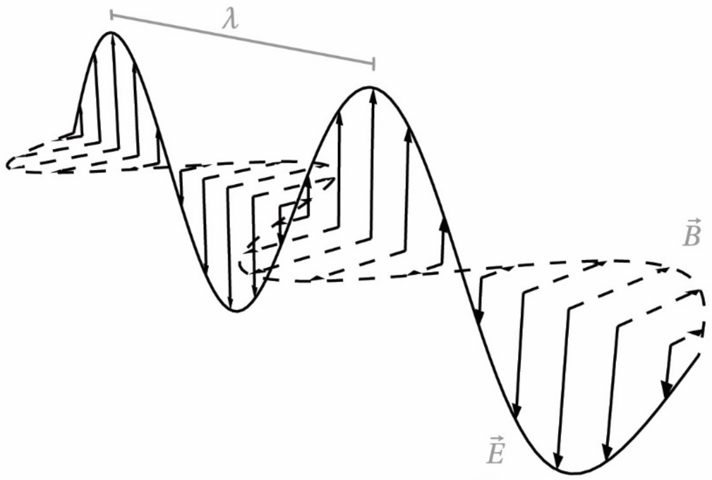
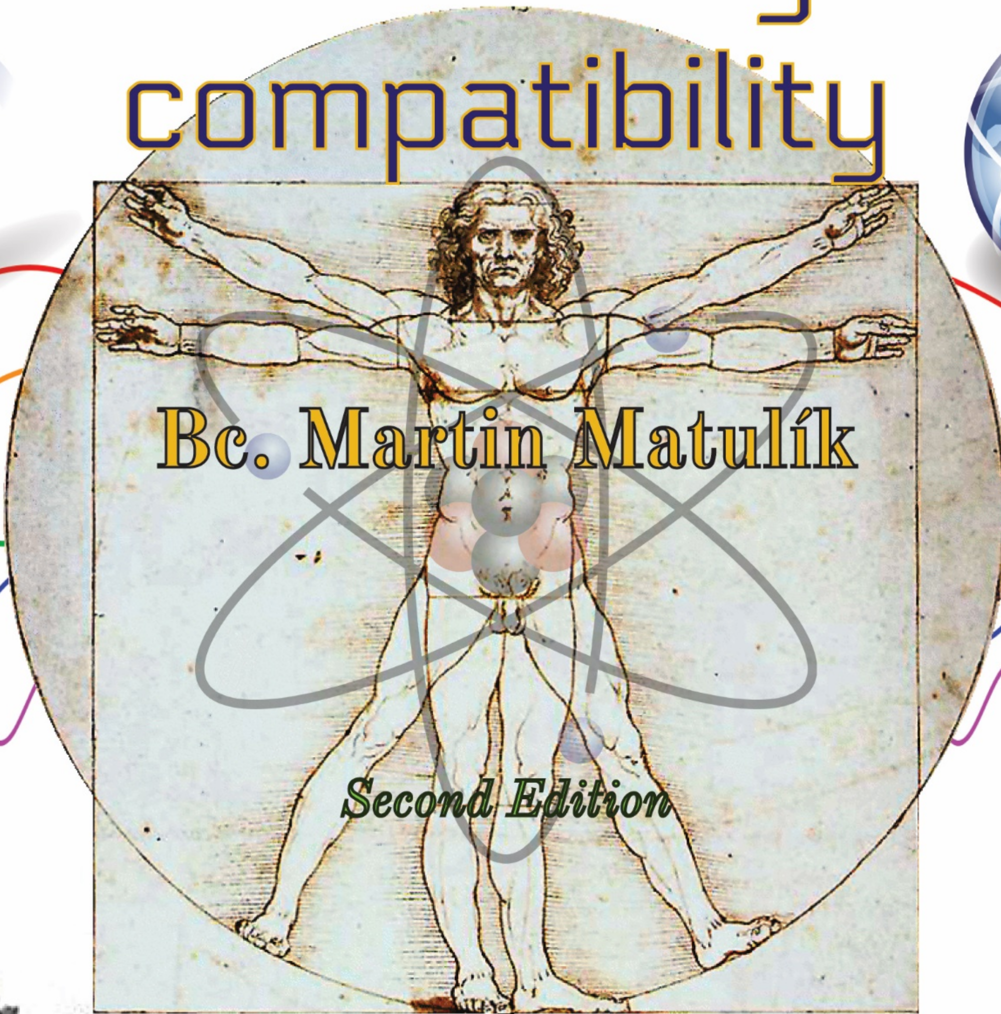


§ 15

Bio-Electromagnetic compatibility



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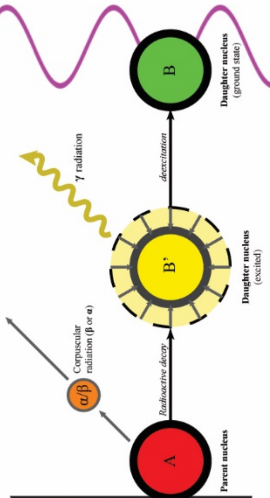

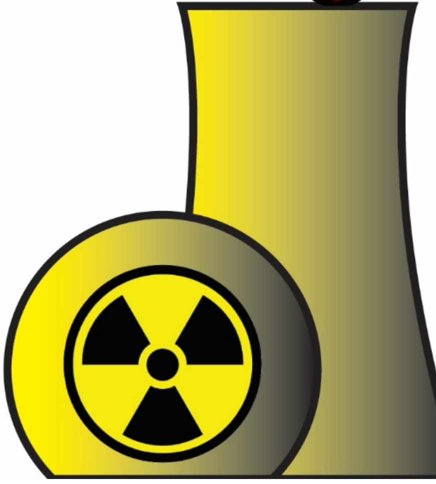

CHANGES IN SECOND EDITION:

Typography:

- Text formatting „*Justify*“.

Content:

- Fig. 1 re-created, based on original image (better graphics, English captions) (1.1.1).
- Examples of tissue’s properties utilization (1.2.3).
- Examples of non-thermal effects (1.2.4).
- **Added current scientific understanding** of non-ionizing radiation interaction mechanisms (resulting from author’s review of more than 300 studies conducted in this particular field up to 2015) (1.2.4).
- **Legislation updated** due to recent changes in Czech legislation – currently valid hygienic limits for non-ionizing radiation exposure (2.1).
- Outdated charts removed (2.1.1), created tables with current limit values, reference sources updated.
- **Factual errors corrected** (electrons -> protons) (3.1.4)
- Added clarifying informations about image processing with “k-space” method (3.1.6).
- Updated technological limits of superconducting electromagnet’s magnetic field, hybrid devices mentioned (3.1.8).
- Added informations about trends in CT design (Cone beam CT) (3.2.1).
- Shielding materials graph graphically improved (4.1.2).
- Mobile communication standards updated, examples added (4.2)
- More appropriate chapter’s title chosen (4.2.2).
- Mobile communication description extended (4.2.4).

- Sentence stylization improved.
- Enhanced clarity and understandability of multiple topics (sentences reformulated, added additional informations and vivid examples from common practice).
- Typing errors corrected.

2.7.2016

BRNO UNIVERSITY OF TECHNOLOGY

FACULTY OF ELECTRICAL ENGINEERING AND COMMUNICATION
DEPARTMENT OF TECHNOLOGY ENGINEERING

BIO-ELECTROMAGNETIC COMPATIBILITY

SECOND EDITION

BACHELOR’S THESIS
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AUTHOR MARTIN MATULÍK

BRNO, 2014

BRNO UNIVERSITY OF TECHNOLOGY

FACULTY OF ELECTRICAL ENGINEERING
AND COMMUNICATION

(DEPARTMENT OF MICROELECTRONICS)
DEPARTMENT OF ELECTRICAL AND
ELECTRONIC TECHNOLOGY

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BACHELOR’S THESIS

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BRNO, 2014

Abstract

Following work deals with problems concerning effects of electromagnetic radiation on living organisms. It goes into interactions of electromagnetic radiation with surrounding environment, effects on living organisms, physical units of biological tissues and classificating types of electromagnetic radiation to determine means of protection against adverse health reactions. It enlightens means of establishing sanitary restrictions, differences in legal aspects of Czech Republic and worldwide, possible medical utilization and even principles of selected diagnostic and therapeutic techniques.

Keywords

Electromagnetic radiation, radioactivity, non-ionizing radiation, mechanisms of interaction, effects on living organisms, thermal effects, protection against adverse health effects, specific absorption rate, dosimetry, sanitary restrictions, legal aspects, legislation, medical utilization, diagnostic methods, magnetic resonance imaging (MRI), computational tomography (CT), thermo-therapy, radio-frequency measurement, GSM band, electric field strength, antenna polarization

Declaration

I declare, that I´ve written my bachelor´s thesis **"Bio-electromagnetic compatibility"** independently, under supervision of Zdenka Rozsivalova, using scientific literature and other informational resources, all of which are quoted in the work and also listed at the end of the thesis.

As an author I also declare, that within the context of creating this work I have complied with copyright law, according to provision § 11 and following copyright law 121/2000 Sb., with understanding to consequences of provision § 152 of criminal law 140/1961 Sb.

At Brno *5th June 2014*

Acknowledgements

I would like to thank to supervisor of this work **Ing. Zdenka Rozsívalová** for effective methodical, pedagogical and professional assistance, and other valuable advices during project development. I also thank to **Ing. Radomir Matulik** for support and incentives in the field of electronic measurement, as well as to **Ing. Thomas Palai-Dany, Ph.D.** for assistance with the implementation of measurement in the area of ionizing radiation, and also **Ing. George Dřínovský, Ph.D.** for renting equipment for radio frequency measurement and devoted assistance during the actual measurement. Special thanks is dedeicated to **Ing. Libor Havlicek**, who lent me high-quality spectrum analyzer, thanks to which I have been able to perform radio-frequency measurement at an appropriate technical level, allowing acquisition of necessary data with high informative value.

At Brno *5th June 2014*

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LIST OF SYMBOLS AND ABBREVIATIONS

BTS	Base transceiver station
CT	Computional tomography
DNA	Deoxyribonucleic acid
ELF	Extremely low frequency
EM	Electro-magnetic
FCC	The Federal Communications Commission
GSM	Groupe Spécial Mobile
HSP	Heat shock protein
ICNIRP	International Commission on Non-Ionizing Radiation Protection
IEEE	Institute of Electrical and Electronics Engineers
IR	Infrared
LED	Light emitting diode
MRI	Magnetic resonance imaging
OSL	Optically stimulated luminiscence
RF	Radio-frequency
RMS	Root mean square
SAR	Specific absorption rate
TLD	Thermo luminiscent dosimetry
UV	Ultra-violet
VHF	Very high frequency
WHO	World health organization

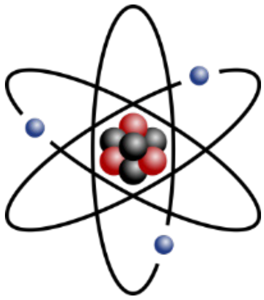
INTRODUCTION

Following project seeks to gather and organize informations concerning effects of various types of electromagnetic radiation on living organisms. With an ever-increasing rate of utilization of electronic devices, gradual usage of free radio frequency bands, but also intensive technical and technological research, there is an increasing amount energy in form of electromagnetic waves spread throughout our environment. They are invisible, usually penetrating organic, as well as inorganic matter. Because certain types of EM waves may interfere with proper function of other devices, the question is: "may they interact with living organisms? And if so, what are consequences of such interactions?" These questions are important in order to ensure *"proper function"* of biological systems coming into contact with electromagnetic waves. It is necessary to carefully select optimal methods that will allow us to evaluate the effects of various radiation forms on living organisms and make qualified conclusions afterwards.

On this basis, we will conclude whether certain types of EM radiation may cause adverse effects to biological systems, but we will also discuss exposure limit values, which should ensure safety of general public and technical workers from those carrying considerable health risks. If, for some reason, it is not possible to reduce amount of interacting radiation, we will try to find adequate countermeasures in order to minimize impact of adverse health effects, resulting from exposure to electromagnetic radiation.

Thus, if radiation may be dangerous in certain cases, how can we protect ourselves against their adverse effects? And can they be used in our favor? Or even use the same mechanisms, which cause various complications, to solve some health problems, treat various ailments and injuries? On which principles are they based? Have they any pitfalls? May be different principles used to achieve similar results? Are some of them more suitable for performing certain tasks, while others seems to be completely useless? How to distinguish from each other and choose the most appropriate solution in a particular situation? What should we look for? What is the legislative point of view on this whole issue? Are there any differences between legal frameworks of Czech Republic in relation to other countries? On what exactly are their provisions based?

1. RADIATION



Any matter can be divided into subcomponents. It consists of molecules composed of atoms, which contain a nucleus and an electron cloud. In the nucleus, we can find protons (positively charged particles) and neutrons (uncharged particles). Both are made of quarks, the smallest known particles [2]. Electron cloud contains electrons (negatively charged particles), even though major part is filled with free space. Elementary particles consists of strings (waves). In other words, radiation of electromagnetic nature.

The **radiation** may be natural – created by natural processes occurring in nature, or artificial - caused by human activity (construction of items emitting electromagnetic radiation). According to the way of interaction with surrounding environment, radiation can be divided into two main groups:

- Particles of **ionizing radiation** have sufficient energy for tearing off an electron from electron cloud [17].

- Particles of **non-ionizing radiation** should not be able to tear off an electron under any circumstances.

1.1 Ionizing radiation

Ionization process is known as transformation of electrically neutral atom to atom with positive or negative electric charge - **ion**. Positively charged ion (cation) may, by reaction with its surroundings, lose excessive negative charge carrier (electron) and become neutral. This phenomenon is known as **recombination**.

Directly ionizing abilities are possessed by electrically charged particles - protons, electrons, positrons.

Indirectly ionizing capability belongs to electrically uncharged (neutral) particles – neutrons and photons. These are not able to ionize their surroundings by themselves, instead of that they release directly ionizing particles when interacting with surrounding matter. Ionization of surrounding matter is therefore caused by these secondary particles. [26]

1.1.1 Physical units

Radioactive substance (parent nucleus) decays and consequently emits corpuscular radiation (alpha, beta), while experiencing its conversion into daughter (excited) nucleus. When de-excitation (charge carriers return to their ground energy level) takes place, hard and high-energy gamma radiation comes out of the nucleus.

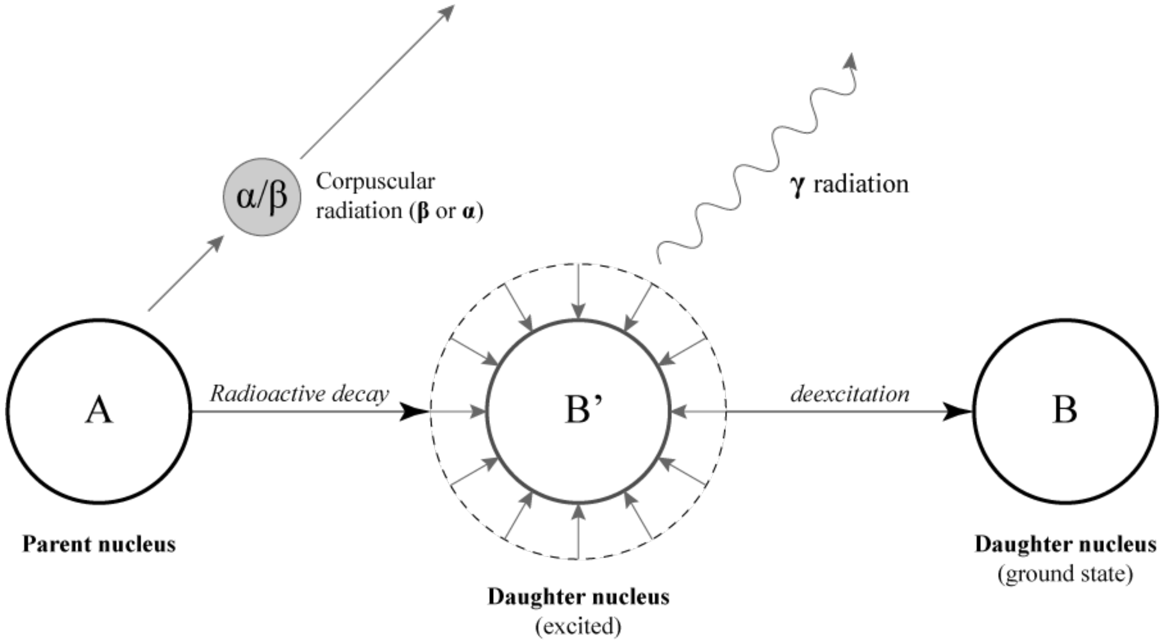


Figure 1: Diagram of nuclear transformation

The number of nuclear transformations per time unit (decays per second) determines the activity of a radioactive substance. 1 Becquerel (*Bq*) = 1 decay per 1 second. This value is quite low, therefore we use its multiples (*kBq*, *MBq*, *GBq*). Time necessary for decaying half of all nuclei is called the **half-life**. After another equally long time period, half of remaining nuclei decays. [60]

Amount of ionizing radiation energy absorbed by certain material is determined with **Gray** unit in Europe, which corresponds to one joule of radiation energy absorbed by one kilogram of the substance (1 *Gy* = 1 *J/kg*). Americans use **rad** units instead, where 1 *rad* = 0.01 *J/kg* = 10 *mGy* => **1 *Gy* = 100 *rad***. [54]

On the other hand, biological effect of absorbed dose of energy (dose equivalent) of 1 Gray corresponds to one **Sievert**. In case of American units (rad), **rem** unit assess biological effects of absorbed energy. [53]

Biological effect of one **Sievert** takes place when absorbing energy of one **Gray** (1 *Sv* ~ 1 *Gy*). Not surprisingly, biological effect of one **rem** corresponds to energy of one **rad** (1 *rem* ~ 1 *rad*).

For the sake of completeness: 1 Curie = 37 billion Becquerel. (1 *Ci* ~ 37 *GBq*)

That is a sequence of 37 billion decays per single second!

This approximately corresponds to the activity of one gram of radium isotope ^{226}Ra. [6]

Table 1: Comparing physical units of radiation intensity

Decays per second:	
Becquerel [Bq]	Curie [Ci]
1	$370 * 10^9$

Table 2: Relations between units

Dose absorbed:		
Elementary	*Europe*	*USA*
J/kg	Gray	Rad
1	1	100
Corresponding biological effect:		
J/kg	Sievert	Rem
1	1	100

1.1.2 Mechanisms of interaction

A gamma radiation photon may interact with electrons of atoms in surrounding environment and pass all its energy to one electron, allowing the electron to leave whole substance. Its kinetic energy is given by radiation energy, reduced by amount required for releasing the electron. This **photoelectric phenomenon** dominates particularly in low energy radiation interactions (energy below 50 *keV*).

Mid-energy radiation (100 *keV* to 10 *MeV*) occurs i.e. during a nuclear explosion. Radiation passes portion of its energy to an electron, kicking it out from the atom, while remaining amount of radiation (reduced by energy depleted on releasing the electron) continues in its journey. That we just described the **Compton scattering** effect.

While photon is flying-by close to atom's core, an **electron-positron pair** may be created. This requires at least 1.02 *MeV* energy. Excessive energy will supply newly formed pair by initial kinetic energy. [69]

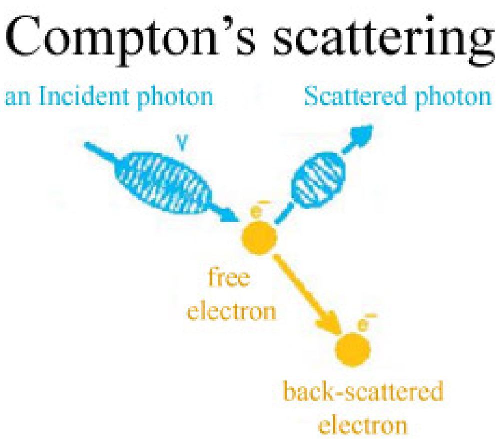


Figure 2: Compton's scattering [70]

1.1.3 Interaction with living organisms

Ionizing radiation, passing through the environment, possess ability to ionize neutral particles ("grant" them with a positive or negative charge). This may, in living organisms, **cause disruption of chemical bonds** followed by molecular disintegration and structural changes in proteins.

Additionally, formation of **free radicals** takes part during interaction of ionizing radiation with water inside the body. Water molecule is broken down to a hydrogen cation (H+) and highly reactive hydroxyl ion (OH-). Free radicals subsequently damage cells in their surroundings and may also adversely affect DNA.

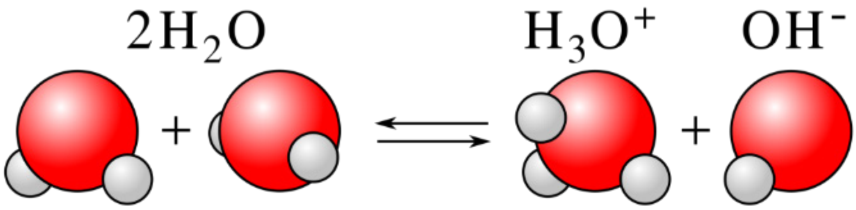


Figure 3: Formation of free radicals [5]

Damaged cells may not undergo apoptosis (programmed cell death) as they should. Instead of that, affected cell may start to proliferate (divide itself), thereby creating many other dysfunctional cells, resulting in **malignancy** (cancer), or changes in DNA - **mutations**.

These aforementioned **stochastic (unpredictable) effects** occur at any level of irradiation. Growing intensity increases amount of damaged cells and thus probability of malignancy. At high doses, on the other hand, tissue is being damaged proportionally to dose received - effects can be quite precisely predicted and extent of overall damage may be **determined** - these are **deterministic effects**. [60]

1.1.4 Ways of irradiation

The most severe conventional way of irradiation is **inhalation** of radioactive particles, due to their deposition in different parts of the respiratory system, which cannot be cleaned of them easily. We may inhale those particles when staying in contaminated areas, where they are dispersed throughout the air. Additionally, irradiance takes place also by **absorption** - direct penetration of ionizing radiation throughout our organism and interactions with its individual parts. **Ingestion** of food enriched with radionuclides is not a brilliant idea, because of their absorption by digestive system (small intestine) and consequent deposition in various parts of human body. In certain cases (medical diagnostics), radioactive substance may be **injected** into the organism intravenously. [60]

More critical than **external contamination** (absorption) is **internal contamination** (inhalation, ingestion, direct skin contact with radioactive material). Radionuclide deposited in an organism may be piled in certain parts of the body and irradiate whole organism on long-term basis.

1.1.5 Protection against radioactivity

The essential **protection by time** is based on shortest possible time of exposure. Sufficient **distance** from sources of ionizing radiation is commonly used method, because radioactivity decreases exponentially with square of distance from the source - spent nuclear fuel obviously should not be buried into the sandbox amidst housing estate, but it would be more convenient to bury it in an uninhabited area. In addition, ionizing radiation can be attenuated by appropriate **shielding**, usually lead, or concrete with barite as an additive. Radiation shielding will not allow us to eliminate radiation comletely - we can, however, radically reduce the amount of waves passing through (most of them will be absorbed by shielding material). For designing shielding properly, we need to know “**half-value layer**” of material - material thickness, which lets half radiation amount pass through. [69]

1.1.6 External dosimetry

Determining the amount of ionizing radiation in surrounding environment, or amount of ionizing radiation absorbed by living organism, is responsibility of **dosimetry** (“dose” metering). Those working in hazardous environments usually carries **personal dosimeters** with them. Earlier, it was a strip of photographic film, which blackened while exposed to an ionizing radiation. After film developement, absorbed dose has been determined by intensity of blackening. Such dosimeters were obviously intended for single use. Newer types has been using **thermoluminescence phenomena** (TLD). Based they were mostly on calcium fluoride, or lithium fluoride. Ionizing radiation can excite electrons of these materials to an exited state - they jump to a higher energy level, where they remain. During **heating** of crystal, the electron descends to its original level, while releasing energy (acquired by ionization) in the form of light.

Releasing of acquired energy can occur also after prolonged period of time (**fading** being observed). This makes it difficult to precisely determine amount of absorbed radiation, so each TLD is labeled with an information of period, during which data possess some validity. The typical period is usually in range of few weeks up to two years, depending on the kind of thermoluminescent material. [58]

Dosimeters stimulated by **optical luminescence** (OSL) utilizes, for descending electron to its basic energy level, energy in form of **light**. After illumination, there is an emission of excessive energy (in form of light again). A suitable detector (photomultiplier) is capable of transforming photons to an electric signal, from which absorbed dose can be calculated. [43]

At the present time, most widely employed are **personal electronic dosimeters**, which can display currently absorbed dose in a real-time manner, provisional total absorbed dose and alarm the bearer, when set values are exceeded. [7]

1.1.7 Internal dosimetry

What to do when, during a stay in radioactive environment, we have absolutely no idea about intensity of radiation? Indirectly, you can specify the amount of absorbed radiation from irradiated person's biological samples. Usually, analysis of urine or faeces is employed. This method is particularly suitable for determining amount of absorbed alpha and beta particles, which are, by other methods, hardly detectable. [24]

Direct method, particularly suitable for determining amount of absorbed gamma particles and X-rays, is provided by a **whole body counter**, which captures ionizing radiation emitted by an exposed person.

1.1.8 Radiation sickness therapy

Treatment is based on determination of **absorbed dose** by evaluation of available dosimetric data, ideally from personal dosimeter, static dosimetry measuring station (roughly indicating level of radioactive contamination in the area), or one of the methods mentioned in previous chapter.

In the event of a nuclear disaster, we should undress the casualty and consequently perform external **decontamination** by showering him with a streaming water, then again with usage of common solvents (shampoo, detergent, citric acid). Followed by **iodine prophylaxis**, i.e. administration of potassium iodide, which prevents accumulation of irradiated iodine in thyroid gland (center of the immune system). Administration of 250 mg tablets provides protection for 5 hours. This precautionary measure is effective either **pre-exposure** (tablets given before exposing to a source of ionizing radiation), or as soon as possible after irradiation (usually in a few hours). Effectiveness of that particular measure decreases with delay between irradiation and administration.

Potassium iodide can protect **only** iodine in thyroid gland. For removing other kinds of radionuclides from the body, appropriate antidote should be administered. Among unconventional ones, alcohol may help us to some extent (strontium removal). Commonly known is case of fishermen in the vicinity of Chernobyl power plant, to which, allegedly, excessive amounts of alcohol helped to overcome undesirable health effects of radiation poisoning.

At an early stage, it is also suitable to **induce vomiting**, if radioactive particles has been inhaled (removal of swallowed mucus, saliva), or ingested with some food. Eyes should be rinsed with **boric water**, mouth with clean water (potassium permanganate solution may be used as well). Furthermore, **drinking water** should be repeatedly administered. Appropriate **adsorbent** (aluminum phosphate, activated charcoal) and some **laxative** (agent accelerating metabolism) such as magnesium sulfate (2 tablespoons), or castor oil, would then greatly enhance internal detoxification processes.

Supportive treatment should be employed consequently, for prevention and remediation of additional complications. As a result of irradiation, human body's defenses (immune system) may be considerably damaged. **Antibiotics** administration can suppress bacterial infections. Diet and fluids should be **sterile**, if possible. **Supporting immune system** with immunostimulants is also favorable. Irradiation disease is usually accompanied by **anemia**, therefore administration of substances promoting **hematopoiesis** (drugs stimulating production of blood cells from remaining stem cells in bone marrow), is highly recommended.

At specialized medical departments, therapy continues with **hematopoietic stem cell transplantation**. Especially their timely administration allows resettlement of hematopoietic areas, resulting in their repopulation with blood cells, subsequently saving the casualty´s life. [31]

1.1.9 Summary

The aim of this chapter has been briefly review and summarize challenges in the area of ionizing radiation effects on living organisms.

Types of radiation were discussed, along with interaction mechanisms with surrounding environment (depending on amount of energy transferred by a radiation), as well as ways of interaction with living organisms and their consequences.

Briefly were classified different types of physical units characterizing ionizing radiation, which often seems to be confusing, even in academic circles. Extraordinary effort was taken for outlining their mutual relations and intelligible categorization for clear and vivid understanding.

There were written various ways of irradiation and severity of different types of ionizing radiation exposition consequences, along with explanation, why some types are more dangerous than others. Followed by listing essential protective means and ways of detecting the ambient radiation, as well as concepts vital for determining the amount of radiation absorbed by living beings, should provide a brief insight into most basic radiation protection concepts.

1.2 Non-ionizing radiation

All the electromagnetic radiation, whose particles (or quanta) do not have sufficient energy to ionize atoms or molecules (knock out electron from an atom) [33], although they are capable of exciting electrons to higher energy (excited) state - moving them i.e. from valence band to conductive band. These excited electrons can release their excessive energy (transferred by radiation) in another form (light, heat), while descending to their original level. This principle is widely used, for example, in the design of semiconductor components (light emitting diode).

Interaction with surrounding environment always occurs. The energy of individual particles (or quanta) determines the **mode of interaction**. Overall radiation intensity (number of particles) affects overall **strength of the effect**. Sufficiently intense radiation can thus significantly interact with surrounding environment.

Essential components of electromagnetic radiation are electric and magnetic fields. The **electric field** arises from **potential difference**, which is the amount of work required for transferring a unitary electrical charge from reference point with zero potential to desired location. A place with potential 1 *V* against ground creates an electric field with voltage of 1 *V*. It is created in all devices connected to a power source, even if electric current is not flowing through the device itself at the time. The **magnetic field** is generated by **electric current** (movement of charged particles) at the moment, when the device is fully operational.

In addition to particle motion, magnetic field can be created using **electron momentum** in ferromagnetic substances. Such sources are referred to as **permanent magnets** (generating magnetic fields without electric current passing through them). Ferromagnetic substances are essentially **paramagnetic** (weakly amplifying the magnetic field) in their basic configuration. Ferromagnetism can be induced by arranging internal particles appropriately (using i.e. magnetization). On the other hand, **diamagnetic materials** (slightly weakening the magnetic field), could, by appropriate organization of internal particles, effectively weaken the magnetic field.

1.2.1 Frequency bands

Frequency is a physical quantity, that indicates number of periodic action repetitions for a given time period [18]. It is usually expressed in Hertz [*Hz*], wherein one *Hz* = 1 cycle per 1 second. Our particular particle (photon quantum) is oscillating from one extreme position to another. It changes its position (moves) in dependence on time – thus producing undulation **(waves)**. Distance between two nearest points of the wave, that are in same phase of different cycle, is reffered to as **wavelength**. [62]

Frequency and wavelength are linked to each other by relation $f = \frac{v}{\lambda}$ whereas $\boldsymbol{v}$ indicates the **speed** of wave propagation in material environment. In the vacuum, propagation velocity is equal to the speed of light, therefore frequently stated formula is $f = \frac{c}{\lambda}$ where $\boldsymbol{c}$ indicates the **speed of light**. [15]

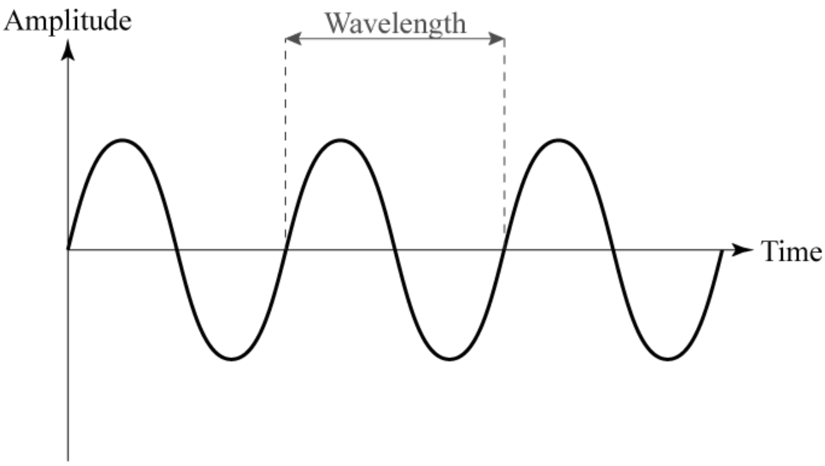


Figure 4: Wavelength visualization

According to frequency, we can almost divide **electromagnetic spectrum** (radiation with all known wavelengths) into several bands.

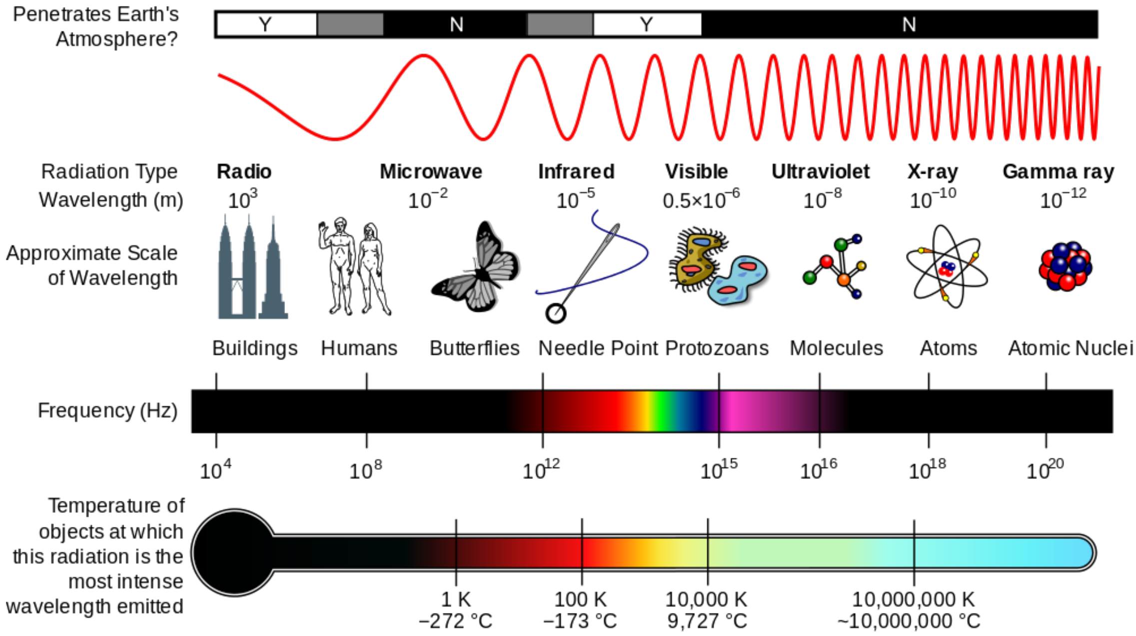


Figure 5: Electromagnetic spectrum [11]

Table 3: Energy of frequency bands [3]

Type of radiation	Photon energy	Wavelength
Ionizing radiation	>1 keV	<1 nm
Ultraviolet radiation	0,3 eV – 1 keV	1 nm – 400 nm
Visible light	0,15 eV – 0,3 eV	400 nm – 780 nm
Infrared radiation	40 meV – 0,3 eV	780 nm – 3 mm
Radio waves and microwaves	< 40 meV	> 3 mm

1.2.2 Interaction with surrounding environment

At the interface between two media, a portion of EM wave is **reflected** back into space. The remainder **passes through** material, whereas part of it is **absorbed** and converted into other forms of energy (typically heat).

Every material has certain **characteristic features** that determines how and to what extent surrounding radiation can interact with it. Some of them can be described by **physical quantities**, thanks to which we can better understand various interaction mechanisms.

Permeability $\boldsymbol{\mu}$ expresses the influence of material, or environment, on resulting effects of applied magnetic field. [44] In biological tissues, which exhibits paramagnetic or diamagnetic properties, permeability has only minor influence. [23] It partially affects how deeply external radiation can penetrate into the tissue.

Permittivity $\boldsymbol{\varepsilon}$ indicates the extent of material polarizability, while the **conductivity** $\boldsymbol{\sigma}$ counts number of electrons that can be brought into an ordered motion.

Table 4: Analogies between electric and magnetic field

Type of field	Relation	Quantity	Material constant
Magnetic	$\vec{B} = \boldsymbol{\mu} * \vec{H}$	Magnetic induction	Permeability
Electric	$\vec{P} = (\boldsymbol{\varepsilon} - \boldsymbol{\varepsilon_0}) * \vec{E}$	Dielectric polarization	Permittivity
Electromagnetic	$\vec{J} = \boldsymbol{\sigma} * \vec{E}$	Current density	Conductivity

1.2.3 Physical properties of biological tissues

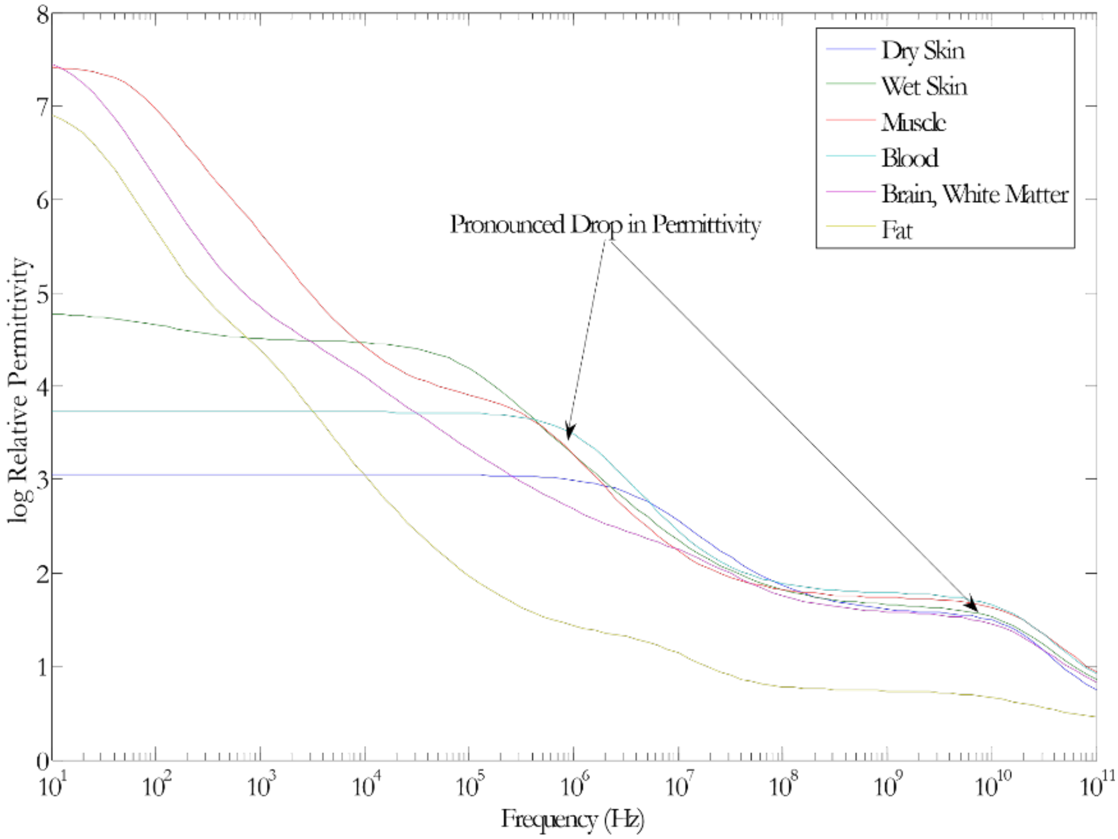


Figure 6: Relative Permittivity versus Frequency for Six Tissues [23]

Chart above shows a dependency of relative permittivity on frequency of electromagnetic radiation penetrating through six biological tissues. Frequency is shown on the horizontal axis, while the magnitude of relative permittivity is shown on the vertical axis, both in logarithmic scale. Blue curve refers to dry skin, green to wet skin, red to muscles, light blue to blood, pink to brain cortex, yellow to fat.

The chart suggests that with increasing frequency of radiation decreases its ability to polarize molecules of biological tissues. The threshold is in the order of 1 *MHz*, for which cells of all tissues cease to be sensitive to polarizing effects of external field. At high frequencies, molecules can no longer follow changes in external alternating field, so their parts with magnetic dipoles remain more or less in the same position.

Dielectric constant (permittivity) have great importance when determining biological impacts of fields with an **extremely low frequency** (ELF). Magnetic dipoles of tissues are following changes in alternating field without any problem, therefore their final angle may be given by an external field. The question remains, however, in which manner this polarization affects biological processes in affected areas?

Muscles and the brain tissue are particularly sensitive to low frequency fields. This quality may be utilized e.g. in muscular regeneration after injury, or neurological therapies. On the contrary, blood and wet skin, containing saline solutions or other conductive substances (iron), exhibit significant conductivity, therefore an outer field, in terms of polarizability, has rather minor influence on them. High conductivity, however, can be used for obtaining bio-signals reflecting activity of important physiological systems (electrocardiography, electroencephalography, electromyography, etc.).

The peculiarity is the adipose tissue, which reacts sensitively to low-frequency fields, while with increasing frequency its sensitivity rapidly decreases and remains extremely low in comparison with other, relatively “insensitive”, tissues. Moreover, it has relatively good insulating properties.

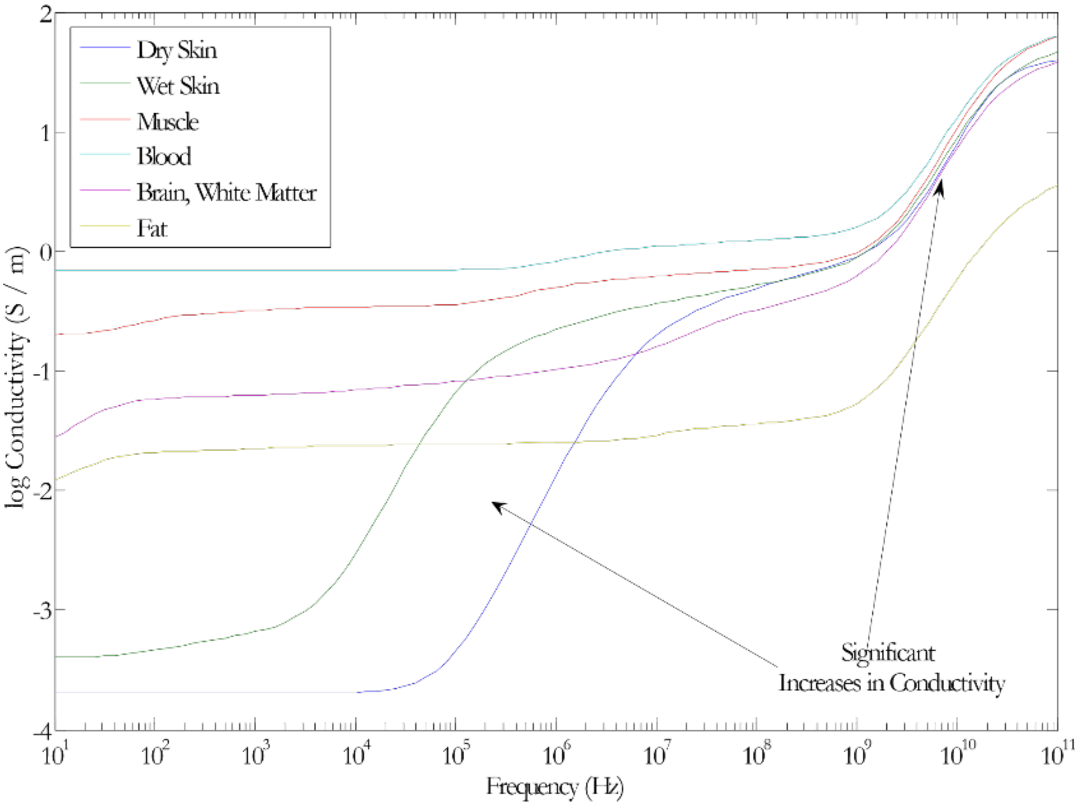


Figure 7: Conductivity versus Frequency for Six Tissues [23]

Figure 7 shows dependency of conductivity on frequency of electromagnetic radiation penetrating through six biological tissues. Frequency (in Hertz) remains on the horizontal axis, while the magnitude of conductivity is shown on vertical axis. Blue curve refers to dry skin, green to wet skin, red to muscles, light blue to blood, pink to brain cortex, yellow to fat.

With an increasing frequency, there is considerable increase in conductivity of all biological tissues. Steep increase in skin conductivity begins around frequency of 2 *GHz*. Blood is relatively good conductor (compared to other tissues) - of all tissues, it possess highest conductivity value.

Skin is a special case. Initially relatively good insulator, but with increasing frequency in magnitude of tens (wet) to hundreds (dry) kilohertz, there is very significant increase in conductivity, which grows up to a level comparable with other tissues.

From this peculiarity comes the term "*skin effect*", since with increasing frequency, electric current starts to flow mainly through surface layers of material - current density on the surface significantly exceeds current density of flux lines inside the material.

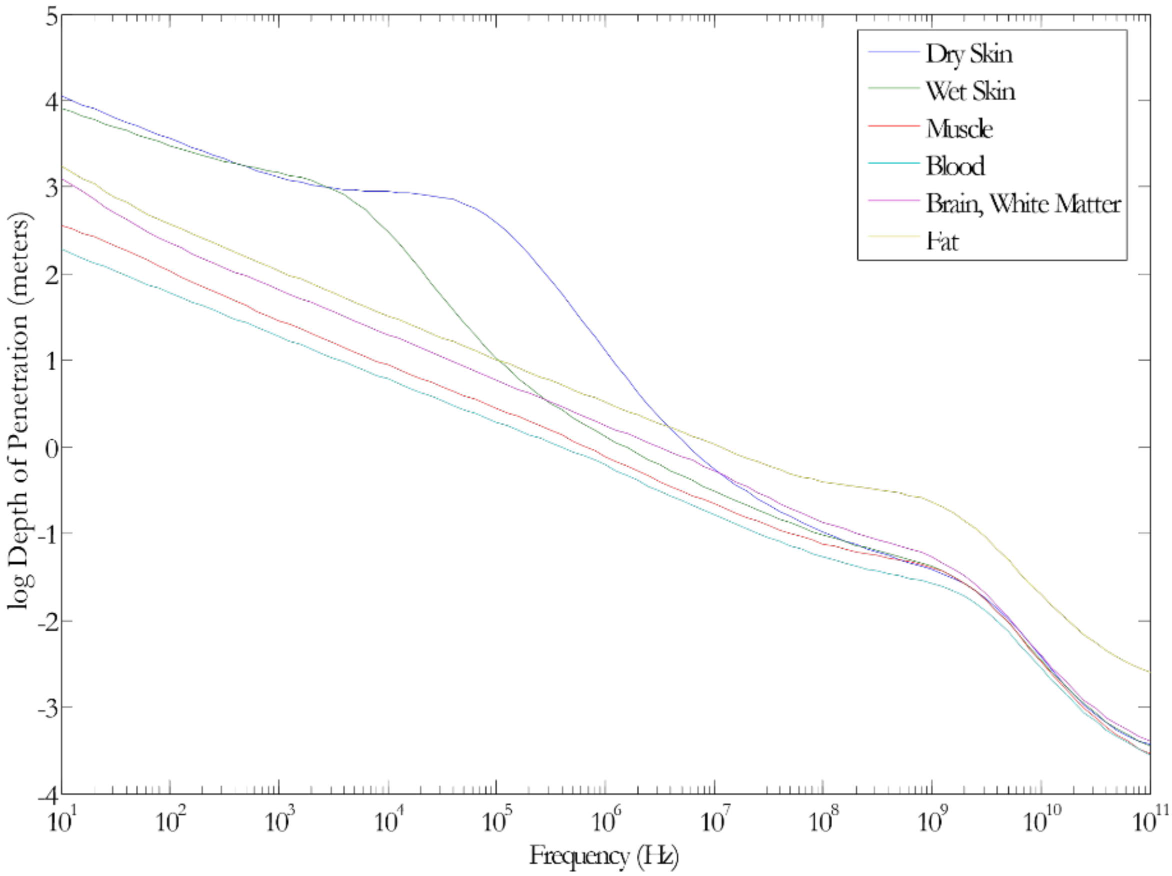


Figure 8: DOP versus Frequency for Six Tissues [23]

Chart above shows how electromagnetic radiation penetration depth depends on frequency of electromagnetic radiation penetrating through six biological tissues. Frequency is shown on the horizontal axis, while the penetration depth, on the vertical axis. Blue curve refers to dry skin, green to wet skin, red to muscles, light blue to blood, pink to brain cortex, yellow to fat.

The depth of penetration (DOP) is distance for any given material, at which amplitude of electromagnetic field quantities dampens *e*-times, where *e* refers to an Euler's number. [12] In other words, penetration depth determines **how deeply** electromagnetic waves, absorbed by biological tissues, **can penetrate** into the tissue. With an increasing frequency, penetration depth decreases. Up to frequencies in order of *MHz*, external radiation penetrates seamlessly through the skin, deeply into biological tissues.

1.2.4 Mechanisms of interaction

The basic division of biological effects consists of thermal and non-thermal effects. **Thermal effects** are mediated – energy, in the form of electromagnetic radiation, is converted to heat, which subsequently warms up tissue and temperature rise may cause biological changes. **Non-thermal effects** include direct interaction with specific compartments of biological systems on cellular level (conformational changes in proteins on the surface of cell membrane), inside cell nuclei (DNA fragmentation), or interfering with important biochemical reactions (creation of reactive oxygen species).

1.2.5 Non-thermal effects

Whereas the thermal biological effects of electromagnetic radiation are well documented and have a strong dependency on frequency, evaluating non-thermal effects may be more complicated. Currently accepted level of understanding about interaction decreases according to increasing scale in which we are examining biological systems (from changes in whole tissue, through cellular level, up to DNA and chemical reactions). [23]

Pre-exposition. Conducting studies is rather complicated, because subjects are already pre-exposed by various types of fields, prior the study itself. Therefore, biological change, that would be triggered by a given radiation, could be induced as a result of exposing subject to radiation with the same biological effect, prior to commencing the actual study (changes will not be observed).

Poor replicability. Minor change in configuration of the experiment may result in entirely opposite results. Even using cells of same kind (in vitro studies) may give different results in replications of particular study.

In recent years, body of various scientific studies accumulated, which strongly suggests mechanisms discussed in previous chapter (1.2.4). Results are generally based on quantitatively evaluated observations of morphological and physiological changes (e.g. profusion of albumin in rat's brain). Actual mechanisms are, due to extreme difficulty of their **direct** observation, usually hypothesized. The sites of interaction seem to be at **bio-physical** level, consequently affecting chemical reactions, as well as state and condition of important biological molecules (conformational changes in proteins, single and double strand breaks in DNA molecule, ion channels gating resulting in unphysiological action potential).[1]

1.2.6 Thermal effects

As an external electromagnetic field may cause polarization of dipole molecules, their kinetic energy increases as well, followed by conversion into heat: molecule tends to rotate against effects of external field.

Dipoles will be rotated in varying proportions, depending on properties of an external field and mutual orientation of other dipoles. Therefore, each molecule receives (even in homogeneous field) different amount of kinetic energy.

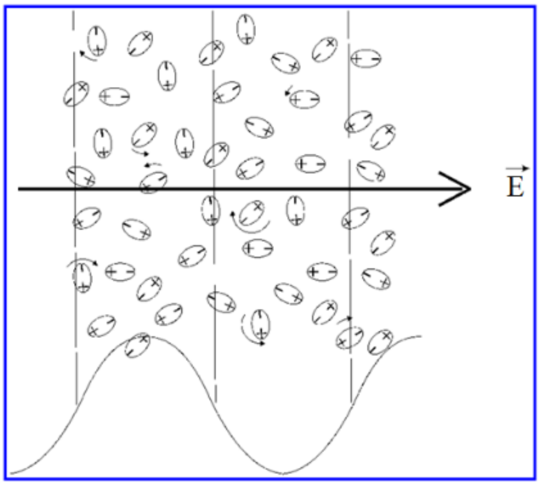


Figure 9: Dipole polarization [67]

[1)] *Based on author´s review of over 300 studies, conducted up to 2015.*

With an increasing frequency, dipoles can no longer follow changes of an external field. Transferred energy is not used for mechanical rotation, but re-utilized in another way by conversion into heat, which raises temperature of dipole molecules and consequently external temperature of their environment.

1.2.7 Thermal regulation

When there is an excessive increase in temperature anywhere inside the human body, thermoregulatory mechanisms start draining excessive heat out of the organism. **Passive thermoregulatory mechanisms** are based on heat dissipation by radiation, evaporation, convection or conduction. **Active mechanisms** utilize fluid flow (blood) to divert excessive heat into distant parts of the body and eventually towards the surface, up to the skin, where heat can be dissipated (radiated) out to the environment.

When, however, temperature rises regardless of organism's regulatory efforts, regulatory mechanisms collapse may occur. As the temperature begins to grow uncontrollably, it may cause extensive damage to various tissues. Reliable indicator pointing to damaging effects of external stimuli is increased activity of **heat shock proteins** (HSPs).

The most vulnerable parts of the human body are eyes, gall bladder and genitals, all of them due to their poor ability effectively dissipate excessive heat through active thermoregulatory mechanisms (blood flow). [23]

1.2.8 Specific absorption rate

Specific Absorption Rate (SAR) refers to a physical quantity most commonly used for describing power absorption by living tissue exposed to an electromagnetic field. It is defined as the power absorbed in tissue of a unitary weight. The physical unit consists of *W/kg*. [50] Usually, values are averaged over volume of one gram or, in some cases, ten grams. Reported values are highest values obtained during measurement throughout whole object.

This specific absorbed power largely depends on shape of each exposed segment, its structure, as well as shape and position of a radiation source. For an unbiased evaulation of scrunitized device, it should be placed in a position, in which it would be situated during normal use: mobile phone would be placed near the ear of person, or manequin. SAR should be then measured in a place, where the highest absorption rate can be found (usually close to the antenna).

1.2.9 Protection against non-ionizing radiation

Depending on the type of non-ionizing radiation, its frequency, intensity and time of exposure, different methods of protection against adverse effects of non-ionizing radiation are being used. Basic protection methods exhibit certain similarity with protective measures against ionizing radiation:

- **Reducing exposure time** to source of non-ionizing radiation, causing health problems, to as short time as possible.
- **Increasing the distance** from EM radiation sources, because intensity of radiation decreases considerably with increasing distance.
- **Covering / shielding** of questionable devices, whose function is not based on emission of non-ionizing radiation.
- **Signaling** (acoustic, tactile) the state of device activity, if it cannot be checked visually.
- **Usage of protective means** and personal protective equipment, if exposure cannot be limited by technical means.
  Full-face shield for welding, goggles impervious to UV radiation, glasses for operating laser instruments, protective clothing, etc.
- **Medical examinations** of employees performing hazardous work. [3]

2 Legislation

Occupational exposure limits, for public health protection against ionizing and non-ionizing radiation, are different in various parts of the world. Each State, or other political system, has its own rules, which usually follows recommendations of selected organizations.

One of the most important organizations, on whose recommendations are usually established standards by European governments, is called **International Commission for the Protection against non-ionizing radiation** (ICNIRP). It claims to be a leading association of independent scientific experts, consisting of a main fourteen-member commission, a scientific expert group and individual project groups, dealing with particular problems. Their main area of activity is disseminating information and recommendations about potential health risks, caused by exposure to non-ionizing radiation sources - optical (ultraviolet, visible, infrared), both static and time-varying electric and magnetic fields, radio frequency waves, microwaves, or ultrasound.[65]

Its "parent" organizations is **International Association for protection against radioactive radiation** (IRPA). Since 1965, organization ensures exchange of information among people dealing with protection against ionizing radiation. [25]

Along with **IEEE** (Institute of Electrical and Electronics Engineers) and WHO (World Health Organization), it establishes basis for experts responsible for legislative proposals.

2.1 Legislation of Czech Republic

Upon disintegration of former Czechoslovakia in 1989, new legislation had come into operation in Czech Republic: The Decree of Ministry of Health of Czech Republic no. 408/1990 Coll. on health protection against adverse effects of electromagnetic radiation. According to this decree, maximum allowable intensity of electric field had been 4.3 *V/m*.

At January 1st, 2001, this decree was replaced by Government Decree no. 480/2000 Coll., where limit values were alleviated more than tenfold. Later it has been amended (in context with accession of Czech Republic to the European Union and consequent harmonization with international criteria for limit determination), by government decree no. 1/2008 Coll. on health protection against non-ionizing radiation, resulting from ICNIRP recommendations.

Currently valid is **amended no. 291/2015 Coll.** on health protection against non-ionizing radiation, which alleviates maximum allowable values twofold to the preceding amendment. Exception being limit values for SAR, which remain same as in decree no. 1/2008 Coll.

2.1.1 Maximum allowable values of electromagnetic radiation

Table 5: Limit values of SAR for Czech Republic [39]

Specific absorption rate (*SAR*) - maximal allowable values			
Valid for frequencies from 10^5 Hz to 10^{10} Hz	Specific absorption rate – *SAR* – averaged over any six-minute interval and whole body	*SAR* averaged over any six-minute interval and for any 10 g of tissue, except hand, wrist, feet and ankles	*SAR* averaged over any six-minute interval and for any 10 g of tissue of hand, wrist, feet and ankles
Employees	0,4 W/kg	10 W/kg	20 W/kg
Other persons	0,08 W/kg	2 W/kg	4 W/kg

When living tissue is absorbing **electromagnetic radiation**, significant portion of its energy may be converted into heat (mainly in high-frequency fields above 100 *kHz*).

For fields with **extremely low frequency** (ELF), dominant are irritating effects, caused by induction of electrical currents within the tissue. Irritation grows proportionally with increasing frequency up to 100 *Hz*. In the area of 100 ÷ 3000 *Hz*, irritation declines significantly and remains up to around 10,000 *Hz*, where it ceases to be noticeable. [36]

Radiation having a **very high frequency** (VHF) is being absorbed in a thin layer at the body surface (skin effect). Therefore, we talk about **radiant flux density** absorbed by living tissue.

"*Other persons*" (general population) are being represented, among others, mainly by children, elders and pregnant women, as well as sick and ailing people. On the contrary, employees (especially in electrical industry) are allowed to stay in much stronger fields, otherwise certain professions could not be routinely performed by human beings and proprietary protective measures would be highly costly. Unless stated otherwise, declared values are valid for unlimited exposure time.

2.1.2 Reference level

For the sake of imposing limits right away, without directly detecting effects of particular type of radiation (which is an expensive affair), there are well established **reference levels of non-ionizing radiation –** comprehensive collection of specific physical quantities values, describing electromagnetic fields, in compliance with which maximal values should not be exceeded under any circumstances. This allows relatively quickly evaluate even complicated situations, or effects of fields with very complex time-varying behavior.

Table 6: Reference levels of electric, magnetic and radiant flux intensity [39]

f [Hz]	**E^{limit} [V/m]**
0 – 25	20 000
25 – 3 000	$5*10^5$ / f
3 000 – $3,6*10^6$	170
$3,6*10^6$ – 10^7	$6,1*10^8$ / f
10^7 – $4*10^8$	61
$4*10^8$ – $2*10^9$	$0,003*f^{0,5}$
$2*10^9$ – 3 * 10^{11}	137
f [Hz]	**B^{limit} [T]**
0 – 1	0,025
1 – 25	0,025 / f
25 – 30	10^{-3}
300 – 3 000	0,3 / f
3 000 – $2*10^4$	10^{-4}
$2*10^4$ – 10^7	2 / f
10^7 – $4*10^8$	$2*10^{-7}$
$4*10^8$ – $2*10^9$	10^{-11} $f^{0,5}$
$2*10^9$ – $3*10^{11}$	$4,5*10^{-7}$
f [Hz]	**S^{limit} [W/m^2]**
10^7 – $4*10^8$	10
$4*10^8$ – $2*10^9$	f / $4*10^7$
$2*10^9$ – $3*10^{11}$	50

2.2 Legislation in the world

Formerly, there were major differences between standards of Soviet Union and Western Europe. Occupational exposure limits in former Eastern bloc countries, China, Russia and several other states were, due to their different cultures and political backgrounds, based on entirely different assumptions than those in United States, European countries, or Australia, which usually follows recommendations of international organizations (WHO, ICNIRP, IEEE), whose member base is made up of scientific workers coming from these countries.

The inability to agree on criteria, on which basis are evaluated results of individual studies, prevents the possibility of **harmonizing** standards in different parts of the world.

In countries, using the recommendations assesed accordingly to similar criteria, may be estabilished different threshold values for certain physical fields, while others can be substantially identical - for example, averaging **specific absorption rate** over different amounts of tissue:

ICNIRP recommends 2.0 *W/kg* averaged over 10 *g* of tissue. This value has been adopted by majority of European Union countries, whereas in the US, limit values are being established on recommendations of **Federal Communications Commission** (FCC), which specifies 1.6 *W/kg*, averaged over 1 *g* of biological tissue. This applies for frequency band ranging from 10 *MHz* up to 10 *GHz*.

This difference may seem insignificant, but relating to different volume of tissue can make a significant difference - 2 *W/kg* averaged over 10 *g* of tissue corresponds approximately to specific absorption rate 4 ÷ 6 *W/kg* averaged over 1 *g*.

During **harmonization** in 2000, IEEE jumped from 1.6 *W/kg* (/1*g*) to 2 *W/kg* (/10*g*) – value recommended by ICNIRP, meanwhile FCC preserved its 1.6 *W/kg* (/1*g*) to this very day. It may be partially due to the fact that, in contrast to Europe, United States lacks precisely defined standard for exposure to radiofrequency radiation.

Table 7: SAR comparison between European Union and United States

	SAR [W/kg]	
	over 10g	over 1g
ICNIRP	2,0	**4 ÷ 6**
FCC	-	1,6

3 Medical use of electromagnetic radiation

All the electromagnetic radiation interacts with surrounding environment and eventually also with biological systems through various mechanisms. Depending on its properties, as well as on properties of the environment, individual interaction mechanisms takes part in different proportions to each other.

That may cause problems in some cases, both technical (mutual interference of communication devices, data processing units failure in the vicinity of power machines), or adversely affect *"proper function"* of biological organisms (tissue burned by microwave radiation, visual impairment resulting from direct contact of ultraviolet radiation with ophthalmic retina, irritation of nervous system in powerful fields with extremely low frequency). These principles also may form basis for certain types of weapon systems (taser, jammer).

On the other hand, we can use the very same principles for enhancing our comfort (central locking system), accelerating technological development (wireless data transmission), or diagnosing serious diseases (magnetic resonance imaging), musculoskeletal injuries (X-ray, computed tomography), relieving pain (TENS), as well as treating many symptoms of various ailments (thermotherapy, electrotherapy, magnetotherapy).

3.1 Magnetic resonance imaging

Magnetic resonance imaging (MRI) is an imaging technique used primarily in healthcare for viewing internal organs of human body, but is being used also in industrial processes. By meaningful utilization can be obtained slices of a particular area belonging to displayed objects, which usually undergo further processing and fusing into resulting 3D image of examined organ, or structure of technical object. Magnetic resonance imaging utilizes strong magnetic field, as well as high frequency electromagnetic waves. [35]

3.1.1 Human body resonance

From quantum physics perspective, matter is made up of waves. Each atom oscillates around its basic position with a certain speed. This can be expressed as number of repetitions per unitary time. In this form, we may call it a **frequency**, unique for each substance, on which any given substance resonates, hence **resonance frequency**. The human body absorbs mainly waves close to its own resonant frequency. That is, 70 *MHz* for grounded man, 35 *MHz* for ungrounded one. [23]

Any alternating electromagnetic signal contains **higher harmonics**. Its fundamental (carrier) frequency, which we are intentionally creating, may be for example 250 *Hz*. But in addition, some additional frequencies will be generated as well. With an increasing frequency, their energy declines rapidly.

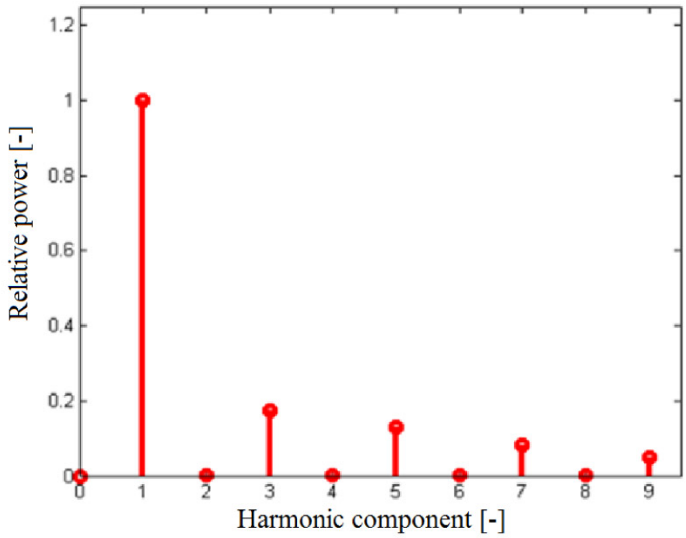


Figure 10: Harmonic components of electrical signal [17]

The figure above shows harmonic components of electrical signal. Horizontal axis shows individual harmonics (0-9), while vertical depicts their power magnitude.

0: Direct current component (power level of signal)
1: Fundamental (carrier) frequency
3: First harmonic component
5: Second harmonic component
7: Third harmonic component

In typical industrial applications, components following after third harmonic are usually neglected, because their power is relatively low.

Radiofrequency waves (*MHz*) are much closer to the resonant frequency of human body, than i.e. power supply distribution network (*Hz*). Higher harmonic component of radio frequency waves, corresponding to 35 ÷ 70 *MHz*, will have orders of magnitude greater amount of energy, than the same higher harmonic of power supply distribution network.

Advantage of this knowing is being used in thermotherapy, magnetic resonance imaging, or during elimination of malignant tumors to name a few.

3.1.2 Physical principles of magnetic resonance imaging

The human body consists mostly of water molecules. In a strong magnetic field, individual nuclei's magnetic moments of these water molecules start to rotate in direction of the external field.

Moreover, if we add a brief exposure to radiofrequency radiation, further change in the direction of proton magnetic moment takes place. However, in aftermath of radiofrequency radiation, protons return back to their original position (ie., where they were rotated in an active magnetic field). Such temporary change in protons rotation produces varying magnetic flux, which induces voltage in a receiver coil, that is subsequently converted into an electrical signal and further processed inside evaluation electronic circuits.

Self-**resonant frequency** of atomic nuclei depends on intensity of applied external field (in quantum physics realm, we would say that an observer affects the outcome of observation). Adding another (transitional) magnetic field, which gradually changes its strength within physical space, allows us to precisely define self-resonant proton's frequency in a particular area and thereby **select specific sectors**, that we are about to scan. Intensity of magnetic field generated by these transitional (transversal) coils may become continuously varrying by switching them rapidly and repeatedly (thus, we are changing also intensity of current flowing through the coils). [34]

3.1.3 Acoustic trauma

As a result of the **Lorentz force** (force acting on electric charge, or (if you like) conductor in electromagnetic field), change in charge direction of particles (electrons) passing through coils takes place, without altering speed of their movement (current magnitude). [45] Thanks to this, coils exhibit efforts to change their position, which generates electromagnetic waves in an audible area (knocking sounds with rather high intensity that may lead to endangering a person undergoing examination, as well as an operating personell). Usually, these are sound waves with intensity around (90 ÷ 115) *dB* for commonly used devices utilizing magnetic field up to two Tesla [1]. This corresponds to noise emitted from a moving train, jackhammer or live rock concert. [19]

Commonly employed devices working with stronger magnetic field (3 *T*) may generate noise with intensity up to 130 *dB*, which corresponds to pain threshold, as well as noise of jet taking off. This may cause **acoustic trauma**, accompanied with acute ear injury (impaired hearing, deafness, whistling in ears, vertigo) and eventually lead to hearing loss, with a maximum decline around 4 *kHz*. [47] Acoustic waves, emitted by devices operating in presence of people without sufficient protective equipment (headphones), should not even come close to such magnitude!

3.1.4 Measured values processing

Various kinds of diseases can be described as tissue deviations from its natural state. Return of protons, excited by radiofrequency field, to their equilibral states after different time period than would be expected, allows us to evaluate tissue pathologies and estimate their actual condition.

By changing resonance frequency of water protons in certain part of human body, using a magnetic field generated by transient coils, we can affect time required for returning protons to their equilibral state. Evaluation of this time allows us to determine which part of the body we scan at the moment. Basic imaging methods utilize two-dimensional Fourier transformation (2DFT), or its three-dimensional variant (3DFT).

By evaluating intensity of signal captured by receiving coil, we can create image segments with different brightness (contrast). The signal intensity, and thereby contrast among individual parts, is determined by certain parameters (density of excited protons, different relaxation times). Careful design of an imaging pulse frequency (switching sequence of gradient coils, RF signal transmission, precise moment of receiving signals modulated by excited protons) allows us to choose one of the factors determining resulting contrast of final image and ensure, that its impact will be dominant. Effect of other factors should be also subsequnetly reduced as much as possible. [34]

The choice of a contrast factor opens up lots of possibilities. Different contrast among various kinds of tissue can be easily created, example given - white cortex appears white, gray cortex is in grayscale, whereas cerebrospinal fluid (transluscent body fluid filling the brain and spine) appear to be black. Another possibility results in very low contrast of healthy tissues, whereas damaged/diseased tissues exhibit severe disparities (if we use amount of protons density per tissue’s unit area as the contrast factor). [49]

3.1.5 Contrast agents

In some cases, it may be difficult to create image with contrast sufficient for precise determination of tissue's types and eventual classification of their condition as pathological. If it cannot be done by changes in imaging parameters, or contrasting factors, **contrast agent** may be administered in an appropriate manner to a person undergoing examination.

The contrast agent may be as simple as orally administered water, for more detailed view of pacient's stomach, or small intestine. Generally, however, we choose contrast agents with respect to their specific magnetic properties. Most commonly used are paramagnetic materials (Gadolinium $_{64}$Gd compounds). Tissues and body fluids, into which the gadolinium agent penetrates, exhibit extreme brightness in the final image. This provides considerable advantage in terms of sensitivity, when using imaging methods for detecting tumors, vascular ruptures, as well as damaged portions of brain tissue (stroke).

Contrast agents based on gadolinium compounds, however, exhibit significant toxicity, therefore are completelly unsuitable for persons suffering from renal impairment. In such cases, it is necessary to use more suitable substantional substance.

It is possible to use solutions of iron oxide (rust) in the form of nanoparticles, which appear as extremely dark. This is particularly useful, when we need to evaulate actual condition of patient’s liver. Healthy tissue captures nanoparticles, whereas damaged (ruptures, tumors) passes them through. We can also administer these nanoparticles orally to improve contrast characteristics of digestive system, or display pancreas, usually obscured by water molecules inside digestive system. [34]

3.1.6 „K-space” image processing

The signal captured by receiving coils is discretized, converted to a number in complex form (which specifies magnitude and phase of measured signal), recalculated by Fourier transformation (2DFT or 3DFT) and stored into memory for further processing.

Besides process described above, *“k-space”* also refers to a matrix memory, temporarily storing measured data in digital form. When filled with all measurement data, these are subsequently forwarded for further processing - image reconstruction of examined biological tissue. The image created by magnetic resonance imaging is basically a *“map”* of complex numbers, describing spatial distribution of transversal magnetization (produced by using the gradient coils) within given sample at precise moment after excitation (caused by radiofrequency radiation).

Using Fourier analysis should lead to prevailance of areas with low **spatial frequency** values in the midst of reconstructed image (number of repetitions of the same structure at specific distance). Central areas usually provide us information about the image as a whole (shape, spatial orientation, proportions between individual parts). Areas with low spatial frequency values gives us information about **signal-to-noise ratio** and **contrast** between individual parts, while areas with high spatial frequency valus determines **maximum resolution** of reconstructed image, allowing us to distinguish fine details in captured scene. [30]

3.1.7 Superconductivity

Currently, we utilize **superconductivity** phenomena in magnetic resonance imaging. Certain materials, at very low temperatures near to absolute zero, exhibit undetectable, almost **zero resistivity**, i.e. energy brought into the material passes through it endlessly (until superconductivity is disrupted), whereas at ambient temperatures, substantial amounts of energy are converted into heat (which is necessary to drain away), so that particular device must be continuously supplied with energy from power source. Superconductive material expels magnetic lines from its volume, which efficiently shields off external magnetic fields and (when an electrical current passes through) generates a strong magnetic field around itself.

Superconductivity is possible thanks to generation of so-called **Cooper pairs**: In superconductive state, as electron is moving through crystal lattice, it creates positively charged region, to which another electron is attracted (this pair of electrons forms Cooper pair). In normal state, electrons collide with oscillating impurities of conductor's crystal lattice, whereby forwarding them some of their energy, most of which is subsequently transformed into a heat. These collisions may seem mutually independent at a first glance, but the truth is that Cooper pairs exhibit considerable dependency amongst themselves.

First ever discovered superconductors lose its properties in strong magnetic fields and require extremely low temperature for their proper functionality (up to 30 *K*, whereas ordinary room temperature is 293.15 *K*, corresponding to 20 *°C*). Cooling may be acheived by **liquid helium**, which is quite an expensive substance. These **superconductors of the first type** are generally pure metals.

Groundbreaking milestone was discovery of **second type superconductors** - metallic alloys and composite (dielectric) materials, that exhibit superconducting properties at temperatures around 100 *K*, allowing cooling by **liquid nitrogen**, whose boiling point (temperature at which the substance changes from liquid to gaseous state) is 77 K. This caused extensive research on possible commercial use of superconducting phenomena, since liquid nitrogen is, in comparison to liquid helium, relatively inexpensive and easily accessible (can be extracted from the air). [55]

3.1.8 Superconductive magnet

A fundamental element of magnetic resonance imaging device is electromagnet with usuall inductance about 1.5 *T*. **Permanent magnet**, which can be easily serviced, is not able to generate sufficiently strong magnetic field (max. 0.4 *T*), has low accuracy, as well as low stability of its parameters. Additionally, its magnetic field cannot be, if necessary, *"switched off"*, which entails considerable security risks in case of failure.

Formerly, we used **conventional electromagnets** made of copper wire coiled into solenoid, which was, on one hand, relatively inexpensive, but because of non-zero copper resistivity and enormous electrical currents, its operation was extremely costly. [34]

Superconducting electromagnets, consisting of metal alloys (titanium - niobium, niobium - tin), possess their superconductive properties at temperatures around 4 *K*, thus they must be cooled by liquid helium. They generate an extremely strong magnetic field, at very reasonable dimensions, and moreover, they tend to be very stable. Their construction, as well as operation, (considering the coolant price) is quite expensive, but for their technical properties (accuracy, size, stability), they are most widely used type in routine clinical practice.

Liquid helium flows through a container (cryostat). Due to non-zero ambient temperatures, it slowly evaporates, so its quantity needs to be periodically replenished. Some types are stored inside secondary cooling tank filled with liquid nitrogen reducing amount of evaporated helium (reducing operating costs at the expense of increased purchase costs).

A common shape of superconductive electromagnets is usually a toroid (unlike conventional electromagnets shaped to the letter *"C"*), although there are also some *"C"* shaped superconducting electromagnets in clinical practice. [45]

Intensity of the magnetic field determines **signal to noise ratio**. Increasing its value allows us to use higher resolution, or shorten examination time. Construction of these stronger electromagnets, as well as their operation, however, tends to be much more expensive. For routine applications, electromagnets are used with magnetic field intensity around (1.0 ÷ 1.5) *T*, due to their best cost/performance ratio. For special use and more demanding applications (detailed view of brain tissue), devices with magnetic field intensity around three Tesla are frequently employed, while commercially available systems operate with intensities within seven Tesla. Research electromagnets reaches up to twenty Tesla (upper limit of reasonably feasible magnetic field strength with suprerconductive electromagnet), provided that steady fields of over 40 *T* can be currently achived by hybrid devices, combining superconductive magnet with Bitter magnet. [34]

Table 8: Magnetic field strength for various applications [34]

Type of application	**Typical magnetic field strength [T]**
Routine Clinical Practice	0,2 – 1,5
Specialized examination	3
Commercial systems	7
Scientific research	20
Hybrid devices	45

3.1.9 Contraindications

Due to very strong magnetic fields, undesirable interactions with different types of **metal implants** may occur. Without appropriate precautions, MRI may cause death, especially among people with pacemakers (mostly devices manufactured before 2000). By using convenient precautionary measures, even people with certain types of implants can undergo MRI examination. Apart from pacemakers, common problems are usually with various hearing aids. Eliminating all metal objects (rings, necklaces) from examined person, as well as unanchored metal equipment from the vicinity of magnet, is absolute necessity. The only remaining problem may be metallic objects, made of ferromagnetic materials, in inappropriate places (brain), or large tattooed areas.

Fast switching of gradient coils produces powerful **sound waves**, that may cause an acoustic trauma, therefore the examinee and personnel must have headphones, or additional protective measures have to be implemented, in order to prevent unnecessary injuries. [47] Radio frequency waves, used for exciting hydrogen nuclei, can be absorbed by biological tissue and transformed into heat. This **warms up surrounding tissue** and if the body can not cool down the affected area rapidly enough, excessive temperature may lead to tissue damage. Therefore, amount of energy, emitted by RF radiation, must not exceed a certain threshold (SAR), to ensure patient’s safety.

In event of an accident, when the magnet needs to be immediately switched off (quenching), **liquid helium boils off** rapidly. If it can not be, for some reason (clogged ventilation), taken away, this substance may fill up examination room by pushing out breathable air. Such situation endangers examined person and medical personnel with possible suffocation. Therefore, examination room is usually equipped with a device monitoring level of oxygen within the room. Furthermore, transition of liquid helium into gaseous state may cause an extensive explosion, therefore appropriate deployment of overpressure valves should ensure constant pressure at appropriate places (even during an emergency situations).

Quenching takes place only rarely (it is very dangerous and expensive procedure). It may severally **damage the magnet**, whose repair is quite a costly affair. Refillment of cooling containers, as well as launching the entire device, is also extremelly expensive. Emergency release of helium (quenching) is therefore more frequently triggered by equipment failures, than by intentional switching off.

Pregnant women (especially during the first trimester) may undergo examination only when absolutelly necessary, because the fetus is much more sensitive to adverse effects of MRI examination. It may be harmed and consequently developing in unfavourable way. Exceptionally, MRI scanning is being used for monitoring fetal congenital anomalies, because it provides more accurate data than ultrasonography.

MRI causes intense discomfort to patients suffering from **claustrophobia** (fear of enclosed spaces), therefore some devices have slightly abnormal design and shorter examination times. In extreme cases, an **open MRI device** may be used, which is, however, much more expensive to purchase. Another possibility is **sedation** and temporal narcotization of examined persons. [34]

3.1.10 Pros & Cons

Imaging biological tissue by magnetic resonance meant a completely new level of non-invasive examination possibilities. It allowed physicians to obtain very detailed data for accurating final diagnosis. This approach eliminates necessity of large number of biochemical tests, whose evaluation takes considerable time, during which would, in certain emergency cases, patient die. Furthermore, MRI examination can undergo persons for whom are other types of examination methods out of the question (eg. due to nature of their injuries/illnesses).

The biggest advantages of MRI are particularly:

- Accurate representation of biological tissues.
- Very high spatial resolution.
- Non-utilization of ionizing radiation.
- Non-invasive examination.
- Real-time displaying of organ’s condition (MRI fluoroscopy).

Magnetic resonance imaging also possess certain properties for which its use is not advisable in all situations and may become even dangerous under certain circumstances:

- Metallic materials inside the body.
- Pacemakers.
- Poor representation of rapidly moving parts (heart). [34, 35]

- Considerable initial costs.
- Expensive operation.
- Costly mainterance.

3.2 Computed tomography (CT)

Computed tomography (CT) refers to a non-invasive examination for imaging biological tissue of a living organism with **ionizing radiation** (X-ray). The type of used radiation makes fundamental difference between MRI and CT.

Examinated person is positioned in a *"tunnel"* visually similar to that for magnetic resonance imaging, but instead of a huge magnet, CT uses X-ray tube assembly (source of x-rays) and a plurality of detectors. Radiation passes through examined object to a detector, wherein portion of radiation energy is absorbed by examined object.

From amount of energy received by radiation detector, we can determine amount of energy absorbed by the object. Different biological tissues absorb different amounts of energy. The most absorbive are bones, a bit less soft tissues (liver, kidney) and least lungs (air), along with adipose tissue.

When we irradiate examined person throughout from many different angles, we get a large number of projections. Processing them with appropriate computive algorithms allows us to evaluate data from individual projections, each of which is represented by a number of points (volume elements - voxels). We then assign actual value of absorbed energy to every voxel. By subsequent processing all projections, we can create an overall picture of examined area. [46]

3.2.1 CT design

Conventional devices are constructed as **circular**, with a rotating X-ray tube, while detectors are fixed around whole device's perimeter. This leads to detection of reflected (undesired) rays and their subsequent processing, which reduces resulting image quality (eg. lowering spatial resolution). **Spiral** construction possess rotational X-ray tube with a detector array that also rotates. This can dramatically reduce influence of reflected rays and subsequently enhance image quality, allowing physician to evaluate patient's condition more accurately. Systems with a very large number of detector rows are often reffered to as **cone beam CT**, whose design is currently increasingly utilizied also in medical fluoroscopic devices.

Formerly, tomographs performed one complete rotation of whole scanning assembly (gantry), then moved table with the patient, performed another assembly rotation… and this process continued until we acquired all data necessary for evaluation of examined area. The downside of this approach was considerable examination time. Additionally, examinee's continuous breathing caused significant blurriness of the final image. Currently favoured is **helical scan** method, where examinee's table moves simultaneously with X-ray tube, minimizing influence of patient's motion. [46]

At the end of the nineties, devices were divided into two main groups: **Fixed computer tomographs** are bulky, require specialized external power supply, private wiring unit chamber, the HVAC system (sophisticated air conditioning system), specifically designed workplace and a large room with thick lead walls, all those meaning high purchase costs. Newer **mobile tomographs** are usually light, small and have wheeled chassis, so they can be moved as required. They also have built-in lead shielding (eliminating need to shield entire room) and may be powered directly from a regular power distribution network, or with built-in rechargeable batteries. [68]

3.2.2 Tomograph in clinical practice

Computed tomography allowed high-quality diagnosis of various diseases, as well as determining tissue damage extent caused by an injury. Whole body imaging may be performed, with consequent image evaluation and handovering results, with all related informations, to the examined person.

It is suitable for examinating pathological changes in **lung tissue,** with extended possibility of repeated scanning, which provides detailed images (HRCT) with very high spatial resolution. Using high speed scanners, in combination with precisely timed injection of contrast agent, is currently primary method for diagnosing pulmonary embolism.

Heart scanning requires a relatively high dose of ionizing radiation (about 12 *mSv*), therefore we should carefully consider reasons, for which we would prefer computed tomography over other methods. High sensitivity of this imaging modality is suitable for excluding heart diseases, when figuring out source of thoracic problems with unknown cause. Particular disease is then usually determined by other examination techniques.

CT scanning has considerable significance when monitoring progress of digestive tract cancer in the **abdominal cavity**, where contrast agents are often administered to optimize final imaging of individual organs. These may be either gases (air, carbon dioxide), liquids (water) or various suspensions and concentrated drugs (barium sulfate) with specific group of iodinated contrast agents.

Great importance it has also during diagnosis of **osteoporosis**, however, given tremendous financial cost of the examination, and relatively high dose of radiation, other methods are more frequently used. On the other hand, it is usually irreplaceable when diagnosing **complex musculoskeletal injuries** - it can reveal important subtelties of complex limb fractures, especially in joints, because this technique allows us to see injury in different planes, so we can precisely evaulate extent of particular fracture, as well as ligament damage. [46]

3.2.3 Strengths and pitfalls of computerized tomography

Compared to conventional radiological examination (RTG), CT provides better representation of examined areas (acquisition contrast), at cost of lower spatial and temporal resolution. It allows us to create multiple slices, which can be subsequently used to reconstruct scene and display organ's anatomy to a great extent (bones), even rapidly moving ones (heart). Moreover, it can be currently deployed in those situations where, for some reason, magnetic resonance imaging cannot be used. Its main advantages are:

- Highly accurate representation of biological tissues (acquisition contrast).
- Many planes, in which tissue can be displayed (longitudinal, coronal, sagittal).
- Suitable for people with implants (pacemakers) or metal objects within the body.
- Short examination time (injury diagnostics).
- Non-invasive examination.

Despite its advantages, CT also possess some characteristics that make it undeployable in many cases (especially for periodical examinations), when we must select another method (RTG, MRI):

- Increased risk of cancer/promoting its development (ionizing radiation).
- Contrast agent toxicity.

Table 9: Comparison of absorbed doses (ionizing radiation) [46]

Examination	Routine effective dose [*mSv*]
Chest X-Ray	0,02
Mamography	0,4
Head CT	1,5
Natural background (annual dose)	2,4
Chest CT	5-7
Abdominal CT	5-8
Chest, abdomen and pelvis CT	9,9
Heart CT	7-13
Barium enema	15
Infant abdomen CT	20

3.3 Comparing magnetic resonance with computed tomography

Both diagnostic methods have their advantages and disadvantages, but they are rather complementary. Magnetic resonance imaging does not utilize ionizing radiation, therefore is usually preffered, when both examinations provide comparable information. It is, however, more expensive in terms of continuous operation, so this examination technique may not always be available at a particular location.

CT makes possible to display sharply not only bones, but also rapidly moving parts of human body. In addition, people with certain types of legacy pacemakers cannot use MRI, while CT may often provide sufficient basis for determining health condition of examined person. Short examination time is particularly useful when determining extent of acute injuries, since MRI usually lasts 10 to 45 minutes, depending on required precision and extent of performed tests, provided that patient is already prepared for the examination. [34]

For each case, it is necessary to select examination individually. One particular method may not only be more appropriate, but another one can be even dangerous, or inherently undeployable, in a specific situation. Physician should therefore be familiar with strengths and pitfalls of all currently available imaging methods, in order to be able competently select the most appropriate method of examination in a particular situation, based on its total cost, suitability and safety, as well as type of data needed for comprehensively assessing whole situation.

3.4 Thermoterapy

Albeit conversion energy of high-frequency electromagnetic waves (radiofrequency and microwave radiation) into heat is usually undesirable, the very same effect may be advantageously used for specific treatment of various diseases.

Heating biological tissue increases blood circulation in affected areas. This accelerates metabolism, and thus the intensity of ongoing immune responses, which should result in speeding up course of inflammatory processes, reducing pain, or relaxing spasms.

Whole organism may be warmed throughoutly (sauna, bath), as well as only selected parts (hot clothes). During **contactless heating**, there is no tangible contact with patient's body (electrodes), so we can also intentionally warm deeper biological structures (muscles, tendons, internal tissues). [56]

3.4.1 Rehabilitative thermotherapy

We may utilize dielectric properties of biological tissues (permittivity) for heating selected regions in **capacitor array**. An applicator consists of two capacitor plates, which are supplied with an alternating voltage. Thanks to this, time-varying electric field appears between the plates. Dielectric materials are polarizing, when located in an electric field, thus part of field’s energy transforms into thermal energy. Because the field is alternating, dielectric polarization does not stop and follows external field, therefore this neverending energy transformation ensures continuous heating. Dielectric *“capacitor”*, in this case, is region within the organism we selected for warming. This method is especially suitable for muscular rehabilitation.

We can also use **induction heating**, based on tissue’s conductivity. Positioning selected areas inside time-varying magnetic field will induce eddy currents within them. These currents passes through the tissue, generating heat proportional to resistivity of the tissue and square of the currents passing through. Like the capacitor array, induction heating possess substantial application potencial in (especially sports) rehabilitation therapies. [57]

3.4.2 Thermal tumor elimination

Heat can be also used for eliminating malignant tumors. The goal here is to find amount of energy transformed into heat that healthy biological tissue can regulate, without causing any substantial damage, while tumor tissue is unable drain it off effectively – so local temperature slowly, but continuously, increases, until thermoregulatory mechanisms breaks down and tissue temperature stteply rises to the point, at which necrosis takes place. In healthy tissue, this happens at temperatures above 45 *°C*, therefore its heating to a temperature within (41-45) *°C* organism can sufficiently compensate, while in the tumor tissue temperature rises uncontrollably. Temperature rises proportionally to size of the tumor - a highly damaged tissue in last stage of cancer will respond to temperature rise much more actively than in its initial stage. Described method exhibits significant efficiency in treatment of gross tumors occupying large areas within the body. [37, 38]

In contrast to interventional radiotherapy (irradiation), **microwave thermotherapy** acts not only at the surface of selected tumors, but most strongly in their center. It is particularly suitable for treating tumors larger than two centimeters. [38]

3.4.3 Infrared regeneration

Treatment with **infrared (IR) light**, sometimes called **photon therapy**, utilizes unique properties of electromagnetic radiation within a frequency range 300 *GHz* ÷ 400 *THz*. Human body is mostly composed of water, which absorbs major portion of electromagnetic radiation energy from infrared region of its frequency spectrum. The absorbed energy is subsequently converted into heat, warming an exposed area throughtly.

Near infrared radiation (IR-A) with wavelengths (760 ÷ 1 400) *nm* (short-wave radiation), is mostly absorbed by our skin. That we perceive as warming sensations. **Long-wave radiation** (IR-C), with wavelengths (3 000 ÷ 10 000) *nm*, possess an ability to penetrate profoundly into hypodermis and deeper parts of human body (4 *cm* from a body surface), where being strongly absorbed. Our body starts warming through without creating warming sensations. Caution is required, because this very important mechanism, signaling that temperature rises to undesirable values, is out of operation. [27]

Photon therapy, or infrared sauna, is usually used for regeneration, promotion of healing processes within tissues, or worn-out muscles rehabilitation.

3.4.4 Effect of thermotherapy

We use temperatures up to the heat tolerance limit (the highest temperature, which our body is able to withstand). For water environment up to 42 *°C*, air environment up to 130 *ºC* (sauna with zero humidity).

Various principles of warming biological tissues have different effects on the human body, so different methods are suitable for different purposes, depending on particular situation. Generally, however, controlled temperature increase within biological tissue exhibits some coincidental manifestations, independently of method employed, therefore most types of thermotherapy shares similar beneficial health effects. Among these are particularly:

- Increasing blood flow (accelerating metabolism).
- Accelerating post-acute phase of healing process.
- Reducing ignitions/swellings.

- Blocking pain receptors.
- Stimulating endorphin production.

- Eliminating certain pathogenic organisms.
- Speeding up healing of flesh burns.
- Moving calcium ions into individual cells (healing process).

- Relaxing muscles near body surface, increasing flexibility (elasticity).
- Reducing amount of lactic acid in muscles (accumulated during exercise).
- Loosening stiff joints. [57, 27]

3.4.5 Cryotherapy

Apart from warming parts of the body (positive thermotherapy), heat can be also carried away from it intentionally (negative thermotherapy).

For relieving pain and soothing inflammatory processes, **ice chunks/icing clothes** are usually applied.

When treating minor injuries, cooling effects of some **volatile compounds** (alcohols) may be utilized. These are commercially available in spray form, often with menthol as an additive for increasing cooling sensations.

Rapidly induced hypothermia of tissue to a temperature well below freezing point (**cryoablation**), necrotizates frozen tissue. Necrotic tissue falls off, or creates scars. Cryoablation gained considerable popularity in **warts treatment**, where healthcare professional touches affected area with a cotton swab soaked with liquid nitrogen. This particular method is almost painless. [57]

Whole-body exposure to an extremely low temperatures (down to -150 *°C*), followed by moderate physical activity (exercise, riding a stationary bicycle), causes blood to intensively perfuse superficial parts of the body (dermis, subcutaneous tissue, tendon-muscular apparatus) due to an intensive influence on cold receptors. This will initiate elimination of large quantities of toxic substances - toxins and free radicals, along with lactic acid.

Pain relieving hormones starts being produced in large quantities, as well as those dampening inflammation, or stimulating muscle growth. Extreme cold activates defensive abilities of whole organism by profoundly stimulating immune system. Therefore, it is being used in treatment of autoimmune diseases.

An exposure to extremely low temperatures happens in a **cryochamber**, which is a complex of antechamber with temperature ranging from (-40 ÷ -60) *°C* and main chamber, where temperature is regulated between (-110 ÷ -160) *°C*. Several people may use cryochamber at the same time. Necessary protective equipment consists of gauntlets, airtight shoes and facemasks, preventing adverse health effects by directly exposing inappropriate body parts to freezing temperature. Hands and feet are relatively poorly perfused with blood – they cannot be heated rapidly enough by flow of body fluids, so frostbites might occur.

This procedure gained considerable popularity among rehabilitation and regeneration techniques, and particularly among sportsmen who can financially afford this kind of therapy. Apart from benefits mentioned above, low temperature restricts action potential firing rates in nervous system, thus patients feel some relief from pain. Cryochamber also helps in treatment of rheumatism, skin diseases (psoriasis), and posttraumatic or postoperative conditions. [29]

4 Practical application

4.1 Shielding for ionizing radiation

Due to the ever-increasing number of nuclear power plants, the importance of protection against ionizing radiation is continually increasing, whether in regard to processing spent nuclear fuel, or developing shielding materials, commonly used in these devices, for ensuring necessary health protection of technical workers, as well as general public.

Therefore, we are going to focus on shielding materials, verifying effectiveness of some commonly used types and comparison of their possible application in daily practice.

4.1.1 Equipment

As a source of ionizing radiation was chosen emitter containing radioactive **cobalt isotope "Co-60"** manufactured by **Isotrak**. It is basically a source of beta particles with five year's half-life. The device we used already undergone one half-life period.

Detector chosen was **Geiger-Müller counter** manufactured by **PHYWE**. Attached probe detects radiation that counter process in pulse form of electric signal. From their count for a certain time period, we can assess intensity of ionizing radiation emitted by a particular object, or evaluate radioactive contamination of surrounding environment. The device we used was not calibrated, since it is being used for demonstrative and experimental purposes, thus our measurement has a rather tentative character.

Figure 11: Geiger-Müller counter PHYWE [16]

As samples served us platelets of various materials with precisely defined thickness. In order to ensure performed measurements consistency, as well as high informative value of measured data with respect to the practical utilization of materials, **platelet's thickness** was chosen to ***d = 3 cm.*** Chemical composition of individual plates corresponds to aluminum (Al), steel (Fe-Fe_3-C), brass alloy (Cu-Zn) and lead (Pb).

4.1.2 Practical measurement

Ionizing radiation source had been placed at a **distance of 8.5 cm** from the most sensitive point of Geiger-Müller (GM) counter' s detection probe. For ensuring the most accurate measurement, **100 seconds interval** had been chosen, as the time during which GM counter was assessing incoming radiation. To reduce effect of random errors, measurement had been repeated three times. Higher number of repeated measurements was not feasible for time reasons. Obtained values were mathematically processed by calculating their **arithmetic average**.

Table 10: Dependency of ionizing radiation intensity on the type of shielding material

Environment	**Number of impulzes**			
	1.	2.	3.	Average
Natural background	25	28	27	27
Radioactive source	613	571	547	577
Aluminium	427	409	408	415
Brass	299	280	253	277
Steel	274	282	245	267
Lead	154	180	159	164

Before actual measurement of various shielding materials, we assessed radioactivity level of surrounding environment without an external source of ionizing radiation. Measured values thus correspond to natural loads due to a geological bedrock, cosmic rays and other sources from surrounding environment. We then measured reference level of radioactive emitter itself. During subsequent insertion of shielding material between the ionizing radiation source and the detector, measured value should always be lower.

As expected, aluminum showed the weakest shielding effect from all examined materials. Not very surprisingly, steel was quite comparable to brass alloy. Compared to aluminum, a noticeable drop in detected radiation was observed. Best shielding properties exhibited lead, confirming the general presumption of choosing it as the most suitable shielding material. For the same shielding effects would be necessary to use much stronger steel walls, which could be build more cheaply on one hand, but overall demands on greater amount of space would be highly undesirable for many practical applications (eg. nuclear power plant).

Brass is the least suitable of all materials - shielding effectiveness comparable to steel, but for a much higher cost.

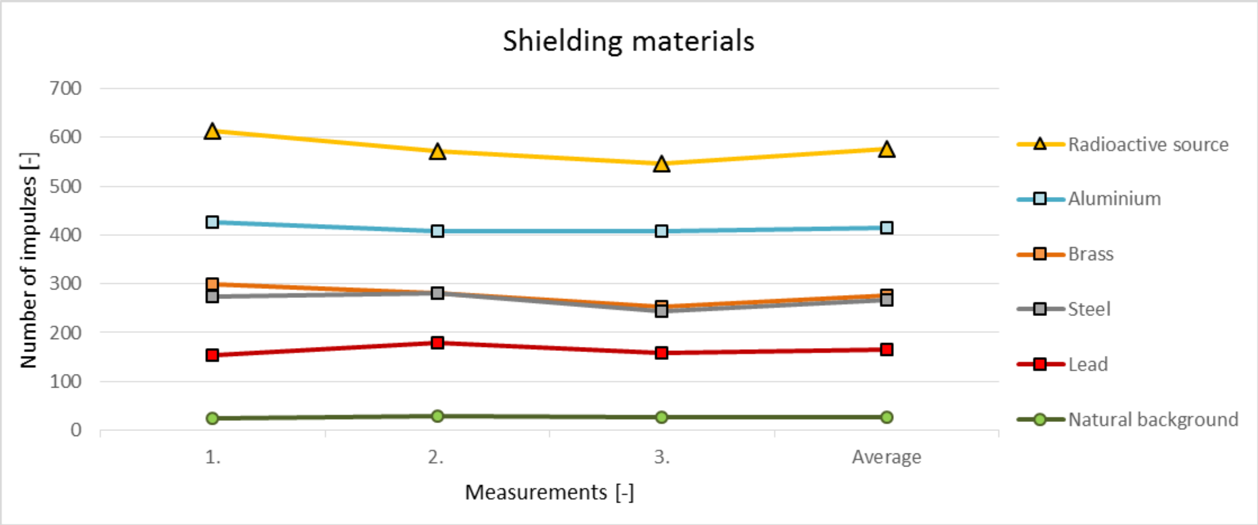


Figure 12: Graphical dependence of the number of impulses on the type of shielding material

4.1.3 Lead shielding

Due to the best shielding properties, lead has been measured more profoundly. We have focused particularly on how lead platelet's thickness affects efficiency of shielding.

Table 11: Dependency of number of impulses on the lead platelet's thickness

Thickness [cm]	No. of impulzes
0,5	391
1	355
1,5	**283**
2	232
2,5	**217**
3	185
3,5	141
4	130

The highest slope of decrease in detected radiation has been observed at a thickness $d = 1{,}5\ cm$.

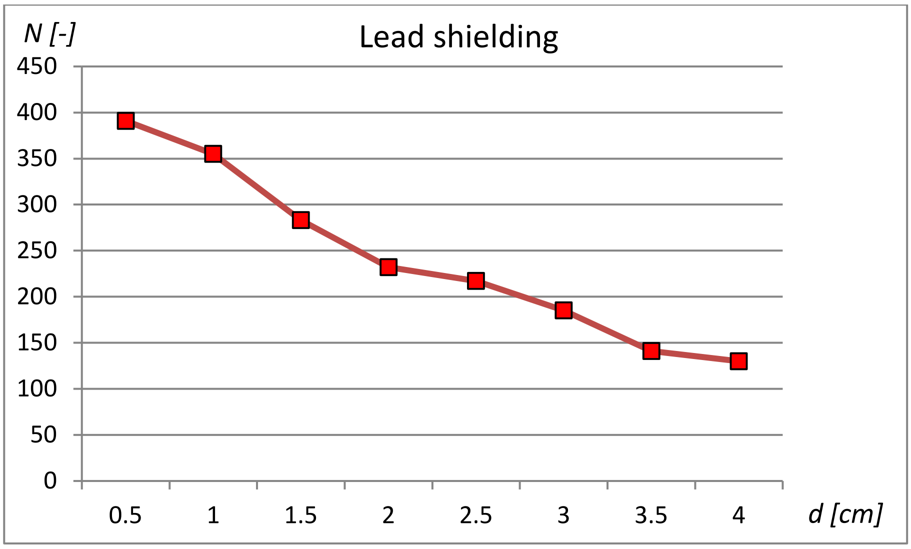


Figure 13: Graphical dependence of the number of impulses on the lead platelet's thickness

Lead platelet's thickness of 1.5 cm exhibited shielding effect comparable to steel wall with double thickness. According to current prices (25. 3. 2014) of lead and steel, shielding made of steel should be cheaper.

This remarkable thickness has been therefore re-measured in-depth for acquiring more accurate values, allowing data comparison with higher precission.

Table 12: A more accurate measurement for selected thicknesses of lead platelets

Thickness [cm]	**Number of impulzes**			
	1.	2.	3.	Average
1,5	265	289	295	**283**
2,5	207	239	205	**217**

4.1.4 Evaluating real-world shielding possibilities

So why do we use in practice mainly lead shielding when the steel is cheaper? One of main reasons is simply demand for space. Hospital in the city center can hardly afford expand its size because of the need to shield its radiological departments. However, there might be other applications, where space does not play such an important role. This brings us to the main reason, and that is, once again, the financial costs. Imagine a large nuclear power plant. Twice the thickness of shielding means necessity to dimension wall girders for much higher weight and even if lead possess higher density than steel, steel still represents significantly higher weight load in this case. Thus, the ceiling under nuclear reactor will need to have significantly larger area, which also needs to be designed for retaining increased load. And these secondary, hidden costs, represent very good reason to prefer more expensive leaden shielding. Ironically, situation arises, where seemingly more expensive solution comes much cheaper at the bottom line, not to mention reducing security risks, as well as other complications.

Side-note: During actual measurements, an interesting situation has occurred. Upon inserting one shielding platelet into a measuring circuit, detected radioactivity level suddenly jumped at twice the value of radioactive source itself. After replacing that particular platelet with another, values were down as expected. This would suggest that this lead platelet exhibited behavior of statistically significant radioactive source.

4.2 Radio-freqency spectrum measurement

In recent decades, an intensive expansion of wireless technologies took place. With increasing technical capabilities of various types of portable electronic devices (phones, tablets, watches), new possibilities for their practical utilization arise. Video calls, mobile internet, GPS tracking. And why the user, in today's fast time, should be satisfied with slow internet connection in his mobile phone? Earlier standards GSM (Global System for Mobile communications) were sufficient to make phone calls on long distance, as well as for sending text messages. To be able to use the convenience of internet connection with mobile phones of third generation (3G), it has been necessary to increase overall amount of forwarded data, so an imaginary crown has been passed to UMTS standard (Universal Mobile Telecommunication System). For really fast connection, comparable to that of metallic cable internet, many companies currently utilize LTE technology (Long Term Evolution), more commonly known as fourth generation (4G) mobile devices.

All these technologies have to function simultaneously, so in densely populated areas, there are places with extremely high density of microwave radiation. That causes strictly technical problems, when inappropriately constructed and poorly adjusted transmitters may interfere with communication systems utilizing other technologies, or even make any meaningful communication of these systems completely impossible. Moreover, large amounts of data transmitted goes hand in hand with increased power necessary for their transmission. Therefore, it is necessary to control amount of radiofrequency radiation in free space and the observance of recommended hygienic limits, not only for individual signals, but also the overall intensity of all types of radiation in surrounding environment, as well as in areas of particular interest (hospitals, computational facilities, secured areas).

4.2.1 Equipment

To guarantee high accuracy of all measurements, spectrum analyzer **„ANRITSU - Spectrum Master MS2726C“**, was used in hand-held design, providing high mobility, especially when searching for interfering signals.

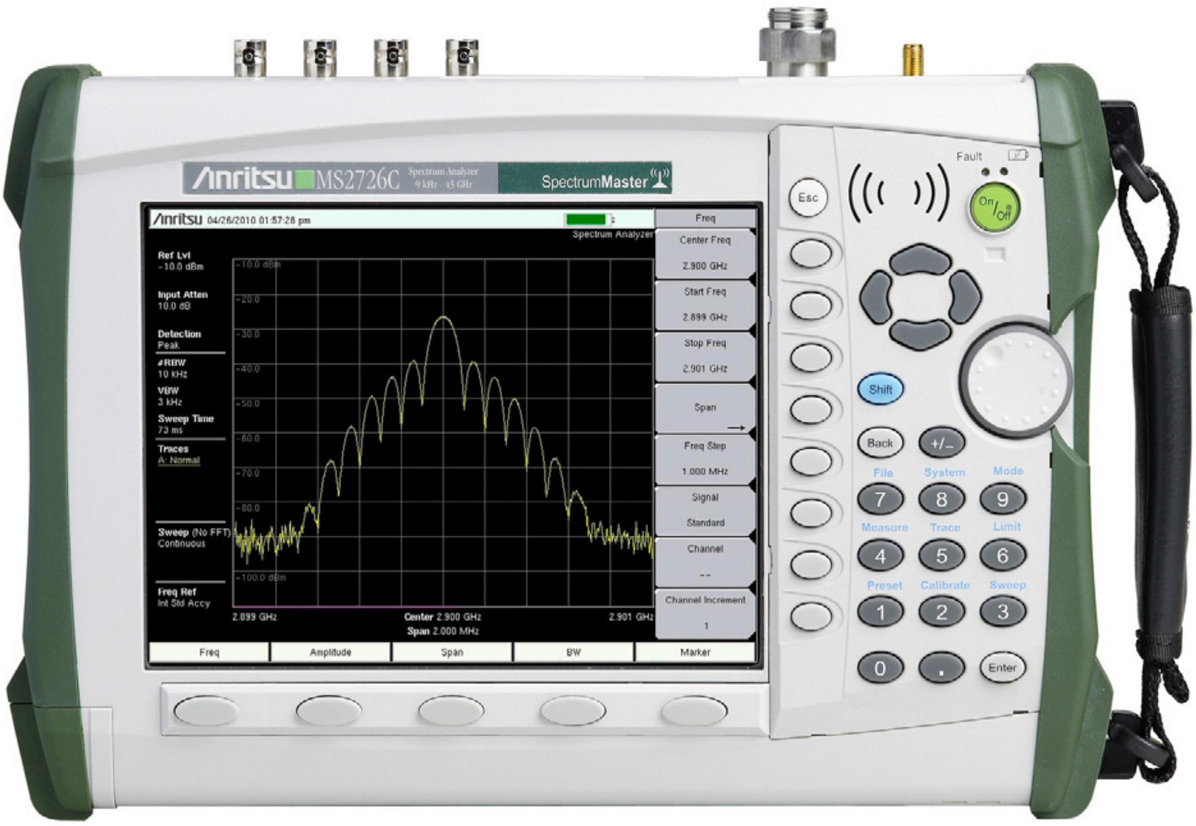


Figure 14: Spectrum analyzer „Spectrum Master“ [52]

For a thorough measurement of radio-frequency spectrum was also used high-gain antenna „**AARONIA - HyperLOG 7025”** with a frequency range of *700 MHz* to *2.5 GHz*. [33]

Figure 15: Antenna „HyperLOG 7025“[33]

Resulting version of chart has been created on a personal computer using software toolkit **"Master Software Tools"** (MST), allowing easy data transfer from the spectrum analyzer into PC, their subsequent adjustments and export as standardized protocol file.

4.2.2 Antenna factor

For checking measurements has been chosen restaurant on the outskirts of Brno with wireless internet access, well covered with mobile signal.

But first, it was necessary to specify an antenna factor for selected frequencies of whole frequency band of HyperLog antenna. Antenna factor, in the form of numerical values, was provided by the manufacturer. We consequently converted it into a text file in a format readable by spectrum analyzer and loaded it into device via USB interface. Then we connected antenna to analyzer and seleced appropriate file with antenna factor values, necessary for accurate measurement of electric field intensity.

Thereafter, it was possible to perform individual measurements and consequently evaluate obtained data.

4.2.3 Setting up the spectrum analyzer

As an initial value was specified frequency *700 MHz*, as final frequency *2500 MHz*, for ensuring thorought measurement of electric field intensity in the whole antenna’s frequency range.

In order to ensure real informative value of acquired data, it was necessary to set appropriately certain parameters, which contribute substantially to assessment process of measured signals. For example, the way in which spectrum analyzer detects magnitude of measured signals, was selected as ***“effective value”***, because AC signal of this size has **identical thermal effects**, as would have direct current. [10] Therefore, data defined in this way have, in relation to thermal biological effects of electromagnetic radiation, relevant informative value.

The tracing method set to ***“Max Hold”*** ensures, that displayed curve for each frequency represents maximum measured value (the highest value of entire measuring period). [51]

Table 13: Set values of selected spectral analyzer parameters

Parameter:	Set value:
Detection method:	RMS
Reference level:	-30 dBm
Tracing:	Max Hold
PreAmp:	„ON“
RBW:	10 (MHz)

4.2.4 Electric field intensity

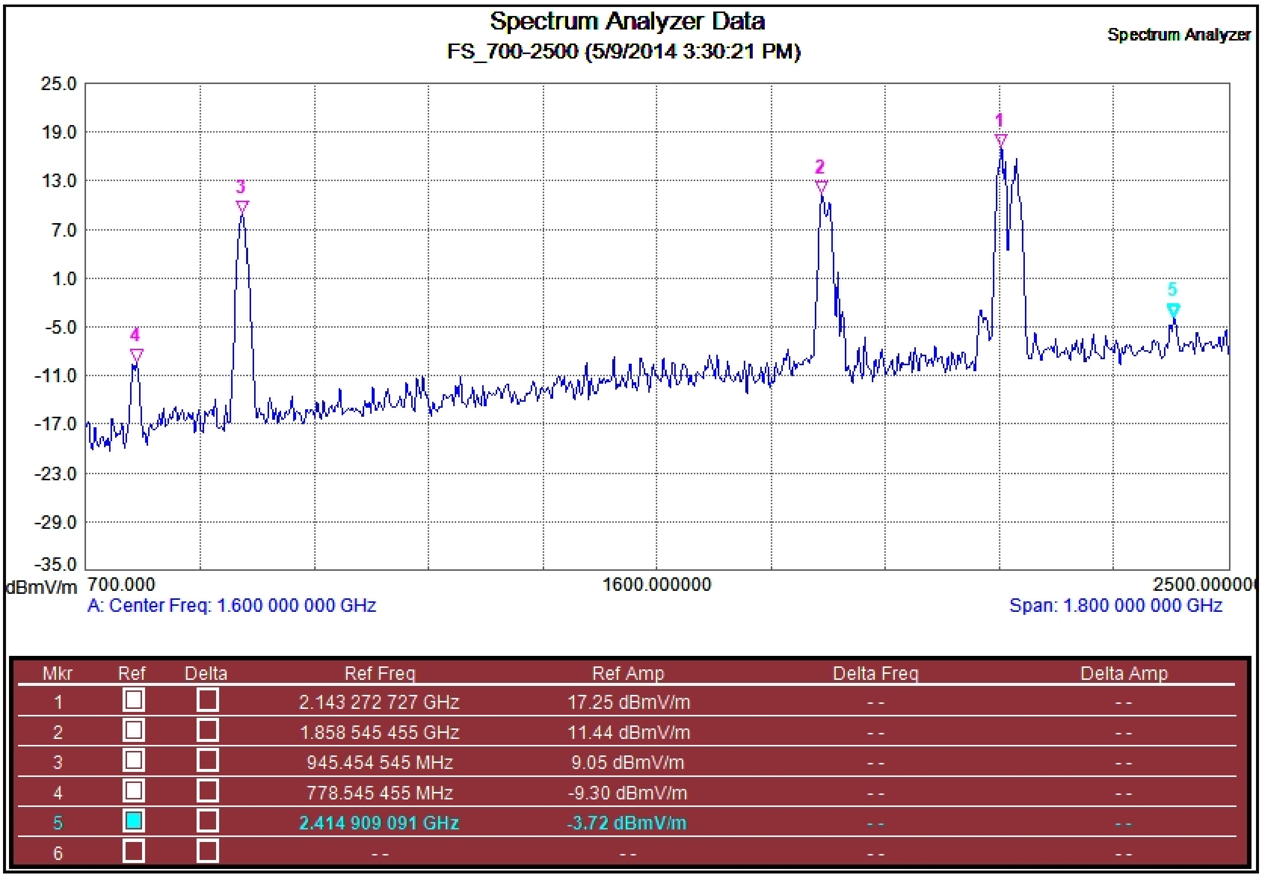


Figure 16: Electric field intensity (700 - 2500 MHz)

Within measured frequency band can be clearly seen multiple signals with intensities significantly above the noise floor. The highest detected value has been 17.25 *dBmV/m* (1) at frequency of 2.143 *GHz*. Together with the fifth signal (5) at 2.414 *GHz*, this is probably Wi-Fi communication, running generally within frequency range 2.4 – 2.5 *GHz*.

Signal at 945 *MHz* (3) is a classic representative of mobile communication. The band 890-960 *MHz* is reserved for standard GSM 900, where 935 *MHz* frequency is being used for *"downlink"*, whereas base transceiver station (BTS) emits signal towards individual mobile phones. [61] This signal has to be present, even if there would not be any mobile phone (operating within transmitter's range) turned on. Base stations emit signal continuously, at least for *"authentification"* of each mobile phone - when turned on, mobile device receives this signal and consequently emits another one towards the base station. If there **would not** be any signal present in this band, it would probably indicate inappropriately selected equipment, or incorrectly adjusted measurement parameters.

Let's try to find out whether intensity of the strongest signal detected meets current standards. At frequency of 2.143 *GHz*, electric field intensity is 17.25 *dBmV/m.*

Reference level of electric field intensity specified by national standards (value, which must not be exceeded) for frequency range 400 *MHz* – 2 *GHz* is determined by equation (see table no. 6):

$$E = 0{,}003 * f^{0{,}5} = 0{,}003 * (2{,}143 * 10^{9})^{0{,}5} = \mathbf{139\ [V/m]}\ [39] \qquad (1)$$

Signal intensity 17.25 *dBmV/m* corresponds to intensity 77.25 *dBμV/m*. With this knowledge, we can use following formula for converting logarithmic values of electric field intensity into absolute ones:

$$E_{\mathrm{V/m}} = 10^{(\mathrm{E_{dB\mu V/m}}-120)/20} = 10^{(77{,}25-120)/20} = \mathbf{0{,}0073\ [V/m]}\ [13] \qquad (2)$$

By comparing both values is immediately clear, that the measured signal meets current standards by a very large margin. It can be concluded, that electric field intensity of any signal within measured radiofrequency band, did not exceed hygienic limits of Czech Republic.

4.2.5 „Downlink" versus „Uplink"

Each frequency band, reserved for a certain mobile communication standard, consists of two parts. *"Downlink"* is a communication of base stations with individual mobile devices, while the *"Uplink"* corresponds to all the data emitted by mobile phone towards nearest base station. [4]

Table 14: Freqency band of standard GSM 1800

GSM 1800	
Uplink (MHz)	Downlink (MHz)
1710 – 1785	1805 - 1880

For measuring purposes, we have selected freqency band (1700 ÷ 1900) *MHz*, a reference level of -50 *dBm*, resolution (RBW) = 1 *MHz*, tracing *"Max Hold"*, detection method *"RMS"*.

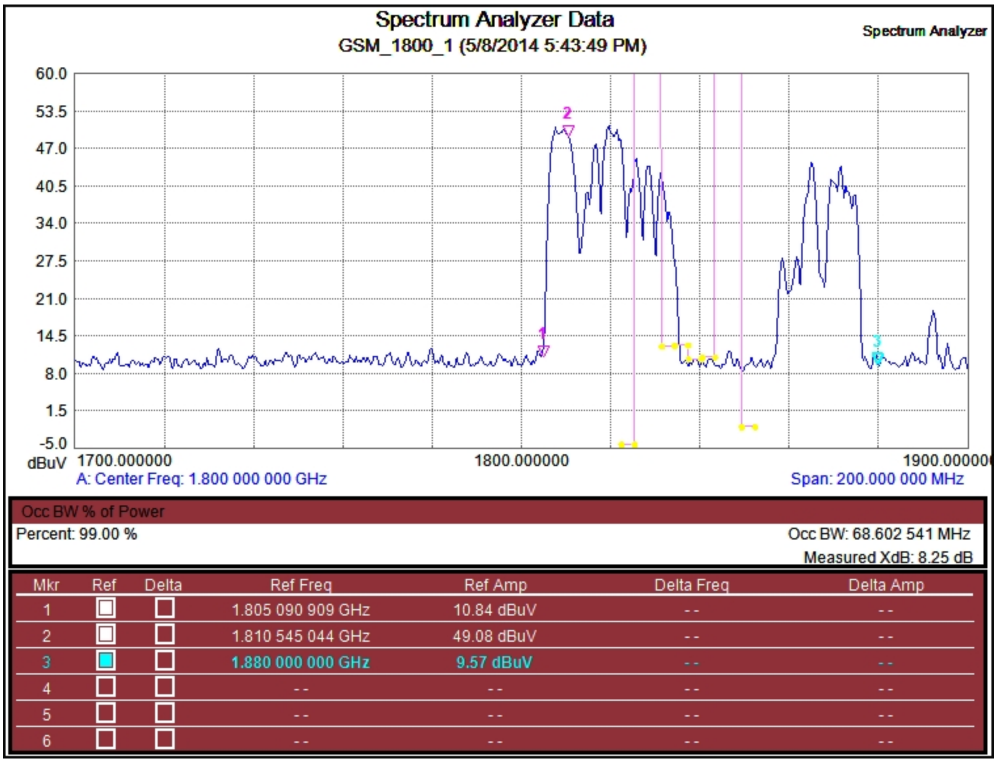


Figure 17: Measuring of frequency band GSM 1800

First signals significantly above the noise level start at frequency 1805 *MHz* (1). This indicates that all mobile communication at a time have been running only from base station towards mobile devices. Due to the fact, that band dedicated to *"Uplink"* has been empty, presumably no person in the examined area telephoned at the time. Above frequency 1880 *MHz* (3) we can clearly see signals with not negligible intensity, however, these are outside frequency band of GSM 1800, therefore not corresponding to mobile communication within given standard.

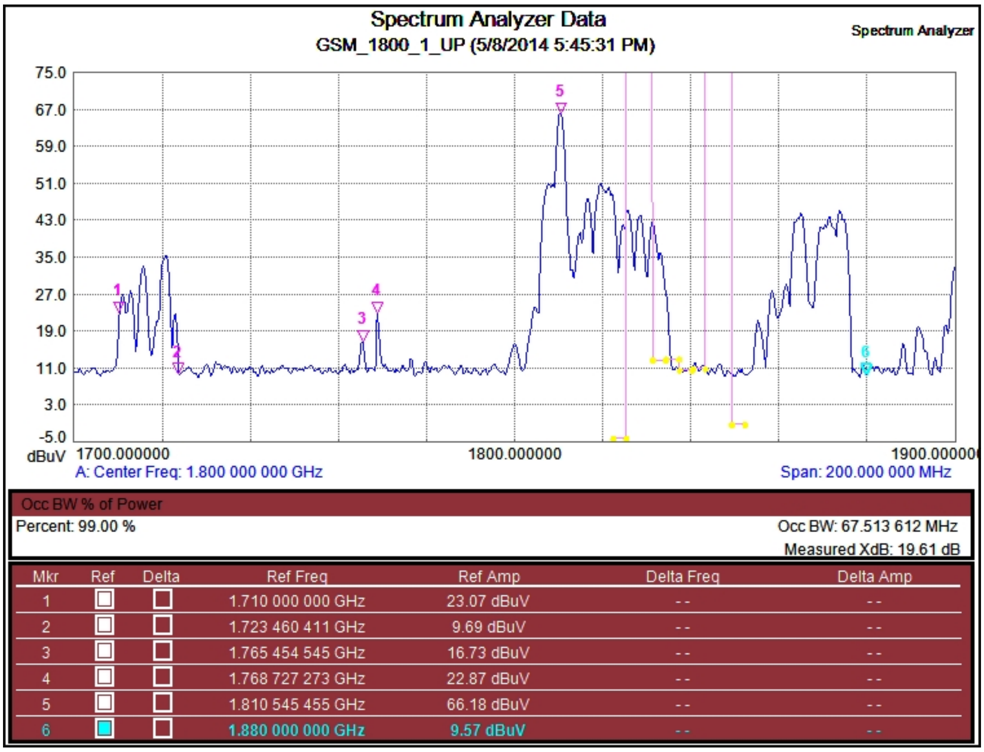


Figure 18: "Uplink" of freqency band GSM 1800

More interesting situation occurred a few minutes later. Within the band 1710 – 1724 *MHz* (1-2) relatively strong signals arised during just a few second. Their quantity and intensity indicates, that someone has been probably phoning actively. Other peaks around 1767 MHz are still within the *"Uplink"* range, however, they are sporadic and have a relatively low intensity suggesting *"Authentification"* of suddenly turned on mobile devices to the nearest base station.

In the *"downlink"* range, we can see signal at a frequency of 1810 *MHz*. It is probably transmission of a phone call, comming from the nearest base station towards phoning person.

4.2.6 Measuring the impact of antenna polarization

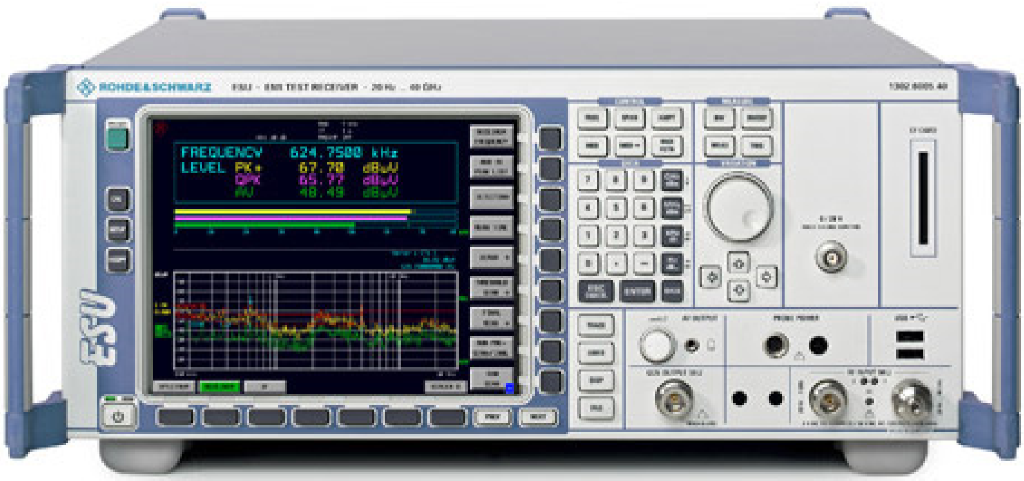


Figure 19: Spectrum analyzer "R&S ESU-26" [67]

For following measurements, we used *"big & bulky"* Spectrum Analyzer **"ROHDE & SCHWARZ ESU-26"**, which provided very high accuracy and large frequency range (20 *Hz* - 26 *GHz*). [48]

Signals were received with hybrid BiLOG antenna **"Teseq Schaffner 6192 UPA"**, commonly used for measuring inside EMC chambers for verifying electromagnetic compatibility of electronic devices. [40]

Figure 20: Antenna "Teseq Schaffner UPA-6192" [68]

The magnitude of measured signals was acquired with a **quasi-peak detector**, which simulates perception of auditory sensations by human hearing, such as interfering radio broadcast with impulse noise signal. [59] It is therefore a measurement appropriate for determining the quality of received signal, as well as biological effects of electromagnetic radiation to sensory organs, especially auditory system.

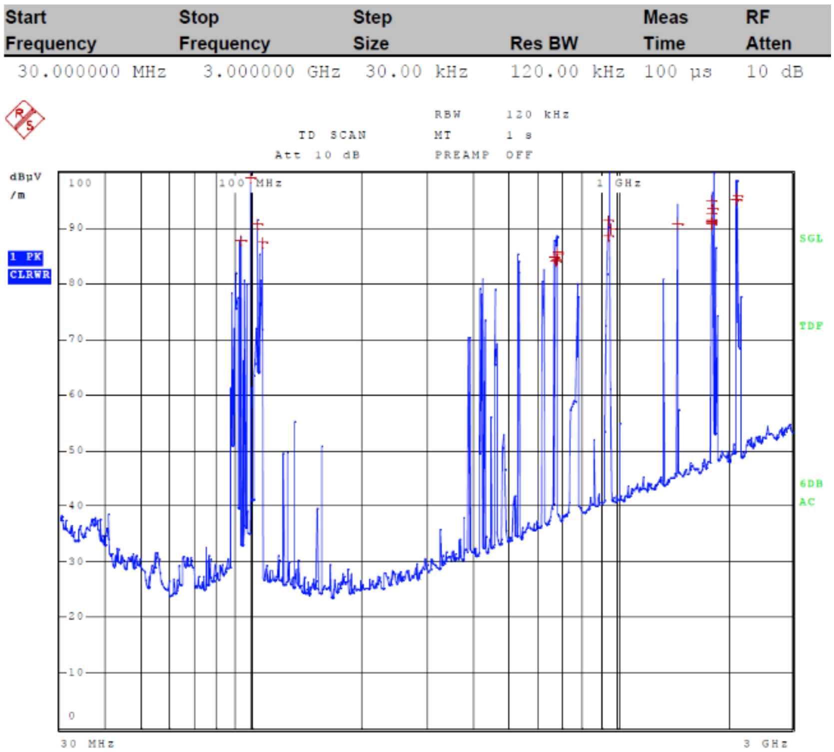


Figure 21: Measurement with vertically polarized antenna

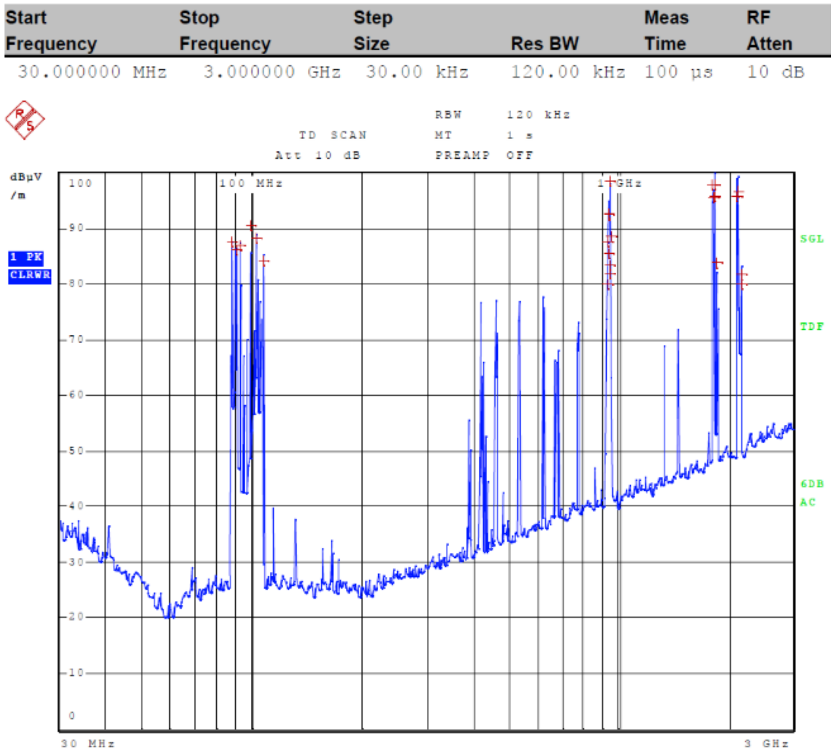


Figure 22: Measurement with horizontally polarized antenna

By visually comparing both charts, we can find out that some signals exhibit much lower intensity during horizontally polarized antenna, but in some other cases, it is exactly the opposite.

Transmission antennas of various RF services (radio and television broadcasts, mobile communication) can be polarized vertically, or horizontally. If you want to receive a specific signal, you need to choose the correct antenna polarization, in order to be rewarded with a strong, quality signal. If, however, receiving antenna would be polarized rather inappropriately, you will catch a much smaller portion of the signal - it will have lower intensity, badly reflecting on its quality. [9]

Furthermore, we can see that relatively strong signals can be found in frequency bands well below 700 *MHz* (significantly around 100 *MHz* in our particular case), **therefore it is necessary to examine the frequency spectrum as a whole - from 0 Hz up to the highest frequencies currently utilized by electrical and electronic devices, including EM field's magnetic component** (especially at low frequencies), so that we could really competently determine actual load level of electromagnetic radiation in surrounding environment and select the most appropriate measures to ensure safety of general public, as well as technical workers.

4.2.7 Evaulation of radio-frequency spectrum measurements

A series of most common radio frequency measurements has been conducted, with measurement device's parameters modified for obtaining data useful to evaluate the safety of electromagnetic radiation intensity within a particular location. For accurate measurements with high informative value were chosen precise spectrum analyzers and antennas carefully selected for different types of measurements.

For making such measurements, it is necessary to select a suitable spectrum analyzer and learn to use it properly, as well as to understand the essence of different approaches for data acquisition in sufficient depth, in order to get meaningful data with real informative value, which can be consequently processed and evaulated.

The basis consisted of radio-frequency spectrum measurement, determination of most probable signal sources and evaluation of their intensities, verifying that their levels did not exceeded the currently applicable hygienic limits.

Furthermore, we outlined issues of different frequency bands for different standards commonly used in mobile communication. GSM 1800 standard was chosen, on which we clearly shown how, in practice, communication between the transceiver base station and individual mobile devices takes place, from the perspective of telecommunication operator.

Then we focused on one of the most common telecommunications problems (antenna polarization), which has a major impact on quality of received signal, as well as measurement and subsequent evaluation of electromagnetic radiation intensity.

Finally, based on the results of actual measurements, we emphasized the need to evaluate electromagnetic spectrum as a whole, because individual types of simultaneously applied electromagnetic radiation may interfere with each other and exhibit synergistic effects. Therefore, the safe levels of electromagnetic radiation in a particular location can not be established solely on intensity of the strongest signal in a selected frequency band, but it is necessary to consider all components of every currently applied electromagnetic signals across entire frequency spectrum, so we can really competently determine actual electromagnetic load in surrounding environment and select the most appropriate measures to ensure the safety of general public, as well as technical workers, especially in telecommunications field.

Conclusion

The aim of this thesis was to summarize possible effects of electromagnetic radiation on biological systems, carry out the classification of various types of electromagnetic radiation, according to their interaction with surrounding environment and describe its various forms (gamma radiation, microwaves, infrared light) with their specific features, problems and possible utilization. Furthermore, interaction of ionizing and non-ionizing radiation with matter has been described, along with conversion of absorbed electromagnetic energy into heat, as well as its amount, that living organisms are able, under normal conditions, to manage without immediate adverse reactions. Common ways in which living organisms regulate their internal temperature were clarified, along with possible medical applications of effects produced by increased temperature. Finally, we also outlined common ways of protection against electromagnetic radiation, carried out practical measurement and subsequently verified the effectiveness of proposed protective measures.

Selected interaction mechanisms of various kinds of electromagnetic radiation with biological systems were discussed, along with methods commonly used for determining the amount of absorbed radiation, as well as up-to-date legislation, including hygienic limits currently used in Czech Republic and some other countries (USA). Matter of course is reference to relevant organizations, based on whose recommendations these limits are estabilished in individual countries, as well as ways in which are determined limit values of electromagnetic radiation within corresponding regulations. Radio frequency spectrum was measured, sources of different signals identified, intensity of those signals evaluated and subsequently verified that their levels did not exceeded currently applicable hygienic limits.

Protection methods against various types of radiation were summarized, as well as different non-ionizing radiation types utilization in health care, with a focus on modern diagnostic and therapeutic methods. Principles of their function, data processing, potential benefits and pitfalls in relation with various kinds of situations and possible contraindications were assessed, along with design of selected devices and physical nature of their interaction with biological systems. A comparison has been made for these methods, considering their suitability in various situations, which may provide brief guidelines for determining the most appropriate method by a medical professional in a particular case.

Propriety of recommendating lead as the most commonly available shielding material to ionizing radiation has been verified, followed with detailing main reasons, why other materials are less suitable and rarely used in common practice.

Given the diversity of electromagnetic radiation effects, it is necessary to examine different types separately, as well as all radiation as a whole at the same time. To understand various ways they affect living organisms, it is useful to first understand how EM radiation interacts with surrounding environment, mechanisms of these interactions, along with resulting effects on biological systems, exposed to them directly. Legislation and relevant regulations should thereafter, based on potential adverse effects, ensure sufficient protection of general public and technical workers, which comes into contact with hazardous materials and dangerous types of EM radiation.

Many kinds of electromagnetic radiation may be, due to their properties, used for diagnosing health impairments, evaluating organism’s health status, treating various ailments and supporting healing processes, or relieving pain. Some, however, may also adversely affect the persons involved, therefore it is necessary to throughoutly consider possible benefits and risks of selected approaches and consequently choose the best option in terms of required outcomes, possible health complications, time demands, as well as availability of them in particular geographic area, along with financial costs of individual methods.

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