Ministry of Health of Ukraine
Ukrainian Medical Stomatological Academy

It is approved
on meeting of department of
medical informatics, medical and biological physics
27 August 2020
Minutes №1 of 27 August 2020

Head of department ________O.V.Silkova

Methodical instructions
for students' self-preparation work at preparation for a practical lesson
at home and at the classroom

Subject matter	**Medical and biological physics**
The unit	2. Bases of medical physics
Theme of lecture:	**Medical equipment. Devices for medical-biological information pickup.**
Year	1
Faculty	Medical, Stomatological
Speciality	Medicine, Stomatology

Poltava - 2020

The topic significance:

Sensor (measuring converter, transducer, data unit, sensing element, monitor, sensing unit, transmitter) is part of measurement device that directly communicate with object of examination and transform measurand [measured quantity] into form easy-to-use of researcher; generally it is electric signal which is passed, processed, represented, measured or registered next.

Most often measurand is physical quantity (pressure, displacement, temperature, voltage and so on). Further only sensors with electrical output signal [pickup signal] will be considered.

Specific targets:

To have general knowledge of the topic studied;

To understand, to remember and to use the knowledge received;

To know electrodes classifications, general demands to electrodes, demands to biomedical electrodes, methods of use in medicine.

To know sensores classifications, physical principles of different sensores.

To know general demands to sensores, demands to biomedical sensores, methods of use in medicine.

Basic knowledge, experience, skills necessary for studying the topic in connection with other subjects:

Previous (providing disciplines)	**Obtainable skills**
Physics	To define basic concepts of physical parameters: pressure, sound intensity, resistance, conductivity, capacitance, inductance, temperature, illuminance, optical spectrum. To know measurement units of physical quantities.

Materials for the before-class work self-preparation work:

List of main term, parameters, characteristics, which student have to learn at preparation to class:

Term	Definition
Biomedical sensor	Biosensors are sensors used for reception of information on functioning alive organisms, their organs and systems.
Electrode	conductor of the special shape and construction with which help the explored field of a body or an organ of an alive organism is connected in an electric circuit of the measuring device
Sensibility	minimal change of measured parameter which can be steady detected
Dynamic range	range of input quantities in which measurement is carried out without significant errors
Accuracy	maximal difference between obtained and nominal output values
Response time	minimal time range during that output value reach the level corresponding to level of input parameter
Reproducibility	difference between output signals on equal input influences in different time moments must be absent
Requirements for biomedical sensors	– reception of an steady informative signal (functionally reliable); – minimum of distortions of the useful signal; – maximum noise immunity; – convenience of use and arrangement; – absence of the side influences on an organism (safety); construction of the sensor contacting to a body (in vivo applications) must be nontoxic and nonthrombogenic; – opportunity of sterilization (for sensors of reusable use); – low cost (for sensors of unitary use).

Theoretical questions to class:

1. Classifications of sensors (electrodes and transducers; in dependence on the quantity to be measured; bio-controlled and energy; according to physical nature of input signal).
2. Requirements for biomedical sensors.
3. Metrological characteristics of sensors.
4. Electrodes types.
5. Requirements to electrodes of medical and biologic purposes.
6. Electrodes classification.
7. Mechanical measurement sensors.
8. Magnetic measurement sensors.
9. Temperature measurement sensors.
10. Optical Biosensors.
11. Piezoelectric transducers.

Content of the topic.

Sensor (measuring converter, transducer, data unit, sensing element, monitor, sensing unit, transmitter) is part of measurement device that directly communicate with object of examination and transform measurand [measured quantity] into form easy-to-use of researcher; generally it is electric signal which is passed, processed, represented, measured or registered next.

Most often measurand is physical quantity (pressure, displacement, temperature, voltage and so on). Further only sensors with electrical output signal [pickup signal] will be considered.

Biosensors (biomedical sensors, biomedical transducers) are sensors used for reception of information on functioning alive organisms, their organs and systems.

All measured biomedical parameters can be divided into two groups: directly measured and mediately measured. Mediately measured parameters are that can't be measured or that can be measured hardly or with the risk to healthy or uncomfortable. If they influence on other parameters more comfortable for measuring, and these other parameters are measured, we tell about mediately measuring.

Examples of directly measured parameters are motions of extremities and chest, body temperature, biopotentials, body pressure in blood vessel. Examples of mediately measured parameters are blood pressure (by sounds in time of blood flow), oxygenation of hemoglobin by spectral characteristics of blood by light transmission of tissues and further.

Sensors designed for medicine (biosensors**)** use must to meet the next **requirements**:

- reception of an steady informative signal (functionally reliable);
- minimum of distortions of the useful signal;
- maximum noise immunity;
- convenience of use and arrangement;
- absence of the side influences on an organism (safety); construction of the sensor contacting to a body (in vivo applications) must be nontoxic and nonthrombogenic;
- opportunity of sterilization (for sensors of reusable use);
- low cost (for sensors of unitary use).

Additional issues are the long term biocompatibility of the sensor.

Output electrical signal of sensor can be: current, voltage, impedance, frequency of phase of alternating current or pulse signals.

Classifications of sensors

1). Biomedical sensors are divided on two groups: electrodes and proper sensors (transducers).

Biomedical sensors are classified in dependence on the quantity to be measured:

- electrical;
- mechanical (linear and angular displacement, pressure, velocity, acceleration, frequency of oscillations,…);
- physical (temperature, illuminance, sound intensity, humidity,…);
- physiological (filling of tissue by blood);
- chemical (concentration of certain ions, activity of ions,…).

2). Biomedical sensors can be bio-controlled and energy.

Bio-controlled sensors can be ***generator (active)*** or ***parametric (passive)***.

Parametric sensors change own electrical parameters (resistance, capacitance or inductance) under the influence of measured object.

Generator sensors directly transform energy of input signal into electrical output signal that is they generate corresponding signal. Some types of such sensors are: a) piezosensors or piezoelectric transducers, b) thermoelectric transducers, c) induction sensors used electromagnetic induction, d) photoelectric sensors.

Energy sensors are complex: firstly, part that influence of the organs and tissues and, secondly, proper sensor. Energy flux of influence has strict characteristics; measured parameter changes these characteristics, modulate them. Examples of such equipments are ultrasound and photoelectrical sensors.

Metrological performances of sensors:

1) ***sensibility*** (sensitivity resolution) – minimal change of measured parameter which can be steady detected; it shown as $z = \Delta y/\Delta x$, where Δy – change of output signal at change of input value Δx, and measured thereafter in Ω/mm (Ohm per millimeter) or mV/K (millivolt per Kelvin) and the like;

2) ***dynamic range (operating range)*** – range of input quantities in which measurement is carried out without significant errors;

3) ***accuracy*** – maximal difference between obtained and nominal output values;

4) ***response time (response speed)*** – minimal time range during that output value reach the level corresponding to level of input parameter;

5) ***reproducibility*** – difference between output signals on equal input influences in different time moments must be absent.

Next terms are used often:

transducer gage – measuring device with converter;

transducer-converter – sensor- converter;

transducing apparatus – converter, device for converting.

Artefact - process or the formation not peculiar to an object of interest and incipient during examination. They distort obtained information and often are result of mistakes at matching or fulfilling of investigation method or sensors. For example, when substance of sensor interacts chemically with investigated object. Struggle against undesirable influences and artefacts is important and obligatory side of investigations.

According to physical nature of input signal sensors are divided on: mechanical, acoustical (sound), optical and so on.

Electrical measurement
(include biopotential measurements)

Electrodes are conductors of the special shape and construction with which help the explored field of a body or an organ of an alive organism is connected in an electric circuit of the measuring device. More often they use at electrocardiographies (ECG), electroencephalography (EEG), electromyography (EMG), electro-oculography, electro-gastrography (EGG), rheography (REG).

Electrodes use also for electrical action on an organism from the outside, for example, at medicinal electrophoresis, at rheography, at physiotherapeutic treatment by pulsing currents, at using the device "electrodream".

Separately it is necessary to view the microelectrodes used for pickup of electrical signals or electrical action at a level of separate cells and cellular ensembles.

Requirements to electrodes of medical and biologic purpose:

- are promptly fixed and removed;
- high stability of electrical parameters, absence of artefacts and noises;
- low losses of an electrical signal, including small transition resistance in zone of contact to object;
- mechanical strength;
- absence of irritant action;
- low price.

Particularly strict requirements are made to implanted electrode, which must work long time (many years in case of heart control).

When a metal is placed in an electrolyte (ionizable solution), an uneven charge distribution is created at the metal/electrolyte interface. The charge distribution causes an electric potential across the interface between the metal and the electrolyte. In more details these processes are described in the chapter "Electrokinetic phenomena". As result of these processes chemical change of the material of electrodes and studied object, irritation of tissue, errors of measured signals can be observed.

Hydrogen is the standard half-cell potential. Stronger oxidizing agent have more potential ($F_2>Cl_2>Ag>Cu>H_2$), weaker oxidizing agent have less potential ($Li<Mg<Zn<Pb<H$). For example, standard reduction potential at 25ºC for H equal to 0 V, for Ag 0,8 V, for Zn –0,76 V. It’s mean that if used two electrodes – Ag and Zn – in one vessel with electrolyte, electric potential arises between them equal to 1,56 V.

The transient resistance "electrode - skin" can achieve hundreds kiloohms at a dry clean skin. It depends on properties of a skin, such as metal of which the electrode is made, contacting areas and a conducting medium between a skin and an electrode. For diminution of the transient resistance the napkins imbued by a normal (physiologic) saline solution, or more effective special conductive electrode pastes (electroding ink) are used.

The major contacting area provides diminution of resistance, however gives in distortions of a registered signal.

To manufacturing electrodes apply gold, platinum, iridium, tungsten, argentum, palladium, stainless steel of a special composition, alloys with iridium, etc. Frequently use the argentum electrodes coated by very thin layer of chloride argentums (Ag/AgCl electrodes). The exact selection of metal and structure of the surface stratum of an electrode, use of special electrode pastes allows to lower transient resistance and effects of polarization too.

Tungsten is the most versatile and widely used probe material because of ifs stiffness, biocompatibility and cost. It is ideal for most recording and electro-stimulation purposes.

Platinum/iridium are extremely inert and is much more resistant to corrosion than either tungsten or stainless steel when used in long time stimulation examinations.

Stainless steel is widely used due to its stiffness and it can be easily electrochemically coated with other metals used in certain type of studies.

Pure iridium has by far the lowest concomitant tip impedance of any of the noble metals. It is extremely inert and very resistant to corrosion.

Construction and performances of electrodes depend on the purposes of application. To destination electrodes part on 4 groups:

1) For disposable application (for the functional diagnostics).
2) For the long-lived continuous observation (reanimation, intensive therapy).
3) For dynamic application (sports medicine, the check of a patient state in time of sports rehabilitation).
4) For emergency application.

Main shapes of electrodes:

1) electrode plate;
2) vacuum cup (sucker);
3) olive at the ending of rubber or plastic catheter (used for esophageal registration of ECG);
4) piercing (needle-type, acicular, trocar) electrode;
5) multipoint electrode;
6) capacitive pickup electrode;
7) snare (electrode with loop shape – active electrode).

Microelectrodes

Biopotential electrodes with an ultra-fine tapered tip are used that can be inserted into individual biological cells. Commonly used in neurophysiology studies.

The tip of these electrodes must be small with respect to the dimension of the biological cell wall.

Kinds of microelectrodes:

1) glass micropipette;
2) metal microelectrode;
3) solid-state microprobes.

Intra-operative electrod microelectrodes es can be available in Tungsten and Platinum/Iridium core conductors covered by polymer insulator. Length of free tip can be equal from 5 mm (electrodes for work with neuronal pools) to 5 μm (electrodes for work with separate cells), thickness of covered layer can reach 1 μm.

Mechanical measurement

Sensors which are used for measuring of displacement (stretching or contraction) term as strain gages (strain indicator, strain sensor). Devices used strain gages term as tensometers (extensometer, strainometer). These names are used for pressure sensors too, since object of measuring in both cases the same: displacement of sensor parts.

Displacement transducers (position transducer)

Potentiometer transduces linear or angular displacement into a voltage. When a moving contact of variable resistor move, resistance between it terminals change; taked off voltage changes correspondingly.

Elastic resistive transducers

Resistance of electric conductor equal: $R = \rho \frac{l}{S}$, where ρ – resistivity constant (specific resistance) of material, l – length of resistor, S – cross-section area of resistor.

If resistor is elastic (can stretch and restore after removing of stretching force), during the elongation cross-section area decrease.

Such sensor used for measuring of amplitude and frequency of respiratory movements and for plethysmography (research of blood supply changing).

For example, elastic transducer is wrapped around the chest. The chest diameter during exhalation is 33 cm; corresponding circumference is near 104 cm. During inspiration volume and circumference increase, length of transducer increase, and its resistance increase too.

Strain gauges

Gauge insensitive to lateral forces

It's used in blood pressure transducers. Change in resistance is quite small.

Inductive displacement transducers (variable-reductance transducer)

Inductive displacement transducer or LVDT sensor (linear variable displacement transducer, linear voltage differential transformer).

When the core moves towards one coil the voltage induced in that coil increases proportionally.

Inductance of solenoid $L = \mu\mu_0 \frac{n^2 S}{l}$, where n – coil turns, μ – relative magnetic permeability of the core material, μ_0 – absolute magnetic permeability of vacuum, l – solenoid length, S – cross-section area of solenoid.

Semiconductor strain gages are used for measuring of pressure.

Capacitors and capacitive transducers

The most common method to measure displacement is to change the plate separation distance d.

This arrangement can be used to measure force, pressure or acceleration.

The capacitor capacitance is equal: $C = \varepsilon\varepsilon_0 \frac{S}{d}$, where S – the area of a plate (armature) of the condenser; d – distance between plates; ε – an inductivity of medium between plates; ε_0 – absolute inductivity of vacuum.

If the distance between plates varies, the capacity varies inversely.

They are used to measure respiration or movement studies (when placed on a mat). Capacitance sensors can measure ranges up to 300 nm with 0,1 nm resolution.

Piezoelectric transducers

Piezoelectricity – is originating of electrical charges displacement at strain of a crystal (*direct piezoelectric effect*). If the crystal is mechanically strained, it generates a small potential.

Inverse piezoelectric effect is a strain of a crystal under activity electric field in case an electric field is applied across its plates.

Crystal contracts in direction perpendicular to direction of applied electric field and turn, direction of originated electric field is perpendicular to direction of compression.

Piezoelectric sensors are active bio-controlled sensors.

Piezoelectric properties are observed at some kinds of monocrystal (native or artificial), for example, quartz, and at artificial materials as piezoceramics and piezopolymers. On the figure flexible polymer sensor is observed.

Piezoelectric sensor of simplest type is piezoelectric plate squeezed between two metal facings.

Used widely in different – all – branches of science and techniques.

They are used in cardiology to listen to heart sounds (phonocardiography), to automated measure of blood pressure, physiological forces and acceleration measurements. Also they are employed as sources of sound and supersonic signals. High frequency-sound waves greater than 20 KHz due to inverse piezoelectric effect.

Modern microphones used for studying of heard sounds are piezoelectric. Sometimes used electrodynamic microphones in which inductance coil bound with elastic membrane moved in static magnetic field under the influence of variable electric current through coil that originates variable magnetic field in coil.

Using magnetic fields

Blood flow through an exposed vessel can be measured by means of an electromagnetic flow transducer.

The probe contains coils that produce an electromagnetic field transverse to the direction of blood flow.

The electric charges in blood (the anions and the cations) experience force induced by the presence of the magnetic field. $F = qvB$, where F – induced force, q – charge of particle, v – velocity of charge, B – inductance of magnetic field.

Charge of electron $q = –1,602 \cdot 10^{–19}$ C; it is equal to absolute value of positive monovalent ion as Na^+ or K^+.

Oppositely charged particles move in opposite directions this movement causes an opposing force: $Fop = qE = qV/d$, where V – voltage formed consequently, d – diameter of vessel.

At equilibrium $qV/d = qvB \Rightarrow V/d = vB$, therefore $v = V/dB$. Here V – measured value.

Temperature measurement

It is the most often controlled physiological values and one of the four basic vital signs.

Distinguish temperature of nucleus (core) of a body and temperature of body surfaces – skin.

Inner (core) temperature is remarkably constant (37±0,5ºC). Temperature of the skin changes in more wide limits. If slightly dressed person is in room with normal conditions – 20ºC, temperature is equal to 36,6ºC in armpit, rectal temperature – 37ºC, and lower at other skin areas (in the center of footstep 27–28°C), particularly on open sites of extremities. Temperature is measured routinely in contact with the skin or inside a body cavity. At measuring the surface temperature it is important to estimate symmetry of temperature allocation that corresponds to norm and reflects intensity of a blood supply of a body fields, and also presence possible inflammatory or neoplastic processes. Temperature of a skin influence also a state of a surrounding medium (temperature, air humidity), tone of vegetative nervous system, a body hair development, clothes.

Temperature sensors are:

– wire-wound termoresistors;
– semiconductor-resistance thermometers;
– difference thermoelements.

Thermistors (termoresistors) – require direct contact with skin or mucosal tissues. They can be made of compressed, sintered metal oxides (Ni, Mg, Co) or semiconductors that change their resistance with temperature. Sensitive element of device is small to produce a rapid response. Shapes of sensor are difference from needle to flat.

Non contact thermometers used for determination of body core temperature inside the auditory canal as temperature of temperature of ear canal near the tympanic membrane is known to track the core temperature.

Noncontact thermometer

Temperature of the ear canal near the tympanic membrane is known to track the core temperature very accurately – by 0,5–1ºC. Infrared radiation from the membrane is channeled to a thermopile detector through a metal waveguide. Thermopile converts heat flow into current.

Next step of distant thermometry are thermovision or thermography. Sensors convert the infrared radiation into electrical signals. For more details see chapter "Thermal radiation".

Optical Biosensors

Usually as optical sensor are used photoresistors (for more details see chapter "Interaction between light and tissue"), which change resistance under the influence of incident light.

Arterial blood gases

Blood changes its color depending on the amount of oxygen bound to the hemoglobin in the erythrocytes. Oxygenated arterial blood is light red; vein blood is dark red with shifted spectral maximum of optical transmission.

Normal physiological conditions 98% of the total amount of oxygen is contained in the erythrocytes in a loose combination of hemoglobin Hb and oxyhemoglobin $Hb0_2$. The remaining 2% of oxygen is dissolved in the blood plasma. Oxygen saturation (S_{O2}) is the relative amount of oxygen carried by the hemoglobin in the erythrocytes. During oximetry S_{O2} is determined.

Oximetry is based on the light absorption properties of blood and on the relative concentration of hemoglobin (dark-red) and oxyhemoglobin (red).

Measurement is based on Beer-Lambert's law that relates absorption of light to the properties of the material through which the light is transmiting.

Electronic circuits turn on and off sequentially the LEDs (light-emitting diodes) and synchronously measure the output when corresponding LED are turned on. Pulse oxymetry relies on photoplethysmographic changes in the arterial blood volume synchronous with periodic contractions of the heart. Amplitude of the signal depends on the amount of blood ejected from the heart in the peripheral vascular bed with each cycle, the optical absorptions of the blood, the composition and color of the skin and underlying tissues and the LEDs used to illuminate the blood. This method allows obtain information about heart work and oxygenation of peripheral blood simultaneously.

Other types of biosensors

Many sorts of sensor have specific functions. For example, biosensors can have some sort of recognition element like an enzyme, antibody or receptor which provides the selectivity to the object of interest that researcher wants to detect or to measure. The transducer converts the biochemical reaction energy into the form of an optical, electrical or physical signal proportional to the presence of a certain chemical characteristics.

Optical fibers

In optical biosensors can used part included optical fibers (for more details see chapter "Elements of wave optics"). They allow to illuminate, to observe and to measure optical characteristics of inner cavities of a body. At the same time other procedures can be provided in studied cavities, for example, surgical operation. In one bunch with optical fibers (illuminant and observation) other systems for distant influence and measuring can be used, including different sensors.

Endoscopic methods

Endometry is diagnostic technique at which measuring are carried out far off, outside of a field of vision in various cavities, for example, in a gastrointestinal tract, blood vessels and cardiac cavities, in abdominal cavity. Thus manifold data units, for example, pH (acidity), pressures, temperatures, optical and others are applied. In heart cavities it is possible to measure pressure using electrical micromanometer (Ø 1–2 mm) at the end of heart catheter.

Radioprobe (endoradiosonde) is used for examination of gastrointestinal tract. It is similar to pill enclosed power source, sensors and microradiogenerator. After swallowing on radioprobe goes by native path and sends signals to the receiver.

Pacemaker, pacing lead

Pacemaker (pacing lead, cardiomonitor) is device for control of heart work. It is miniature generator of electrical pulses with frequency and form necessary to set heart contraction disturbed as result of illness. It is implanted device. Now power supply can be made through skin without skin damage by way electromagnetic induction link. Modern pacemakers use built-in sensors, logical microcircuitries and change frequency of stimulus under needs.

Literature recommended

Main sources.

1. Chaliy at all., Biological and medical physics. – A.V. Chaliy et all.– Ed.A.V. Chaliy. – Vinnitsia, Nova Knyha, 2013. – 480 pp.
2. L.D.Korovina. Biophysics with beginnings of mathematical analysis and statistics. Extended course of lectures. – Vol.1. Basis of mathematical analysis, probability theory and mathematical statistics. Biomechanics. –Poltava, 2017. –127 p. – Chapter 4.
3. Compendium of Medical Physics, Medical Technology and Biophysics for students, physicians and researchers. Nico A.M. Schellart. – Amsterdam.– 2009 (electronic book).

Additional

- Paul Davidovits. Physics in Biology and Medicine, Third Edition (Complementary Science). – 2007.
- Bengt Nölting. Methods in Modern Biophysics.– 2009.
- Roland Glaser. Biophysics: An Introduction.– 2010.
- Philip Nelson. Biological Physics (Updated Edition).– 2007.
- Paul Davidovits. Physics in Biology and Medicine, Third Edition (Complementary Science). – 2007.
- Bengt Nölting. Methods in Modern Biophysics.– 2009.
- Biological Physics. Energy, Information, Life. Philip Nelson, (Freeman and Company, New York, 2004).

Methodical elaboration have prepared by senior lecturer, PhD biol.Sc. Korovina L.D.