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# Medical Physics in Radiological Practice: Imaging Technologies and Protection Practices

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**Abbreviations:** Computed Tomography (CT), Magnetic Resonance Imaging (MRI), Positron Emission Tomography (PET), Single-Photon Emission Computed Tomography (SPECT), As Low As Reasonably Achievable (ALARA), gray (Gy), milligray (mGy), sievert (Sv), millisievert (mSv)

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## Abstract

This paper aims to highlight the pivotal role of physics in radiology, emphasizing its critical importance in both diagnostic and therapeutic applications. Radiology relies on a variety of imaging techniques, all of which are grounded in fundamental physical principles. These techniques include X-ray imaging, computed tomography (CT), magnetic resonance imaging (MRI), positron emission tomography (PET), and single-photon emission computed tomography (SPECT). The paper provides an overview of the core physical principles underlying these technologies, discusses their applications in medical diagnostics and treatment, and underscores the importance of radiation safety and protection. Special attention is given to the role of medical physicists in the maintenance and calibration of equipment, treatment planning, as well as the training of medical staff.

## Introduction

In recent years, there has been a significant increase in the application of physics in medicine, directly improving the diagnosis and treatment of numerous diseases. Physics is a fundamental science that studies natural laws and phenomena. It has a crucial role in advancing healthcare by providing a deeper understanding of these principles and finding practical applications in medical fields.

One of the most important fields where physics is indispensable is radiological technology. Radiology employs various imaging methods, such as X-rays, magnetic resonance imaging (MRI), computed tomography (CT), and hybrid positron emission tomography (PET). Each of these technologies relies on physical principles to generate detailed images of the body's internal structures, helping physicians to make accurate diagnoses and develop effective treatment plans. Additionally, this article discusses the use of ultrasound in diagnostics, a technique that utilizes high-frequency sound waves to produce images of internal organs. Ultrasound is a safe and non-invasive tool in cardiology, gynecology, and pregnancy monitoring, providing reassurance and effectiveness.

Besides diagnostics, physics also plays a crucial role in therapeutic procedures. Radiation therapy, commonly used to treat cancer, delivers ionizing radiation to destroy malignant cells.

Proper knowledge of radiation physics is essential to ensure that the patient receives the appropriate dose for a tumor while minimizing harm to surrounding healthy tissue. Medical physicists are responsible for the proper functioning of equipment used in radiation treatments.

These applications illustrate that physics has become an integral part of modern medicine, leading to more precise diagnostics, more effective treatments, and overall improvements in patient care worldwide. As the technology and knowledge in this field continue to advance, we can anticipate an even greater role for physics in medicine, bringing new solutions and innovations to healthcare.

The aim of this paper is to present an overview of the fundamental physical principles behind these technologies, explore their uses in medical diagnostics and treatment, and highlight the significance of radiation safety and protection. Emphasis is placed on the role of medical physicists in equipment maintenance and calibration, treatment planning, and training of medical personnel.

After the introduction, in the second chapter, the paper covers the historical development of physics in radiology. This chapter presents key milestones in radiological techniques, beginning with Wilhelm Röntgen's discovery of X-rays in 1895, which enabled physicians to view the internal structures of the human body without invasive procedures. It explains how early discoveries in radiation science, such as Becquerel's work on natural radioactivity, led to the expansion of radiation therapy. Technological advances, such as the development of linear accelerators and the first CT scanners in the 20th century, are included to show how these innovations have shaped modern diagnostic and therapeutic methods. The chapter concludes with the introduction of MRI and nuclear medicine techniques, such as PET and SPECT, which transformed imaging by allowing detailed, functional visualization of internal processes.

## Historical development of physics in radiology

The development of radiological techniques began in 1895 when Wilhelm Röntgen discovered X-rays. The breakthrough helped physicians to visualize the interior of the human body for the first time without the need for invasive surgery. X-rays were rapidly adopted in medical diagnostics, particularly for detecting bone fractures and foreign objects.[1] In 1896, the year after Röntgen's discovery, Antoine Henri Becquerel discovered natural radioactivity, which spurred further research into the use of radiation for medical purposes. The advancement of radiation therapy accelerated throughout the 20th century, driven by technological progress and a deeper understanding of tumor biology. The introduction of the linear accelerator in the 1950s marked a significant milestone, allowing for the precise and controlled delivery of high doses of radiation to tumors while minimizing damage to surrounding healthy tissue. Linear accelerators have since become standard equipment in modern radiation therapy.[1]

The next major advancement in radiology came with the development of CT in the early 1970s. Sir Godfrey Hounsfield and Allan Cormack developed the first CT scanner in 1972, providing detailed three-dimensional visualization of the body's internal structures. Over time, advanced nuclear medicine techniques such as PET and SPECT emerged, enabling the visualization of functional processes within the body.[2]

MRI was also developed in the 1970s as a non-invasive method for producing detailed images of soft tissues within the body. MRI has proven particularly useful in diagnosing neurological disorders, spinal injuries, and various other conditions.[2]

## X-rays

X-rays are a form of electromagnetic radiation characterized by very short wavelengths and high energy. They are produced when electrons, accelerated under high voltage, are abruptly stopped upon striking a metal target within the X-ray tube. This process releases energy in the form of X-rays.[1]

The X-ray tube consists of two electrodes, a cathode and an anode, enclosed in a vacuum. Electrons emitted from the cathode accelerate towards the anode and collide with a metal target, typically made of tungsten, resulting in the emission of X-rays. As X-rays pass through the body, different tissues absorb the rays to varying degrees. Bones, being dense and rich in calcium, absorb more X-rays, while softer tissues, such as muscles and organs, absorb less. This differential absorption creates contrast images that reveal the internal structures of the body.[3]

In radiology, X-rays are most commonly used to detect bone fractures, diagnose lung diseases such as pneumonia and lung cancer, and examine the oral cavity.[1] A specialized application of X-rays in mammography is used for the early detection of breast cancer. Mammograms use low-dose X-rays to produce detailed images of breast tissue, facilitating the early identification and treatment of malignant tumors.[3] Besides mammography, X-rays are also essential in fluoroscopy, which generates real-time images of the internal structures of the body. Additionally, CT scanners utilize X-rays to create detailed cross-sectional images of the body, which are then reconstructed into three-dimensional visualizations.

## Computational tomography

CT is an advanced diagnostic technique that utilizes X-rays and computer technology to produce detailed cross-sectional images of the body. CT scanners operate by directing X-rays through the body from multiple angles. Detectors positioned on the opposite side capture these rays after they have passed through various tissues. The collected data is then processed by a computer to reconstruct layered images of the internal structures of the body, resulting in three-dimensional visualizations that allow for an in-depth examination of organs and tissues.[1]

CT scanners provide highly detailed images of internal structures within minutes, enabling the accurate diagnosis of various conditions, including tumors, internal bleeding, bone fractures, and other abnormalities.[4]

## Magnetic resonance

MRI technology is based on nuclear magnetic resonance (NMR). When a patient's body is placed in a strong magnetic field, the protons in water and fat molecules align with the field. Upon applying a radiofrequency pulse, the protons absorb energy and are displaced from their equilibrium state. Once the radiofrequency pulse is turned off, the protons return to their equilibrium, releasing energy that can be detected and used to generate an image.[1] The data collected during this process is transformed into images using complex computational algorithms. MRI scanners use magnetic field gradients to obtain spatial information for creating detailed three-dimensional images of internal organs and tissues.[2]

Unlike CT and X-ray imaging, MRI does not use ionizing radiation, reducing the risk of radiation exposure for patients. This fact makes the method particularly useful for repeated scans and for sensitive populations, such as children and pregnant women.[1]

## Positron emission tomography and hybrid single-photon computed tomography

The underlying physical principles of PET technology rely on the emission of positrons from a radioactive isotope. When a positron collides with an electron, annihilation occurs, releasing energy in the form of two gamma photons traveling in opposite directions.[2] Detectors in the PET scanner capture these gamma photons, and a computer processes the data to reconstruct three-dimensional images that depict the distribution of radionuclides within the body.[1]

The physical principle of SPECT is the detection of gamma rays emitted by radionuclides inside the body. Gamma-ray detectors rotate around the patient, collecting data from various angles. The computer then processes this information to reconstruct three-dimensional images that show the distribution of radioactive material in the body.[2]

PET is particularly useful in oncology for detecting and monitoring tumors, while SPECT is commonly used in cardiology to assess blood flow in the heart muscles.

## Quantum physics in medical imaging

Quantum physics plays a significant role in enhancing the precision, safety, and informational value of diagnostic procedures. Technologies such as MRI and PET utilize quantum phenomena to produce detailed images of the internal structures of the body. Based on quantum mechanical principles, MRI and PET scanners can achieve exceptionally high resolution and detailed visualization of internal structures, which is critical for early disease detection and diagnosis. For instance, MRI exploits the quantum properties of protons, primarily in water molecules, which possess magnetic moments and spin. When exposed to a magnetic field, these protons align with the field. Upon applying a radiofrequency pulse, the protons absorb energy and transition to a higher energy state. As the pulse is turned off, the protons return to their ground state, emitting a radiofrequency signal that is captured by detectors. A computer then processes these signals to reconstruct detailed images of the internal structures of the body.[1]

PET, on the other hand, uses positron-emitting isotopes that decay by releasing positrons. When a positron collides with an electron, annihilation occurs, releasing two gamma photons. Detectors capture these photons, and a computer reconstructs images based on their trajectories.[2]

# Contrast agents

Contrast agents are a critical component of many radiographic diagnostic procedures. Their primary purpose is to provide better visibility of specific anatomical structures and functions within the body. Contrast agents are substances that absorb or transmit X-rays differently than the surrounding tissue, providing improved visualization of targeted structures. They play a key role in diagnosing otherwise difficult-to-detect anomalies. These agents are used in various imaging techniques such as MRI, X-ray, and CT scans. Depending on the type of imaging and diagnostic requirements, contrast agents based on iodine, gadolinium, or barium are used.[5]

## Application method

Oral contrast agents are used when imaging the upper digestive tract, including the mouth, esophagus, and stomach. The contrast is ingested prior to the examination to create a clear image of these structures. The agents of choice are generally based on barium sulfate or iodine (Gastrografin).

Intravenous contrast agents are injected into the veins to enhance the visibility of blood vessels, the heart, kidneys, and other organs. Iodinated contrast, commonly used for this purpose, provides improved imaging of blood vessels and blood circulation.

Gastrointestinal contrast agents are typically used to examine the digestive system, including the stomach, small intestine, and large intestine. Two main types of contrast agents are used for this: barium-based and iodinated contrast agents. Barium contrast is used to scan the upper digestive system, such as the esophagus, stomach, and intestines, while iodinated contrast is employed for scanning the small and large intestines.[5]

Articular contrast agents, often iodine-based, are used to examine joints and surrounding soft tissues. They improve joint visualization during imaging procedures like arthrography.

In CT imaging, contrast agents play a crucial role. Automated injectors are devices that deliver precise, controlled, and consistent administration of contrast agents into a patient's vein during CT scans, enhancing the contrast of internal organs and tissues. CT scans with contrast lead to better visualization of blood vessels, tumors, inflammatory processes, and other pathological changes. Automated injectors offer adjustable injection rates, contrast volumes, and injection times based on the patient's condition. They also reduce the risk of human error, thus improving the safety and reliability of the procedure. Automated injectors are indispensable for administering contrast agents in CT examinations, as their precision and adaptability for each patient are key to achieving high-quality diagnostic images.[6]

## Health risks and protection

In addition to the benefits of contrast agents, they also carry various risks and contraindications. Patients who are allergic to the components of contrast agents, such as iodine, or those who have experienced allergic reactions to contrast during previous procedures may be prone to adverse reactions. Furthermore, even if a patient has had no negative experiences with contrast in the past, medical professionals report that there is always the potential for developing an allergy. Therefore, monitoring patients closely during the administration of contrast and remaining vigilant for any signs of a reaction is crucial.

Moreover, patients with certain kidney conditions or impaired renal function may be sensitive to contrast due to the risk of contrast-induced nephropathy. Common side effects of contrast agents include nausea, vomiting, warm or cold sensations, and changes in taste. The most severe, though fortunately rare, side effect is anaphylactic shock, for which most imaging centers are equipped with epinephrine auto-injectors as a temporary measure and immediate response for treating anaphylaxis.

Despite these risks, the benefits of contrast agents far outweigh the potential harm, which is why they are still widely and carefully used in daily medical practice.

Safety guidelines and restrictions in radiology play a crucial role in protecting patients, radiologic technologists, and other healthcare workers from the potential risks of exposure to X-rays and ionizing radiation. Restrictions in radiography focus on techniques that minimize radiation exposure, especially for vulnerable groups such as children, pregnant women, and other sensitive populations. These guidelines focus on optimizing diagnostic procedures, ensuring the highest level of safety, and minimizing radiation doses. For radiologic technologists to effectively protect both the patient and themselves, understanding the actual dangers overcome by protective measures is important.[7]

## Radiation doses

Radiation doses are key concepts in radiology as they describe levels of exposure to ionizing radiation and the potential risks associated with radiation exposure. The absorbed dose (*D*) is a measure of the amount of energy transferred by radiation to tissue. The unit of measurement for absorbed dose is gray ($G_y$), though due to typically small quantities, the subunit milligray (m$G_y$) is often used. It is defined as the absorbed energy per unit mass, and derived from this definition is the following formula for calculating the absorbed dose:

$$D = \frac{E}{m} \tag{1}$$

where *D* represents the absorbed dose, *E* is the energy received by the tissue, and *m* is the mass of the tissue. Based on this formula, it becomes evident that 1 $G_y$ can also be expressed as J/kg (joules per kilogram), given that J (joule) is the unit of energy and kg (kilogram) is the unit of mass.[8]

The equivalent dose (*H*) is "a dosimetric quantity that describes the biological effect of a specific type of ionizing radiation in a given tissue."[9] Its uniqueness lies in the fact that it accounts for different types of radiation and describes stochastic risks. The equivalent dose is expressed as the product of the absorbed dose (*D*) and the radiation type weighting factor ($W_r$).

$$H = D \times Wr \tag{2}$$

The unit of measurement for an equivalent dose is the sievert (*Sv*), and the subunit millisievert (mSv) is also commonly used. The effective dose (*E*) describes the overall risk of harmful radiation effects on the entire human body. Different types of tissues in the body vary in their sensitivity to radiation, which is why the effective dose is important in risk assessment. It is defined as the product of the equivalent dose in specific body regions and the corresponding tissue weighting factors ($W_t$) for those tissues. The effective dose is expressed in sieverts (*Sv*) and is used to estimate the total risk from exposure to ionizing radiation. The formula is as follows:

$$\begin{gathered} E = H \times Wt \\ E = D \times Wr \times Wt \end{gathered} \tag{3}$$

## Dosimetry

Dosimetry and radiation exposure monitoring are indispensable parts of any radiology department (Fig. 1), where the primary function is safety and minimizing radiation exposure risks. The most commonly used thermoluminescent dosimeters (TLDs) are tools used by all radiologic technologists to measure exposure to ionizing radiation. They are made of a plastic casing and a material that absorbs radiation energy during exposure, which is then released as a light signal when heated during reading. The amount of light released is proportional to the amount of radiation received, allowing for precise measurement and monitoring of radiation doses.[10]

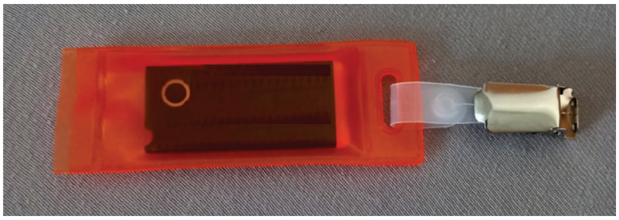

Figure 1. **A thermoluminescent personal dosimeter**

## Equipment maintenance, treatment planning, education and training

Medical physicists are responsible for the precise calibration and regular maintenance of radiological equipment, including X-ray machines, CT scanners, MRI devices, and linear accelerators. Calibration ensures that the equipment delivers accurate radiation doses and that imaging quality is optimal. Routine maintenance reduces the risk of malfunctions and ensures the safety and reliability of this equipment.[1]

In therapeutic radiology, medical physicists use advanced computational programs to calculate the optimal radiation dose that maximizes the impact on tumor tissue while minimizing harmful effects on surrounding healthy tissue. Additionally, medical physicists train healthcare staff on the proper use of protective equipment and best practices for reducing radiation exposure. They also develop and implement safety protocols and guidelines for the use of radiological equipment.

## Principles of protection

The ALARA (as low as reasonably achievable) principle is a core concept in radiology aimed at minimizing radiation exposure to patients while maintaining diagnostic image quality. This principle applies not only to patients but also to radiologic technologists and is achieved through careful positioning, ensuring proper distance from the radiation source, and using shielding when possible. Technologists must position the patient as quickly as possible and exit the room, ensuring a physical barrier, such as a closed door, is between them and the radiation source. Minimizing the patient dose requires properly positioning the patient and optimizing machine settings, such as amperage (mA) and voltage (kV). In CT imaging, ALARA is implemented by selecting the appropriate scanning protocol and accurately marking the area being imaged.

In addition to ALARA, three other principles are essential in radiology practice. The principle of limitation refers to the need to balance diagnostic value with the associated risk of radiation exposure. Importantly, no level of ionizing radiation is considered completely safe. Hence, the aim is to reduce the dose to the lowest level necessary to obtain the required diagnostic information or achieve therapeutic goals. Justification means that each radiological exam or treatment must be medically necessary, weighing the potential benefits against the risks and considering non-radiation alternatives when possible. Optimization stresses the need to fine-tune technical settings and procedures to achieve the best possible diagnostic or therapeutic outcome with minimal radiation exposure tailored to each patient's specific situation.[11]

Finally, protection is a key element in radiology, involving the use of appropriate measures to minimize radiation exposure for both medical staff and patients. For medical personnel working with radiation-emitting equipment, protective gear like lead aprons and goggles are necessary to reduce radiation dose. Correctly positioning the patient and maintaining a proper distance from the source also plays a crucial role in limiting exposure. Special care should be taken with more sensitive populations, such as young people and pregnant women, to ensure they are protected. This approach ensures that radiological practices remain safe, effective, and ethically sound.

## Conclusion

The aim of this paper was to highlight the crucial role of physics in radiology and to explain how physical principles have led to advancements in diagnostics and therapy in medical practice. The paper describes various radiological techniques, including X-ray imaging, CT, MRI, PET and SPECT, and associated principles in physics.

X-ray imaging, which uses X-rays to create images of internal body structures, was the first major discovery that transformed medical diagnostics. CT produces detailed cross-sectional images of the body and is a tool for physicians to precisely diagnose various conditions, including tumors and internal bleeding. MRI relies on quantum principles to visualize soft tissues, which is particularly useful for diagnosing neurological and musculoskeletal conditions. PET and SPECT use nuclear imaging techniques to visualize metabolic and functional processes, providing an in-depth assessment of biological functions and the detection of abnormalities.

Quantum physics is the basis of advanced diagnostic methods such as MRI and PET, which provide high-resolution, noninvasive interventions and functional information. These technologies result in precision diagnostics and therapy planning while improving patient outcomes.

Radiology safety incorporates the physical principles of radiation protection, such as distance, time, and shielding barriers. Medical physicists have an important role in ensuring the safety of both patients and staff through equipment maintenance, treatment planning, and staff training.

In conclusion, physics is an essential part of modern radiology, the foundation for the development of technologies that have provided precision diagnostics and effective therapy. Radiologists rely on physical principles every day to improve healthcare. Continued progress in science and technology will ensure that the role of physics in radiology continues to grow, bringing innovations and improvements to medical practice.

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# MEDICINSKA FIZIKA U RADIOLOŠKOJ PRAKSI: TEHNOLOGIJE SNIMANJA I MJERE ZAŠTITE

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## Sažetak

Cilj je rada istaknuti središnju ulogu fizike u radiologiji, naglašavajući njezinu ključnu važnost u dijagnostici i primjeni terapije. Radiologija se oslanja na niz tehnika snimanja, a sve su utemeljene na temeljnim fizikalnim principima. Ove tehnike uključuju rendgensko snimanje, kompjutoriziranu tomografiju (CT), magnetsku rezonanciju (MRI), pozitronsku emisijsku tomografiju (PET) i jednofotonsku emisijsku kompjutoriziranu tomografiju (SPECT). U radu se iznosi pregled ključnih fizikalnih principa na kojima se ove tehnologije temelje, raspravlja o njihovoj primjeni u medicinskoj dijagnostici i liječenju te naglašava važnost sigurnosti i zaštite od zračenja. Posebna pozornost posvećena je ulozi medicinskih fizičara u održavanju i kalibraciji opreme, planiranju liječenja, kao i obuci medicinskog osoblja.

**Ključne riječi:** radiologija, fizika, X-zrake, CT, MRI, PET, radijacijska sigurnost, medicinski fizičari

**Kratice:** CT (engl. *computed tomography* – kompjutorizirana tomografija), MRI (engl. *magnetic resonance imaging* – magnetska rezonancija), PET (engl. *positron emission tomography* – pozitronska emisijska tomografija), SPECT (engl. *single-photon emission computed tomography* – jednofotonska emisijska kompjutorizirana tomografija), ALARA (engl. *as low as reasonably achievable* – onoliko nisko koliko se razumno može postići), Gy (engl. *gray* - grej), mGy (engl. *milligray* – miligrej), Sv (engl. *sievert* – sivert), mSv (engl. *millisievert* – milisivert)