inspired air (inadequate ventilation, smoke inhalation, toxic gas inhalation)
- A low atmospheric pressure (high altitude hypoxia)
- Inadequate ventilatory mechanics, hypoventilation
- A lack of central voluntary respiration (a brain stem lesion or a drug effect)
- Peripheral neuronal system, neuromuscular transmission, or disturbances of respiratory musles (e.g. muscular dystrophy, the effects of muscle relactants, etc.)
- Strong pain (pleurisy or rib fracture)
- Obstructive and restrictive lung diseases, or the retention of excretion
- Problems with ventilatory mechanics (unstable thorax, pneumothorax, or hemo- and hydrothorax)
- Traumatic injuries: crushing injuries of the neck and chest (traumatic asphyxia)

2. **Inadequate oxygen diffusion**

- Lung edema and restrictive respiratory distress (extension of the alveolo-capillary junction, disturbances of diffusion)
- ARDS (Acute Respiratory Distress Syndrome) pneumonia (see above + reduced respiratory surfaces area because of alveolar occlusion—shunt circulation)
- COPD (air trapping in alveoli—loss in respiratory surface area).
- Pulmonary emboli (the surface area available for respiration is unchanged, but is hypo/inadequately ventilated; the membrane surface is functionally appropriate for respiration decreases)
- Upper respiratory tract obstruction (epiglottitis, croup, or pulmonary edema-anaphylaxis)
- Lower respiratory tract obstruction (asthma, pulmonary edema proceed to inhalation of toxic substances)

3.1.2. Inadequate oxygen transport

The main feature of *in vivo* oxygen delivery (DO_2) is that a sufficient arterial oxygen content saturates Hb molecules. The prerequisites of transport are the capacity (a sufficient cell number and sufficient Hb molecules) and an adequate macrocirculation and microcirculation.

The main causes of inadequate transport:

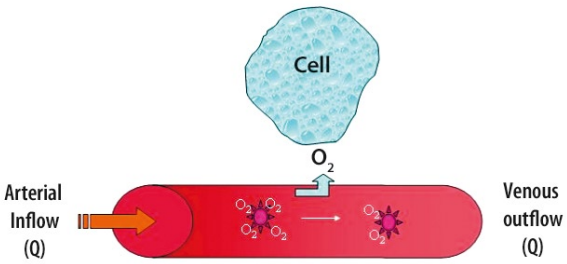
- In anemia, the decreased red blood cell number leads to a decreased transport capacity; or the inadequate amount of Hb leads to an inadequate oxygen delivery capacity and a decreased oxygen content.
- An important cause is carbon monoxide poisoning, with a decreased level of saturation or transport because of the higher affinity of carbon monoxide for Hb (more effective CO binding).
- In circulatory shock, the lower perfusion pressure decreases the oxygen supply.

3.1.3. Inadequate internal respiration

Internal respiration is gas exchange between blood and tissue cells. The Hb molecule must be able to off-load oxygen. Again, the oxygen supply is directed from an area of higher to an area of lower oxygen concentration. The degree of internal respiration may be inadequate in shock (oxygen is not available due to massive peripheral vasoconstriction, microemboli, acute myocardial infarction, etc.); the cellular environment is not conduct to the effective off-loading of oxygen (an acid-base imbalance; a lower than normal temperature); in poisonings (e.g. carbon monoxide poisoning).

3.2. Characteristics of oxygen delivery and utilization

Arterial oxygen content = CaO_2 (vol%) = Hgb × 1.34 × (SaO_2 / 100) + (PaO_2 × 0.003) = ~20 vol%=200 mℓ/ℓ
Venous oxygen content = CvO_2 (vol%) = Hgb × 1.34 × (SvO_2 / 100) + (PvO_2 × 0.003)) = ~15 vol%=150 mℓ/ℓ
Arterio-venous oxygen—partial pressure gradient = CaO_2–CvO_2; normally it is about 5 vol%.

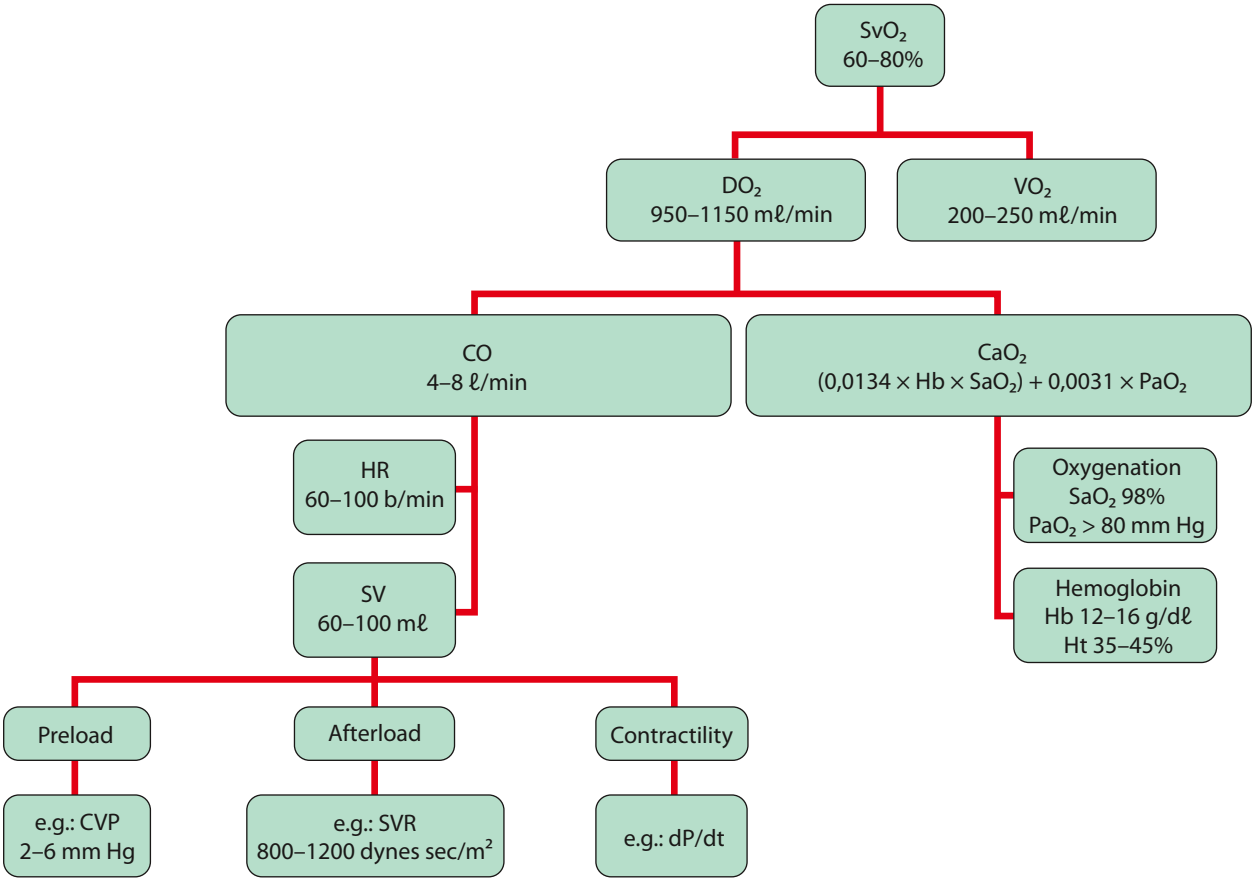


Oxygen transport (DO_2 mℓ/min/m²) = CI (cardiac index ℓ/min/m²) × CaO_2 (mℓ/ℓ) = CI (ℓ/min/m²) × [(Hg × 1.34 (g/ℓ) × (SaO_2 + 0.003 × PaO_2 kPa)]. = 520–570 mℓ/ℓ/m²

The main determinants of the oxygen delivery are Hg, CO, or CI and SpO_2.

The oxygen extraction (ExO_2) is a component of the oxygen availability (%) depending on the metabolism. The oxygen extraction rate (ER) = (SaO_2–SvO_2 / SaO_2) × 100; a normal ER = 20–30%. The rate of extraction varies from tissue to tissue. If ER is 0.65–0.75 for a prolonged period, the danger of organ impairment and a tissue oxygenation disturbance is very high.

The oxygen consumption (VO_2 mℓ/min or mℓ/kg) can be measured precisely by using the Fick equation: it



Factors influencing the oxygen supply/consumption

is calculated on the basis of the relationship between the difference between the arterial and venous blood oxygen contents and the blood flow: $(CaO_2–CvO_2) \times CO$. Its normal physiological value is 250 mℓ/min.

If the Hg concentration, the CO and the A/V saturation are known, VO_2 can be calculated without a knowledge of PaO_2 (the physically dissolved oxygen is less than 0.3 vol% of the total oxygen). In this case VO_2 (mℓ/min) = $CO \times Hb \times 1.34 \times [(SaO_2–SvO_2) / 100]$.

The basal oxygen consumption/extraction can be changed by several factors. For instance if a patient is lying under deep anesthesia on the operating table, relaxed and mechanically ventilated in hypothermia (at –1 °C, a decrease of 7% is expected), then the metabolic need can be 30% or less than in the physiological situation; thus, about a VO_2 of 170 mℓ/min is acceptable occasionally, and a lower DO_2 can be better tolerated.

3.3. Oxygen dynamics

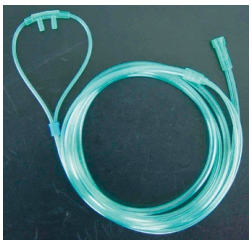
Oxygen delivery (DO_2) > oxygen consumption (VO_2). The physiological DO_2 range is 520–570 mℓ/min/m² on the average. The turning point for a critical minimal DO_2 is the elevation of lactic acid (lactate) in the circulation and an increased tissue CO_2 content ($PtiCO_2$). This indicates the change from an aerobic to an anaerobic metabolism. A cumulative oxygen uptake or consumption deficit develops with an ATP level decrease and a mitochondrial function disturbance, and hence the ATP production decreases. The consequences of an oxygen transport disturbances are:

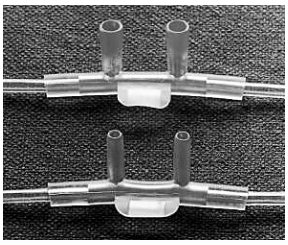
- An altered Na^+-K^+ ATPase activity: cell swelling/dysfunction
- A Ca^{++} influx: activation of phospholipases and proteases
- A decreasing antioxidant defense: a decreasing glutathione level
- Inflammatory cell "priming"
- ATP catabolism (the ADP → AMP → the process passes on to the next, hypoxanthine step. The hypoxanthine → xanthine step is energy-consuming. Hence in hypoxia hypoxanthine accumulates in the tissues, and in reperfusion, reactive oxygen intermediates can be produced by the enzyme xanthine oxidase from the newly available molecular oxygen).

3.4. Oxygen therapy

If the oxygen therapy is provided via a face mask, the oxygen is mixed with air. The oxygen content in the inspired mixture depends on the oxygen flow rate, the construction of the mask and on the amount of expired air exhausted through the opening of the mask.

Nasal prongs fit into the nostrils, they are generally made of plastic.





4. Hypoxia monitoring

The estimation of the oxygen transport and uptake of the body is based primarily on measurement of the oxygen concentration of the inspired gas and oxygen concentration of the arterial blood (see later).

4.1. Low-tech monitoring: laboratory biochemical examinations

Determination of the plasma lactate level (arterial or central venous) is of prognostic value. The examination is sensitive, but not specific (e.g. the plasma lactate level can be elevated in sepsis without any obvious disturbance of the organ perfusion). These methods provide "snapshots of the past".

The base deficit (the amount of base needed to adjust pH to the normal value) is an indirect parameter that is not sensitive but may be specific (a change indicates the adequate elimination of lactic acid). SvO_2, VO_2 and DO_2 are sensitive, but nonspecific parameters of hypoxia diagnosis.

4.2. „High-tech" monitors. Non-invasive blood gas analyses

4.2.1. Historical background

1793 The first detection of gas flow through the human skin (J. Abernathy inserted his arm into a mercury-filled closed glass barrel and noticed gas bubbles over the level of mercury. In: *Surgical and Physiological Essays, London, 1793*).

1851 Von Gerlach fixed a container (a horse bladder) impermeable for external gases to the human skin and observed that the oxygen concentration in the container decreased while the concentration of carbon dioxide increased. He concluded that gas exchange takes place through the skin in close connection with the local blood flow.

1956 The description of the polarographic Clark electrode (*Clark LC: Monitor and control of blood and tissue oxygen tensions. Trans Am Soc Artif Intern Organs 1956; 2: 41–48*).

1967–69 Modified electrodes with temperature control (for maximization of the local blood flow). Noninvasive $PtcO_2$ monitoring was introduced in the neonatal intensive care departments.

1980–84 Parallel measurements of transcutaneous CO_2 and O_2 tensions with one sensor (*Whitehead MD and colleagues, in: Lancet*).

4.2.2. Transcutaneous determination of oxygen and carbon dioxide pressures

For room temperature electrodes, the baseline level of transcutaneous partial oxygen pressure ($PtcO_2$) is nearly zero; with increasing temperature, the blood flow of the skin gradually rises and at 45 °C maximal electrode temperature it reaches a fixed value (the autoregulation of the blood flow and the vasoconstrictor responses stop, and measurements of $PtcO_2$ and $PtcCO_2$ become independent of the blood flow). This is also one of the disadvantages of the method, because a 10–20 min warming period is needed before the beginning of the measurements. Its advantage is that the current generated by modern polarographic electrodes (calibrated with gas-phase oxygen) is also linear between 0 and 100%. The relationship between $PtcCO_2$ and $PaCO_2$ between 2.7 and 8 kPa is also linear. The main fields of *indication* of the method:

- the diagnosis and treatment of prenatal hypoxic states, vascular surgery, plastic surgery, orthopedic surgery, and pressurized medicine
- monitoring of peripheral circulatory oxygenation
- a quantitative description of the seriousness of peripheral vascular diseases
- diagnosis of the optimal level of amputation
- diagnosis of the level of tissue hypoxia in venous circulatory distress

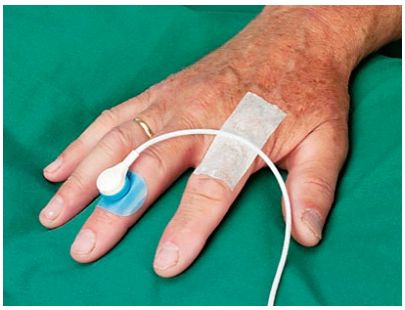
A $PtcO_2$ determination at two or more sites usually gives a complete picture of the patient's oxygenation status. The standard technique of $PtcO_2$ measurement is detailed in the guidelines of the IFCC (International Federation of Clinical Chemistry); here, only the main points are listed:

An indicator/display and an alarm system must be attached to the equipment, which denotes if the measured $PtcO_2$ values are outside the pre-set limit or if the electrode temperature deviates from the selected level.

Calibration should be performed immediately prior to each use and if the site of the electrode is changed. In the case of oxygen (because of the linearity) two-point calibration is enough (see in chapter I).

If the target is not specifically the extremity then the electrode should be applied to the skin of the chest or abdomen (the circulation of the limbs is affected primarily by vasoconstriction, hypothermia, or hypotension).

To avoid skin burns in $PtcO_2$ measurements, the electrode temperature should not exceed 44 °C, and the site of the electrode should be changed at least every 4 h (for newborn infants and peripheral circulation distress it should be changed every 2–3 h).

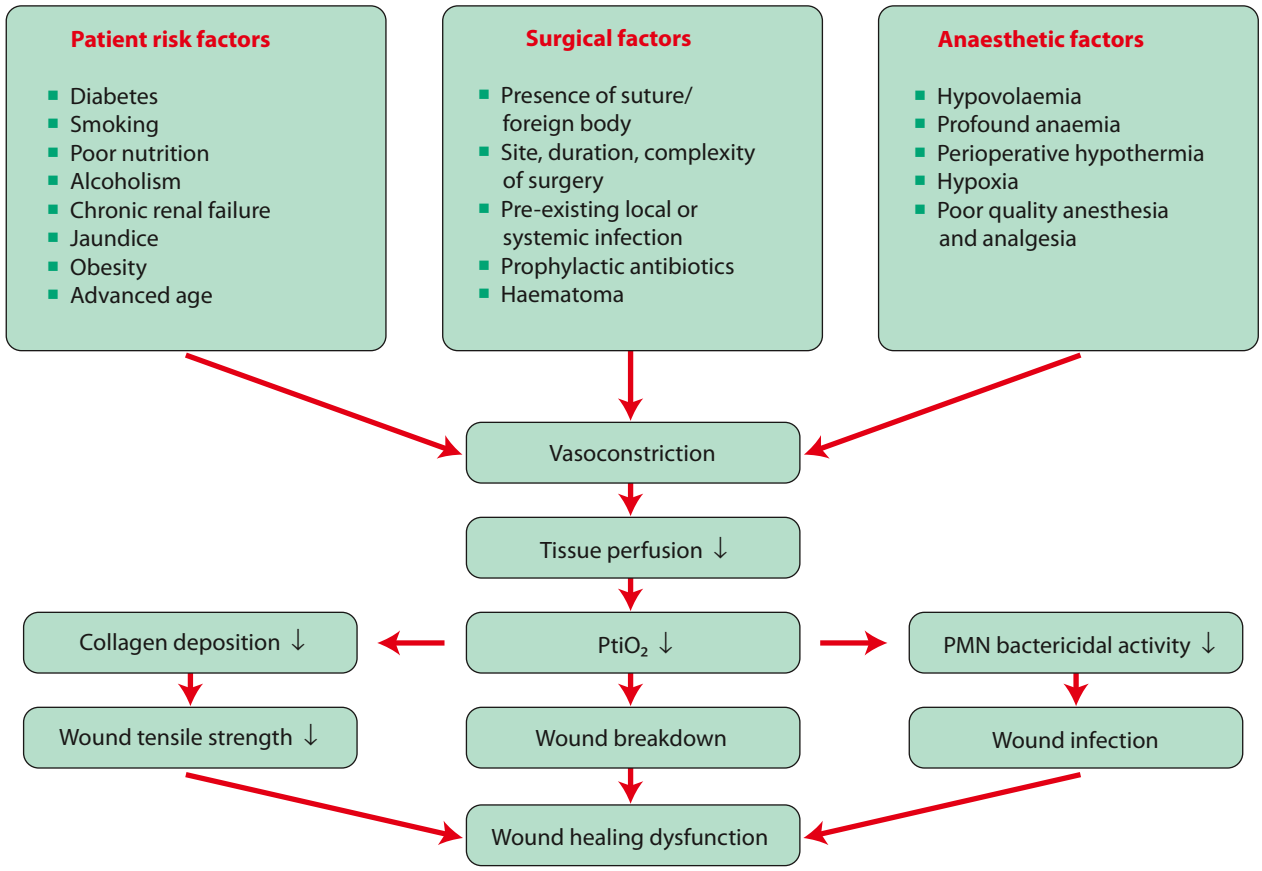


4.2.3. Subcutaneous Clark electrode

The partial oxygen pressure in the subcutaneous tissue ($ptiO_2$) is relatively constant and lower (~1 mℓ kg^{-1} min^{-1}) than overall body average (~ 4 mℓ kg^{-1} min^{-1}); thus, $ptiO_2$ in the subcutaneos tissue is a sensitive indicator of tissue perfusion.

In a polarographic technique (e.g. with the Tissue Oxymeter), an oxygen-permeable catheter (0.8 mm i.d.) is introduced via a 14 G i.v. cannula into the subcutaneous tissue of the deltoid region of the upper arm or the surgical wound. Hypoxic saline, obtained by bubbling nitrogen gas through normal saline for 5–10 min, is introduced into the tube. This is allowed to equilibrate with the tissue oxygen for 15–20 min, after which the saline is sampled for $ptiO_2$.

$PtiO_2$ can be determined with miniaturized, insertable Clark electrodes too, and the monitoring can be direct and continuous in the organs and body fluids.



$PtiO_2$ values provide information on the oxygen supply at a cellular level, and on the tissue oxygen delivery and utilization. Moreover with a dual sensor system, local action potentials can be measured simultaneously (*Thompson et al. Single-neuron activity and tissue oxygenation in the cerebral cortex. Science 2003*).
The main fields of *indication* of measurement:

- Intensive care
- Neurosurgery (the absolute level of oxygenation can indicate the neurological outcome)
- Skeletal muscle $PtiO_2$ monitoring (an early and reliable indicator of stagnant blood flow and tissue hypoxia after hemorrhage, resuscitation, and shock)
- In malignant tumors, $PtiO_2$ may define the hypoxic cell radio resistance

Limiting factors:

- Dependence of electrode currents on tissue temperature
- Errors in $PtiO_2$ readings due to tissue trauma and edema from electrode insertion
- Intravascular misplacement

Surgical significance of tissue oxygen tension determination:

In wounds, the oxygen tension is generally low. $PtiO_2$ is the most important determinant of wound healing and an effective predictor of wound infection (surgical site infection; or SSI). In ventilated patients after colorectal resection, the SSI ratio was 11.2% vs 5.2% when the intraoperative oxygenization was carried out with 30% or 80% FiO_2 (*Greif et al: NEJM 2000*). The bactericidal activity of the neutrophil leukocytes related directly to the $PtiO_2$: the oxygen utilization and generation of reactive oxygen intermediates diminished in parallel with the oxygen pressure. As $PtiO_2$ may be influenced by certain clinical methods, it can be a good indicator of the effectiveness of prophylactic procedures and the treatment of wound infection (*Hopf et al: Arch Surg 1997*).

4.2.4. Fiberoptic pulmonary artery catheter

SvO_2 changes can be measured continuously online with special arterial catheters. The principle of the measurement is based on the absorbance and reflection of light passing through the blood (Beer-Lambert's law).

Indications:

- Intensive monitoring in surgical patients with unstable hemodynamics, e.g. trauma, septic shock
- Serious burns
- Acute respiratory insufficiency, multiorgan failure
- High-risk cardiovascular states

4.2.5. Near-infrared spectroscopy (NIRS)

NIRS is a continuous, noninvasive method in which the principles of light transmission and absorption are applied to determine tissue oxygen saturation. According to Beer-Lambert's law, the absorption of a solution of constant layer thickness depends on the concentration.

NIRS measures oxygenated and deoxygenated Hb and also the redox state of cytochrome C oxidase as an average value for the arterial, venous and capillary blood. The cytochrome of cytochrome C oxidase (c3, the terminal member of the respiratory chain) is responsible for ~ 90% of the cellular oxygen consumption through oxidative phosphorylation. The redox state of cytochrome c3 is decisively determined by the available oxygen. A decrease in cellular DO_2 is linked to the reduction of oxidative phosphorylation and a decreased level of cytochrome c3 oxidation.

Monitoring of the redox state of cytochrome aa3 is a key indicator of an impaired cellular oxidative metabolism and tissue dysoxia. The main field of *indication* is the monitoring of cerebral oxygenation and peripheral muscle (e.g. in the palms at the eminentia thenaris) oxygenation after different types of hypoxic injuries (but NIRS may be applied in almost any organ, e.g. the kidneys). One limitation is the inability to make quantitative measurements (because of the contamination of the light by scattering and absorption).

4.2.6. Intravital video-microscopy

Every molecule has a characteristic set of energy levels, and a set of allowed transitions between them. The emission spectrum is characteristic of the molecule, and is independent of the excitation wavelength: a stable part of the molecular signature. Once reached by radiation, fluorochromes can partially absorb light and partially reflect it: the re-emitted radiation has a lower energy than that of the incident energy and thus a longer wavelength. If the incident radiation is an ultraviolet ray, i.e. invisible, the emitted radiation can usually be seen. Fluorescence microscopy permits the localization of molecules labeled with fluorochromes in cells or tissues.

Most biological samples emit fluorescence only after labeling with fluorochromes (secondary fluorescence), but various natural molecules, e.g. collagen, cellulose, etc. emit fluorescence naturally (primary or autofluorescence). Autofluorescence is occasionally a diagnostic advantage (there is no need to apply a fluorochrome). NADPH and NADH emit strong fluorescence at 460 nm; NAD and NADP fluoresce three orders of magnitude more weakly. By fluorescence intravital video-microscopy, the local NADH and NADPH changes can be monitored (a general consequence of hypoxia is elevation of the local tissue NADH and NADPH concentrations).

In an intensified fluorescence intravital video-microscopy system, fluorescence dyes are used to stain nonfluorescent samples. The fluorescent signal is received through the microscope by the CCD camera. The image is sent to the frame grabber to digitize the signal for image processing. The processed signal is then sent to a monitor for display, and permanently recorded for later playback and analysis.

4.2.7. Indirect tonometry

The detection of oxygenization and ischemia may be possible independently from the blood flow by measuring the regional pCO_2 and pH directly (direct tonometry). The main field of application of the indirect method is the determination of the intramucosal pH by tonometry in the stomach and sigmoid intestine. The method is based on intragastric (or intra-sigmoid, etc.) CO_2 partial pressure ($PgCO_2$) measurements. The significance of PCO_2 accumulation can be best described in the small intestine, where the counter-current villus circulation with decreasing pO_2 toward the tip cannot provide the tip of the villi with sufficient oxygen in the event of decreasing perfusion. The mismatch between mucosal perfusion and regional metabolism leads to a regional imbalance between CO_2 removal and production, and as a result CO_2 accumulates in the mucosa.

$PgCO_2$ indicates the balance between CO_2 production (metabolism) and removal (perfusion). An elevated $PgCO_2$, and regional hypercapnia is therefore a marker of inadequate tissue perfusion and/or a deranged metabolism, and this can be detected by measuring $PgCO_2$. The normal $PgCO_2$ value approximates to the arterial PCO_2 ($PgCO_2$ = 45 mmHg (6 kPa). It is recommended to compare it either with $PaCO_2$ or with $ETCO_2$. The intramucosal pH (pHi) is then calculated via the Henderson-Hasselbalch equation.

The $PgCO_2$ measurement is minimally invasive. A special tonometry catheter and monitor are used to analyze PCO_2 with infrared sensor technology. In saline tonometry, the multiple-lumen catheter includes a semipermeable silicone balloon at the distal end of the catheter, which is positioned in the stomach. CO_2 equilibrates freely between the gastric mucosa, the gastric lumen and the balloon. A gas sample is drawn from the balloon and analyzed every 30 min (conventional tonometry); or in air-automated tonometry, a 10-min equilibration time is used. This latter technique can improve the precision of $PgCO_2$ determination significantly. The *indication* is a low-flow state in general (hypovolemic, cardiogenic shock) when vasoconstriction is established in the gastric mucosa. Gastric tonometry works as an early warning measurement to detect gastric hypoperfusion prior to systemic variables. $PgCO_2$ may provide earlier information as compared with pHi (a better therapeutic index). When DO_2crit is

reached, anaerobic CO_2 production contributes to the increased $PgCO_2$, while the arterial pH decreases and favors a decrease in intramucosal pH (pHi). When pHi is used to guide treatment, therapeutics might prove to be ineffective if pHi is already low. Conditions requiring gastrointestinal mucosal PCO_2 monitoring:

- Trauma, major surgery, e.g. cardiac patients
- Hemorrhagic shock, cardiogenic shock
- Severe acute respiratory failure
- Severe acute pancreatitis
- Major burns

5. Hypoxia in general circulatory disturbances. Direct monitoring of the acid-base balance

5.1. Basic principles

pH is the negative logarithm of hydrogen ion concentration; because of the logarithmic scale, a significant change in H^+ concentration results in only a small pH change (e.g. the pH decrease from pH 7.4 to 7.0, is associated with a 2.5-fold increase in acidity). Among the buffer systems of the human body, bicarbonate regulates the pH of the whole system, because CO_2 diffuses well. (It acts at two points: HCO_3^- through the kidneys, and CO_2 through the lungs: $H^+ + HCO_3^- <=> H_2CO_3 <=> H_2O + CO_2$).

The aims of blood-gas analysis are to establish the blood-gas status of the patient (oxygen uptake, CO_2 release in the lungs, blood pH, to acquire information on the normal function of the lungs and kidneys (these organs are important in maintaining the acid-base balance) and to diagnose diseases (respiratory system, kidneys, gastrointestinal tract, etc.).

5.2. Blood-gas analysis

The analytical process has three main stages: **1.** in the first stage a sample is taken for gas analysis in accordance with the instructions, and the sample is than transported (immediately or after temporary storage) to the site of analysis followed by; **2.** the analysis itself (with a blood-gas analyzer), and **3.** interpretation of the results, start or change the therapy. Modern, up-to-date blood-gas analysers are automated instruments supplied with printer and microprocessor control. The following parameters can be measured and calculated:

Depending on the type, measured blood-gas and acid-base parameters:

- pO_2 = partial pressure of oxygen
- pCO_2 = partial pressure of CO_2
- pH = blood pH

Calculated parameters with temperature and cHb data:

- BE = actual base excess/deficit
- BEecf = standard base excess in the interstitial fluid
- HCO_3^- = actual bicarbonate
- SaO_2 = oxygen saturation
- ctO_2 = total oxygen concentration (content)
- p50 = oxygen pressure at 50% saturation of the blood

Metabolite concentrations (cLactate, cGlucose) and electrolyte concentrations (cK^+, cNa^+, cCl^- and cCa^{2+}) are also measured. The input parameters are the data on the patients, the type of sample (detected by modern instruments), the body temperature, and ctHb (total Hb concentration). The instrument has a sample sensory system which detects air bubbles in the sample, controls the position of the sample, and determines the volume of the sample. About 55 μℓ total blood is required; the results are ready within 20 s. Major parameters influencing blood-gas analysis:

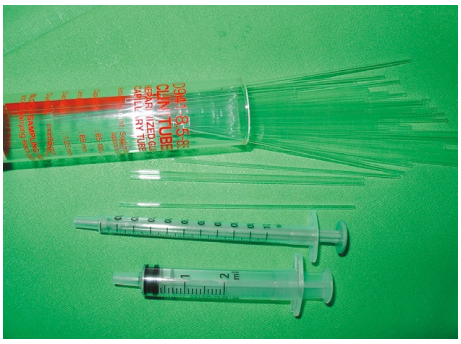
- increase (paO_2 and $paCO_2$ increase) or decrease (paO_2 and $paCO_2$ decrease) in temperature
- paO_2 and $paCO_2$ decrease in hypothermia
- smoking (CO generation): paO_2 decrease
- air bubbles in sample: false paO_2 increase
- long time (more than 30 min) storage

5.3. Fundamental acid-base parameters

Parameter	Normal value	Unit	Remarks
pH	7.35–7.4–7.45	No units	
pCO_2	4.8–5.3–5.9 36–40–44	kPa mm Hg	Respiratory component Not determined on capillary blood
pO_2	11.9–13.2 90–100	kPa mm Hg	At sea level, $FiO_2 = 21\%$; at high altitude it is lower. It indicates the oxygenization of the patient; it should not be confused with the acid-base equilibrium.
HCO_3^- (actual bicarbonate)	22–24–26	mmol/ℓ	Lung component. It changes if pCO_2 is pathological.
Standard bicarbonate	22–24–26	mmol/ℓ	More useful than the actual bicarbonate level. It is measured after the sample has been equilibrated with CO_2 at 40 mm Hg (5.3 kPa).
Base excess	–2, 0, +2	mmol/ℓ	A renal, metabolic component. A negative number indicates base deficit.

5.4. Sampling

- Appropriate tools have to be used in sampling and the samples should be handled according to the prescriptions as otherwise an inaccurate result is obtained. An erroneous result can be more dangerous than no result.
- An arterial blood sample can be obtained by direct puncture or through an arterial catheter. The requirement for arterial sampling sites are that the artery should be large enough, superficial and easily accessible (in particular radial-brachial-femoral arteries). The puncture should be performed quickly; there is usually no need to introduce a catheter. It may be painful, and sometimes it is difficult to find the vessel, so it carried out only by experts.
- With a catheter, it is easier to draw blood, it does not cause pain, and sampling can be repeated without risk; but the risk of infection is higher and thrombus may occur. Through a central venous catheter, mixed venous blood sampling is possible (only in a steady state, in ambulant cases in a lying position, 3–5 min following introduction of the catheter (in a ventilated patient 10–20 min later); the respiratory parameters should be changed only after a steady state has been achieved).
- Tools for sampling include sterile gloves, a sterile syringe (with 23–25G sterile needles), micro-sampling capillary tubes, disinfection solution and heparin.



The accessories of the sampling instrument (in this case the AVL Medical Instruments device is shown) are a 26G (0.45 mm diameter) sterile needle and heparinized capillaries. The micro method is simple and atraumatic.

Arterial puncture

- An adequate amount of anticoagulant (heparin, 50–100 U/mℓ blood) is inspired into the syringe before sampling.
- The skin is disinfected at the site of sampling (similarly as in venous sampling).
- After pulse control and local anesthesia of the wrist, the puncture follows. A pulse-oxymeter clip is placed on one of the fingers for noninvasive oxygenation monitoring (optional).
- The artery is punctured at 45–90°, the needle being held against the blood flow. The blood pressure in the artery fills the vacuum capillaries in the syringe (240 μℓ) with blood.
- Air bubbles are removed from the syringe and it is closed with a cap. The sample is carefully shaken with the heparin inside, so that microthrombi do not form (thrombi lead to inaccurate results and occlude the blood-gas analyzer).
- Pressure is applied to the site for several minutes to ensure that there is no bleeding.
- The blood-gas parameters can change significantly in a short time. Accordingly besides the date and time, other parameters (as the data relating to the patient's state, body temperature, sampling site, made of respiration, as well as the continuously monitored respiratory and circulatory parameters) must be recorded, in order to correlate the blood-gas values with these data.
- After sampling measurement is performed at once (or within at most 10 min). If this is not possible, the sample should be stored cooled (in chilled water, at 0–4 °C) for not longer than 30 min (the cell metabolism decreases).
- The homogeneity of the sample is important: it should be mixed directly before analysis to prevent sedimentation of cells. The first few drops are not typical of the whole sample and hence should be discarded from the syringe.

Capillary blood samples

- A heparinized glass capillary is used. Before sampling, the circulation of the fingertip (or earlobe, or possibly the heel) is enhanced by massage or by heat. Then, after disinfection, a wound of standard depth is made.
- The first drop of blood is removed with a sponge. The capillary is filled from the next drop, without air bubbles, and both ends are then closed simultaneously.
- The blood in the capillary is thoroughly mixed with the anticoagulant and the sample is transported to the laboratory immediately.

Venous blood sampling

- Sampling is made regularly via a central venous

catheter; in the case of a peripheral vein, the blood is drawn without strangulation. For plasma, sampling is made from the venous blood. Equilibration through atmospheric air should be avoided during centrifugation or handling of the sample.

5.5. Most common causes of acid-base disturbances from a surgical aspect

Respiratory acidosis
pH < 7.35 and $paCO_2$ > 45 mm Hg. $PaCO_2$ increases (CO_2 formation is higher than CO_2 elimination) in airway obstruction, ventilation-depressing drugs, head trauma, ARDS, and lung diseases: in all cases when the ventilation is not adequate.

Respiratory alkalosis
pH > 7.42 and $paCO_2$ < 35 mm Hg. $PaCO_2$ decreases due to pain, respiration stimulating drugs, cardiac failure/heart attack, hypoxia, fever, shock and lung emboli. CO_2 elimination from the lungs is more effective than the O_2 uptake, and thus lung patients in the first phase of their illnesses are often hypoxemic with a normal or low CO_2.

Metabolic acidosis
pH < 7.35 and HCO_3^- < 22 mEq/ℓ. HCO_3^- decreases (base deficit) because of gastrointestinal bicarbonate loss, chronic renal disease, inorganic acids (e.g. diabetic ketoacidosis or lactic acidosis with tissue hypoxia), salicylates, ethylene glycol, toxins or renal failure (because of decreased acid secretion).

Metabolic alkalosis
pH > 7.42 and HCO_3^- > 26 mEq/ℓ. A HCO_3^- increase (base excess) occurs during gastric acid loss (e.g. vomiting or pyloric stenosis) or in loop diuretic therapy (a low serum chloride level).

Several other, mixed forms are known (two or three of the alterations can occur in parallel). Mixed respiratory and metabolic acidosis ($PaCO_2$ increases and HCO_3^- decreases) is an example; it occurs in severe diseases such as Multiple Organ Failure (MOF), heart and/or respiratory failure.

5.6. Hypoxemia and hypercapnia

	Hypoxemia (arterial pO_2 kPa)	Hypercapnia (arterial pCO_2 kPa)
Mild	>11	6.1–6.6
Moderate	6–10	6.7–8
Serious	<6	>8

5.7. Endogenous restoration of acid-base balance

Deviation	Response	Blood pH	Blood pCO_2	Blood BE	Urine pH
Metabolic acidosis	decompensated	decreased	normal	decreased	
	compensated	nearly normal	decreased	decreased	decreased
Metabolic alkalosis	decompensated	increased	normal	increased	
	compensated	nearly normal	increased	increased	increased
Respiratory acidosis	decompensated	decreased	increased	normal	
	compensated	nearly normal	increased	increased	decreased
Respiratory alkalosis	decompensated	increased	decreased	normal	
	compensated	nearly normal	decreased	decreased	decreased

5.8. Algorithm for blood gas analysis evaluation

1.	Is the overall picture normal acidemia or alkalemia?	pH < 7.35 = acidosis [→ point 2] pH > 7.45 = alkalosis [→ point 5]
2.	If there is acidemia: is the primary defect metabolic or respiratory or mixed?	CO_2 high = respiratory acidosis [→ point 3] HCO_3^- low or Base Excess (BE) negative = metabolic acidosis [→ point 4] Both of the above = mixed metabolic and respiratory acidosis
3.	If there is respiratory acidosis, is there metabolic compensation?	The CO_2 is high (respiratory acidosis) but the metabolic component has moved in the opposite direction (BE or SB high, towards metabolic alkalosis), i.e. metabolic compensation
4.	If there is metabolic acidosis, is there respiratory compensation?	BE is negative (metabolic acidosis) but the respiratory component has moved in the opposite direction (CO_2 low, towards respiratory alkalosis), i.e. respiratory compensation
5.	If alkalosis is present, is the primary cause respiratory or metabolic?	The primary defect moves in the same direction as the pH (towards alkalosis): respiratory alkalosis gives a low CO_2 while metabolic alkalosis gives a high SB (Serum Bicarbonate) and a positive BE (Base Excess)
6.	If there is metabolic or respiratory alkalosis, is there any compensation by the other?	Same principles as above.
7.	What is the oxygenation picture?	Is the pO_2 consistent with the FiO_2? If it is lower than expected, This indicates either lung disease, a right to left shunt, or a venous sample. (A venous sample usually has pO_2 < 40 mm Hg, saturation < 75%). If CO_2 is very high, the oxygen level is generally low The lung is much more efficient at eliminating CO_2 than absorbing oxygen so lung disease will show in a low pO_2, whereas the pCO_2 is often normal or even low. If the CO_2 is very high, the oxygen level low
8.	Can the cause be established?	For instance there is metabolic acidosis (because the pH is low and BE is negative) with respiratory compensation (because pCO_2 is low)

VI. Temperature monitoring

"If the thermometer had been an inch longer we'd have frozen to death"
Mark Twain (1835–1910)

The normal human temperature is usually 37 °C, but it can vary by 1–1.5 °C. The core temperature is controlled to ~ 0.2 °C. The core temperature is the temperature of the inner organs. Depending on the site, the temperature is 4–5 °C less on the surface. The body temperature depends on the covering, the tissue water content, the lifestyle, the time of day (it is higher in the late afternoon, due to emotion, work, etc.) and the site of measurement:

- in the rectum: 37,1± 0,4 °C
- oral cavity: 36,7± 0,4 °C
- axillary: 36,5 ± 0,4 °C

The rationale for the use of temperature monitoring may be diagnosis, the prevention of hypothermia or fever, the monitoring of deliberate hypothermia, the monitoring of cooling or rewarming during cardiac surgery and measurement of cardiac output by thermodilution. Measurement sites include the esophagus, nasopharynx, axillary region, rectum and bladder.

1. Measurement of body temperature

The scaling is very important. Zero on the Fahrenheit scale is the temperature of a mixture of equal parts of ice, water and salt (ammonium chloride). Zero point on the Celsius scale (also known as centigrade) is the freezing point of water. Zero on the Kelvin scale (the natural point for a temperature scale) is the point at which all particle motion stops. Its unit (Kelvin) is equal to the magnitude of 1 °C.

1.1. Mercury thermometer

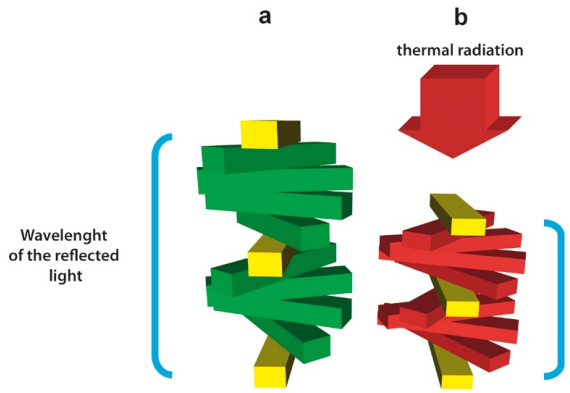
With a mercury thermometer, the measurement is based on an exponential curve. The set time is 3–4 min (10 min in the axillary region). The precision is ± 0.1 °C (between 35 and 42 °C).

1.2. Thermography

In infrared thermography devices, the equipment detects the infrared energy emitted from an object, converts it to temperature, and displays an image of the temperature distribution (infrared is the electromagnetic wavelength between 0.7 and 1 μm; the frequency is 300 GHz or more).
Indications are:

- breast pathologies
- inflammation
- research
- nerve problems/arthritis diagnosis
- predisposition (varicose veins)

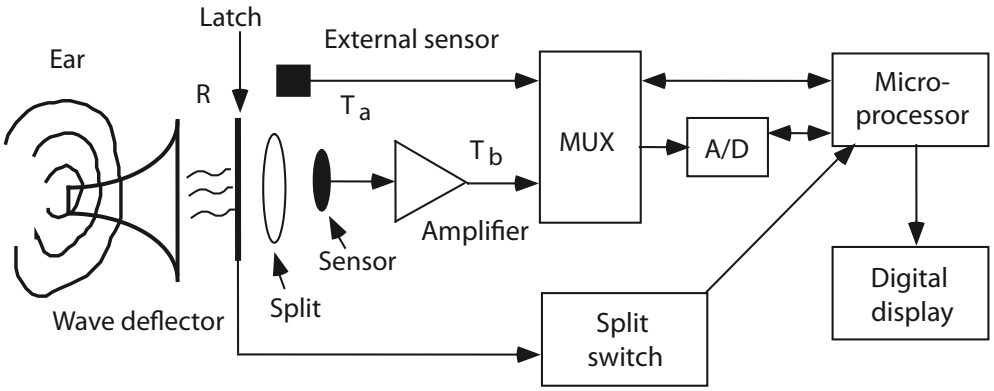
1.3. Liquid crystals (home diagnostics)



The principle of liquid crystal temperature measurement. The crystal structure, resembling a spiral stairway, reflects long-wavelength light (a) under resting circumstances. When the crystal is exposed to heat, the layers are compressed on each other, their torsion is increased and the distance between the spirals decreases (b). The crystal now reflects light with lower wavelength.

1.4. Electronic temperature measurement

- Platinum-based sensors (the resistance changes linearly between 0 and 100 °C).
- In thermistors (tainted metal oxide semiconductors with negative temperature coefficients), the resistance decreases as the temperature rises. The large output signal results in a high degree of precision. Thermistors give stable signals and are capable of maintaining in-calibration performance for long periods of time. They are more accurate than thermocouples.
- Temperature-sensing integrated circuits: amplifiers with built-in temperature-sensitive semiconductor elements.



Infrared thermometer: During measurement, an interlock opens and thermal radiation (*R*) passes to the sensor from the air. The infrared radiation flux is: $NT = A\,\sigma\,\varepsilon a\ (T^4b - T^4a\ )$ where *A* is the target area, σ is the Stefan-Boltzmann constant, εa is the environmental radiation (sensor), Tb is the body temperature, and Ta is the sensor temperature.

VII. Monitoring of the central nervous system

"The chief function of the body is to carry the brain around"
Thomas Alva Edison (1847–1931)

Monitoring of the central nervous system is one of the main topics in the neurology and radiology courses. Only the most important methods will be mentioned here:

- Sensorium, reflexes, "wake-up test"
- Electroencephalography
- Evoked potentials (especially somatosensory, acoustic and visual EPs)
- Brain angiography, DSA
- Monitoring for venous air emboli (see the section on capnography),
- Cerebral oximetry (see section on NIRS),
- Intracranial pressure (ICP) monitoring (see the details in the traumatology and neurosurgery material)

Intracranial pressure

The ICP is the sum of the pressures of the brain tissue, the cerebrospinal fluid (CSF) and the cerebral blood supply within the intracranial space. The skull is basically a closed system, and thus an increase in volume will produce an increase in pressure. The Monro-Kellie theory states that the body can compensate for changes in the volume of these three components so as to maintain a normal ICP: *Vintracranial Vault* = *Vbrain* (80% of the total volume) + *Vblood* (10%) + *Vcsf* (10%).

The normal ICP in an adult is 0–15 mm Hg, it can not surpass 40 mm Hg without causing harm. Values in the interval 25–30 mm Hg are considered fatal if they are prolonged, while over 60 mm Hg the mortality is 100%.

The main etiologies of an ICP increase include conditions increasing the brain volume, the blood volume or the CSF volume:

- Anxiety/stress
- Elevated pCO_2
- Brain edema
- Bleeding/other mass lesions
- Traumatic brain injuries
- Lyme disease
- Hydrocephalus
- Brain tumor
- Severe hypertension
- Venous sinus thrombosis
- Restricted jugular venous flow

ICP-monitoring technologies

To monitor ICP, a catheter is placed inside the skull. Ideally, it can be used for monitoring and treatment simultaneously (it can be used to take out excess CSF, thereby decreasing the ICP). The main types of devices for monitoring ICP are intraventricular catheters, fiberoptic monitors, subarachnoid bolts and epidural monitors.

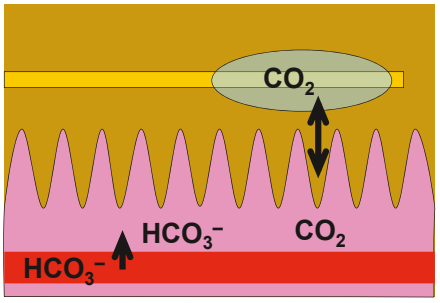
- Ventricular catheters are external strain gauge transducers or catheter tip pressure transducer devices. These widely used, accurate and reliable, relatively low cost devices allow therapeutic CSF drainage. A complication can be meningitis (~ 7% if monitoring is prolonged over a week).
- A fiberoptic probe is relatively new technology; it is inserted into the brain/ventricles/epidural or subdural space. The probe contains a transducer that measures pressure on the tip. It gives very accurate waveforms comparable to those with intraventricular catheters; it does not require a fluid-filled transducer system, but no CSF can be withdrawn.
- The subarachnoid bolt is a hollow metal screw which is placed just through the skull in the space between the arachnoid and cerebral cortex so that the tip is resting in the subarachnoid space. It is relatively easy to install. It measures ICP directly. Access for drainage, sampling and volume-pressure response measurements is possible, but it has limited accuracy.
- The epidural monitors are recording devices that are placed into the epidural space (between the inner surface of the skull and the dura mater). These are the least invasive, but their accuracy is uncertain.

VIII. Monitoring of the gastrointestinal tract

Monitoring of the gastrointestinal circulation, oxygen dynamics and structure have in part been summarized above (see indirect tonometry, intravital video-microscopy, etc. in Chapter VI) and for further details the relevant parts of radiology and internal medicine textbooks (i.e. endoscopy, imaging techniques, etc.) are available. The main subject of this module is the functional monitoring of the gastrointestinal tract, including the nutritional status and feeding.

1. Indirect measurement of the mucosal pH of the stomach / small intestine /sigmoid bowel

The counter-current exchanger system of the intestinal microcirculation results in the tissue pO_2 content decreasing from the base of the villi toward the villus tip. During flow reduction, adequate tissue oxygenation can not be ensured at the apical part of the villus. The mismatch between regional perfusion and metabolism, however, leads to an imbalance between CO_2 removal and production: as a result, CO_2 accumulates in the mucosa. This phenomenon can be detected in the cavernous organs (the stomach and intestines) through the luminal measurement of CO_2 ($PgCO_2$). In the stomach, the mucosal pCO_2 ($PgCO_2$) is indicative of the balance between the CO_2 production (metabolism) and removal (perfusion). An increase in PCO_2 (regional hypercapnia) can be a good indicator of an inadequate tissue blood flow and/or an exaggerated metabolism. Under physiological conditions, $PgCO_2$ (normal value) is equal to the arterial pCO_2 ($PgCO_2$ = 45 mm Hg (6 kPa). Comparison of $PgCO_2$ and the arterial PCO_2 or $ETCO_2$, however, is highly recommended.



$$pH_{mucosa} = 6,1 + \log \frac{HCO_3^-}{CO_2 \times 0,03}$$

1.1. Advantages of $PgCO_2$ monitoring

The gastrointestinal mucosa is the target of blood flow redistribution during shock, trauma and major surgical interventions: vasoconstriction evolves in the mucosa in low cardiac output states. The small intestine is one of the first organs to suffer from hypoperfusion and one of the last to be restored upon resuscitation. Hence, a gastrointestinal mucosal damage caused by a splanchnic circulatory failure can play a crucial role in the etiology of sepsis and multiple organ failure. Gastric tonometry is an appropriate tool for the diagnosis of early gastric hypoperfusion (before the development of systemic symptoms).

1.2. Determination of $PgCO_2$ with minimal invasive tonometry

1. A special tonometry catheter and monitor are used to analyze PCO_2 with infrared sensor technology.
2. Saline tonometry: a multiple-lumen catheter includes a semipermeable silicone balloon at the distal end of the catheter, which is positioned in the stomach. CO_2 freely equilibrates between the gastric mucosa, the gastric lumen and the balloon.

2a. A gas sample is drawn from the balloon and analyzed every 30 min (conventional saline tonometry);

2b. A 10-min equilibration time is necessary in automated air-tonometry. This technique can improve the precision of $PgCO_2$ determinations significantly.

1.3. Gastric tonometry

The idea of gastric tonometry was developed by Domokos Boda (professor of pediatrics at the University of Szeged, see in *Lancet, 1959*). *Indications* of gastrointestinal $PgCO_2$ monitoring:

- trauma
- major surgical interventions, e.g. cardiac surgery
- bleeding, hemorrhagic shock
- cardiogenic shock
- severe acute respiratory failure
- severe acute pancreatitis
- major burns
- sustained artificial respiration

The advantage of $PgCO_2$ over pHi (the intramucosal pH calculated on the basis of the Henderson-Hasselbalch equation) is the better diagnostic value. The reason for this is that anaerobic CO_2 production contributes to the increased $PgCO_2$ when DO_2 reaches a critical level. Meanwhile, the arterial pH also decreases and contributes to the decrease in pHi. If we wait for the changes in pHi in these cases (when pHi is already low), therapeutic intervention can be late and ineffective.

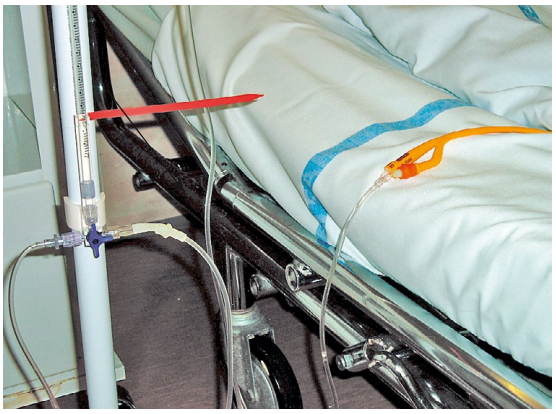
2. Measurement of intraabdominal pressure

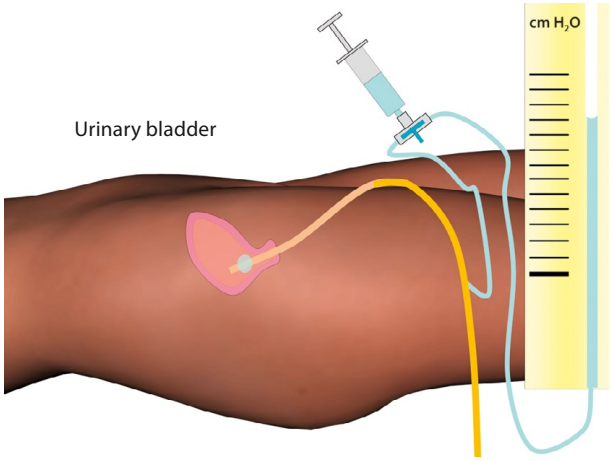
The abdominal compartment syndrome (ACS) is one of the major indications of intraabdominal pressure measurements. This is a severe, often life-threatening syndrome which usually develops as a consequence of pancreatitis, pneumoperitoneum (surgery), trauma, bleeding, ascites, malignancies, outer compression (burns), peritonitis or sepsis. Its pathophysiological basis is a sudden increase in intraabdominal pressure (IAP). As the abdominal pressure is transmitted to the urinary bladder, the IAP can be determined reliably and noninvasively by measuring the intravesical pressure. A Foley catheter is inserted into the bladder (see later) and is filled with a standard volume (e.g. 100 mℓ) of physiological saline. A pressure transducer is attached to the catheter through a 3-way stopcock. The fluid pressure in the bladder can be detected with a system used for the measurement of CVP. Attention should be paid to the setting of the zero point of the system at the level of the bladder. The values are expressed in cmH_2O (1 mm Hg = 1.36 cmH_2O = 0.13 kPa) during expiration after waiting for 1 min.

The normal abdominal pressure is 5–7 mm Hg. The abdominal perfusion pressure is calculated as mean arterial pressure minus abdominal pressure. The stages of intraabdominal hypertension are:

Stage I: 12–15 mm Hg; the splanchnic perfusion decreases
Stage II: 16–20 mm Hg; hypervolemic fluid therapy for maintenance of the perfusion pressure gradient for the intraabdominal organs
Stage III: 20–25 mm Hg
Stage IV: >25 mm Hg; urgent decompression surgery is indicated

The ACS is thus defined as permanent, severe intraabdominal hypertension (>25 mm Hg), accompanied by a potential new organ failure.





3. Monitoring of the nutritional state

Appropriate nutrition ensures the normal activity of the organism and the energy balance. Determination of the nutritional state can be important when an invasive intervention is planned as malnutrition results in a higher frequency of complications. The occurrence of marasmus (a protein-energy deficiency) or kwashiorkor disease (a nutritional disorder involving a protein deficiency) is nowadays very rare, but the Hungarian statistics indicate that 15–60% of patients are malnourished upon hospital admission. A nutritional assessment comprises a synthesis of subjective and objective data.

The basal energy expenditure (BEE) is measured at an indifferent room temperature, in immobilized patients with an empty stomach. The basal daily calorie expenditure can be calculated via the Harris-Benedict equation:

BEE (male) = 66 + (13.7 × W [kg] + (5 × H [cm]) + (6.8 × [age]).

BEE (female) = 655 + (9.6 × W [kg] + (1.8 × H [cm]) + (4.7 × [age]).

The normal resting energy expenditure (REE) is BEE + 10%.

3.1. Measurement of the basal energy expenditure

BEE can be measured indirectly or directly, by means by calorimetry:

- In a layer-gradient calorimeter, thermocouples measure the temperature difference across the wall of the device. The accessories are the ventilatory and measuring units.

- The air-flow calorimeter measures the temperatures of the inhaled and expired air, their flow and humidity, and the heat loss is then calculated by using the following equation: $Qa = mca\ (T_2–T_1)$, where m= air flow rate, ca= a heat constant, and $T_2–T_1$= temperature difference.
- The water-flow calorimeter measures the temperatures of the in- and outflowing water.
- The supplementary (compensatory) calorimeter requires less thermal energy when the patient produces more heat.
- The indirect calorimetry is based on measurement of the inhaled O_2 and the CO_2 produced; measurements can be made continuously on artificially ventilated patients with adequate equipment.

3.2. Perioperative nutrition

The international statistics demonstrate that 5–15% of hospitalized patients require complete, partial or artificial (enteral or parenteral) nutrition. A balanced feeding-nutrient supply and the optimal nutritional status are essential for the prevention or treatment of surgical complications. Malnutrition delays wound healing, and is accompanied by a decreased respiratory output, an impaired immunological status and an increased risk of infections.

A pathological nutritional status, or malnutrition, occurs as a consequence of a relative or absolute deficiency, or an excess of one or more nutrients. Malnutrition which is not due to economic-social reasons is primarily a consequence of organic and/or psychological diseases. A secondary, iatrogenic nutritional status, however, is a more frequent phenomenon, which often results from an inappropriate medical approach. Malnutrition can *per se* lead to hazardous conditions: an increased risk of infections, enhanced edema formation, intravasal transport disorders and coagulopathy can evolve as a consequence of decreased protein synthesis, with the slowdown of intellectual activities.

If malnutrition is combined with other pathological states (operation or trauma), it can lead to delayed wound healing, a higher risk of complications and increased mortality. The relationship between weight loss and increased surgical risk can be expressed as follows:

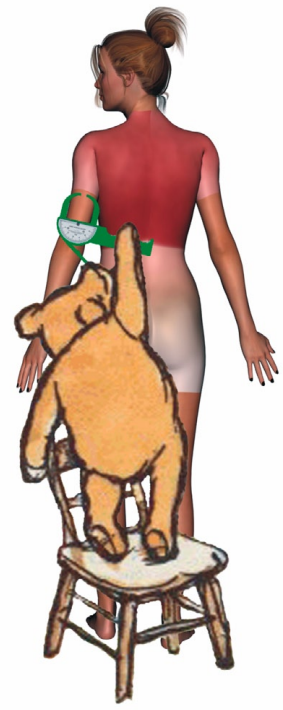
- 10–15%: mild
- 20–25%: moderate
- 30–35%: severe
- 40%: life-threatening

The protein malnutrition of hospitalized patients is the most common pathological nutritional state. Malnutrition can develop rapidly in stress situations (acute disease, trauma, burns or operation) and chronic disease states.

- A 2–3-day period of fasting is not accompanied by consequences other than a 2–3% weight loss in healthy adults.
- A decreased nutrient uptake lasting for more than 1 week can lead to serious consequences, even in healthy, young adults.
- A 60–70-day nutrient withdrawal (i.e. food denial) can be lethal. In childhood and old age, these hypercatabolic states notably speed up. The aims of artificial nutrition are the prevention and treatment of malnutrition states, or the normalization of pathological nutritional states.

3.3. Assessment of a pathological nutritional state

Nutrition can be judged clinically via the weight loss, and the assessment of a nutritional state can be based on subjective and objective data such as 1. the nutritional history, 2. anthropometry, 3. laboratory and 4. immunological tests. When the case history is recorded, primarily the nutritional habits and dietetic factors should be clarified, together with the changes in body weight over a time period. During the anthropometric evaluations, the current body weight and height are measured, as is the thickness of the skinfold over the triceps muscle for an estimate of the fat depots. For muscle mass measurements, the circumference of the nondominant upper arm is used. The measured values can provide the basis of further calculations (e.g. body mass index, body surface and upper arm circumference). The muscle power can be judged on the basis of the ripping power. The above anthropometric measurements allow the nutrition to be judged as appropriate, or moderately or severely impaired.



Lange skinfold calipers are used to assess the thickness of the subcutaneous fat, which is performed above the triceps skinfold, in the midline posterior surface of the arm over the triceps muscle. The male skinfold is >10 mm and the mid arm circumference is >23 cm. The female skinfold is thicker, at >13 mm, and the female mid arm circumference is >22 cm. Values <60% of the standard indicate malnutrition.

Laboratory-biochemical examinations provide nutritional data on the basis of the protein metabolism. Blood levels of albumin prove an inadequate indicator of malnutrition (under physiological hydration circumstances). Short-term changes can be better evaluated by using short half-life protein fractions (transferrin, prealbumin, retinol-binding protein, etc.). Increased urine creatinine levels, together with increased 3-methylhistidine excretion and creatinine/body height index, primarily point to a loss of skeletal muscle and nitrogen loss (catabolism).

The immune system, and mainly the cellular immunity, is impaired in the early phases of malnutrition.

	Serum conc. (g/ℓ)	Deficit	Half-life	Reserve
Albumin	30–36	21–30	20 days	4–5 g/bw
Transferrin	2.5–3.0	<2.5	8–10 days	5
Prealbumin	0.15–0.3	<0.14	2 days	1
Retinol-binding protein	0.026–0.076	?	10–12 hrs	–

3.4. Indications of artificial nutrition

1. For patients who are unable to eat or maintain an adequate nutrition intake, e.g. unconsciousness, dysphagia, mechanically ventilated patients, operations and injuries on the pharynx and oral cavity and strictures of the upper gastrointestinal tract.
2. Patients who refuse to take food, e.g. lack of appetite or psychiatric diseases.
3. Patients who can not eat or where the natural nutrition is contraindicated, e.g. acute abdominal diseases (acute pancreatitis, ileus and abdominal sepsis), gastrointestinal operations, serious inflammatory bowel disease and absorption problems. A certain degree of protein malnutrition is present and artificial nutrition is highly indicated in those cases when at least 4 of the following states are present simultaneously:
   - More than 5 days of inadequate nutrition
   - More than 10% weight loss (without diet) within 4 weeks
   - The current body weight is less than 80% of the ideal body weight
   - BMI < 20 kg/m^2 (bodyweight [kg]/height [meter]^2)
   - The measured anthropometric values are less than 80% of the ideal values,
   - Serum albumin < 30 g/ℓ (in normovolemia)
   - Lymphocyte count < 1.2 g/ℓ
   - A decreased/anergic response to the applied skin test

3.5. Keywords of artificial nutrition

Of the two major types of artificial nutrition (parenteral and enteral nutrition), enteral nutrition is usually used because it is more physiological and much cheaper than total parenteral nutrition. Early enteral nutrition notably reduces postoperative morbidity, inhibits the atrophy of the intestinal mucosa, supports gut-associated lymphatic tissue, diminishes the hypermetabolic reaction caused by trauma and has fewer complications. If the nutritional needs of the patient can not be ensured because of the insufficiency of the gastrointestinal tract, total parenteral nutrition must be applied.

Primarily enteral nutrition should be chosen as it prevents intestinal atrophy, has immunological advantages, and is natural and cheap.

Parenteral nutrition: in cases of a failing gastrointestinal tract, a gastrointestinal discontinuity, dyspepsia, malabsorption, and when sufficient amounts of nutrients can not be taken enterally. The main parts of nutrients are:

- water and ions (Na^+, K^+, Cl^-, Ca^{2+} and Mg^{2+})
- energy carriers (carbohydrates and fats)
- nitrogen sources (amino acids)
- vitamins
- trace elements (Zn, F, I, Co, Cr, Mn, Mo, Cu, Se and Fe)

3.5.1. Enteral nutrition

This method is similar to the natural feeding of a healthy individual; it has numerous advantages over parenteral nutrition as complications are less frequent and the patients tolerate it better. Nutrients produced for these purposes meet special needs of metabolism requirements (renal and liver insufficiency, deficiency diseases, enzyme deficiencies, etc.). As a general rule, enteral nutrition has priority over parenteral nutrition. The distribution of different modes of enteral feeding in clinical practice at present:

Mode	Frequency
Percutaneous endoscopic gastrostomy	58%
Nasogastric tube	32%
Jejunostomy	6%
Others	4%

3.5.1.1. Tube feeding

A feeding tube is inserted trans-nasally (noninvasively) into the gastrointestinal system. Nasogastric or nasoduodenal tubes are indicated for at most 2–3 weeks. If feeding is indicated for a period longer than 2–3 weeks, a feeding fistula should be made surgically. The possibilities for this include percutaneous endoscopic gastro- or jejunostomy, laparoscopic gastro- or jejunostomy, and conventional surgical gastrostomy or intestinal fistula. General features of nutritional tubes are:

- The earlier used PVC tubes contained emollient substances, became loose after use for 24 h, and also became rigid. This increases the risk of ulcer formation, particularly in the nasal-cavity and larynx.
- Tubes made of polyurethane or silicone rubber do not include emollient substances and do not lose their flexibility. Their internal diameter is 1–2 mm as opposed to that of PVC tubes (2–4 mm). The patients can also tolerate them better.
- To facilitate the insertion of a nasogastric tube into the small intestine, 125-cm-long, double-ballooned tubes supplied with a mandrin have been developed. First, the tractive balloon is inflated in the stomach, which helps further insertion into the small intestine, where the balloon is exfoliated in alkaline milieu, freeing the apertures at the end of the tube. The second, fixing balloon stabilizes the position of the probe.
- The development of thinner and thinner tubes, and the need for a continuous nutrient supply necessitated the use of enteral-feeding pumps. These rolling pumps are small, portable and user-friendly, and can function with electric power or a battery.
- Enteral nutrients should be chosen according to the calorie-, protein-, carbohydrate- and fat-uptake requirements. An energy uptake of 1–2 kcal/mℓ/min is usually needed to avoid excessive hormone release. Mononutrient solutions contain only one sort of nutrient (carbohydrates, fat emulsions or amino acids); multicomponent nutrient solutions contain mixtures of the above, and "all-in-one solutions" (which contain all of the above) are also available.

3.5.1.2. Complications

- Technical complications: a dried/occluded tube, excursion from the origin location, mucosal lesions due to the irritating effects of the tube, and aspiration caused by regurgitated nutrients
- Metabolic complications: an inappropriate nutrient and/or a wrong dosage
- Infectious complications: inadequate nutrient storage, and the use of nonsterile water for the dissolution of powder-based nutrients.

3.5.1.3. The technique of enteral nutrition

Enteral feeding can be performed through the oral cavity, targeting either the stomach or the small bowel. If the swallow reflex is intact and the food passage is free, nutrition or complementary feeding is executed naturally through the oral cavity, using flavored nutrients. The advantage of feeding through the natural route is that the uncomfortable nasogastric tube can be avoided, but, on the other hand, the patients have to consume even 2–3 ℓ of nutrient solution to cover the energy needs, which can be overwhelming for the patient. Blind insertion of the nasogastric tube can be easily studied (apart from special cases), and should become part of the general medical routine.

4. The nasogastric tube

Methods of nasogastric tube insertion are **1.** through the nasal cavity in a blind fashion (most frequent), **2.** X-ray-guided, or **3.** aided by an endoscope (particularly when inserted into the duodenum and jejunum).

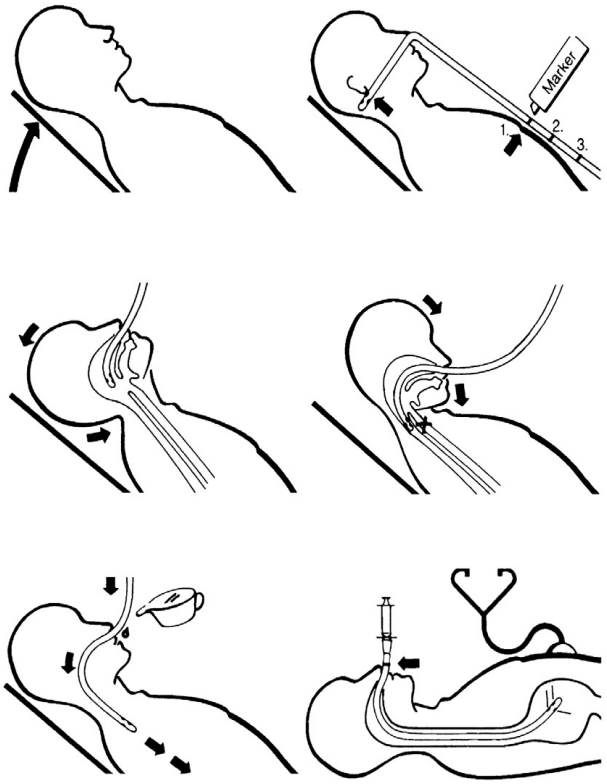
4.1. Tools of tube insertion

- A plastic nasogastric tube (40 cm)
- A local anesthetic spray for nasomucosal anesthesia (tetracaine-ephedrine or lidocaine-phenylephrine)
- For lubrication: paraffin oil, vaselinum album or lidocaine paste
- A stethoscope
- A 100–150 mℓ Farkas syringe
- Rubber gloves, and a gauze strip ~ 60 cm long and 2 cm wide for tube fixation

4.2. Technique of nasogastric tube insertion

1. The patient is placed, if possible, in a half-sitting or sitting position.
2. The tip of the nose is elevated and a finger-search is made for strictures caused by a deviating nasal septum.
3. 2×2 doses of local anesthetics are sprayed into the wider nostril. (If the pharyngeal reflex is brisk, 2×2 doses of anesthetics can be sprayed onto the pharyngeal mucosa, e.g. 10% lidocaine spray. Lidocaine spray can not be applied to the nasal mucosa because it contains alcohol.)

4. 5–10 min later, the patient is asked to tilt his/her head backward, and the tube smeared with lubricant is inserted horizontally in the sagittal direction along the base of the wider nostril and pushed until it reaches the nasopharynx (about 10 cm).
5. The tube usually stops at the posterior nasopharyngeal wall. When rolled and pushed between two fingers, the tube begins to curve down the pharynx and can be forwarded toward the oropharynx. If the patient is cooperative, he/she is asked to swallow and, synchronic with the swallowing movement, the tube can be inserted into the esophagus.
6. If the patient is not cooperative or unconscious, the tube appearing in the mesopharynx in the mouth is stabilized with the index finger and advanced slowly on the lateral pharyngeal wall through the sinus piriformis into the esophagus. In the event of a difficult insertion, the guidance of the tube can be aided with a laryngoscope and Magill forceps.



Slow and delicate movements should be applied. If the tube stops, it can be advanced after being pulled back slightly or rolled between the fingers. If the patient starts to cough heavily or suffers stridor or dyspnea, this indicates that the tube is likely to have slipped toward the larynx and trachea. It must then be pulled back and advanced again in the correct direction. The correct position of the tube can be confirmed by epigastric auscultation. When air is blown suddenly into the stomach with a Farkas syringe (100–150 mℓ), rumbling sounds can be heard. Feeding of the patient is begun with fluids (e.g. tea) in small doses; then, from the next day, crushed solid food can be started.

4.3. Indications

- Substrate administration: nutrition, fluid or drugs
- Decompression: to remove fluid and gas, to decrease the risk of aspiration or to increase the chance of surgical wound healing (usually with periodic suction)
- Lavage (washing of a cavity): irrigation and the removal of toxic substances
- Decompression of esophageal varices (a special, e.g. a Sengstaken tube is necessary)
- Aspiration of gastrointestinal contents for analysis

4.4. Characteristics of tubes

- Made of rubber, latex, plastic, silicone or polyurethane
- Different sizes, the lumen is measured in French units (Fr); see details later (urinary bladder catheterization)
- Radiopaque, i.e. impenetrable to X-rays
- Basic types: short, standard (medium) or long; some go into the small intestine

Short tubes

These can be inserted into the stomach via the nose (e.g. Levin, Salem, etc. types); they are often used before/during esophageal and gastric surgery. The main *indications* are for the removal of fluid and gas from the upper gastrointestinal tract, to take samples and for a short period of feeding/treatment (up to 3–4 weeks).

Standard (medium) tubes

These have a single lumen (opening at the tip and several along the sides) measuring 14–18 Fr (the cardia sphinc-

ter closes more tightly around a tube measuring 6–12 Fr); some are made of red rubber or plastic and should be placed in ice for 15–20 min prior to insertion. To decrease the irritation of the nose and throat, some newer models are covered with a water-activated lubricant.

Nasoenteric tubes are also available for feeding and are inserted into the duodenum and jejunum. It takes ~ 24 h to pass from the stomach to the small intestine (e.g. Dobhoff, Entraflo, etc. tubes). They can be made of polyurethane or silicone rubber measuring 8–12 Fr; with a tungsten-weighted tip; radiopaque; and with or without a stylet.

Long tubes

Indications for the use of long nasoenteric tubes (from the nose to the intestines): to remove the gastrointestinal contents, to prevent decompression, intestinal distension, a postoperative obstruction or vomiting, and to reduce tension on the suture line.

The Miller-Abbott tube is appropriate for intestinal decompression; this measures 12–18 Fr, and has a double lumen, for aspiration and balloon inflation.

The Harris tube is used for suction and irrigation; it has a single lumen connected to Y tubing, measures14 or 16 Fr, and is mercury-weighted (safety considerations).

The Cantor tube is a long, single-lumen rubber tube, with mercury, water or saline instilled to weight; it may be inserted only by a doctor.

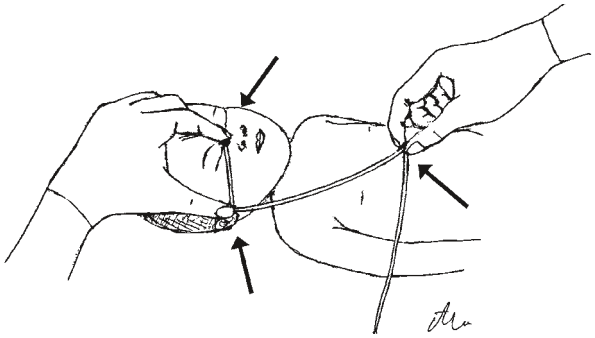
4.5. Emergency tube insertion

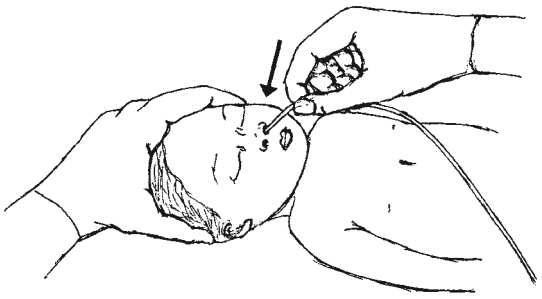
Required equipment: the same as usual (a gastric tube, a topical anesthetic or lidocaine, lubrication, a 30–50 mℓ syringe, a stethoscope, suction and tape). *Indications*: treatment of aspiration or the application of lavage. *Contraindications*: an esophageal obstruction (extreme caution is necessary in cases of esophageal disease or trauma, and facial trauma). Advantages: it is well tolerated by conscious patients, does not interfere with intubation, does not cause recurrent gastric distension, and the patient can still talk. Disadvantages: it is uncomfortable for the patient, vomiting can occur during insertion, and it can interfere with the bag-valve mask-seal. *Complications:*

- Soft tissue trauma or lung bleeding (from a poor technique, or the trauma caused by insertion)
- Endotracheal placement (accidental tracheal intubation)
- Esophageal perforation
- Supragastric placement
- Tube obstruction, torsion or looping
- Pleura effusion (infiltration) or pneumothorax
- Accidental sinus intubation (rarely)

Main steps of the technique:

- The head in a neutral position, ensuring oxygenation (if possible)
- Suppression of the pharyngeal reflex with anesthetic and tube lubrication
- Tube insertion into the stomach (see above)

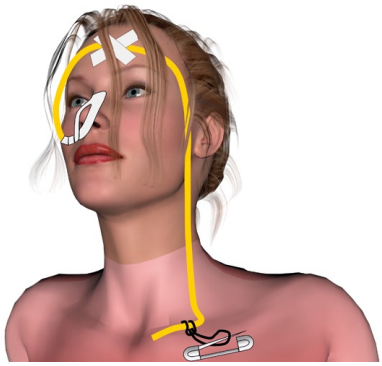




Control of the position:

- Can the patient breathe? (If the patient gives any indication of respiratory distress, e.g. falling oxygen saturation, dyspnea, coughing, or cyanosis, the tube must be removed.)
- Can the patient talk? (A properly placed nasogastric tube bypasses the vocal cords, and does not disturb their function.)
- Is the tube straight (not coiled)? (If a penlight and tongue blade are used for inspection, the tube should be visible as a straight line in the pharynx.)

- Can air be heard? (10–20 mℓ of air is injected with a 60 cm^3 piston syringe while auscultation is performed over the left upper abdominal quadrant)
- Aspiration of the gastric contents
- Verification of the nasogastric tube placement by X-ray is the most reliable method
- To exclude that insertion has been made into the lung, the gastric contents are checked with a pH strip: the stomach pH is usually 1–5.0; the small intestine pH is 6.0; and the lung pH is >=7.0
- Final fixation



Insertion of an orogastric tube

The *indications* and *contraindications* are the same as above. Advantages are the larger diameter, the safe insertion in cases of nasal cavity traumas, epipharyngeal tumors, or fracture of the base of the skull and maxillofacial fractures since it avoids the nasopharynx. Complications: the same as for nasogastric tube insertion (the patient can bite the tube). The steps of the technique:

- A neutral or flexed head position, and tube insertion in the midline
- Thereafter, the procedure is the same as for nasogastric tube insertion

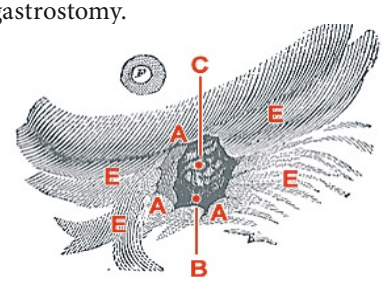
5. Gastric nutrition

Gastric nutrition can be achieved by means of nasogastric tubes (in spite of their disadvantages, 50-cm PVC tubes are generally applied for gastric nutrition) or gastrostomy. Gastrostomy can be performed surgically or endoscopically.

5.1. Historical background of gastrostomy

1833 Dr. William Beaumont (1785–1853) described the first "gastrostomy"—the description of Alexis St. Martin's wound (In: *Experiments and Observations on the Gastric Juice and the Physiology of Digestion, 1833*).

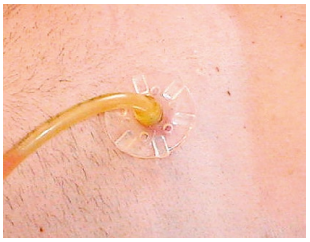
1981 Gauderer and Ponsky described the method of minimally invasive percutaneous endoscopic gastrostomy.

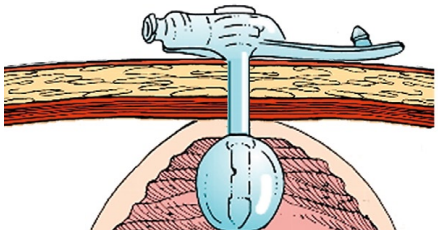


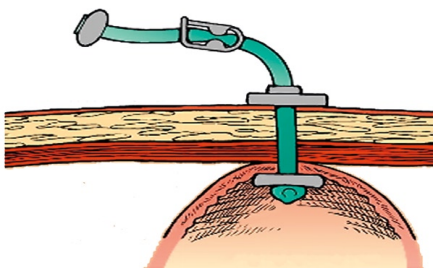
The original description of Alexis St. Martin's wound: "*This engraving represents the appearance of the aperture with the valve depressed. A A A: Edges of the aperture through the integuments and intercostals, on the inside and around which is the union of the lacerated edges of the perforated coats of the stomach with the intercostals and skin. B: The cavity of the stomach, when the valve is depressed. C: Valve, depressed within the cavity of the stomach. E E E E: Cicatrice of the original wound.*"

5.2. The types of gastrostomas

In Europe, Witzel and Kader fistulas are most commonly used, while in the Anglo-Saxon world Beck-Jianu's procedure and percutaneous endoscopic gastrostomy have become widespread.







5.2.1. Percutaneous endoscopic gastrostomy (PEG)

According to the original description, the stomach is inflated with air and an endoscope is introduced into the stomach (the light of the endoscope is visible through the abdominal wall). The ideal site for the insertion of a catheter is in the line linking the umbilicus and the left costal arch, at the upper third of this distance. At this site, the abdominal wall is pressed with the fingers, when the wall of the stomach will round up, which can be visualized with an endoscope.

A plastic catheter is inserted into the stomach with the aid of a puncture needle under local anesthesia, a guide wire is pushed through the catheter with an endoscopic foreign body forceps and led through the oral cavity, and a special tube is then attached.

The tube attached to the thread is inserted into the stomach and onto the external abdominal wall by slow pulling so that one end of the tube stays in the stomach. A ring made of silicone-rubber prevents the tube from slipping out. The tube is pulled until it stops, and it is then fixed on the abdominal skin.

Westweber and Troidl simplified the process. A Foley catheter is inserted into the stomach through a thick puncture needle under intragastric endoscopic visulization, a balloon is then inflated and the catheter is pulled back until it stops. Thus, the use of a guide thread becomes unnecessary and the procedure takes only a few minutes in contrast with the 15–20 min of the original procedure.

The end of the tube can be led into the small intestine with an endoscope. In cases of malignant head and neck tumors, the insertion of the endoscope can be difficult due to strictures. Laparoscopic or surgical gastrostomy should therefore be performed.

6. Intestinal nutrition

Primarily postoperative atonia developes in the stomach and colon after laparotomy, whereas the motility and absorption of small intestine are undisturbed for a few hours after the operation. This recognition and the development of formulas created a basis for the introduction of early postoperative nutrition.

6.1. Methods

The nutrients are administered into the small intestine via catheters that can be inserted into the jejunum through a nasointestinal tube, a surgical jejunostomy, a needle catheter jejunostomy or a PEG.

6.1.1. Nasojejunal tube insertion into the small intestine

Insertion of a nasojejunal tube into the small intestine can be tried blind in a similar way to that of the gastric tube. The tube is led into the stomach with the patient lying on the right side (in this position, peristalsis is expected to push the tube forward through the pylorus).

As blind insertion often fails, it is wise to lead the tube under X-ray monitoring. After the mandrin is pulled out, the drawing balloon is filled with contrast material. With the patient lying on the right side, the tube is advanced into the duodenum under X-ray monitoring. The drawing balloon dissolves in the alkaline environment, and detaches from the tube, so that the contrast material passes into the small intestine.

Both cases necessitate an intact gastric function so that the tube can reach the small intestine. This is not always the case, which is why the procedure of endoscopic introduction of the tube was developed.

A 250 cm long special tube with an outer diameter of 1.8 mm and equipped with a mandrin is introduced under eye control through the biopsy channel of the endoscope into the duodenum. As the endoscope is removed, the tube is continuously advanced into the jejunum. Then the tube is led out orally and replaced into the nose.

6.1.2. Enteral nutrition via surgically prepared jejunostomy

Two basic methods can be differentiated: temporary enterostomy (Marwedel) and permanent enterostomy (Maydl).

6.1.3. Needle catheter jejunostomy

The procedure of needle catheter jejunostomy was first desribed by Delany in 1973; it gained its current form following modifications by Heberer in 1983. *Indications* for early postoperative needle catheter jejunostomy: esophageal surgery, gastrectomy, pancreas resection, hepatic resection and transplantation, and the development of threatening complications after surgery.

The technique of the intraoperative method:

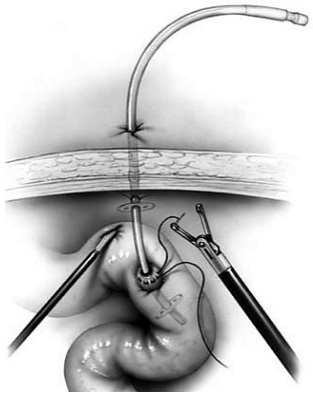
- A special set is used to insert the catheter. First, a polyurethane catheter with a diameter of 1.5 mm is led through the abdominal wall into the abdominal cavity with the help of a puncture needle, and a 4–6-cm long submucous tunnel is formed in the intestinal wall with a needle equipped a mandrin.

The catheter is then led into the intestines through it. The significance of this submucosal "anti-reflux" tunnel is to arrest fistula formation after catheter removal.

- The intestinal loop is fixed to the peritoneum with 2–3 stitches.
- The intervention takes only a few minutes, and thus the surgery will not be significantly longer. The silicone-rubber plug of the catheter is attached to the sack containing the formula and it is dosed with the aid of an enteral pump.

6.1.4. PEG—jejunostomy

In this mode of intestinal nutrition, a tube is inserted into the stomach through a percutaneous endoscopic gastrostomy and its end is led into the small intestine with an endoscope.



6.2. Dosage of nutrition

Gastric nutrition can be started 3–4 days after surgery, while jejunal nutrition can be started immediately.

In the event of gastric feeding, the osmolarity is increased first, and only then is the volume administered, whereas this sequence is the opposite for intestinal nutrition.

With gastric nutrition, the total energy needs are already covered on the second day, while intestinal nutrition requires 4 days for this adjustment.

It is favorable to administer nutriments in boluses, as a large amount of formula given within a short time stimulates the distension receptors in the stomach, so that peristalsis is increased. Thus, the majority of authors suggest that food should be administered in boluses. It is of vital importance to rinse the tube 2–3 times a day.

In jejunal nutrition, the food has to be administered continuously; pumps make continuous 24-h dosing possible. The continuous administration of food decreases the frequency of bowel movements and diminishes the risk of infections. The administered amount is continuously increased until the fourth day; then, after the time of adaptation has passed, the energy intake can be raised by increasing the concentration of the formula.

7. Tube feeding

The main goal is to prevent or to treat malnutrition. It provides nutrients when the gastrointestinal system is unable to ingest adequate nutrients orally. It is low-cost, safe, generally well tolerated, and preserves the gastrointestinal integrity and flora.

7.1. Formulas

Home-made nutrients do not yet correspond to modern nutritional principles. Commercially available products can be:

- Polymeric, high molecular-weight protein-carbohydrate-fat-containing solutions
- Chemically defined, predigested, easy-to-absorb nutrients (high particle size and high osmolarity)
- Modular products containing only one major nutrient, e.g. protein solutions
- Disease-specific nutrients, e.g. in renal failure and liver failure, after trauma, or high fiber content nutrients

7.2. Methods

The method of insertion depends on the location of the tube, the patient's tolerance, etc.; intermittent boluses (300–400 mℓ formula intake/4–6 h); intermittent infusion (a feeding bag attached to the tube allows fluid to flow by gravity; usually 200-400 mℓ is administered over 30 min at designated intervals), and continuous infusion (with an infusion pump at constant velocity).

7.3. Absolute and relative contraindications of tube feeding

- Blockage in forwarding food (i.e. ileus or perforation)
- Esophageal varices (insertion of a nasogastric tube is contraindicated, but placement of PEG tubes or catheter jejunostomy is possible)
- Hemostatic failure (it is advisable to be careful, because the tube can injure the mucosa, resulting in

nasopharyngeal or esophageal bleeding, which is hard to arrest)
- In the early period after surgery of the upper part of the gastrointestinal tract (esophagus or stomach). The patient can be fed via the jejunum at this time. The tube must be placed at least 20 cm distally from the operation site

7.4. Complications

- Regurgitation / aspiration
- Tube dislodgement
- Tube clogging
- Bacterial contamination
- Excessive gas formation
- Diarrhea or dumping
- Nasopharyngeal irritation: the thick and inadequate material of the tube can cause ulcer, perforation or sinusitis in the nasal cavity, nasal pharynx or esophagus
- Hyperglycemia
- Dehydration and a fluid volume deficit
- Pulmonary complications: erroneous insertion can lead the tube into the respiratory system (trachea or lung), particularly in recumbent, unconscious patients. Especially a too heavy mandrin can cause serious complications or, in the hope of easier insertion, if the tube is cooled, it can be inserted into the cranial cavity via the basic cranial lamina.
- Diarrhea is a common complication which is sometimes difficult to tackle. *Causes and therapy:*
- Too high doses are given at one time. The dose should be decreased to at most 20 mℓ and the duration of administration increased to 15–20 min. A break of 1–2 h should be kept between two doses.
- Too high osmolarity of food products. The osmolarity must be adjusted to the physiological level (300 mosmol/ℓ).
- Too cold food preparation and too fast administration. The food preparation should be at room temperature and administration should be slow. The gradient principle should be adhered to, e.g. the nutrition should be started at 20–40 mℓ/h, and the dose should then be gradually raised to reach 120 mℓ/h on day 3 or 4. The daily intake should not exceed 3000 mℓ.
- Lactose and lipid intolerance
- Bacterial infections of nutrient solution. Ready-to-use and open solutions must be kept in a refrigerator and for 24 h at the longest. They should be warmed up to the appropriate temperature before direct application. Care should be taken with antibiotics so that the normal intestinal flora is preserved.

8. Parenteral nutrition

Nutrition with intravenously administered infusion preparations (i.e. parenteral nutrition) can be justified only if the gastrointestinal tract is not suitable for enteral artificial nutrition or if adequate amounts of nutrients cannot be administered in this way. A decrease in the size of the gastrointestinal system and/or its absorptive potential can be reversible if the affected enteric section accommodates to the circumstances after the closing of an enterocutaneous fistula or enteral resection (the intestinal section adapts to the situation), but damage can also be irreversible, e.g. in cases of short intestinal syndrome accompanied by extensive damage to the small intestine.

In the event of intestinal failure, the functioning gut mass is greatly reduced to below the critical minimum necessary to ensure adequate digestion and absorption (this principle can be useful to judge the necessity of total parenteral nutrition).

Absolute indications of total parenteral nutrition:
- High-volume enterocutaneous fistulas
- Hemodynamic instability, serious intestinal ischemia (accompanying a serious degree of malnutrition)

Relative indications:
- Moderate or severe malnutrition and impossibility of enteral nutrition for several days
- Abdominal sepsis, pancreatitis or ileus
- Severe inflammatory bowel disease or Crohn disease

8.1. The technical possibilities of parenteral nutrition

Total parenteral nutrition can be performed via either a peripheral or a central line.

8.1.1. Peripheral parenteral nutrition

Peripheral parenteral nutrition or partial nutrition is indicated:
- If enteral nutrition is impossible or not sufficient
- The duration of nutrition is presumably less than 7 days and the patient does not have a CV cannule
- Peripheral parenteral nutrition is to be planned for a short period (a maximum of 2 weeks). It is insufficient in severe catabolic conditions, but it is an excellent method with which to nourish patients for

some days if they do not suffer from malnutrition or if they need only supplementary enteral nutrition. Thrombophlebitis presents a great problem (the cannula has to be changed every 24–48 h). Attention must be paid to the limits of the osmolarity.

8.1.2. Central parenteral nutrition

Indications of central parenteral nutrition:
- Hyperosmolar, low pH solutions which can irritate the vessel walls
- Parenteral nutrition is needed for longer than 7–10 days
- If access through the peripheral veins is limited (e.g. wrong veins, or the necessity of a high calorie-intake)
- Central parenteral nutrition can be performed only through a central venous cannula. The lumen of the cannula used for nutrition must not be utilized for other purposes (e.g. taking blood samples or drug administration).

8.2. Types of parenteral nutrition

Nutrient solutions should be administered continuously for 12–20 h, with a drop-regulator or infusion pump. The use of all-in-one, one-sack solutions (the total daily portion in one closed system is to be preferred).

8.2.1. Hypocaloric feeding

The energy requirements of the organism are only partially covered (for liberation of the endogenous fat pools). The carbohydrate intake is 2 g/kg, which can be supplemented with 10% fat emulsion. N_2 source: 1–1.5 g/kg amino acids; further, electrolytes, vitamins and trace elements can be given. The osmolarity of the solution is not higher then 900 mOsm/ℓ; thus, it can be administered into a peripheral vein.

8.2.2. Isocaloric feeding

The total nutrition requirements of the organism are covered parenterally. The average energy intake is usually 30–40 kcal/kg. N_2 source: 1.0–2.0 g/kg amino acids; the ratio of carbohydrate to fat is 2:1. These solutions can be administered only via central veins.

8.2.3. Amino acids

Solutions: 5, 8, 10 and 15% infusion solutions. Components: L-amino acids (Ile, Leu, Lys, Met, Phe, Thr, Trp, Val, Arg, His, Ala, Pro, Cys, Gly, Gln, Ser and Tyr). These can be supplemented with electrolytes. *Indications:* parenteral feeding. *Relative contraindications*:
- deficiency of amino acid metabolism
- metabolic acidosis
- hyperhydration
- liver insufficiency
- renal insufficiency (if the patient is not treated by dialysis)
- insulin-refractory hyperglycemic state
- shock

Warning: drugs should not be injected into these solutions. An adequate intake of K^+ and an energy source are required for their metabolism. Monitoring of electrolytes (PO_4^-) and pH is mandatory. Further advice: in cases of a liver dysfunction, special solutions should be applied which contain less aromatic amino acids and methionine.

8.2.4. Fat emulsions

Solutions: 10, 20 and 30% infusion solutions. Contents: triglyceride-phospholipide emulsions (derived from soybean oil, fish oil and egg yolk).
Indications:
- ensurance of energy source during parenteral feeding
- intake of essential fatty acids

Contraindications:
- coagulation failures
- thrombosis
- shock
- acidosis
- fat embolism
- pregnancy
- deficiency of fat metabolism
- liver insufficiency
- early stage of post-aggression syndrome.

Warning: assessment of the triglyceride, glucose, pH and electrolyte levels are required. The parallel intake of carbohydrates and amino acids helps the metabolism.

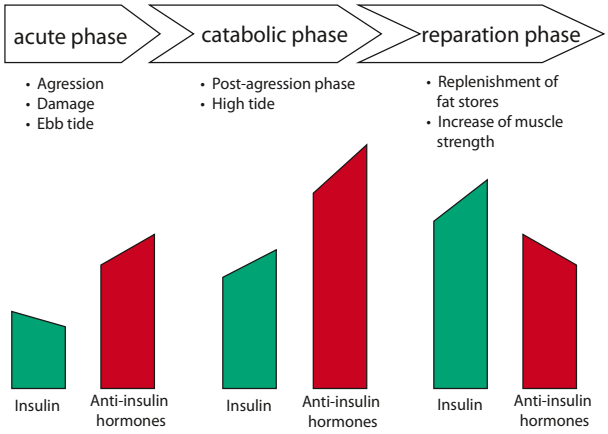
8.3. Complications of parenteral nutrition

Technical complications of parenteral nutrition are related to the introduction of the cannula into the vessels (complications occur in 5–10% of the cases and the mortality rate is 0.5%). Metabolic complications during PT usually have iatrogenic causes (inadequate solution or an improper dosage). The most common and most

dangerous complication of PT is infection (complications of infections exceed 10%; about 40% of persistent cannulas are bacteriologically positive).

9. Post-aggression syndrome

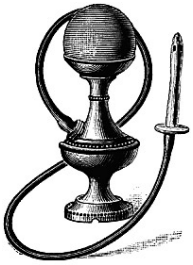
Definition: deleterious effects targeting the organism result in the activation of endocrine stress reactions which aim at enhancing a rapid and permanent energy supply and protective immunological mechanisms. Main components: predominance of catabolic processes (glyconeogenesis, lipolysis and an increased protein catabolism) and a negative nitrogen balance (Arg, His, Pro and Gln are semi-essential; catecholamines, glycocorticoids, glucagon and thyroid hormones are predominant).

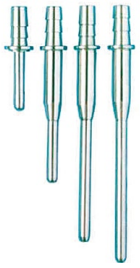


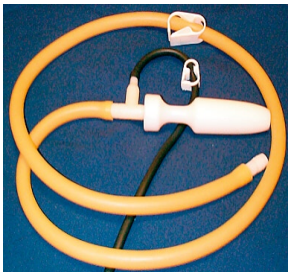
Phases of the post-agression syndrome

10. Enema and laxation

These are important procedural steps in the preparation/diagnosis/therapy of the gastrointestinal tract (e.g. preparing the tract before operations and colonoscopy, or the conservative therapy of ileus, detensioning before operation; fluid and electrolyte supplementation and a nasogastric tube are needed). Methods before elective operation: rectal examinations, a 4-day diet without vegetable fibers. Laxatives: X-Prep, supp. Glycerini. Solutions: Yal-Trommsdorff klysma, Rins-Sal, Rins-Ringer, etc. could be given.







IX. Monitoring of the urinary system

1. Clinical signs—low-tech monitoring

Discoloration
- Blood (hematuria)
- Very concentrate
- Jaundice, hemoglobinuria
- Drugs (e.g. antibiotics)
- Food (e.g. beetroot)
- Disease (e.g. porphyria—see madness of King George III (1738–1820), whose urine became purple; this illness occasioned the constitutional review known as the Regency crisis. *See details in Lancet 366, 2005*)

Chemical testing strip analysis
- Blood: very sensitive, 2 or more cells can produce a result, but can not distinguish between blood and free Hb, and thus a double-check with a microscope is usually required.
- Protein: strips detect 100 mg/ℓ or more in the urine—reaction with albumin. A check must be made throughout a 24-h period. The time of day of the checks is important (lying down causes the protein to settle and it is not detected in the urine).
- Glucose: a positive test can mean diabetes mellitus, but the ingestion of a high-sugar diet must be excluded.

Blood laboratory tests (indirect indicators of the renal function) are easy, routinely done, and provide a large amount of information quickly concerning:

- Hyperkalemia
- Decreased bicarbonate—poor filtration or acid/base disorders
- Elevated urea
- Elevated creatinine
- Elevated uric acid
- Hypocalcemia
- Hyperphosphatemia
- pH—acid/base disorders
- pCO_2 away from 40 mm Hg—acid/base disorders
- Hypernatremia

Quantitative tests of renal function; commonly used imaging techniques:
- Plain X-ray
- Cystoscopy
- Excretion urography
- Ultrasonography
- Computed tomography
- Magnetic resonance imaging
  - Antegrade pyelography
  - Retrograde pyelography
  - Micturating cystourethrography
- Aortography or renal arteriography
- Renal scintigraphy—dynamic and static
- Transcutaneous renal biopsy

Bladder pressure: the pressure inside the abdomen can rise to the point where it actually threatens organ perfusion—this is the abdominal compartment syndrome (see earlier).

2. Catheters

2.1. Background

Catheterization usually denotes artificial emptying of the bladder. Several diseases may disturb normal bladder emptying. Hyperplasia of the prostate gland, tumor, strictures, drugs (e.g. opiates), spinal cord injuries, polyposes and calculi are the most frequent disorders which change the normal voiding. Catheterization can be a basic intervention in both chronic diseases and emergency states. Both diagnostic and therapeutic aims can require catheterization.

Diagnostic goals:
- assessment of the fluid status in critically ill patients
- obtaining urine samples for microbiological examinations
- proving residual urine in the bladder
- obtaining exact results in urological diagnostic tests

Therapeutic goals:
- treatment of urine retention
- maintenance of incontinence
- lavage of the bladder
- preoperative preparation
- prevention of urine obstruction
- tamponade (hemostasis)

2.2. General rules of catheterization

- Patients should not be catheterized, unless it is absolutely necessary
- Catheterization must be performed in accordance with the rules of asepsis
- Catheterization must be carried out carefully in order to prevent injuries
- It must be made sure that the sterile covering package of the catheter is intact
- Catheterization should be avoided in cases of urethral injuries

2.3. Catheters

- Several types of catheters are known and used. Plastic and latex catheters are proposed for a shorter time and silicone catheters for a longer period of catheterization. The use of silicone catheters decreases the chance of peri-catheteric urine leakage, urine infection and catheter obstruction. There are some advantages of silver and antimicrobial coatings, but the value of these catheters has still not been established.
- The external diameter of catheters is given in French (F) or Charriére (Ch) units, according to Charriére's French scale. 1 F = 1 Ch = 0.33 mm, e.g. 3 F is equal to 1 mm.
- The type of catheter applied depends on the aim of the catheterization. Straight catheters (Nélaton or Robinson) are usually used for single or intermittent catheterization in a size of 16–20 F. A Foley catheter of the same size is proposed in cases of continuous urinary drainage.
- The prolonged use of catheters of larger caliber in males may lead to the retention of urethral secretion and accordingly urethral inflammation, strictures and epididymitis. Nevertheless, it is advisable to insert a thicker (20–24 F) catheter after endoscopic operations on the bladder and prostate gland in order to facilitate the removal of clots.
- The use of Thiemann catheters (a catheter with a curved tip) can be advantageous in the event of urethral obstructions and/or in male catheterization (due to the physiological curve of the male urethra).

2.3.1. Soft catheters

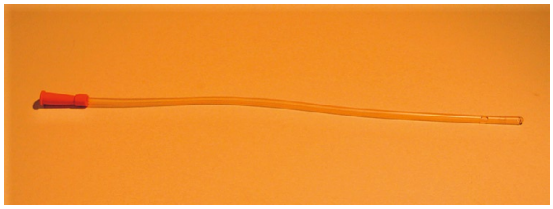
- The Nélaton catheter (after Auguste Nélaton, a French urologist, 1807–1873) is a straight tube with a blunt end and an oval window.
- The Thiemann catheter (a sub-type of the Foley catheter, "*coudé*", French for elbowed) has a tip 1–1.5 cm long; it is curved at 45°. During insertion, the tip should be set toward the patient's face. A small fin on the external end of the catheter can help to indicate the right direction for the tip.
- The Pezzer (or de Pezzer) catheter is made of latex. The end is round and flat (it looks like a mushroom) with a few windows. This device was earlier placed into the urethra after urological operations. At present it is seldom applied.
- The Foley catheter (designed by Frederick E.B. Foley (1891–1966), a Boston medical student, in 1934) is a frequently used soft catheter. A balloon is situated at its end in order to fixate the catheter in the bladder. The balloon must be filled with sterile fluid to avoid infection in the event of balloon injury.

2.3.2. Medium catheters

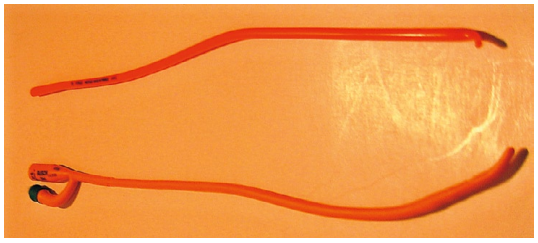
Mercier catheters are made of silk with a special impregnation. They are soft at body temperature and become rigid as the temperature falls. This may facilitate insertion in cases of urethral strictures.

2.3.3. Hard catheters

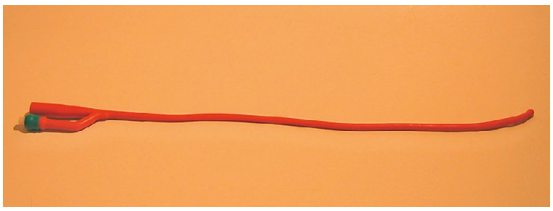
Hard catheters can be made of metal, plastic or glass (in the past). Metal catheters are slightly curved tubes with an oval window. Glass catheters were earlier used for female catheterization.



Nélaton catheter



Thiemann catheter



Foley catheter

2.4. Technique of catheterization

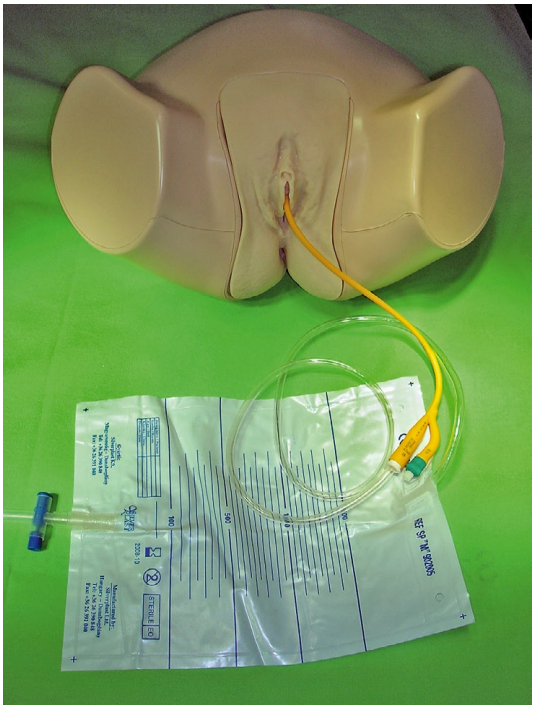
Before catheterization, all of the required devices should be prepared. It is advisable to have the help of an assistant available, especially when the patient is not able to cooperate. If necessary, one person can put an unconscious patient into an adequate position for catheterization. The legs should be fully abducted and the knees flexed in females, but this position is not necessary in male catheterizations.

2.4.1. Devices for catheterization

- A catheter of appropriate size (14–24 F)
- A urine container sack
- Sponges with which to clean the genital area
- Disinfectant
- A syringe filled with sterile saline or water (if a Foley catheter is used)
- A sterile lubricant
- Sterile gloves
- (Sterile forceps)

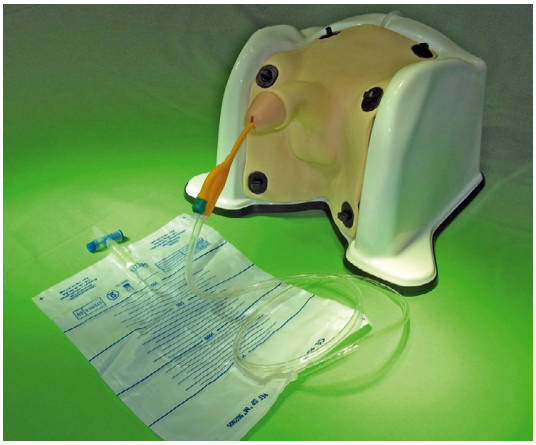
2.4.2. Female catheterization

- The operator's hands must be washed and covered with sterile gloves. The patient is lying in a supine position, with her legs abducted and the knees flexed.
- The labia are spread gently with the left hand. The urethra is located above the vagina, under the clitoris.
- Sponges in the right hand are used to clean the introitus with disinfectant three times. Important: a sponge is used only once, and cleaning is performed from front to back to avoid contamination of the area.
- Water-soluble lubricant is placed onto the first 7–8 cm of the catheter. (The help of the assistant is required.) The catheter is then grasped in the same way as a pencil (or with the use of a forceps), and inserted into the urethra.
- No non sterile area should be touched with that part of the catheter which is to be inserted into the urethra.



2.4.3. Male catheterization

- The male urethra is long and curved twice, which is why catheterization here may be more difficult than in females. Thus, it is advisable not to attempt catheterization without assistance, unless the case is urgent.
- The male patient should be lying with his leg slightly abducted. The penis is lifted with the left hand and the foreskin is retracted. The urethral meatus is cleaned as mentioned above.
- The catheter is prepared and held as described above. The penis is held at an angle of 60° in order to eliminate one of the curvatures.



- The catheter should be introduced carefully. After 15–20 cm, resistance may be met because of the prostate gland. If the difficulty cannot be overcome, a better size of catheter should be chosen. Another suggestion: sterile lubricant should be injected into the catheter, so that the fluid may dilate the way for it.
- At the end of the catheterization, the foreskin should be replaced on the glans.

2.4.4. Remarks

- In the choice of a catheter, the goal of the catheterization and the individual properties of the patient must be considered. The use of a catheter with a smaller caliber is usually suggested, because it results in fewer complications than with a larger one. The advantage of thicker catheters (20–22 F) is that they are less able to perforate the urethral wall. The constriction of the internal sphincter may cause resistance when the catheter is inserted. After a pause of a few seconds, the sphincter may relax, and insertion becomes easier. Hyperplasia of the prostate gland and urethral strictures can make catheterization more difficult. The catheter must always be in-

serted gently in order to avoid edema and perforation.
- If patient reports pain during filling of the balloon, it must be understood that the balloon is still in the urethra. Thus, it must be inserted a few more cm. In cases of urethral injury, bleeding or unsuccessful catheterization, retropubic puncture of the bladder is mandatory.
- An overfilled bladder can be recognized by palpation. Hiccough and abdominal pain are characteristic symptoms. The patient appears to urinate frequently. In fact, it is leakage from the overfilled bladder. This symptom can be noticed at a retention of 600–800 mℓ. The overfilled bladder should be emptied slowly, because rapid vasodilatation of the bladder vessels can result in bleeding or hypotension. First, 500–800 mℓ of urine is allowed to drain. The catheter is then closed for 15 mins. Decompression is continued, 100 mℓ being allowed to drain every 15 mins, until the bladder is empty.
- Males are seldom catheterized for diagnostic purposes nowadays. In females, urine samples can be obtained for diagnostic tests if the urethral meatus is cleansed as mentioned above. However, such samples are not always suitable for microbiological examinations. Catheterization provides sterile urine for these tests.
- Patients in shock or an unconscious state should be catheterized for monitoring of the fluid status and renal function.
- The catheter should be changed every week. Complications necessitate more frequent changing. Silicone catheters can be used longer. The catheter is removed carefully in order not to damage the urethral wall.
- If a Thiemann catheter is applied, it must be made sure that its tip is in the right direction (as mentioned above). Catheterization with this device must not be attempted unless the operator has previously practised this technique.

2.4.5. Collection of a urine sample from a catheter

The aims of taking urine samples:
- Simple examinations of the urine:
  - Inspection, and measurement of specific gravity and osmolarity
  - Microscopic examinations
  - Qualitative and quantitative lab tests
  - Microbiological examination
- Assessment of the fluid status:
  - Urine collection for 24 h; daily fluid balance. Determination of fluid intake and output
  - Hour diuresis: in patients in shock, or with burns, critical circulatory disorders, renal insufficiency, etc. This is a very important point of monitoring.

2.5. Chronic catheterization

Chronic catheterization is often used in elderly, chronically ill subjects in cases of voiding problems. *Indications* for prolonged catheterization are:
- urine retention, which cannot be maintained either by medication or by surgical interventions
- the prevention of superinfection of decubitus
- patients with end-stage diseases
- the intensive care of patients with serious diseases.

However, complications of chronic catheterization must be considered and this solution should be chosen only when absolutely necessary. Antibiotic prevention is required. The main *complications*:
- If the rules of asepsis are not kept, patients are threatened by the danger of urinary tract infections. Fever and shivering can be the first symptoms of infection; they may appear within a few hours. More than 60% of fever episodes in older patients with a chronic catheter originate from urinary tract infections. Thus, the temperature of catheterized patients must be checked regularly. Changes in mental state, sweating, abdominal pain, tachycardia, hypotension, nausea, vomiting or agitation can also be findings in bacteriemia and urinary sepsis. In cases of such infection, the choice of antibiotics should be based on appropriate microbiological examination, because many uropathogenic bacteria are resistant to conventional antimicrobial medication.
- Urethral injuries. If the suspicion of urethral or prostate injury arises, immediate urological consultation is mandatory.
- Encrustation means the deposition of detritus around the catheter end, a process which may lead to catheter obstruction. This state can be prevented if the catheter is regularly changed. Further, it is advisable to keep the pH of the urine in the acidic range. An appropriate diet, which contains meat, corn, eggs, plums and raisins may contribute to the required urine pH. Of course, it must be remembered that other diseases may possibly contraindicate these foods. A fluid intake of 2000–3000 mℓ is suggested in order to decrease the chance of obstruction via the continuous urine flow in the catheter.
- Urine leakage can occur in connection with catheter obstruction and spasm of the bladder. Several diseases may lead to irritability and spasm of the bladder. Urinary tract infections, constipation, calculi and an oversized catheter balloon are the most

frequent reasons. In cases of urine leakage, the cause must be found and treated. If it proves to be unsuccessful, spasmolytic drugs should be applied.

- Effluvium can be prevented by careful nursing. The perineal region should be cleaned every day and it is suggested that the urine container sack with the catheter should be changed.
- Excessive urine drainage may lead to shock (see above).

2.6. Other methods for catheterization

- When the urethra cannot be catheterized, percutaneous suprapubic catheterization is very useful. This technique is often applied after urological and gynecological operations, in intensive care units and in cases of urethral injury. Infection is the primary complication of this intervention. These catheters must be maintained like chronic catheters.
- External catheters are suggested for the management of bladder dysfunctions, when other anti-incontinence treatments have proved to be unsuccessful. The external catheter designed for males has a cone, which can be fixated to the pubic bone. Other types have a condom which is secured with an elastic band. These catheters may lead to edema, irritation of the skin, strangulation of the penis and urethral diverticuli. External catheters for females are available, but their efficacy is still unproven.

X. List of abbreviations

ARDS =	Adult Respiratory Distress Syndrome
BEE =	Basal Energy Expenditure
BMI =	Body Mass Index
CCD =	Charge-Coupled Device
CSF =	Cerebrospinal Fluid
CI =	Cardiac Index
CNS =	Central Nervous System
CO =	Cardiac Output
COPD =	Chronic Obstructive Pulmonary Disease
CVP =	Central Venous Pressure
DIC =	Disseminated Intravascular Coagulopathy
ECG =	Electrocardiography
EEG =	Electroencephalography
EP =	Evoked Potential
ESPVR =	End-Systolic Pressure-Volume Relation
$ETCO_2$ =	End-tidal CO_2
Hb =	Hemoglobin
IAP =	Intraabdominal Pressure
ICP =	Intracranial Pressure
LED =	Light-Emitting Diode
MOF =	Multiple Organ Failure
MRI =	Magnetic Resonance Imaging
MRA =	Magnetic Resonance Angiography
NIR =	Near Infra Red
NIRS =	Near Infra Red Spectroscopy
OPS =	Orthogonal Polarisation Spectral (imaging)
PEG =	Percutaneous Endoscopic Gastrostomy
PMN =	Polymorphonuclear
PCWP =	Pulmonary Capillary Wedge Pressure
PPN =	Peripheral Parenteral Nutrition
SpO_2 =	Percentage of Hemoglobin Saturated by Oxygen
TEE =	Trans-Esophageal Echocardiography
TPN =	Total Parenteral Nutrition
US =	Ultrasound