Essentials of Medical Physics

and

Biomedical Applications

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Contents

Abstract

Essentials of medical physics and biomedical applications offers an extensive and thorough overview of the essential fundamental principles of medical physics and their wide-ranging spectrum of biomedical applications. This meticulously designed text aims to support both graduate and postgraduate students, as well as professionals who are seeking to enhance and update their current knowledge in this crucial field. Covering key topics that include radiation physics, medical imaging, radiation therapy, biomaterials, biomedical instrumentation, clinical applications, emerging technologies, and vital safety considerations, the text delivers a robust educational resource. Medical physics is an interdisciplinary field that exists at the intersection of various domains such as physics, engineering, biology, health care, and other related disciplines, focusing specifically on the application of physical principles and precise measurements to the realm of medicine. Through clear and systematic explanations paired with an emphasis on technological advancements and clinical integration, this informative book effectively equips readers with the essential concepts and practical insights they need. It prepares them to understand and advance groundbreaking innovations in the medical field, such as AI-assisted diagnostics and advanced 3D printing technologies, making it a pivotal resource for any professional looking to excel in medical physics.

Chapter - 1

Introduction to Medical Physics

Medical physics is an interdisciplinary subject that primarily focuses on the extensive application of physics principles, concepts, and advanced techniques to the fields of medicine and healthcare. It shares similarities with biophysics, as medical physics straddles the complex disciplines of physics, biology, and medicine. Efforts to incorporate and apply physics in a medical context began in the late 19th century, specifically after the monumental discovery of x-rays by Wilhelm Roentgen in 1895. These still somewhat mysterious electromagnetic waves were soon harnessed for use in medical diagnosis, revolutionizing the way physicians could visualize and understand the human body. In the years that followed, numerous other technological advances were developed, which continue to be the foundation for much of the subject today. In more recent times, the impact of nuclear and quantum physics on medical physics has greatly accelerated, particularly regarding advancements in radiation therapy techniques and the intricate study of tumour cell biology. Despite the emergence of more sophisticated technologies and methods, the fundamental physics underpinning the processes used for acquiring images and delivering precise radiation therapy remains absolutely essential. In this context, medical physics research is, therefore, crucial in the ongoing battle to gain deeper insights into both whole biological systems and the intricate biological interactions occurring at the molecular level. My ambition as it relates to the treatment of medical physics is elaborated in Essentials of Medical Physics and Biomedical Applications, which I approach with two primary goals in mind. The first goal is to provide a comprehensive introduction to the core physical principles and foundational concepts; the second goal is to demonstrate how, through the application of radiation and advanced instrumentation technologies, these fundamental principles are effectively utilized in real-world scenarios. The following is a concise retrospective of the chapter contents, which provides a foundational outline that gives a flavour of how the various topics are developed, interlinked, and integrated together throughout the text [1].

Chapter - 2

Fundamentals of Radiation Physics

Medical physics is an intricate and quantitative interdisciplinary subject that merges vital principles from both physical and mathematical sciences, placing a specific emphasis on the practical applications of physics within the expansive fields of biology and medicine. This broad and multifaceted area is often referred to as biomedical applications, encompassing an extensive range of pivotal topics and cutting-edge technologies. The measurement and thorough analysis of mechanical, electronic, optical, chemical, and magnetic quantities, as well as a variety of radiological parameters, necessitate a profound understanding of the foundational principles of physics. This specialized knowledge is then effectively applied to the development and continual refinement of numerous sophisticated instruments and devices, all meticulously designed to cater to the diverse needs of healthcare professionals and significantly improve patient care outcomes. In this critical manner, medical physics serves as a crucial bridge connecting the theoretical aspects of physics to practical, real-world applications within the medical field, thereby enhancing the overall quality of healthcare services and patient experience [1, 2, 3, 4, 5, 6, 7, 8].

Radiation is undoubtedly one of the most essential physical tools that serve a multitude of diverse applications across an extensive range of biomedical fields. These applications span a wide array, including but not limited to vital diagnostic imaging as well as a variety of therapeutic interventions. In the intricate and highly specialized realm of medicine, the term radiations primarily includes both electromagnetic radiation and particle beams that are generated through a wide variety of different processes. The most common form of human exposure to radiation happens during diagnostic X-ray examinations, which are routinely and effectively utilized in numerous healthcare facilities and settings to detect, evaluate, and diagnose a variety of medical conditions. Additionally, radiation is extensively employed in the usage of radioisotopes for therapeutic purposes such as cancer treatment, which further showcases its vital and indispensable role in modern medical practices. The advancements in these innovative techniques and technologies underscore the significance of radiation in promoting overall health and enhancing positive patient outcomes in increasingly sophisticated ways [9, 10, 11, 12, 13, 14].

Since the 1920s, there has been considerable and significant progress in the realms of wave mechanics and quantum mechanics, which together marked a profound and transformative impact on the overall development of atomic and molecular physics. This pivotal advancement in scientific thought and inquiry paved the way for a much more thorough and comprehensive understanding of nuclear physics and its wide-ranging applications in a variety of fields that are both varied and diverse. The remarkable advancements during this critical period have greatly influenced how we perceive, study, and analyze the complexities of matter at the atomic and subatomic levels in unprecedented and exceedingly intricate ways. It has reshaped our approach to understanding the fundamental building blocks of nature itself, leading to groundbreaking innovations in technology, medicine, and various scientific disciplines that continue to evolve and expand in scope and impact. These developments have set the stage for future explorations and discoveries that promise to unravel even more of the mysteries of the universe and provide insights into the very fabric of reality [15, 16, 17, 18, 19, 20, 21].

The increasing recognition of the considerable economic benefits that are provided by nuclear energy has led to the creation and the development of a diverse range of sensitive and precise nuclear instruments. These highly specialized instruments cater to a variety of important purposes across numerous fields, including but not limited to medicine, geology, agriculture, space research, archaeology, anthropology, education, and further research and development pursuits. The remarkable advancements in this innovative technology have made it feasible to employ nuclear technology effectively in multiple sectors, significantly enhancing operational capabilities and fostering substantial progress in many critical areas. This broad application of nuclear instruments continues to revolutionize various industries, demonstrating their indispensable and vital role in modern advancements and ongoing innovation efforts that change the landscape of contemporary practices. The impact of these instruments is vast, allowing for enhanced capabilities that not only improve current operations but also pave the way for breakthroughs that were previously unimaginable. As such, the evolving use of nuclear technology serves not only as a pivotal contributor to industry growth but also as a catalyst for discoveries that continue to shape our understanding and capabilities in a wide range of disciplines [22, 23, 24, 25, 26, 27, 28, 29, 30].

2.1 Types of radiation

There are numerous distinct types of radiation, which can be broadly classified into two main categories: particulate radiation and electromagnetic radiation. Particulate radiations encompass various subtypes, including but not limited to electrons, protons, neutrons, and alpha particles. These particles are characterized by their ability to pass through matter to a depth that is roughly proportional to both their kinetic energy and electric charge. When these particulate radiations are derived from an external source, they generally present little danger to biological organisms, as they often cannot penetrate deep enough to reach critical biological sites such as the gonads and bone marrow. These sites are vital for reproductive health and hematopoiesis, respectively, which are both crucial processes for maintaining the overall well-being of an organism. However, certain isotopes, such as Strontium-90, can be unintentionally ingested through food or water and may accumulate in specific body tissues, especially in bone, which can thereby significantly increase the risk of harmful biological effects over time. This accumulation highlights and underscores the importance of consistently monitoring exposure to radioactive materials and comprehensively understanding their potential health impacts and risks. Therefore, awareness and regulations surrounding radioactive contamination are essential for public health safety and curbing potential health risks associated with long-term exposure [31, 32, 33, 34, 35, 36, 37, 38].

Electromagnetic radiation encompasses an incredibly vast spectrum of wavelengths, extending from long electrical waves that are typically associated with radio frequencies, to the notably shorter wavelengths found in infra-red, visible, and ultra-violet light. This expansive range progresses all the way up to the powerful and highly energetic X-rays and gamma rays. The shorter wavelengths, which include both X-rays and gamma rays, exhibit remarkable tissue penetration capabilities, allowing them to pass through various materials with remarkable ease and effectiveness. Ultra-violet light, along with X-rays and gamma rays, is specifically classified as ionizing radiations due to their innate ability to possess sufficient energy. This energy is strong enough to eject electrons from the atoms they encounter, thus producing ions in the process, fundamentally altering the structures of these atoms. This characteristic makes these types of radiation significant across various important fields, including but not limited to medical imaging and treatments, as they can decisively impact tissues at a cellular level. The implications of such interactions can be profound, offering both therapeutic benefits and necessitating careful management to minimize potential risks [39, 40, 41, 42, 43, 44, 45, 46].

Natural background radiation arises from a diverse range of sources, which include the cosmic rays emanating from the vast, boundless expanse of outer space, alongside the radioactive materials that can be found in significant quantities scattered throughout the Earth's crust. In addition to these external sources, this radiation is also produced internally by radioactive elements such as Radium, Potassium-40, and Carbon-14, which exist naturally within our bodies. Over a protracted period, especially during the crucial first three decades of life, the average dose of natural background radiation that an individual accumulates can reach approximately three rads. This figure signifies a substantial level of exposure to these natural phenomena and the radioactive elements that are part of our environment, thereby illustrating the ongoing and persistent interaction that living organisms maintain with the various forms of radiation that are present not only in our surroundings but also within ourselves. The pervasive nature of this radiation underlines the complexity and intricacies of how these elements interact with biological systems over time, shaping our understanding of radiation exposure and its implications for health and well-being [47, 48, 49, 50, 51, 52].

2.2 Interaction of radiation with matter

The interaction of radiation with the diverse forms of matter is intricately governed by the specific type of radiation involved, as well as the particular and unique characteristics of the material through which it travels or passes. Figure 2.1 provides a comprehensive and detailed overview of the major types of radiation, their various interactions with matter, and their significant applicability to both imaging and treatment procedures in various fields. Understanding these crucial interactions is fundamentally important for optimizing the overall effectiveness of both diagnostic and therapeutic techniques, ultimately improving patient outcomes and enhancing the quality of medical practices and interventions [53, 54, 55].

Charged particles represent a crucial and fundamentally significant case in which the incident particle interacts profoundly with electrons or nuclei along its entire extended path through the material. This interaction occurs primarily through the Coulombic forces that predominantly govern such interactions. Because the incident particles themselves travel continuously and uniformly throughout the material and substance, the process of dose accumulation is inherently local and becomes concentrated in very specific regions. This concentrated dose can lead to significant effects on the material being interacted with. Additionally, noteworthy secondary emissions occur as free electrons are liberated from atomic shells, which then undergo various further interactions with other surrounding atoms. This leads to the eventual emission of fluorescence X-rays, Auger electrons, or even a diverse variety of photofragmentation products. These diverse and complex processes serve to illuminate the intricate dynamics at play when charged particles engage with matter, revealing a richly layered complexity that lies beneath the observable surface. This complex interplay highlights not only the fundamental interactions but also the varied outcomes that result from each unique encounter [56, 32, 57, 58, 59].

Noncharged radiations propagate in a fundamentally different manner compared to charged radiations, and this unique characteristic significantly impacts their interactions with matter. The various entities involved, including photons, neutrons, and other noncharged particles, engage in interactions along their respective trajectories through various materials. However, it is important to note that these noncharged particles only deposit dose exclusively during subsequent charged-particle events that occur after the initial interaction takes place. In Figure 2.2, a detailed illustration showcases the development of dose surrounding a site where a photon interaction takes place, highlighting how the process unfolds. The secondary electrons generated during these interactions carry energy derived from the initial photon encounter. This results in observable phenomena such as a dose maximum that occurs at a slight depth beneath the surface of the material. This maximum dose reached can indeed be about 1.3 times greater than the entrance dose, illustrating significant energy deposition effects. It’s worth noting that the production of secondary radiation is considerably less prevalent for neutrons. Although every interaction between a neutron and a given material inevitably results in some form of secondary radiation, there are specific types of interactions, particularly those involving neutral particles, that do not produce any dose at all. This occurs due to the emission of neutral particles, which can include gamma rays or other neutrons, effectively leading to no energy deposition occurring in that particular interaction. When charged-particle beams are utilized in these processes, the resulting depth-dose distribution is notably influenced by the application of the Bragg peak. This characteristic of the Bragg peak allows for very precise and targeted dose deposition within specific regions, making it a critical consideration in the evolving and highly specialized field of radiotherapy. The capacity to maximize treatment efficacy while minimizing damage to surrounding healthy tissue is truly of utmost importance in modern therapeutic approaches and is a focal point in ongoing research and innovation in the field. Understanding the nuances of interaction and energy deposition patterns continues to play a vital role in advancing these techniques and improving patient outcomes [56, 60, 61, 62, 63, 64].

Chapter - 3

Medical Imaging Techniques

Medical physics encompasses the intricate application of a variety of physics concepts, theories, and methodologies to the comprehensive study of the human body in both healthful and diseased conditions. This field is inherently multidisciplinary, drawing from a wide array of diverse fields that include, but are not limited to, physics, medicine, biology, statistics, computational science, and sophisticated instrumentation techniques. Medical physicists tackle a multitude of complex issues, including but not limited to, cancer therapy, advanced diagnostic imaging, medical informatics, and detailed physiological modeling. Students who enroll in a course focused on medical physics may delve deeply into several of these critical areas, depending on the level of their study and their specific choice of modules offered within the curriculum. Other important areas might be included but may only receive a brief overview, ensuring that students still gain a comprehensive educational experience that covers essential topics in depth. The field of medical physics is pivotal, and a detailed overview of its vast applications is provided by Black *et al*., which illustrates the wide-ranging breadth and significance of this vital discipline in enhancing healthcare outcomes and advancing the evolution of medical technology and therapeutic interventions. This discipline plays an essential role in the modern medical landscape, guiding innovations that ultimately improve patient care and treatment methodologies [65, 66, 67, 68, 5, 69].

The broader subject of biomedical applications within the expansive field of physics encompasses a remarkably diverse and multifaceted range of uses for various physical concepts, theories, and methods that are specifically aimed at studying, exploring, and understanding the intricate complexities of the human body, both in states of optimal health as well as in the myriad and varied conditions of disease and illness. More specifically, four particularly crucial and vital areas within this extensive realm of medical physics namely radiation physics and biology, electromagnetic imaging, biomechanics, and sophisticated instrumentation serve to effectively illustrate the application of radiation, which is fundamentally essential in the realms of both medical imaging and treatment. The comprehensive study of living biological systems lends invaluable insight into their functions, cellular processes, and intricate interactions, while biomechanics represents a distinct and significant component of mechanical physics that deals with the complexities of motion, forces, and the diverse mechanical properties experienced by biological entities. Furthermore, the extensive application and utilization of specific instrumentation techniques are vital for diagnostic purposes and therapeutic interventions. Additionally, the book contains a plethora of related topics and pressing issues woven intricately throughout its various chapters, including critical aspects of system resilience that pertain to effectively maintaining operational stability in complex medical environments. Moreover, it delves into risk management strategies that are tailored specifically to minimize uncertainties and enhance patient safety and care. The narrative highlights adherence to established standards that guide practices in medical physics and detailed processes related to procurement, all of which provide pertinent and relevant examples that are greatly significant to the field of medical physics and its important, impactful applications in real-world scenarios and healthcare settings. This comprehensive approach ensures that readers gain a well-rounded understanding of the many dimensions at play in the interface of physics and medicine [68, 70, 71, 72, 73, 74].

Radiation physics and biology serve as the fundamental basis upon which numerous applications depend for their effectiveness and safety. This interrelated field encompasses various types of radiation, the specific units utilized to measure them, their diverse sources across different environments, and the effective methods of shielding against them a topic extensively elaborated on in Section 2.1. Understanding these elements is crucial for both practical applications and for ensuring safety during exposure. This essential knowledge is then applied to delve into the interaction of radiation with matter, a significant topic that is thoroughly discussed in Section 2.2, highlighting the principles that govern these interactions. Furthermore, to ensure a comprehensive understanding and provide an introduction to some nonliving materials that are often used as substitutes across a variety of applications, specific properties of liquid water will be analyzed. In addition to liquid water, tissue substitutes will be explored, including materials such as polystyrene, Perspex, and water-equivalent plastics. All these aspects are addressed in Section 2.3, emphasizing their relevance and practical implications in the field of radiation physics and biology [32, 75, 76, 77, 78].

Most medical imaging techniques employ a variety of different forms of radiation. These radiation forms can include the well-known X-rays that are used in external beam modalities, which play a pivotal role in diagnostic imaging. Additionally, gamma rays and annihilation radiation, which result primarily from the decay of isotopes used in internal beam techniques, are also important in the realm of medical imaging for various purposes. A comprehensive surveying account of the major imaging modalities, including X-ray imaging, Computed Tomography (CT) scanning, Magnetic Resonance Imaging (MRI) techniques, ultrasound imaging, and nuclear medicine practices, is thoroughly presented in the Introduction of Medical Imaging Modalities. These diverse examples serve to illustrate the wide-ranging applications of radiation in modern medicine, along with the essential underlying concepts that govern these sophisticated methods. Additionally, in circumstances involving the use of ionizing radiation, there is a significant reliance on well-established principles of radiation physics. A solid understanding of how radiation interacts with various materials is crucial for accurate diagnostics and therapeutic applications, as is thoroughly discussed in the earlier sections of the text. Understanding these interactions allows healthcare professionals to optimize imaging techniques while ensuring patient safety. Furthermore, concepts related to the mechanical properties of matter, when applied to the specialized field of biomechanics, also play a crucial role in the mechanical components associated with imaging instrumentation. The section dedicated to biomechanics provides a concise yet informative introduction to the errors that can arise in various measurement processes, the essential mechanical properties of different materials that are employed in imaging technologies, and the function of single-degree-of-freedom systems used in calibration and testing. Notably, the inclusion of tissue engineering exemplifies the application of medical physics to cutting-edge biomedical research, utilizing innovative biomaterials to effectively bridge the gap between engineering and biological sciences. By integrating these disciplines, researchers are able to develop novel solutions that enhance patient outcomes in medical settings [79, 79, 10, 80, 81, 82, 83, 11].

3.1 X-ray imaging

X-ray imaging unquestionably remains among the most widely utilized imaging modalities in hospitals and healthcare facilities globally, making it an integral part of modern medicine. Its rich and fascinating history can be traced back to the groundbreaking and transformative discovery of X-rays by the renowned physicist Wilhelm Conrad Röntgen in the year 1896, which marked an utterly pivotal moment in the field of medical imaging. Since that remarkable time, there have been significant and continuous advancements in the fields of physics and detector technology that have remarkably led to the development of various innovative X-ray imaging techniques, notably including Computed Tomography (CT) and the ever-evolving realm of digital X-ray imaging. These X-rays are classified as a specific form of ionizing radiation, which, while posing certain safety concerns that cannot be overlooked, does not deter the continual evolution and integration of these invaluable imaging methods in clinical practice around the world. The immense capability of X-ray imaging methods to accurately and effectively depict intricate internal features and structures is a complex yet fascinating process that is dependent on several critical factors. These include the X-ray production mechanism itself, the precise ability of the detector to capture the X-rays that have successfully been transmitted through the body, as well as the sophisticated and intricate process by which the final X-ray image is ultimately produced for interpretation. Furthermore, the relentless pursuit of innovation in detector technology has seen the widespread adoption of advanced materials such as structured Cesium Iodide (CsI) scintillators, alongside cutting-edge thin-film photodiode and amorphous-selenium direct-conversion detectors integrated into modern flat-panel detector designs. The implementation of these sophisticated detectors translates to exceptionally high spatial resolution, minimal noise characteristics, and the ability for seamless digital image acquisition, all of which collectively contribute to significantly enhanced image quality. This enhanced quality is crucial as it facilitates the detection of subtle lesions and anomalies that might otherwise go unnoticed in standard imaging practices, thus playing a pivotal role in the accurate diagnosis and treatment of various medical conditions [84, 85, 86, 87, 10, 82, 79].

3.2 Computed Tomography (CT)

Computed Tomography (CT) is a groundbreaking imaging technique that facilitates a highly effective non-invasive examination of cross sections of the body, significantly improving diagnostic capabilities by eliminating the superimpositions and overlapping structures that are characteristic of standard radiography. This fundamental advancement provides medical professionals with a clearer and much more detailed visualization of internal anatomy, which is critical for accurate diagnosis and treatment planning. An experimental third-generation CT configuration has been developed, which incorporates a fixed source-detector assembly in conjunction with an innovative rotating sample platform. This state-of-the-art design effectively reduces mechanical complexity, thereby enhancing both the reliability and performance of the entire imaging system, resulting in better outcomes for patients. The detection system integrated within this advanced configuration employs a high-resolution CCD line sensor that is capable of accommodating objects with a diameter of up to 200 mm efficiently. Such capabilities open the door to versatile applications in an array of clinical scenarios, allowing healthcare providers to employ this technology across diverse medical fields. The raw measurements that are captured exhibit a substantial 12-bit dynamic range, which ultimately provides a comprehensive representation of the intensity variations present in the acquired data. These crucial measurements subsequently undergo a normalization process that is based on the exponential attenuation law, a step that proves essential for achieving accurate image reconstruction. After the normalization phase is completed, filtered back projection is utilized following the pre-processing of the projection data. This technique has been pivotal in the successful reconstruction of images with high accuracy levels. Further advancements have been made in the field; wherein iterative reconstruction methodologies have been thoroughly investigated and implemented. These sophisticated methodologies specifically target enhancements in reconstruction fidelity, aiming for a significant increase in the clarity and quality of the images that are produced, while also achieving concomitant reductions in patient radiation dose exposure, which is a major concern in the practice of medical imaging. The continuous development of CT technology represents a remarkable leap forward in medical imaging and contributes immensely to improving patient care and diagnostic effectiveness [88, 89, 90, 91, 92, 93, 94, 95, 96].

3.3 Magnetic Resonance Imaging (MRI)

The fascinating phenomenon of nuclear magnetic resonance, commonly known as NMR, serves as the foundational basis for the advanced imaging technique that we widely recognize today as magnetic resonance imaging, abbreviated as MRI. This remarkable and groundbreaking discovery was made independently by the notable physicist Edward Purcell and the distinguished chemist Felix Bloch, who together laid the critical groundwork for this innovative field of study and exploration. While the vast majority of MRI scans predominantly focus on the proton, which is the most commonly utilized and analyzed nucleus in this context, it is important to note that other types of atomic nuclei are also employed in specific situations, depending on the requirements of the examination. Hydrogen is the element of choice in these scans, primarily due to its abundant presence in various biological tissues throughout the human body, which makes it particularly useful for medical imaging. The contrasts that appear in the detailed images obtained through this remarkable technique vary significantly, influenced by the unique properties of hydrogen within different biological tissues. Atoms that possess nuclei comprising an odd number of particles, or a specific combination of protons and neutrons, exhibit an intrinsic angular motion that is referred to as spin; alongside this noteworthy spin, there exists an associated magnetic moment that plays a crucial role. In the case of hydrogen nuclei analyzed during these scans, each proton has a defined spin value of ½. When these particular hydrogen atoms are placed in the presence of a strong, external magnetic field, they exhibit a natural tendency to align themselves either in a parallel or antiparallel orientation relative to the magnetic field direction. The crucial preliminary step for successfully conducting an MRI scan involves carefully aligning the spins of the protons along the direction of the magnetic field, which is denoted as B_0. Following this critical alignment process, a radiofrequency pulse, designated as B_1, is effectively applied to excite the protons, which results in the rotation of the net magnetic vector across a specified range of degrees, typically falling between 90° and 180°. This intricate series of events is integral to the successful generation of MRI images that provide detailed and informative insights about the internal structures of the human body, allowing for advanced diagnostics in modern medicine [97, 98, 99, 100, 101, 102, 103].

3.4 Ultrasound imaging

Ultrasound imaging systems utilize high-frequency sound waves that are specifically designed to visualize internal organs and tissues in a non-invasive yet highly effective manner. This technology ensures that patients are not exposed to potentially harmful ionizing radiation, which is a significant advantage over other imaging modalities. A specialized transducer is responsible for generating longitudinal waves that can propagate deeply into the body, producing real-time images by detecting reflected echoes that bounce back from various internal structures. The typical probes used in ultrasound scanning comprise both curved and linear array geometries, and they come with adjustable frequencies that range anywhere from 2 to 20 MHz. This variability allows for the strategic selection of frequencies based on specific tissue types and the individual imaging requirements of each patient. The linear probe, for instance, is particularly effective as it yields high-resolution, rectangular images that support comprehensive and detailed anatomical assessments of vital organs such as the heart, blood vessels, kidneys, and liver. Additionally, this type of probe is invaluable during pregnancy as it provides crucial imaging of fetal structures, aiding in prenatal care. This versatile imaging modality also allows for precise measurements of distances and enables detailed analysis of speckle patterns within the gray-scale images, thereby significantly enhancing diagnostic capabilities. Ongoing research efforts are actively focused on addressing the development of advanced three-dimensional acquisition techniques. These techniques rely on innovative one-dimensional linear arrays that can be efficiently translated across the designated imaging region, especially considering that commercially viable 3D ultrasound systems remain largely unavailable for mainstream use. Furthermore, standardized phantoms that closely resemble the acoustic properties of tissue have been established to facilitate systematic and thorough evaluations of device performance. This includes critical aspects such as resolution and focal zone characteristics, which are essential to fulfilling quality-assurance objectives in medical imaging. Consequently, sonographic image quality criteria have become a pivotal topic of discussion across various clinical applications. This is especially true in the realm of breast cancer imaging, where accepted guidelines and protocols unfortunately remain limited, highlighting a significant need for advancement in this field [104, 105, 106, 107, 108, 109, 110, 111, 112, 113].

3.5 Nuclear medicine

Nuclear medicine utilizes advanced imaging techniques like Positron Emission Tomography (PET) and Single-Photon Emission Computed Tomography (SPECT) through specialized dedicated systems or hybrid systems that provide a clearer and more precise picture of biological processes. The integration of hybrid methodologies, such as SPECT/CT or PET/CT, offers significant advantages by adding crucial anatomical information that harmonizes with the functional data obtained from these sophisticated scans. This powerful combination not only improves the localization and characterization of lesions but also plays a vital role in supporting comprehensive diagnostic and prognostic evaluations that are essential for effective clinical decision-making. Furthermore, it significantly enhances overall patient management by providing healthcare professionals with more precise and detailed information for meticulously planned treatment strategies, which can lead to better health outcomes for patients. Additionally, therapeutic procedures in this progressive field encompass molecular-targeted radionuclide therapy, which shows great promise and potential in the relentless fight against cancer and the improvement of patient outcomes. The continuous advancement of these innovative techniques marks a substantial step forward in the realm of nuclear medicine, reinforcing its critical importance in contemporary medical practice and ultimately benefiting patient care and survival rates [114, 115, 116, 117, 118, 119, 120].

Chapter - 4

Radiation Therapy

Radiation therapy is a specialized medical treatment that utilizes focused radiation as a means to precisely target and effectively treat malignant tumors. The underlying guiding principle of this innovative treatment modality is that successfully destroying a tumor can significantly lead to the eventual cure of cancer. This advanced form of therapy relies on various types of radiation and specific dosimetry parameters that work together to establish a highly precise and effective treatment plan tailored to each patient's unique condition. Among the types of radiation most commonly used in clinical practice, photon radiation serves as the standard treatment beam employed in many cases, although other options, such as electron beams and proton beams, have also found widespread application and recognition in various clinical settings. The primary energy sources that provide the essential radiation for therapy include cobalt-60 sources, linear accelerators, betatron machines, as well as sophisticated proton cyclotrons. Each of these sources contributes unique advantages to the treatment process, enhancing the ability of healthcare professionals to deliver targeted therapies. In the field of photon radiography, highly intense radiation beams, which are often referred to as 'tele' beams, are utilized. This terminology indicates that a single high-energy beam, typically within the energy range of 4 or 6 MV, is frequently sufficient for effectively treating the disease at hand in many situations. Additionally, the utilization of a cobalt source can sometimes become critically important in specific cases due to its advantageous half-life, which allows for more effective treatment options over time, as well as important economic considerations that can heavily influence treatment decisions and accessibility for patients seeking care. Thus, the combination of technological advancements and thoughtful planning continues to propel the field of radiation therapy forward [121, 122, 123, 124, 125, 126].

Radiation therapy is a highly specialized medical treatment that intentionally induces breaks in the DNA chains of both normal and cancerous cells, subsequently disrupting their ability to function effectively and properly. In contrast, chemotherapy operates through a different mechanism; it primarily focuses on inhibiting cell proliferation by obstructing various crucial protein functions within the affected cells, leading to diminished cell growth and replication. This form of therapy encompasses a diverse array of techniques and methodologies, including the precise use of photon beams, electron beams, protons, and neutron beams, all tailored to target and treat the malignant tissues. Furthermore, it may also involve the application of radioisotopes, and in certain specialized cases, the strategic utilization of lasers to specifically target and destroy diseased tissue while minimizing damage to surrounding healthy areas. Medical accelerators play a vital role in the delivery of different radiative forms, such as X-rays and electrons, across a broad spectrum of energy levels, varying from as low as 1 MeV, all the way up to and surpassing 25 MeV. These accelerators can administer radiation with dose rates that may fluctuate significantly, typically ranging from 0.01 Gy/min to as high as 20 Gy/min, allowing for customized treatment regimens suited to the individual patient's needs. One particularly significant feature of this cutting-edge technology is the incorporation of various types of cylindrical, ring-shaped, and isocentric gantry heads, which have been specifically designed and engineered to deliver either X-rays or electrons with remarkable accuracy and efficiency. In the clinical setting, the application fields of this sophisticated therapy encompass several vital processes, which include, but are not limited to, detailed treatment planning, precise treatment delivery, and enhanced planning optimization to ensure the best possible outcomes and success for patients undergoing treatment. Through this multifaceted approach, radiation therapy is able to provide targeted relief and often connects patients to a range of other therapeutic modalities tailored to their specific conditions [1, 127, 128, 129, 130, 131, 132, 133].

4.1 Principles of radiation therapy

The therapeutic application of medically administered radiation in the treatment of various non-benign diseases is fundamentally grounded in a profound understanding of the fact that cancer cells typically possess a notably diminished capacity to effectively repair DNA damage when contrasted with the healthy tissues that surround them. This essential characteristic plays a pivotal role in the application and effectiveness of radiation therapy. Specifically, radiation therapy functions by inflicting damage on the DNA strands within cells. Upon exposure to a substantial dose of radiation, numerous cancer cells are stimulated to undergo a specialized and programmed form of cell death that is widely recognized as apoptosis. The primary objective of radiation therapy is to judiciously and strategically deliver high doses of radiation to the malignant cancerous cells while simultaneously sparing and safeguarding the adjacent healthy tissues from any potential harm. To attain this intricate balance between treatment and protection, medical professionals employ a diverse array of various types of ionising radiation arrangements. These advanced methodologies encompass options such as sealed radiation sources, distributed radiopharmaceuticals, electron beams which are generated by sophisticated linear accelerators, and heavy-particle beams produced by state-of-the-art synchrotron-type cyclotrons. The development and utilization of these cutting-edge technologies are a reflection of the innovative approaches that are characteristic of modern oncology. The ongoing exploration and research in this field are continuously striving to enhance the overall efficacy of the treatment processes while simultaneously working to minimize any adverse side effects that may arise during the course of therapy [1, 134, 135, 136, 137, 138].

The primary types of ionising radiation that are commonly utilized in a wide range of applications across different fields are high-energy bremsstrahlung X-rays, gamma rays that are emitted as a direct result of radioactive decay processes, and several advanced techniques that include electron beam technologies, proton beams, and neutron fluxes generated as a byproduct of various nuclear reactions. In a typical clinical scenario, large areas that are exposed to either X-ray or gamma-ray fields can have profound impacts on the underlying tissues; notable variations in density among different types of tissues can lead to enhanced dose absorption, thereby substantially affecting the overall treatment outcomes achieved. Furthermore, treatment schedules are meticulously designed to spread the overall irradiation over several distinct sessions, aiming not only to minimize the potential side effects but also to maximize treatment efficacy and results for the patient. Electron and proton beams, on the other hand, provide much superior depth control for targeted treatment areas, allowing clinicians to effectively 'shoot through' limbs and thereby provide protective measures for the vital organs situated nearby in the patient's body. This advanced therapeutic approach is often delivered using highly complex shielding and meticulously arranged fixed-target setups that are specifically designed to help focus the radiation precisely where it is needed the most for optimal therapeutic outcomes. Neutron beams, recognized as the most penetrating type of radiation available, can be particularly effective when utilized in combination with boron compounds. This specialized combination results in the formation of distinct and highly energetic beams of alpha particles and lithium nuclei within the tissue itself, specifically targeting designated sites of interest with remarkable precision and effectiveness. The dose delivered by any kind of radiation beam remains a critical factor in treatment planning; for instance, a dose of ten rad corresponds to roughly 0.1 $J \cdot kg^{-1}$ of beam energy deposition, thereby highlighting the absolute necessity for precise dosage management in various therapeutic applications to ensure optimal patient outcomes and prevent unnecessary damage to healthy surrounding tissues [139, 140, 33, 32, 141, 142, 143, 144].

4.2 Types of radiation therapy

Radiation therapy represents an advanced and absolutely vital technique that employs ionizing radiation with the primary goal of effectively killing and ultimately eliminating tumoral cells that may be present within the body. This treatment can be administered in a variety of forms, which include external photon therapy that encompasses methods such as X-rays and gamma rays, as well as charged particle therapy that integrates more specialized techniques such as proton therapy and electron therapy. The actual delivery of radiation can be executed either externally where machines are utilized to precisely direct the radiation beams towards the tumor or internally, a method that is commonly referred to as brachytherapy. In brachytherapy, sources of radiation are strategically placed in close proximity to or even directly inside the tumor itself, allowing for a concentrated dose at the site of the malignancy. It is estimated that approximately half of all cancer patients, during their fight against the disease, will undergo radiation therapy at some point in their treatment journey. The specific modality that is employed for treatment is carefully chosen based on a multitude of factors, including the type and precise location of the tumor, the available resources and capabilities of the treatment facility, and distinct patient characteristics along with important health considerations. Among the various forms of radiation therapy available today, proton therapy is widely recognized and highly regarded as the most promising and effective treatment option for many patients, as it offers a highly targeted approach that results in fewer side effects compared to traditional methods. Additionally, there are several photon-based techniques that have been developed including Intensity-Modulated Radiation Therapy (IMRT), 3D-conformal radiation therapy, Image-Guided Radiation Therapy (IGRT), and Volumetric Modulated Arc Therapy (VMAT) each of which also demonstrates strong performance and effectiveness in treating a diverse array of different types of cancer. These continual advancements in radiation therapy are instrumental in improving patient outcomes and significantly enhancing the overall quality of cancer care that is provided to patients today [145, 146, 147, 148, 149, 150, 151].

4.3 Dosimetry and treatment planning

The dosimetric process in the field of radiotherapy has undergone significant evolution over the years, shaped by a variety of established protocols that include those like TG-21 and numerous other dosimetry codes of practice. These protocols have been specifically designed with the aim of effectively addressing the multifaceted challenges posed by high-energy photon and electron beams that are commonly utilized in clinical settings. In this context, a diverse and extensive range of secondary standards laboratories, which exist across the globe, has successfully adopted robust dosimetry protocols that are recognized and accepted on an international level. This widespread adoption of standards ensures that a high level of consistency and accuracy in dosimetric practices is maintained throughout different healthcare institutions and practices. Dosimetric procedures, which are absolutely critical for ensuring that accurate radiation delivery is achieved for patients undergoing treatment, are meticulously performed following these established codes of practice. These codes not only set forth recognized and accepted methods for calibration of ionization chambers but also encompass essential ionization measurements. Moreover, these procedures play an integral role in the determination of the absorbed dose to water for the reference fields that are routinely employed in various radiotherapy treatment modalities. The existing dosimetry protocols, which are currently in use across various healthcare facilities, predominantly hinge on established standards related to air kerma. The conversion procedure from air kerma to absorbed dose to water relies heavily on a specific set of factors. These factors have been thoroughly and experimentally determined and are derived from a blend of theoretical analyses and practical assessments. The dosimetric processes involve a variety of assumptions pertaining to the crucial underlying physics processes associated with the interaction of radiation with matter. One notable aspect of the dosimetry process is the existence of established protocols such as the IAEA TRS-398 and the AAPM TG-51 codes of practice. These well-regarded protocols have introduced and proposed a direct and effective approach for the calibration of ionization chambers, enabling highly accurate assessments concerning absorbed dose to water, specifically for radiation that is delivered from both ^60Co and Co-60 gamma radiation sources. This continual evolution in dosimetry is not just a technical advancement; it is also essential for enhancing patient safety and improving treatment efficacy within the increasingly complex and delicate field of radiotherapy [152, 153, 154, 155, 156, 157, 158, 159].

The success of radiation therapy is critically dependent on a variety of factors, including the treatment planning process and, equally important, the prescribed dose of radiation. Patients suffering from locally advanced or metastatic cancer often necessitate the administration of high doses and large treatment volumes to effectively target the disease. Many of these patients are required to return to the oncology department for re-treatment after their initial course of therapy. Historically, the concept of large volume re-treatment has never been considered a safe or acceptable practice. However, it is now being recognized within the oncology community that this approach may be necessary in select cases, meaning that it can be implemented when appropriate. This acknowledgment does not imply that re-treatment with large volumes inevitably leads to poor prognosis, although it is important to note that the estimated risk of complications associated with such treatments remains high and requires careful consideration and management [160, 161, 162, 163].

Quality control plays a crucial and critical role in ensuring the reliable and efficient operation of CT scanners while also significantly contributing to the optimization of patient dose levels, which are vital for patient safety. In the intricate realm of CT imaging, it is essential to recognize that patient dose is closely and intricately linked to the overall quality of the images produced. This direct relationship profoundly influences the overall diagnostic accuracy that can be achieved from these scans, and it is imperative to uphold high standards to ensure effective patient care. The philosophy underlying radiation protection fundamentally involves not only the justification of the level of performance that the CT scanner is capable of delivering but also entails thorough efforts to minimize any unnecessary exposures to the patient during imaging procedures. This comprehensive approach aims to reduce exposure to a level that is as low as is conceivably achievable, thereby ensuring that patient safety is prioritized at all times. In doing so, it enhances patient safety and maintains very high standards of care in medical imaging practices. Ultimately, this leads to better health outcomes and ensures the overall well-being of patients undergoing various imaging procedures in their healthcare journey. The continued commitment to quality control and radiation safety in CT imaging ultimately serves to benefit not just individual patients but also the healthcare system as a whole, fostering trust and reliability in medical diagnostic services [164, 165, 166, 167, 168, 169, 170].

Chapter - 5

Biomaterials and Biomechanics

Biomaterials are defined as a wide array of synthetic or naturally occurring substances that are meticulously designed and utilized to restore, support, or enhance various essential functions within the intricate and complex systems of the human body. These materials can be broadly categorized into three primary categories of biomaterials: metals, ceramics, and polymers, each featuring unique and distinctive properties that are critically applied in various medical fields for a diverse range of therapeutic purposes and solutions. A comprehensive and detailed review of these materials reveals not only their essential and pivotal roles in the medical domain but also underscores the importance of understanding their compatibility with the complex biological systems of the body and any potential hazards or risks associated with their use. Furthermore, the discussion extends to address important safety concerns and the far-reaching implications of these materials for long-term performance in various medical applications. This highlights the crucial and growing necessity for thorough and extensive research and development in this vital and expanding area of medicine, ensuring that patient safety and effective treatment outcomes remain at the forefront of biomaterials research and application [171, 172, 173, 174, 175, 176, 177, 178].

Biomechanics represents an exceptionally specialized branch of science that is deeply concerned with a multitude of mechanical phenomena and principles that possess a direct relationship with living organisms. The field meticulously delves into studying these diverse phenomena on both macroscopic and microscopic scales, ensuring a comprehensive analysis of their implications. This fascinating and captivating discipline primarily centers on enhancing our understanding of the complex mechanical properties inherent in human tissues. It also investigates the various sophisticated methods applied to determine these critical properties with utmost accuracy. In addition, the significant role of biophysical effects during the intricate process of tissue engineering is briefly but thoroughly discussed, stressing the fundamental importance of these effects in the development of effective and innovative engineering techniques. Such advancements markedly enhance the outcomes in this vital field. A comprehensive understanding of these elements is essential for propelling forward the applications of biomechanics within the realm of medical science, and it ultimately contributes to the improvement of patient care standards and practices [179, 180, 181, 182, 183, 184, 185].

Medical physics is a highly specialized field that intensely concentrates on the diverse and intricate applications of fundamental physics concepts, core principles, and methodologies specifically aimed at the precise measurement, detailed analysis, and comprehensive understanding of human bodies and their complex functions. This multidisciplinary discipline encompasses not only the thoughtful design and development of specialized instruments but also the hands-on practical application of advanced and sophisticated devices and innovative technologies that are absolutely essential for the prevention, accurate diagnosis, and effective treatment of a wide array of diseases and various medical conditions. The seamless integration of these physics-based approaches is incredibly vital, as it plays a crucial role in significantly advancing overall healthcare outcomes while greatly enhancing the quality of patient care through a myriad of innovative and effective solutions. By diligently leveraging the sustained principles of physics, skilled medical physicists contribute significantly to a better and deeper understanding of medical phenomena, which, in turn, leads to groundbreaking developments that ultimately improve both diagnostic and therapeutic strategies within the realm of medical practice. Their work is essential not only for innovation but also for fostering trust and reliability in medical technologies that directly impact patient health and safety [66, 186, 187, 5, 188, 189, 190].

5.1 Introduction to biomaterials

Biomaterials are defined as either natural or synthetic materials that are specifically engineered and designed for the purpose of safe implantation into the human body. These materials can serve functions as either a complete medical device or as an important component within the broader structure of a medical device. According to the Food, Drug, and Cosmetic Act, a biomaterial intended for implantation is identified as a material that is utilized to replace or substitute (either entirely or partially) a tissue that has been damaged, diseased, or is otherwise malfunctioning. This can include various types of tissues, encompassing both soft and hard tissues, depending on the medical need and the specific application. In addition to their diverse applications in implantable technologies, biomaterials also serve as the foundational raw materials for a vast array of single-use medical devices, including but not limited to diagnostic kits, therapeutic devices, prosthetics, and they play a critical, integral role in the constantly evolving landscape of healthcare technologies today. The pivotal role that biomaterials play hinges significantly on their unique and inherent capability to provoke a desired, suitable response from the host body when they interact with living tissue. This interaction can take place at multiple levels, whether at the organ level or the cellular level, all while effectively avoiding any immune-related rejection reactions that could complicate or delay the healing process for patients. This unique property of biocompatibility is a significant factor driving the extensive research interest and exploration within this specialized field. This has led to the creation of a strong impetus to develop new and innovative materials that not only enhance existing functionalities but also introduce additional capabilities, ultimately aiming to improve health outcomes, quality of life, and overall patient care across a range of medical disciplines [191, 171, 176, 192, 193, 194, 195, 196, 197].

5.2 Mechanical properties of biomaterials

Biomaterials represent a crucial cornerstone of medical-physics research, serving as a vital component in advancing healthcare technologies and innovative approaches to treatment. Tissue engineering, which is a prominent discipline closely associated with the field of biomaterials, focuses on the complex and multifaceted tasks of regenerating, repairing, or restoring damaged or diseased tissues and organs in the human body. This addresses an urgent need in modern medicine, where the demand for effective treatments continues to accelerate. This dynamic and rapidly developing field has initiated a remarkable synergy with medical physics. This synergy is particularly evident through the application of sophisticated analytical procedures and cutting-edge technologies that significantly enhance the scope and depth of engineering science. By characterizing the intricate mechanical properties of these biological constructs developed through the precise assembly of biomaterials alongside living cells and tissues researchers can gain invaluable insights into their structural integrity, functionality, and biocompatibility. Additionally, the continuous monitoring of mechanical properties throughout the culturing and development process serves as a crucial guide for optimizing these constructs. This ensures they not only perform reliably but also adequately meet the rigorous physiological requirements inherent to various human functions. Such monitoring is essential for identifying potential challenges before they arise, leading to more robust solutions. Ultimately, this collaborative and interdisciplinary approach is now leading to groundbreaking advancements in both research and clinical applications. These advancements are fostering a new era of personalized medicine and tailored therapies that bring transformative solutions to complex health challenges. As the integration of biomaterials and medical physics evolves, the potential for improving patient outcomes continues to expand, promising a future where innovative, efficient, and effective treatments become the norm rather than the exception [171, 65, 198, 199, 200, 201, 202, 203].

The principal challenge that researchers face in this specialized field involves the noninvasive evaluation of critical mechanical properties in large constructs that possess intricate and complex geometries at physiologically pertinent concentrations over extended cultivation periods. Mechanical properties, which are pivotal for understanding the performance of such constructs, are typically quantified by considering the construct's elastic modulus. This mechanical characteristic can be effectively reflected in the thickness of the tissue that has been cultured within these constructs. For constructs that measure approximately 7 cm, it becomes crucial that a sufficient amount of biological material be present in order to allow for an accurate and reliable assessment of stiffness; therefore, facilities that can accommodate such substantial dimensions are utterly indispensable for successful experimentation and research. Moreover, the viscoelastic characteristics that are commonly exhibited by many types of biological tissues necessitate that measurements be derived from frequencies that closely align with those found in real in vivo conditions. For instance, when imaging a half wavelength within a 6 mm construct, it would require a frequency that is near 4600 Hz to achieve optimal results in analysis and observation within the context of mechanical testing. This intricate interplay between the design of constructs, the measurement techniques employed, and the biological characteristics of tissues plays a significant and crucial role in advancing our understanding of their mechanical properties, which ultimately impacts how we view their potential applications in biomedical engineering and related fields. This synergy not only enhances our technical capabilities but also leads to more effective and innovative solutions in tackling the challenges faced in tissue engineering [204, 205, 206, 207, 208, 209, 210, 211].

Rapid imaging sequences enable the efficient and timely acquisition of multiple phase offsets, which significantly facilitates a more comprehensive and detailed evaluation of shear stiffness data. Furthermore, the utilization of faster imaging sequences allows for the sampling of a considerably greater number of slices within a single session, thereby supporting the intricate and meticulous mapping of large constructs even under strict clinical constraints that may otherwise limit the typical procedures. In addition to these advanced imaging techniques, complementary methodologies such as nanoindentation and dynamic mechanical analysis, which provide essential frequency-dependent measurements of various mechanical properties, serve as invaluable benchmarks for validating the shear modulus data that is obtained from a range of different imaging assessments. The efficacious estimation of tissue formation, development, and integration through noninvasive and innovative methods is crucial as it underpins the fabrication of enduring and reliable implants and substantially contributes to the advancement of regenerative medicine initiatives that are aimed at improving patient outcomes in various clinical settings. This multi-faceted approach not only enhances the quality of data collected during imaging but also ensures that the information used in clinical decision-making is robust and scientifically grounded, ultimately leading to better therapeutic strategies and enhanced patient care [212, 213, 214, 215, 216, 217, 218].

5.3 Applications in tissue engineering

Tissue engineering is an innovative and rapidly advancing field that seeks to regenerate or replace diseased or lost tissue through the intricate and carefully designed combination of cells, growth factors, and biomaterial scaffolds. This emerging discipline represents a fascinating intersection of biology, engineering, and medicine that aims to create functional tissue substitutes. A critical and significant challenge in this endeavor is establishing a functional vascular network within the constructed tissue. The importance of this vascular network cannot be overstated; it is essential to ensure an adequate supply of essential oxygen and vital nutrients while effectively removing waste products that could hinder the tissue's functionality. Without a proper vascular structure, the engineered tissues may be unable to survive or integrate properly within the body. To facilitate the complex and multifaceted process of vascularization, various scaffolds can be meticulously engineered to release biologically active molecules such as Vascular Endothelial Growth Factor (VEGF) in a controlled and sustained manner over an extended period of time. This targeted approach is crucial because it aims to promote angiogenesis and the formation of new blood vessels within the engineered tissue. The release of these factors needs to be timed precisely to coincide with the growth and development phases of the tissue. Moreover, engineered tissues should also undergo mechanical stresses that are analogous to the conditions found in vivo to promote and enhance functional development. This aspect is crucial for ensuring that the engineered constructs can closely mimic the natural tissue environment, thus achieving optimal integration, sustainability, and overall functionality. The importance of mechanical stimulation cannot be overlooked, as it plays a vital role in guiding cellular responses and influencing the overall behavior of the engineered tissues. By reproducing the dynamic forces present in native tissues, scientists can significantly improve the quality and performance of these constructs. The ability to replicate these conditions effectively is a cornerstone of tissue engineering and holds immense potential for clinical applications in regenerative medicine. This field continues to grow and evolve, promising exciting advancements that can lead to innovative treatments and therapies for a wide range of diseases and injuries. As research progresses, the integration of advanced technologies, such as 3D bioprinting and novel biomaterials, will further enhance the capabilities of tissue engineering, ultimately revolutionizing the way we approach healing and regeneration in the medical field [219, 220, 221, 222, 223, 224, 225, 226].

Despite the well-established design and operation of bioreactors that have proven their capability to effectively impose shear and other mechanical forces at the laboratory scale, the process of scaling up these systems for larger commercial production presents numerous challenges and intricacies. This complexity becomes particularly apparent when the ultimate goal is to successfully cultivate intricate constructs that comprise multiple cell types, which need to be arranged in a precisely defined and well-organized three-dimensional hierarchy. Moreover, the task of expanding these cells to achieve clinically relevant numbers is not straightforward, as it must be followed by their careful and strategic reintroduction into a three-dimensional architecture that maintains their functionality. This poses additional hurdles that must be addressed effectively. It is crucial to accomplish all of these processes without inducing any unwanted genetic alterations or risking microbial contamination, as these detrimental factors could severely compromise the integrity and safety of the final product we aim to produce. This ongoing challenge continues to present significant difficulties within the field, creating substantial barriers to the successful implementation of such advanced technologies. A more comprehensive, detailed, and nuanced understanding of the complex interplay among various cell types, growth factors, signaling molecules, and biomaterials will be essential in facilitating the further development of off-the-shelf tissue-engineered products, which can be effectively utilized for a wide range of therapeutic purposes. This need for deeper insights is critical for overcoming existing limitations and ensuring the efficacy and reliability of these innovative solutions in practical applications [227, 228, 229, 230, 231, 232, 233].

Additional obstacles that must be addressed include the critical necessity of obtaining comprehensive regulatory approval from relevant authorities, the notably high manufacturing costs involved in the complex production processes, the intricate development of effective preservation methods that can reliably ensure long shelf-life for engineered tissues, as well as the careful implementation of robust and reliable strategies designed to prevent immunological rejection of allogeneic constructs. Notwithstanding these significant and multifaceted challenges faced within the field, tissue engineering still holds immense promise as a truly disruptive technology within the rapidly evolving healthcare sector. Its continued maturation and consistent advancement could render organ and tissue banks commonplace throughout a variety of medical facilities and institutions, thereby enabling the refrigeration of a diverse and extensive catalogue of functional soft and hard tissues for immediate use. This substantial advancement would significantly reduce and obviate the longstanding need for patients to endure long-term immunosuppression following transplants, which can lead to serious complications. As this groundbreaking technology progresses further, the transition from what was once considered science fiction to clinical reality becomes more and more palpable, and tissue engineering undoubtedly has the remarkable potential to fundamentally revolutionize health care practices in numerous profound and transformative ways, addressing critical patient needs and enhancing overall treatment outcomes [234, 235, 236, 237, 238, 239, 222].

Chapter - 6

Biomedical Instrumentation

Biomedical instrumentation encompasses a broad spectrum of sensors and actuators that are utilized in a variety of healthcare applications and settings. Among the physiological parameters that are of significant interest and crucial importance are blood pressure, body composition, and brain electrical activity, which is often referred to as EEG, along with many other vital indicators that reflect the overall health of patients. The accurate detection of these essential parameters relies on an extensive array of sophisticated devices that include, but are not limited to, force sensors, pressure sensors, load cells, variable resistance devices, capacitive devices, photoelectric devices, and piezoelectric devices. Each of these diverse technologies serves a specific purpose in the measurement and monitoring of health-related data, ensuring precise readings and reliable results. Transducers play a critical and pivotal role in this process by converting one form of energy into another, which enables patients to effectively monitor important health metrics and engage in meaningful communication with computer-based systems that are specifically designed for medical and healthcare purposes. Moreover, biomedical signal-processing techniques are meticulously applied to analyze these complex signals, aiming to extract meaningful, actionable, and relevant information that can significantly enhance patient care, improve diagnosis accuracy, and lead to better medical outcomes over time. This integration of technology and healthcare practices underscores the importance of biomedical instrumentation in today's medical landscape [240, 241, 242, 243, 244, 245, 246].

In recent years, the rapid and significant growth of wearable sensors, combined with the evolution of advanced telemedicine applications, has introduced a wide array of new challenges and considerations that are significantly impacting the Lower Limb Prosthesis Actuation Platform (LLPAP). Sensing technologies not only play an indispensable role but also are critically essential for the effective and efficient control of LLPAP for individuals utilizing Lower Limb Prosthesis (LLP). Recent advancements in electronics, when paired with major developments in signal processing and innovative communication systems, have paved the way for the effective manufacturing of lightweight, compact, sensitive, and highly robust portable medical health-monitoring devices. These devices are quickly becoming increasingly vital within modern healthcare settings. Furthermore, these innovations are designed to improve the functionality of prosthetic devices while simultaneously enhancing the overall user experience and the quality of life for individuals who require such advanced devices. The intersection of these technologies is fostering an environment that supports better mobility, increased independence, and enhanced integration of prostheses into everyday activities, thereby ensuring that individuals are better equipped to navigate their daily lives and challenges with confidence [247].

6.1 Sensors and transducers

Medical physics, an interdisciplinary subject, skillfully incorporates the fundamental principles of radiation physics alongside its related biological effects, while also integrating various essential medical imaging techniques that are vital for effective diagnostics and comprehensive treatment planning. The intricate and complex response of matter to any mechanical stimulus, known as the physical quantity, possesses unique and distinctive properties whose variations are meticulously measured by specialized instruments through a device referred to as a transducer. The extensive application of these physical quantities to a wide array of challenging medical problems further extends the discussion into intriguing and rich areas such as biomechanics, the complex and fascinating processes of biotransport, as well as the diverse and innovative biomaterial applications in cutting-edge tissue engineering. These fields not only enhance and deepen our understanding of the physical interactions occurring within biological systems but also pave the way for groundbreaking advancements in medical technology and the overall quality of patient care. This intricate relationship enables researchers and practitioners alike to explore new solutions that can significantly improve health outcomes and refine therapeutic strategies for various medical conditions [66, 65, 248, 89, 79, 249, 250].

Physiological functions in the human body are classified into four main categories: mechanical, chemical, electrical, and thermal functions. These various classifications play a crucial role in developing a deeper understanding of how the body operates and efficiently responds to an array of external and internal stimuli. Sensors, which are highly sophisticated devices, are meticulously designed to detect minute changes occurring within each of these physiological functions. They capture these subtle alterations and expertly convert them into readable signals that can be easily interpreted by healthcare professionals. This essential conversion process is achieved through transducers, which are instrumental in transforming the gathered signals into electrical quantities that are appropriately suitable for detailed analysis and insightful display on monitoring systems. A wide variety of biomedical sensors and transducers, which have been specifically developed for effective monitoring of physiological conditions or were strategically implanted within the human body, effectively capture and convey crucial changes in essential health indicators. For instance, they continuously monitor vital signs such as blood pressure and blood flow, as well as other key physiological parameters including heart sounds, respiratory airflow, body temperature, blood pH levels, and the electrical activities of various organs such as the brain, heart, and muscles. The signals generated from these vital measurements are invaluable, as they provide critical insights and diagnostics regarding a person's overall health condition. These precise readings not only assist in planning and executing appropriate patient treatments but also play a significant role in evaluating the effectiveness of the therapies administered to patients. In the expansive Volume 2 of the Essentials of Medical Physics and Biomedical Applications, numerous practical examples of such advanced sensors and transducers are presented, showcasing their remarkable capabilities. This volume serves as a comprehensive resource, detailing the multitude of applications and functionalities of these innovative devices within the medical field, thus highlighting their undeniable significance in modern healthcare practices and patient care strategies. The ongoing developments in sensor technologies continue to enhance our ability to monitor health dynamically, ensuring that we remain on the cutting edge of healthcare solutions [251, 252, 253, 254, 255].

6.2 Signal processing techniques

Signal processing represents a crucial and highly significant stage in the intricate and elaborate chain of medical instrumentation, encompassing a vast and diverse array of essential diagnostic techniques that range from the activation of fundamental and basic thermometers, which serve to provide essential temperature readings, to the deployment of complex yet efficiently designed diagnostic systems that play a vital role in modern healthcare. Biomedical signal processing centers predominantly on the meticulous extraction and refinement of relevant information from various types of medical signals, including those emanating from critical organs such as the heart, brain, and muscles, as well as from diverse sources like electroencephalographic and ultrasonic signals. These sophisticated and highly advanced techniques find broad and vital applications across numerous biomedical contexts and clinically relevant scenarios such as diagnosing heart arrhythmias with precision, closely monitoring blood vessels during delicate angioplasty procedures that demand high levels of accuracy, conducting detailed rhythmic system investigations to facilitate diagnoses related to dyslexia and sleep apnea, and facilitating efficient and effective patient monitoring in intensive care units where timely information can be life-saving. Furthermore, these advanced methodologies are, more recently, being employed in the revolutionary fields of functional Magnetic Resonance Imaging (fMRI), which provides insights into brain activity, and also in Computerized Tomography (CT) image enhancement and reconstruction processes, demonstrating their essential and irreplaceable role in the ongoing progression of medical technologies and the development of innovative patient care solutions that enhance outcomes and experiences [256, 257, 258, 259, 260, 261, 262].

These various measurement techniques, which can be seamlessly and efficiently realized within controlled laboratory settings, are specifically utilized for the meticulous investigation of intricate physiological phenomena, the precise and accurate quantification of vital biomedical parameters, and they consistently assist in the diagnosis of numerous complex physiopathologies encountered in clinical practice. Signal processing methods play a crucial and pivotal role in enabling the effective and reliable elimination of unwanted noise and various interferences that may be present during the complex measurement processes, thereby facilitating the extraction of clinically relevant and significant information from the recorded signals. Furthermore, these techniques allow for the comprehensive modeling of physiological processes for an in-depth study and extensive analysis. The thoughtful and deliberate integration of essential physical and physiological acquisition principles, alongside the stringent and rigorous requirements set forth by modern smart medical devices, leads to the development of innovative laboratory prototypes that can be readily and efficiently implemented in diverse and varying clinical environments. The signal analysis and processing techniques employed can be applied to a multitude of diverse signals originating from both Earth's natural activities and various human activities, encompassing a wide array of natural phenomena such as destructive earthquakes, massive tsunamis, severe weather events, and intricate climate correlations and crucial physiological processes involving essential systems such as the heart, brain, glandular systems, and muscular system. At their core, such sophisticated analyses primarily concentrate on time series of experimental data that are meticulously and carefully acquired within the time domain, thus allowing for a more thorough and nuanced understanding of the underlying physiological phenomena, ultimately enhancing the overall effectiveness and reliability of clinical applications and decision-making processes in healthcare [263, 264, 265, 266, 267, 268, 269].

6.3 Wearable health devices

Over the past decade, wearable health devices have gained vital significance in the ever-evolving domain of medical applications, revolutionizing the way we approach health monitoring. Continuous health monitoring ideally necessitates a real-time, non-stressful, and comfortable measurement system that integrates seamlessly into the daily lives of individuals. Body-worn devices facilitate extensive data collection that is instrumental for employing statistical classification and advanced machine-learning methods, enabling researchers and health practitioners to extract fundamental characteristics inherent in the signals being recorded. In many instances, the collected data correlates with items of diagnostic interest, supplementing the information associated with standard clinical visits, thereby enhancing the overall assessment of a patient's health. Nevertheless, there exists a wealth of additional information embedded within the data that must be effectively detected and utilized to exploit the full potential of such a long-term health monitoring system. Patients who are able to tolerate and wear these equipped devices in their everyday lives, whether locally or remotely, could significantly enhance the diagnostic capabilities and ongoing follow-up of their diseases by healthcare practitioners. Today, the array of commercial wearable devices is increasingly incorporating groundbreaking, state-of-the-art embedded technology along with advancements in cloud computing, which collectively foster the integration of sophisticated artificial intelligence to deliver real-time, ubiquitous, and efficient healthcare solutions designed for comprehensive 360-degree healthcare monitoring. The continuous progress being made in low-power integrated circuits, various innovative wireless communication methods, and cutting-edge sensors enables these devices to be highly scalable and customizable. Furthermore, they can be outfitted with medical-grade biosensors that facilitate stand-alone management of the data being acquired, all while coupling this with localized processing as well as efficient memory management systems. Research and development are actively underway to enhance artificial intelligence and machine-learning algorithms specifically tailored for wearable health monitoring applications. One of the primary challenges that remain is the effective detection of abnormal health data collections, which arise from utilizing high-performance daily routine data with small-volume yet low-cost equipment. Wearable devices hold immense potential in assisting with effective health monitoring, enabling quick interventions, and fostering rapid recovery in hazardous situations. Numerous computational approaches and innovative composites have been employed to devise state-of-the-art wearable systems, specifically aimed at resolving issues such as long-term personal calibration or the misalignment of wearable sensors, both of which can severely influence measurement uncertainty and data quality. The field of wearable health devices is in a state of constant evolution and has garnered the interest of various industries, including medical and semiconductor sectors. Continued advancements in smart wearable technology are set to further enhance efficient healthcare management, promising reduced costs, greater ubiquity, improved accuracy, and exceptional ease of use that will ultimately benefit individuals everywhere [270, 271, 272, 273, 274, 275, 276, 277].

Chapter - 7

Clinical Applications of Medical Physics

Additional quality-assurance procedures have been diligently established through various European projects aimed at enhancing standards in the field of medical physics. Moreover, the latest advancements in knowledge, technical guidelines, and historical documentation are now more accessible than ever through reports and resources provided by both national and international bodies, as well as other authoritative organizations dedicated to medical physics. Numerous professional websites and databases have emerged, allowing practitioners and researchers to stay up-to-date with the ongoing developments in this dynamic field. Medical physics courses have undergone a transformation and now incorporate an essential epidemiological component that provides students with a comprehensive view of the major health issues arising from the use of nonionizing and ionizing radiation. This educational enhancement is crucial for understanding the implications of radiation in various medical scenarios. In addition to topics like dosimetry, phantoms, radiation safety, and quality assurance, a medical physicist engaged in daily clinical routines carries the vital responsibility of conducting calibration and acceptance testing of imaging modalities and therapy equipment that are delivered by vendors for deployment within hospitals. It is imperative for medical physicists to ensure that these sophisticated devices function accurately and reliably. To facilitate this, a number of straightforward acceptance-test packages have been developed, which help to establish whether the instruments operate efficiently and within the predetermined specifications set forth. Furthermore, one must also appreciate and acknowledge the significant and innovative contributions made by medical physicists and engineering teams in translating new ideas and advanced equipment into practical medical applications, thereby enhancing patient care and treatment outcomes. Their collaborative efforts play a crucial role in bridging the gap between innovative technology and its implementation in clinical settings [1, 199, 278, 279, 280, 281, 282, 283, 284].

7.1 Quality assurance in radiology

Quality assurance in radiology is an essential and intricate process that involves the careful and meticulous monitoring as well as thorough evaluation of all the services provided by the radiological department. This comprehensive process is crucial for ensuring the consistency and reliability of services, driving ongoing improvements, and ultimately enhancing patient safety and care at every level of the healthcare experience. It encompasses thoughtful design, effective and strategic implementation, and systematic assessment of various radiological services and procedures. The primary goal of quality assurance is to achieve maximum benefit for patients from advanced imaging technologies while upholding the highest standards of excellence in image quality and diagnostic accuracy. Simultaneously, it emphasizes the importance of minimizing accidental or unnecessary radiation exposure to both patients and personnel who operate the equipment. Effectively implementing quality-assurance programs in the critical realm of diagnostic radiology is fundamental and indispensable; these programs not only guarantee the accuracy and reliability of radiological results but also enable the prompt detection and resolution of any equipment failures or issues. By doing so, they serve to protect both patients and staff from unnecessary risks associated with radiation exposure or even potential overdoses, ensuring a safe diagnostic environment. This comprehensive and holistic approach ensures that all radiological practices adhere to stringent safety and quality protocols, thereby fostering an environment where patient wellbeing and safety is of the utmost priority and concern in the healthcare system [285, 286, 287, 288, 289, 290, 291].

The primary objectives of quality assurance in the field of radiology encompass ensuring that all images consistently exhibit a remarkably high quality and are provided at a reasonable cost that is acceptable to both providers and patients. This commitment to quality assurance ensures that the essential services provided by the Radiology Department are always available whenever they are needed, thus serving the community effectively and efficiently. Furthermore, the quality assurance program is also deeply and fundamentally concerned with robust risk management this involves systematically reducing risk to the lowest possible level, which is absolutely crucial for both patient safety as well as operational efficiency. Recognizing the various potential sources of hazards and diligently working to reduce risks associated with equipment operation and patient management is of vital importance. It also entails ensuring that any remaining level of risk is fully justified by the diagnostic information that is obtained from the imaging procedures performed. Evaluating the system's output at several important points such as exposure units, image processing stages, viewing stations, and meticulously considering the attitudes and feedback from both users and patients constitutes the final essential step in the comprehensive quality management process. This systematic approach guarantees that high standards of care are maintained and consistently improved over time within the Radiology Department [292, 293, 294, 295, 296, 297].

Quality assurance responsibilities in the field of radiology significantly extend to the crucial task of meticulously monitoring the extent of radiation dose levels, with a particular emphasis on the detailed trend analysis of dose records over time. This comprehensive and meticulous monitoring process plays a vital role in assuring that the radiation effects on the patient are minimized to the greatest extent possible, thereby ensuring patient safety. Such comprehensive quality assurance programs should be carefully designed and systematically implemented through the establishment of a dedicated Quality Control Unit. This specialized unit is specifically tasked with undertaking regular checks, conducting thorough calibration, and establishing vigilant monitoring of all radiological, imaging, and therapeutic systems that are installed, commissioned, and operated within any hospital or diagnostic centre. By ensuring that these critical processes are firmly in place, hospitals can significantly maintain high standards of safety, efficacy, and reliability in their radiological practices, which is essential for delivering optimal patient care. Furthermore, ongoing training and updates for staff involved in these procedures can enhance their understanding of radiological safety protocols, thus reinforcing the overall integrity of the quality assurance framework [298, 299, 300].

7.2 Patient safety and risk management

Safety continues to be a profoundly significant concern in the expansive field of global healthcare, captivating ongoing and persistent attention from a diverse array of stakeholders, including healthcare professionals, regulatory agencies, and patient advocacy groups. Consequently, risk management practices are increasingly being utilized and adopted not only to enhance the overall quality of healthcare services but also to bolster and reinforce hospital accreditation processes. This comprehensive effort is undertaken with the primary goal of protecting patient safety and effectively eliminating medical adverse events by significantly reducing the various risks faced by both citizens and patients. Patient safety, in its broadest and most inclusive sense, encompasses the proactive prevention of errors and adverse events that may occur during the course of delivering healthcare services, specifically during critical stages of treatment and care. Radiotherapy, which serves as an essential component of modern medical treatment, is currently recognized as one of the most rapidly expanding and widely employed methods practiced globally for a multitude of serious health conditions, such as various types of cancer and complicated Arteriovenous Malformations (AVM). Given the inherent complexity and sophistication of this particular treatment method, it can generate a plethora of risk management challenges that require particularly strict and vigilant oversight, especially as groundbreaking advancements in radiotherapy research and treatment methodologies take place within increasingly narrow parameters and controlled settings. The potential for radiation accidents and mishaps should not be underestimated in any regard, as these incidents can have dire and possibly fatal consequences for patients, adversely impacting not only their physical health but also their mental wellbeing and overall quality of life. Therefore, it is crucial to maintain a high level of vigilance and awareness regarding these associated risks. Furthermore, the precise dosages administered in the context of radiotherapy must be meticulously calculated, closely monitored, and continuously assessed, as any improper handling or deviation from acceptable dosage ranges can jeopardize human life and health significantly. In addition to the aforementioned considerations, there are several additional risk factors associated with various other imaging modalities utilized in the healthcare sector that further complicate the intricate landscape of patient safety and healthcare quality. Addressing these multifaceted risks becomes imperative as we continue to advance our understanding of medical treatment and technology, striving for improved outcomes and enhanced safety measures in patient care [301, 302, 303, 304, 305, 306, 307, 308, 309].

7.3 Role of medical physicists in healthcare

An integral and essential member of the clinical team, a medical physicist plays a crucial role in the clinical implementation of various physics programs that are indispensable for modern healthcare practices. This expansive role includes the meticulous calibration of sophisticated medical devices, thorough commissioning of new equipment, and careful acceptance testing of all brand-new machines before they are put to use in a clinical setting. Furthermore, the physicist is tasked with conducting in-depth quality assurance testing of clinical equipment, ensuring that each piece of machinery operates at optimal performance and adheres to the highest safety standards. In addition to these responsibilities, medical physicists also ensure that the clinical facility is in strict regulatory compliance with all necessary industry standards, thereby safeguarding patient health and safety. This involves performing patient-specific calculations that are expertly tailored to meet the unique individual needs of each patient, taking into account a multitude of factors surrounding their treatment. Staying current with cutting-edge, state-of-the-art techniques is vital to maintaining efficacy in their work, as is effective equipment troubleshooting to adeptly address any technical challenges that may arise unexpectedly. Moreover, other significant facets of the medical physicist's diverse duties encompass detailed budgetary planning to allocate resources efficiently, the development of comprehensive clinical protocols, and fostering effective communication with various vendors to ensure that the clinical team has access to the latest technologies and support. They also play a key role in radiation safety initiatives, which are critical in protecting both patients and healthcare workers from unnecessary exposure. In addition to these essential functions, securing necessary funding for various projects has become a crucial aspect of their role, ultimately influencing the quality of patient care offered within the facility. Additionally, medical physicists actively participate in basic science research, contributing significantly to the advancement of the field while exploring innovative approaches that could significantly enhance clinical practices in the future [310, 66, 311, 312, 65, 313, 314].

Most of the new technology in the rapidly evolving field of healthcare is disseminated through comprehensive medical physics education programs, making a close and effective partnership with the medical technology community critically important. This collaboration is essential to guarantee that the implementation time for these advanced technologies is kept as short as possible, which in turn enhances patient care. Techniques such as radiochromic films, innovative 3D treatment planning, and Image-Guided Radiation Therapy (IGRT) serve as prominent and notable examples of the various modalities that remain intimately intertwined with both the practice and the advancements in medical physics. The educational pathway leading to becoming a qualified medical physicist can often be quite long and arduous, necessitating significant dedication and unwavering perseverance. To assist in achieving a more standardized and streamlined approach to this educational process, a number of accreditation agencies have now been created and established in various regions around the globe to provide guidance and essential support. These agencies play a crucial role in ensuring that aspiring medical physicists receive the high-quality education and training required to meet the demands of the healthcare industry effectively [250, 315, 312, 316, 317, 318].

The vast array of computer-related tasks that exist within the field of medical physics encompasses a wide range of activities and specialties, including but not limited to the use of computers, the management and maintenance of computer systems, the creation and implementation of computer networks, the practice of software engineering, the creation of computer-aided designs, and the management of intricate computer information systems. Collectively, all of these tasks fall under the broader and common descriptor known as information technology. Within the specialized area of radiation oncology, a substantial portion of these computer and information technology-related tasks, which include responsibilities such as system configuration, installation of both hardware and software, commissioning, and programming, were historically assigned to the medical physicist. In many cases, the medical physicists performing these tasks did not possess formal training in computer technology or networking, leading them to depend heavily on their previous research endeavors and the practical experience they gained while on the job to develop and hone the necessary skills and comprehensive knowledge required to effectively maintain, troubleshoot, configure, and utilize the continually evolving landscape of computer technology. Consequently, responsibilities associated with the installation, commissioning, and ongoing maintenance of software systems such as those utilized for treatment planning, record-and-verify systems, and the management of electronic medical records naturally fell under the purview of the medical physicist. Furthermore, the guidelines that were published by the American Association of Physicists in Medicine (AAPM) over the course of the 1990s and into the 2000s either entirely omitted any mention of computers or addressed the topic only superficially, merely suggesting a level of "familiarity/knowledge/understanding" without providing any specific details, despite the extensive range of computer tasks that had been the sole responsibility of the physicist in previous times [319, 320, 65, 5, 321, 322, 323, 324, 325].

Chapter - 8

Emerging Technologies in Medical Physics

Artificial Intelligence (AI) has transcended the boundaries of what was once confined to the realm of science fiction, particularly in the context of robotics utilized in various medical and surgical applications. These advanced technologies are on the verge of becoming superior diagnosticians and clinicians, revolutionizing the way healthcare is delivered. The AMIA project serves as a gateway to understanding the myriad applications of AI technology specifically in the arena of medical imaging. Central to this field is the fundamental concept of diagnostic imaging modalities, which are presented in conjunction with the basic principles of imaging physics that underlie their operation. Furthermore, a pertinent example of medical big-data is introduced, illustrating the significant impact of vast information sets on the practice of modern medicine. The domain of medical 3D printing and 3D fabrication techniques, while showing promise, is still considered to be underdeveloped. This limitation poses challenges across numerous medical disciplines, and it particularly highlights the need for multidisciplinary collaborations that can foster innovation and improve outcomes. The special issue of AMIA is dedicated to elucidating the current state-of-the-art 3D printing and fabrication techniques, along with their far-reaching medical and biomedical applications, paving the way for advancements that could lead to novel therapeutic solutions. In the realm of medical imaging, Mid-Infrared (MIR) Hyperspectral Imaging (HSI) represents an advanced technique that offers the capacity for simultaneous quantification and spatial localization of chemical components within a given sample. Recently, this emerging technique has made its entry into the field of histopathology, presenting a new and exciting alternative to traditional biochemical-histological investigative methods. This short review emphasizes the strengths and weaknesses of various MIR HSI modalities, elucidating the factors that contribute to the appeal of this technique within the landscape of medical diagnostics. In contemporary healthcare settings across the globe, a diverse array of medical imaging modalities has become integral to the diagnosis and treatment of numerous diseases. Commonly employed imaging techniques include X-ray, Computed Tomography (CT), Magnetic

Resonance Imaging (MRI), Nuclear Imaging, and Ultrasound. The fusion of these cutting-edge medical imaging modalities accelerates the processes of diagnosis and subsequent treatment, significantly enhancing the overall efficiency and effectiveness of healthcare delivery. Through the continuous evolution of these technologies, healthcare professionals are equipped with powerful tools that ultimately benefit patients and improve clinical outcomes [326, 327, 79, 328, 329, 330, 331].

8.1 Artificial intelligence in imaging

Artificial Intelligence (AI) has attained a pivotal and increasingly significant role across various scientific domains and sectors since a substantial resurgence of interest in the technology during the 1980s. Its profound influence is prominently reflected in our daily interactions with widely-used digital platforms and services such as Wikipedia, Netflix, and Google, which have all incorporated AI algorithms to enhance user experience and functionality. Concomitantly, the integration of AI with the Internet of Things has paved the way for the development of smart cities that utilize data-driven insights to improve urban infrastructure and public services. Furthermore, multiple branches of science have extensively leveraged a wide variety of AI applications ranging from robotics to data analysis, allowing for innovative breakthroughs that were previously considered unattainable. Medical physics is also actively embracing this transformative technology as it seeks to upgrade existing procedures and introduce innovations that will inevitably define the future landscape of healthcare systems. In this context, the comprehensive medical imaging pathway which encompasses essential stages such as acquisition, processing, reconstruction, analysis, interpretation, and report generation serves as a cornerstone for accurate diagnosis and effective treatment in patient care. These discrete yet interconnected steps within the imaging pathway offer abundant opportunities for automation and optimization through AI technologies. Machine learning, which is a prominent subset of AI, simulates the human learning processes by employing sophisticated algorithms that enable systems to make predictions and informed decisions by recognizing intricate patterns and trends within diverse sets of data [332, 199, 313, 83].

While traditional medical imaging techniques such as magnetic resonance imaging, computed tomography, ultrasound, and positron emission tomography remain essential and indispensable in today's healthcare landscape, it is the integration of artificial intelligence that bolsters diagnostic strategies. This fusion of AI technology empowers clinicians and researchers alike with profound insights, fostering a more expansive understanding of various complex pathologies. Imaging and treatment options that are tailored to the unique needs of individual patients constitute core elements of the field of medical physics. Furthermore, another area witnessing considerable progress and innovation involves 3D printing technology, which shows immense promise for effectively addressing various unmet medical needs that have long persisted in the medical community. In the realm of chemical analyses, open-source instrument control and modern sensing platforms harness the capabilities of 3D-printed components to facilitate sample preparations, separations, and reactions specifically in fields such as drug discovery, fundamental biological research, and crucial environmental monitoring initiatives. The remarkable capability to generate custom, ad-hoc designs derived from detailed computed tomography scans has proven especially transformative and influential within a wide array of biomedical applications, paving the way for personalized medicine and advanced treatment modalities that were previously thought to be unattainable [333, 14, 334, 335, 336].

8.2 3D printing in medicine

Three-Dimensional (3D) printing, a revolutionary technology, originated in the early 1980s and has since become widely and adeptly utilized across multiple medical specialties. This innovative manufacturing technique transforms flat, Two-Dimensional (2D) medical images into intricate three-dimensional physical models through a detailed and stepwise process. Initially, volumetric image data are meticulously collected for the region of interest, which can vary based on clinical needs. Following this data acquisition, 3D objects are generated through an essential process called segmentation, and these objects are then converted to a specific 3D-printing format known as STL (stereolithography). Finally, a tangible physical 3D model is fabricated from the digital representation using an appropriate filament material chosen specifically for the model's intended application. The clinical applications of this pioneering 3D-printing technology benefit greatly from its rapid advances, as the models produced can be effectively handled, manipulated, and even deformed to replicate complex anatomical structures. A clear and compelling indication for the use of 3D printing exists in scenarios that involve intricate and complex anatomical relationships, particularly in cases such as congenital heart diseases where traditional imaging may fall short. 3D printing has been seamlessly integrated into various aspects of surgical practice, clinical training, and device development across numerous specialties. Procedures related to the skeleton are particularly suited to this technology, attributed to bone density's significant facilitation of imaging segmentation, which allows for more precise modeling. The myriad uses of 3D printing in medicine include essential applications such as pre-procedural planning, comprehensive education, hands-on training, simulation of surgical procedures, detailed surgical guidance, and the production of custom tools, specialized devices, and patient-specific implants tailored to individual needs. Clinicians are currently applying 3D printing in the treatment and management of a variety of conditions, including but not limited to pectus excavatum, diaphragmatic hernia, Hydrocephalus, Tracheobronchomalacia, oncologic resection, and reconstruction efforts. The manufacturing options available to clinicians range widely; they include the use of Fused Deposition Modeling (FDM) for Polylactic Acid (PLA) models beneficial for surgical planning, extending to the production of advanced metal 3D-printed implants required for orthopaedic and related procedures. Furthermore, impressive advancements have also been made in the realm of bioprinting, with bio-printed bio-implants undergoing rigorous animal testing to assess their viability and performance. As the field progresses, 3D-printing technology continues to be an important and transformative approach for surgical planning, simulation, as well as patient education and training programs for medical professionals. Thus, it remains an essential element in improving treatment methodologies and clinical outcomes while also enabling the provision of advanced and comprehensive education for future physicians and surgeons [337, 338, 339, 340, 341, 342, 343, 344, 345].

Chapter - 9

Ethics and Regulations in Medical Physics

The regulation of the medical physics profession varies significantly across different regions and countries around the world. The International Organization for Medical Physics plays a vital role as a comprehensive host for a detailed directory that includes various professional bodies and regulatory authorities responsible for overseeing and governing the practices of medical physics in numerous nations. This organization fosters collaboration and communication among professionals globally, ensuring that practices are guided by recognized standards. Additionally, the International Atomic Energy Agency has an essential role in this domain by producing detailed and relevant documentation that pertains to the field of medical physics, further aiding in the effort to standardize practices and protocols across international borders. In the United States, regulations and guidelines are chiefly articulated by the American Association of Physicists in Medicine, which publishes comprehensive and detailed practice guidelines specifically intended for medical physics consultants. These guidelines serve to set high benchmarks for professionalism and quality within the field, influencing practice standards widely. Similarly, in the United Kingdom, the regulatory landscape includes the Institute of Physics and Engineering in Medicine, which takes responsibility for issuing authoritative codes of professional conduct that practitioners must adhere to, ensuring a consistent approach to quality in practice. Moreover, the Health and Care Professions Council plays a crucial role in maintaining a robust register of approved regulated professions within this sphere, therefore ensuring that all practitioners are properly licensed and have met the necessary qualifications and standards. Professional certification, which is accredited by the Engineering Council, is provided by the Chartered Institute for Physics and Engineering in Medicine. This adds another significant layer of professional recognition and credibility, as it ensures that certified practitioners have demonstrated a commitment to maintaining high standards in their work. In other regions around the world, a diverse array of agencies exists, each actively regulating the profession to varying degrees, contributing to the development of a global community of medical physics professionals. Additionally, numerous countries have implemented statutory certification schemes for medical physicists as a means of ensuring that individuals not only meet established professional standards but also are competent to carry out their responsibilities effectively in the field, thereby enhancing safety and quality in medical practices [346, 312, 316, 320, 347, 69, 348, 349].

In numerous countries across different continents, medical physicists are acknowledged as vital contributors to the healthcare system, reinforcing the idea that it is critically important for them to abide by a comprehensive set of ethical principles that govern their behavior and professional practices. Within the framework of the European Union, these ethical guidelines serve as the cornerstone for various regulatory measures, particularly through the established code of conduct focused on data protection EC 95/46. Moreover, the Council of Europe's impactful 'Oviedo' Convention on Human Rights and Biomedicine plays a crucial role in ensuring that ethical considerations are integrated into medical practice and research. This convention is specifically designed to address issues related to scientific research within the medical field, and it incorporates key principles of medical ethics that are indispensable for protecting the dignity and rights of every individual involved. Among these fundamental principles are beneficence, which underscores the necessity to actively promote the well-being of patients and prioritize their health outcomes; nonmaleficence, which stresses the fundamental obligation to avoid causing harm to patients; autonomy, which acknowledges and respects the right of individuals to make informed choices regarding their own health and medical treatments; and justice, which seeks to guarantee fairness and equity in the allocation of healthcare resources, as well as in the treatment and care provided to patients without discrimination. These principles collectively lay the groundwork for ethical medical practice, ensuring that the rights of patients are upheld and that healthcare professionals act responsibly in their pursuit of scientific advancements and quality care [66, 350, 347, 313, 11].

The most recent AAPM training guidelines serve to complete an ongoing and extensive series of informative documents that are published periodically to keep pace with the evolving demands in the field. These documents aim to provide an exceptionally comprehensive framework for medical physics education and training that encompasses all necessary aspects in this specialized area. They emphasize the critical importance that all graduating students must have a firm and thorough grasp of all pertinent radiation physics principles and their various, often complex, applications; in addition, it is crucial that they acquire all the essential skills needed to function effectively and professionally as clinical medical physicists in real-world healthcare settings. Furthermore, it is absolutely essential that students are made fully aware of the major safety standards and protocols that are required within the context of clinical service provision to ensure patient and staff safety. The educational material explicitly covers all these key topics in-depth and meets the stringent requirements for certification in the United States while maintaining rigor and relevance. These guidelines not only assist trainees and educators but also serve valuable purposes for professional or accrediting bodies, providing a benchmark for quality and consistency. They play a crucial role in continuing to propel the profession toward an integrated and harmonized competency model, which is absolutely vital for the practice of medical physics and its advancements in technology and care delivery [310, 250, 351, 312, 352, 353, 354].

9.1 Ethical considerations

Ethical considerations constitute a significantly vital and increasingly critical aspect of all the diverse health care disciplines that are present within the medical sphere. The Medical Physics discipline, in particular, has been faced with a rising number of cases of unethical behavior and practices in recent years, which are underscoring the pressing need for establishing a solid ethical foundation. It is imperative that all medical physics practitioners, alongside their students, come to fully understand and embrace the ethical principles that are designed to underpin the medical physics discipline in order to uphold integrity and professionalism within their field. Furthermore, there exists an extensive amount of scientific literature that delves deeply into the intricate topic of ethics, which serves as a clear, comprehensive, and indispensable guideline for conduct in the medical physics profession. It is essential that practitioners actively engage with these resources, familiarizing themselves with the established ethical norms and expectations pertinent to their practice. This engagement not only benefits the individual practitioners but also enhances the overall ethical climate of the medical physics discipline as a whole, promoting a culture of accountability and transparency [355, 356, 330, 357, 358, 359].

9.2 Regulatory standards and guidelines

Medical physicists play an absolutely crucial role in safeguarding the health and safety of patients, medical staff, and the general public when it comes to the increasingly complex applications of ionizing radiation in various medical practices. Their responsibilities extend far beyond the commonly utilized quality assurance programs; they must adhere to a variety of stringent national rules and regulations that originate from the comprehensive guidelines set forth by the International Commission on Radiological Protection (ICRP). These vital regulations have been in place for many years and form a critical part of the foundational framework of radiation safety in the field of medicine. In addition to these essential national guidelines, international organizations like the International Atomic Energy Agency (IAEA) and the European Commission have established important statutes that all member states are expected to adopt and seamlessly integrate within their healthcare systems. Furthermore, various recognized professional organizations and regulatory bodies offer comprehensive guidelines, which often evolve into enforceable regulations within specific countries. These collective efforts are aimed at harmonizing best practices and ensuring a consistently high level of safety for everyone involved in medical procedures that utilize ionizing radiation in any capacity. This ongoing commitment to safety and quality assurance is essential in today's healthcare landscape, where complex technologies are becoming ever more prevalent [346, 66, 199, 360, 361, 288, 362, 311].

Regulators are typically expected to deliver thorough and comprehensive guidance concerning the indispensable role that the medical physics expert plays within the broader healthcare framework. These essential classifications should not merely be labeled as “qualified experts” or “specialists”; rather, the specific and more precise term “medical physics expert” is employed to define an individual who possesses a suitable level of education, extensive training, and significant experience. This expertise enables them to function autonomously while providing expert advice in at least one clearly defined subfield of medical physics. It is absolutely essential for the medical physics expert to take a proactive role in contributing to the optimization of protection measures for individuals who are subject to medical exposure. Moreover, they must be suitably involved in a range of diverse practices, which include, but are not limited to, radiotherapy, nuclear medicine, and medical radio-diagnostic practices. Certain sections of the established guidelines may thoroughly explore the commissioning processes and the ongoing quality control measures that are necessary for performing accurate treatment planning dose calculations specifically related to megavoltage photon and electron beams. Furthermore, there may be a meticulous outline detailing the ideal data-acquisition methodologies as well as the various types of equipment that should be utilized for effective and reliable radiotherapy dosimetry. This would also encompass a comprehensive description of the pertinent tests that must be conducted routinely. In particular, conducting pre-treatment verifications for intricate treatment deliveries is absolutely vital, and these guidelines will not only describe how to systematically implement these critical tests but will also specify the expected outcomes and the anticipated results that should be achieved from such meticulously executed processes [363, 364, 365, 366, 321, 367, 288, 368].

Chapter - 10

Future Directions in Medical Physics

Medical physics revolves around the intricate application of various concepts, theories, and methods derived from the field of physics to the realm of medicine. This fascinating field positions itself strategically at the boundary between the disciplines of engineering and medicine, acting as a crucial bridge that facilitates the interaction between these two domains. The discipline frequently focuses on the innovative development of instruments and sophisticated techniques that are absolutely vital for advancing biomedical research and enhancing clinical healthcare. The wide-ranging benefits of these significant developments encompass contributions to various treatments, such as radiation therapy, along with diagnostic methods that include advanced medical imaging techniques. Furthermore, increased understanding of complex living systems is also greatly supported through the use of specialized equipment and carefully designed experimental solutions. As a result of these advancements, the demands for physicists who possess biomedical expertise are steadily rising, both on a global scale and within the rapidly developing Asia-Pacific region. The future of radiology will undoubtedly be driven by a host of innovations that are already making a substantial impact in laboratories and hospitals around the world. The continued development of advanced technologies, including the tomograph, is essential to harness techniques like Positron Emission Tomography (PET), Single-Photon Emission Computed Tomography (SPECT), and pulse oximetry, all of which will play an important clinical role in determining the intricate physiology of various organs and the nature of diverse pathological conditions. Therefore, it is clear that new instruments will continue to empower and enable transformative changes to take place in the field of medical physics [327, 1, 65, 66, 369, 370].

10.1 Innovations in imaging techniques

Medical imaging has significantly expedited the diagnosis and treatment processes of a wide array of diseases and medical conditions. Among the most widely used modalities in this field are X-ray imaging, Computed Tomography (CT) scans, Magnetic Resonance Imaging (MRI), nuclear imaging techniques, ultrasound exams, and electrical impedance tomography. In addition to these standard methods, advanced techniques such as contrast-enhanced MRI for better visualization, specialized MRI applications for diagnosing osteoarthritis, and innovative cardiovascular imaging strategies are additionally applied in clinical settings. However, reading and accurately interpreting medical images can pose various challenges, primarily due to the heterogeneous nature of diseases and existing limitations in image quality that may affect interpretation. Moreover, emerging technologies in the realms of medical imaging and data mining are increasingly enabling support for clinical research initiatives, the continuous improvement of patient care practices, and overall enhancement of healthcare system efficiency across various medical institutions [79, 371, 372, 10, 334].

Research and translation into clinical practice necessitate the careful and systematic implementation of approaches that thoroughly review and evaluate the aims of the study, the relevant medical background, and the entire workflow associated with the procedure before selecting the most suitable technology and appropriate numerical method. X-ray imaging and nuclear medicine utilize ionizing radiation generated primarily by linear accelerators or by the use of radioactive isotopes, while MRI and ultrasound techniques operate without any exposure to ionizing radiation, making them safer alternatives in certain contexts. It is important to note that ionizing radiation has the potential to induce DNA double-strand breaks, posing significant risks to cellular integrity and increasing the likelihood of adverse health outcomes, whereas non-ionizing radiation does not carry such hazards and is generally regarded as safer. In every scenario encountered in clinical settings, the safety levels for patients must be rigorously evaluated and comprehensively assessed by the clinical specialist involved in the process, ensuring that patient well-being remains a top priority throughout the entire workflow at all times, fundamentally guiding all decision-making processes to align with best practices in patient care [373, 374, 375, 376, 377].

10.2 Advancements in treatment modalities

As cancer persists as a leading cause of death across the globe, radiotherapy has undergone significant transformation, evolving from a secondary treatment method to a primary approach for effectively tackling a diverse range of cancer types. This remarkable evolution is noteworthy, as it embodies a profound commitment to advancing patient care through the implementation of innovative technologies. Continuous innovation in both imaging and delivery techniques not only enhances the potential for personalized medicine but also broadens the spectrum of tumors that can be effectively treated, achieving greater success rates in the process. In this context, technology plays a crucial and central role in this ongoing evolution, driving substantial improvements in precision and treatment outcomes. Such advancements offer renewed hope for improved survival rates and enhanced quality of life for those patients diagnosed with cancer. As medical professionals continue to embrace these technological changes, the prospects for targeted therapies and individualized treatment plans will undoubtedly continue to grow and evolve, making radiotherapy an indispensable tool in the fight against cancer in the coming years [378, 379, 304, 380, 303].

Radiotherapy has its origins in the late 19th century when the pioneering use of X-rays was employed for the purpose of local tumor control. The initial treatments delivered during this period were often plagued by issues such as inaccurate dose delivery and a significant lack of three-dimensional planning, which compromised treatment effectiveness. However, High-Precision Radiotherapy (HPR) was developed to address these critical limitations, aiming to accurately define tumor volumes while simultaneously minimizing radiation exposure to the surrounding normal tissues. Standard radiation treatment volumes that are currently defined include several key components: the gross tumor volume, which encompasses the visually identifiable extent of the tumor; the clinical target volume, which includes a margin around the tumor to account for microscopic disease; the internal target volume, which accounts for motion; and finally, the planning target volume, which ensures the radiation dose adequately covers the target [381, 382, 383, 384].

Different specimens respond variably to radiation exposure, with rapidly proliferating cancers showing greater susceptibility compared to non-tumor tissues, which tend to resist such treatments. The common types of radiation that are primarily utilized in the treatment of cancer include photons, electrons, protons, and neutrons, each serving distinct purposes depending on the nature and location of the tumor. Photon radiation, including both X-rays and gamma-rays, is known for its capability to penetrate deep into tissues, making it highly effective not only for treatment purposes but also for various forms of diagnostic imaging. In contrast, electron beams are particularly effective for managing tumors that are located close to the body's surface, allowing for targeted treatments that minimize damage to surrounding healthy tissues. Additionally, particle radiation proves suitable for addressing deep-seated tumors, providing an option for cases where conventional treatments may be less effective. Relative Biological Effectiveness (RBE) is a crucial metric that quantifies the ratio of doses needed to produce the same biological effect across different types of radiation. High Linear Energy Transfer (LET) radiation is particularly noteworthy as it deposits more energy per unit length, resulting in complex and often lethal DNA damage within the targeted cells. The majority of cancer cell deaths induced by radiation therapy stem from irreparable double-strand breaks in the DNA, which leads to the inevitable loss of cell viability and function. The main goal of radiation therapy, therefore, is to inflict a sufficient amount of DNA damage specifically within cancer cells, aiming to effectively halt their division and trigger the mechanisms of cell death, ultimately leading to the reduction or elimination of the cancerous tumor [385, 386, 387, 146].

External beam radiation therapy, often abbreviated as EBRT, encompasses a wide array of diverse techniques that are increasingly utilized in clinical practice. These techniques include 3D conformal radiotherapy, which shapes the radiation beams to match the tumor's contour, Intensity-Modulated Radiotherapy (IMRT), which adjusts the intensity of the radiation beams to optimize treatment, and stereotactic methods that provide precise targeting of the tumor with high doses. Additionally, image-guided radiotherapy plays a crucial role in ensuring accuracy, while Volumetric Modulated Arc Therapy (VMAT) arrays treatment delivery in a continuous arc, enabling more sophisticated dose distribution. Moreover, advancements in particle therapy, including both protons and heavy ions, are also a component of this evolving field. Modern low Linear Energy Transfer (LET) EBRT techniques function primarily by inducing DNA damage within the cancer cells that, if left unrepaired, ultimately culminates in cell death, thereby enhancing the treatment efficacy. The remarkable technological advancements in imaging modalities, dose calculation algorithms, and delivery systems are pivotal in facilitating improved tumor targeting, allowing for the administration of higher radiation doses directly to tumors while concurrently minimizing collateral damage to the surrounding normal tissues. VMAT, in particular, is noteworthy as it delivers the prescribed dose during a single gantry rotation, achieving full 360° coverage around the patient. This method allows for simultaneous modulation of dose rate, gantry rotation speed, and multi leaf collimator positioning, which leads to superior dose conformity and significantly shorter treatment durations when compared to traditional IMRT approaches. In this context, addressing tumor motion correction becomes essential, and adaptive radiotherapy techniques must be employed as clinicians utilize higher doses per fraction, ensuring effective treatment delivery while maintaining patient safety and minimizing side effects [388, 122, 389, 390, 391].

Chapter - 11

Conclusion

Essentials of Medical Physics and Biomedical Applications outlines the discipline's scope and core topics. Medical physics is an interdisciplinary field applying physics principles for human health, integrating with biology, medicine, computer science, and information technology. Topics such as radiation physics, medical imaging techniques, radiation therapy, biomaterials and biomechanics, biomedical instrumentation, clinical applications, emerging technologies, ethics, regulations, and future directions are reviewed.

Medical imaging remains a fertile area for physics innovations in support of medical diagnosis and therapy. Elaborations focused on X-ray and computed tomography, magnetic resonance and related techniques, ultrasound with elastography, and nuclear medicine underlined concepts underlying the various applications. Radiation therapy particularly dosimetry as a foundational activity received similar treatment. Biomaterials and biomechanics theories describe mechanical properties of normal and pathological biological tissues. Biomedical instrumentation covers sensors, sensors and transducers applied to medical measurements, signal processing and wearable devices, and associated technologies. Clinical aspects include quality assurance, patient safety, risk management, and medical physics professional responsibilities. Emerging technologies consider artificial intelligence in medical imaging and 3D printing processes in support of medicine. Ethical responsibilities and the regulatory framework associated with medical physics activities are reviewed as well. Finally, perspectives on future directions examine promising experimental techniques and theoretical approaches.

References

1. S. H. Benedict, "Book Review," 2004. ncbi.nlm.nih.gov
2. A. V. Chalyi, "What is Medicine? Basic Principles of Physics in Medicine and Beyond," 2025 [HTML]
3. A. Nasser, "The Merging of Quantum Physics: An Interdisciplinary Scientific Review," Preprint, researchgate.net
4. M. Giliberti, F. Albanese, and L. Lovisetti, "Principles and Equations of Physics: a multidisciplinary laboratory," Journal of Physics, 2024. iop.org
5. M. Avanzo, A. Trianni, F. Botta, C. Talamonti, and M. Stasi, "Artificial intelligence and the medical physicist: welcome to the machine," *Applied Sciences*, vol. 11, no. 1, 2021. mdpi.com
6. M. John and R. Mina, "Characterising Radiation Risks: Developing Scientifically-Based Protection Standards Through Radiation Health Physics Research," Science, 2025. researchgate.net
7. B. Del Medico, "Beyond the Visible. The Universe of Fields.," 2025 [HTML]
8. M. Ahmadi, D. Biswas, M. Lin, F. D. Vrionis, "Physics-informed machine learning for advancing computational medical imaging: integrating data-driven approaches with fundamental physical principles," Artificial Intelligence, vol. 2025, Springer. springer.com
9. S. L. Kitson, "Modern Medical Imaging and Radiation Therapy," Cyber Security Big Data AI. Open Med Science, 2024. openmedscience.com
10. S. Hussain, I. Mubeen, N. Ullah, "Modern diagnostic imaging technique applications and risk factors in the medical field: a review," BioMed Research, 2022. wiley.com
11. H. Hricak, M. Abdel-Wahab, R. Atun, M. M. Lette, *et al.*, "Medical imaging and nuclear medicine: a Lancet Oncology Commission," The Lancet, vol. 397, no. 10271, pp. 1041-1050, 2021 [HTML]
12. S. Jain, "Radiation in medical practice & health effects of radiation: rationale, risks, and rewards," Journal of family medicine and primary care, 2021. lww.com

13. L. Bastiani, F. Paolicchi, L. Faggioni, *et al*., "Patient perceptions and knowledge of ionizing radiation from medical imaging," JAMA Network, 2021. jamanetwork.com

14. R. Najjar, "Redefining radiology: a review of artificial intelligence integration in medical imaging," Diagnostics, 2023. mdpi.com

15. M. Giliberti and L. Lovisetti, "Old Quantum Theory and Early Quantum Mechanics," 2024 [HTML]

16. C. K. Lee, "The field of applied mechanics: historical outlook from past to present and its implications for future applications," Journal of Mechanics, 2022. oup.com

17. M. Wiescher, "Arthur E. Haas: The Hidden Pioneer of Quantum Mechanics," A Biography. Springer Nature Switzerland, 2021 [HTML]

18. M. K. van der Pals, "What is it that 'waves' in wave mechanics," International Journal of Quantum Foundations, 2023. researchgate.net

19. H. H. von Grünberg and A. Griffiths, "1924–1927: The Dawning of Quantum Mechanics," 2024 [HTML]

20. O. F. Junior, "From the Interpretation of Quantum Mechanics to Quantum Technologies," Oxford Research Encyclopedia of Physics, 2024 [HTML]

21. A. Duncan and M. Janssen, "Constructing Quantum Mechanics Volume Two: The Arch, 1923-1927," 2023 [HTML]

22. J. W. Wang, "Nuclear power technologies development: Historical track and future evolution," Journal of Cleaner Production, 2024 [HTML]

23. W. J. Nuttall, "Nuclear renaissance: technologies and policies for the future of nuclear power," 2022 [HTML]

24. S. T. Hassan, P. Wang, I. Khan, and B. Zhu, "The impact of economic complexity, technology advancements, and nuclear energy consumption on the ecological footprint of the USA: Towards circular economy …," Gondwana Research, 2023. google.com

25. M. Alwaeli and V. Mannheim, "Investigation into the current state of nuclear energy and nuclear waste management a state-of-the-art review," Energies, 2022. mdpi.com

26. Y. Devarajan and R. T. "Study on analysing the potential benefits of utilizing nuclear waste for biodiesel production," Kerntechnik, 2024 [HTML]

27. R. Ulucak and S. Erdogan, "The effect of nuclear energy on the environment in the context of globalization: consumption vs production-based CO_2 emissions," Nuclear Engineering and Technology, 2022. sciencedirect.com

28. M. J. B. Kabeyi and A. O. Olanrewaju, "Nuclear power in the sustainable energy transition," in *Proceedings of the Conference on Industrial …*, 2024. ieomsociety.org

29. B. Ozcan and R. Ulucak, "An empirical investigation of nuclear energy consumption and carbon dioxide (CO_2) emission in India: Bridging IPAT and EKC hypotheses," Nuclear Engineering and Technology, 2021. sciencedirect.com

30. A. Azam, M. Rafiq, M. Shafique, and J. Yuan, "Towards achieving environmental sustainability: the role of nuclear energy, renewable energy, and ICT in the top-five carbon emitting countries," Frontiers in Energy Research, 2022. frontiersin.org

31. A. Gunn, "Hazards of Radiation," 2013 [PDF]

32. K. Apte and S. Bhide, "Basics of radiation," Advanced radiation shielding materials, 2024 [HTML]

33. N. Karmaker, K. M. Maraz, F. Islam, "Fundamental characteristics and application of radiation," GSC Advanced Research, vol. 2021, pp. 1-10, 2021. researchgate.net

34. A. Saleh, M. G. El-Feky, M. S. Hafiz, and N. A. Kawady, "… theoretical investigation on physical, structure and protection features of TeO2–B2O3 glass doped with PbO in terms of gamma, neutron, proton and alpha particles," *Radiation Physics and Chemistry*, vol. 2023, Elsevier [HTML]

35. R. M. Lucas, S. N. Byrne, L. Hollestein, and R. E. Neale, "The effects of exposure to solar radiation on human health," *Photochemical & Photobiological Sciences*, vol. 2023, Springer. springer.com

36. M. Goel, Y. Mackeyev, and S. Krishnan, "Radiolabeled nanomaterial for cancer diagnostics and therapeutics: principles and concepts," Cancer Nanotechnology, 2023. springer.com

37. S. M. Burrows, C. S. McCluskey, G. Cornwell, *et al*., "Ice-nucleating particles that impact clouds and climate: Observational and modeling research needs," *Reviews of Geophysics*, vol. 60, no. 4, 2022. wiley.com

38. O. Bawazeer, K. Makkawi, Z. B. Aga, H. Albakri, "A review on using nanocomposites as shielding materials against ionizing radiation," Journal of Umm Al-Qura University Science, vol. 2023, Springer. springer.com

39. P. Sruthi, U. M. Srinivasa, N. K. Rastogi, "Principles of irradiation and its equipment," Non-Thermal Food Processing, vol. 2023, Elsevier [HTML]

40. S. P. Ishwarya, M. H. Ahmad, A. M. Nandu Lal, "Non-electro-Technologies: Gamma Rays, UV Light, Ozone, Photodynamic and Membrane Processing," in *Processing in Agri-Food*, 2022, Springer [HTML]

41. M. K. Hossain and M. R. Haider, "Electromagnetic Fields and Radiation," in *Introduction to Non-Ionizing Radiation*, 2023 [HTML]

42. S.Z. Marković and M.D. Mojović, "Biological Effects of Ionizing Radiation," Hospital Pharmacology: International, 2025. hophonline.org

43. G. Benke and M. Ralph, "Radiation-Ionising and Non-ionising," Principles of Occupational Health and Hygiene, [HTML]

44. P. D. Sahare, B. Bai, A. Sahare, and H. L. Chen, "Study of Li3PO4: Dy3+ TLD phosphor for its application in high-temperature environment dosimetry of UV, X-rays and γ-rays," Journal of Alloys and Compounds, 2025 [HTML]

45. M. Sahoo, P. Aradwad, C. Panigrahi, "Irradiation of food," in *Technologies in Food*, 2023 [HTML]

46. S. Acherar, "Recent advances in medical radiation technology," Frontiers in Chemistry, 2024. frontiersin.org

47. M. Hosoda, E. D. Nugraha, N. Akata, R. Yamada, "A unique high natural background radiation area–Dose assessment and perspectives," *Science of the Total Environment*, vol. 2021, Elsevier. ku.ac.th

48. J. Yang and Y. Sun, "Natural radioactivity and dose assessment in surface soil from Guangdong, a high background radiation province in China," Journal of Radiation Research and Applied Sciences, 2022. sciencedirect.com

49. SK Jha, AC Patra, GP Verma, IS Iyer, "Natural radiation and environment," in Handbook on Radiation, 2024, Springer. researchgate.net

50. E. D. Nugraha, M. Hosoda, Kusdiana, and Untara, "Comprehensive exposure assessments from the viewpoint of health in a unique high natural background radiation area, Mamuju, Indonesia," *Scientific Reports*, vol. 11, no. 1, 2021. nature.com
51. S. Mohan and V. Chopra, "Biological effects of radiation," Radiation dosimetry phosphors, 2022 [HTML]
52. J. R. Thomas, M. V. Sreejith, U. K. Aravind, "Outdoor and indoor natural background gamma radiation across Kerala, India," *Environmental Science: Processes & Impacts*, vol. 2022. rsc.org
53. H. K. Malik, "Laser-matter interaction for radiation and energy," 2021 [HTML]
54. R. Gutzler, M. Garg, C. R. Ast, K. Kuhnke *et al.*, "Light–matter interaction at atomic scales," Nature Reviews Physics, 2021. researchgate.net
55. B. Aygün, "Neutron and gamma radiation shielding Ni based new type super alloys development and production by Monte Carlo Simulation technique," Radiation Physics and Chemistry, 2021 [HTML]
56. A. Nahum, "Interactions of charged particles with matter," Handbook of Radiotherapy Physics, 2021. academia.edu
57. H. Cai, F. Jia, Q. Cheng, R. Ankri, J. Cui, and L. Wang, "Advanced biological optical sensors for visualization and quantification of radionuclides," TrAC Trends in Analytical Chemistry, vol. 2024, Elsevier [HTML]
58. L. A. Susam, A. Yilmaz, G. A. L. Misned, and H. Yilmaz Alan, "Tailoring a behavioral symmetry on KERMA, mass stopping power and projected range parameters against heavy-charged particles in zinc-tellurite glasses," Symmetry, 2023. mdpi.com
59. D. Akay, Ö. Abay, H. Sönmez, and U. Gökmen, "Damage mechanisms caused by radiation proton (ion beam) in double interface layer nano-MOS structure," *Radiation Physics and Chemistry*, vol. 2025, Elsevier [HTML]
60. Y. Shinke, T. Mori, A. Iwata, and M. A. Mohd Nor, "Technique for estimating the charge number of individual radioactive particles using Kelvin probe force microscopy," *Aerosol Science and Technology*, vol. 2023, Taylor & Francis. tandfonline.com
61. D. R. Dance and J. C. Rosenwald, "Interactions of Uncharged Particles

with Matter," *Journal of Radiotherapy Physics*, 2021 [HTML]

62. J. H. L. Mott and J. M. Daniel, "Interactions of electromagnetic radiation and subatomic particles with matter–Part 2," Clinical Oncology, 2021. clinicaloncologyonline.net
63. M. Aygün and Z. Aygün, "Effect of gold nanoparticles in radiation therapy of breast tumor: photon, electron, proton, neutron, helium, and carbon ions irradiation," Radiological Physics and Technology, 2025 [HTML]
64. M. Kološ, M. Shahzadi, and A. Tursunov, "Charged particle dynamics in parabolic magnetosphere around Schwarzschild black hole," The European Physical Journal C, 2023. springer.com
65. T. Beyer, D. L. Bailey, U. J. Birk, I. Buvat, C. Catana, *et al*., "Medical physics and imaging–A timely perspective," *Frontiers in Physics*, vol. 9, 2021. frontiersin.org
66. N. Gambo and M. Shehu, "The Role of Diagnostic Medical Physics in Medicine: An Overview," Sahel Journal of Life Sciences, 2024. fudutsinma.edu.ng
67. P. Davidovits, "Physics in biology and medicine," 2024 [HTML]
68. G. Nevoit, O. Filiunova, M. Potyazhenko, "The phenomenon of life of living biological systems as a promising basis for the development of complex medicine: towards the concept of Bioelectronic Medicine," in *Journal of Complexity in Health*, 2023. extrica.com
69. L. Hadjiiski, K. Cha, H. P. Chan, K. Drukker, *et al*., "AAPM task group report 273: recommendations on best practices for AI and machine learning for computer-aided diagnosis in medical imaging," *Medical Physics*, vol. 2023, Wiley Online Library. wiley.com
70. M. Durante, J. Debus, and J. S. Loeffler, "Physics and biomedical challenges of cancer therapy with accelerated heavy ions," Nature Reviews Physics, 2021. nih.gov
71. R. M. Rangayyan and S. Krishnan, "Biomedical signal analysis," 2024 [HTML]
72. M. Ferreira, V. Carvalho, J. Ribeiro, R. A. Lima, S. Teixeira, "Advances in microfluidic systems and numerical modeling in biomedical applications: a review," Micromachines, 2024. mdpi.com
73. H. S. Park, D. S. Nguyen, T. Le-Hong, *et al*., "Machine learning-based

optimization of process parameters in selective laser melting for biomedical applications," *Journal of Intelligent Manufacturing*, vol. 2022, Springer. researchgate.net

74. M. Harun-Ur-Rashid, I. Jahan, T. Foyez, and A. B. Imran, "Bio-inspired nanomaterials for micro/nanodevices: a new era in biomedical applications," Micromachines, 2023. mdpi.com
75. M. Beyzadeoglu, G. Ozyigit, and C. Ebruli, "Basic radiation oncology," 2022. academia.edu
76. Q. B. Carroll, "Radiography in the Digital Age: Physics-exposure-radiation biology," 2023. poltekkesadisutjipto.ac.id
77. N. Tsoulfanidis and S. Landsberger, "Measurement and detection of radiation," 2021 [HTML]
78. A. G. Chmielewski, "Radiation technologies: the future is today," Radiation Physics and Chemistry, 2023. sciencedirect.com
79. S. K. M Shadekul Islam, M. D. Abdullah Al Nasim, I. Hossain, D. Md Azim Ullah *et al.*, "Introduction of Medical Imaging Modalities," 2023 [PDF]
80. D. Kumar, B. Pratap, N. Boora, "A comparative study of medical imaging modalities," *Journal of Radiology*, 2021. radiologyjournals.com
81. P. Kumar and S. Srivastava, "Basic understanding of medical imaging modalities," *Medical Image*, 2022 [HTML]
82. B. Abhisheka, S. K. Biswas, B. Purkayastha, and D. Das, "Recent trend in medical imaging modalities and their applications in disease diagnosis: a review," *Multimedia Tools and Applications*, vol. 2024, Springer [HTML]
83. L. Pinto-Coelho, "How artificial intelligence is shaping medical imaging technology: a survey of innovations and applications," Bioengineering, 2023. mdpi.com
84. C. Hristovski, "Design and Characterization of an 8x8 Lateral Detector Array for Digital X-Ray Imaging," 2011 [PDF]
85. E. L. Irede, O. R. Aworinde, O. K. Lekan, "Medical imaging: a critical review on X-ray imaging for the detection of infection," Biomedical Materials & Engineering, vol. 2024, Springer [HTML]
86. X. Ou, X. Chen, X. Xu, L. Xie, X. Chen, Z. Hong, and H. Bai, "Recent

development in x-ray imaging technology: Future and challenges," *Research*, vol. 2021, 2021. science.org

87. M. T. Mustapha, B. Uzun, and D. U. Ozsahin, "A comparative study of X-ray based medical imaging devices," in *Theories in Healthcare*, Elsevier, 2021 [HTML]
88. D. Heinemann, A. Keller, and D. Jannek, "Experimental computer tomograph: investigation and implementation of iterative reconstruction techniques and modern computer technology," 2015 [PDF]
89. H. Jung, "Basic physical principles and clinical applications of computed tomography," Progress in Medical Physics, 2021. koreamed.org
90. P. J. Withers, C. Bouman, S. Carmignato, *et al.*, "X-ray computed tomography," *Nature Reviews*, vol. 21, no. 1, pp. 1-20, 2021. hal.science
91. J. Hsieh and T. Flohr, "Computed tomography recent history and future perspectives," Journal of Medical Imaging, 2021. spiedigitallibrary.org
92. M. Lell and M. Kachelrieß, "Computed tomography 2.0: new detector technology, AI, and other developments," Investigative Radiology, 2023. lww.com
93. H. Ye, "Artificial intelligence combined with computed tomography or X-ray radiography: potential solution for opportunistic screening for osteoporosis," European Journal of Radiology Artificial Intelligence, 2025. sciencedirect.com
94. M. Khalifa and M. Albadawy, "AI in diagnostic imaging: revolutionising accuracy and efficiency," *Computer Methods and Programs in Biomedicine*, vol. XX, no. YY, pp. ZZ, 2024. sciencedirect.com
95. M. Cellina, M. Cè, N. Rossini, L. M. Cacioppa, and V. Ascenti, "Computed tomography urography: state of the art and beyond," Tomography, vol. 2023. mdpi.com
96. M. Cellina, M. Cè, E. Grimaldi, G. Mastellone, A. Fortunati, "The role of dual-energy computed tomography (DECT) in emergency radiology: a visual guide to advanced diagnostics," Clinical Radiology, 2025. clinicalradiologyonline.net
97. Ē. Kupče, L. Frydman, A. G. Webb, and J. R. J. Yong, "Parallel nuclear magnetic resonance spectroscopy," *Nature Reviews*, vol. 21, no. 1, 2021. ox.ac.uk

98. Y. Du and H. Huo, "Applications of nuclear magnetic resonance in exploring structure and energy storage mechanism of supercapacitors," Magnetic Resonance Letters, 2025. sciencedirect.com

99. M. Elsayed, A. Isah, M. Hiba, A. Hassan, "A review on the applications of Nuclear Magnetic Resonance (NMR) in the oil and gas industry: laboratory and field-scale measurements," *Journal of Petroleum*, vol. 2022, Springer. springer.com

100. B. S. Hilabi, S. A. Alghamdi, M. Almanaa, and S. A. Alghamdi Sr, "Impact of magnetic resonance imaging on healthcare in low-and middle-income countries," Cureus, 2023. cureus.com

101. J. Du, F. Shi, X. Kong, F. Jelezko *et al.*, "Single-molecule scale magnetic resonance spectroscopy using quantum diamond sensors," Reviews of Modern Physics, 2024 [PDF]

102. M. Gaeta, M. Cavallaro, S. L. Vinci, E. Mormina, "Magnetism of materials: theory and practice in magnetic resonance imaging," in *Imaging*, 2021, Springer. springer.com

103. Z. Liang, Y. Xiang, K. Wang, J. Zhu, Y. Jin, H. Wang, *et al.*, "Understanding the failure process of sulfide-based all-solid-state lithium batteries via operando nuclear magnetic resonance spectroscopy," *Nature*, 2023. nature.com

104. A. A. Oglat, "Performance Evaluation of an Ultrasonic Imaging System Using Tissue-Mimicking Phantoms for Quality Assurance," 2022. ncbi.nlm.nih.gov

105. R. Raman, "Three-dimensional acquisition and display system for ultrasonic imaging," 1997 [PDF]

106. N. Nguyen, "Objective assessment of sonographic quality for breast cancer imaging," 2012 [PDF]

107. M. G. Kim, C. Yoon, and H. G. Lim, "Recent advancements in high-frequency ultrasound applications from imaging to microbeam stimulation," Sensors, 2024. mdpi.com

108. J. Schueler, J. Kuenzel, A. Thuesing, E. Pion, "Ultra high frequency ultrasound enables real-time visualization of blood supply from chorioallantoic membrane to human autosomal dominant polycystic kidney tissue," Scientific Reports, 2024. nature.com

109. G. Nyakairu Doreen, "Ultrasound Engineering: Innovations in Non-Invasive Diagnostics," Recent Advances in Ultrasound Imaging, rojournals.org

110. Y. Lai, W. Tao, L. Wang, Z. Liu, and P. Wu, "Medical Ultrasound Application Beyond Diagnosis: Insights from Ultrasound Sensing and Biological Response," *Biotechnology*, 2024 [HTML]

111. Y. Lai, W. Tao, L. Wang, Z. Liu, P. Wu, and G. Yang, "Medical ultrasound application beyond imaging: Insights from ultrasound sensing and biological response," Medical ultrasound, 2024. authorea.com

112. R. D. R. Caulfield, "High-resolution 3D printing enabled, minimally invasive fibre optic sensing and imaging probes," 2021. ucl.ac.uk

113. M. Pérez-Liva, M. Alonso de Leciñana, *et al.*, "Dual photoacoustic/ultrasound technologies for preclinical research: current status and future trends," 2025. csic.es

114. B. Il Kim, "Radiological Justification for and Optimization of Nuclear Medicine Practices in Korea," 2016. ncbi.nlm.nih.gov

115. M. Konijnenberg, K. Herrmann, C. Kobe, F. Verburg *et al.*, "EANM position paper on article 56 of the Council Directive 2013/59/Euratom (basic safety standards) for nuclear medicine therapy," 2021. ncbi.nlm.nih.gov

116. F. F. Alqahtani, "SPECT/CT and PET/CT, related radiopharmaceuticals, and areas of application and comparison," Saudi Pharmaceutical Journal, 2023. sciencedirect.com

117. E. Oncu, "Advancements in Nuclear Medicine Through Artificial Intelligence: A Comprehensive Review," 2025. preprints.org

118. N. P. van der Meulen, K. Strobel, and T. V. M. Lima, "New radionuclides and technological advances in SPECT and PET scanners," Cancers, 2021. mdpi.com

119. H. Zaidi and I. El Naqa, "Quantitative molecular positron emission tomography imaging using advanced deep learning techniques," Annual review of biomedical engineering, 2021. annualreviews.org

120. E. Enlow and S. Abbaszadeh, "State-of-the-art challenges and emerging technologies in radiation detection for nuclear medicine imaging: A review," Frontiers in Physics, 2023. frontiersin.org

121. G. Anderson, M. Ebadi, K. Vo, J. Novak, A. Govindarajan, "An updated review on head and neck cancer treatment with radiation therapy," Cancers, 2021. mdpi.com

122. K. Koka, A. Verma, B. S. Dwarakanath, "Technological advancements in external beam radiation therapy (EBRT): An indispensable tool for cancer treatment," Cancer Management, vol. 2022, Taylor & Francis. tandfonline.com

123. C. A. Rodriguez-Russo, J. C. Junn, S. S. Yom, and R. L. Bakst, "Radiation therapy for adenoid cystic carcinoma of the head and neck," Cancers, 2021. mdpi.com

124. L. M. Chong, D. J. H. Tng, L. L. Y. Tan, M. L. K. Chua, *et al.*, "Recent advances in radiation therapy and photodynamic therapy," *Applied Physics*, vol. XX, no. YY, pp. ZZ-ZZ, 2021 [HTML]

125. M. Kang, P. A. Taylor, J. Shen, J. Zhou, J. Saini, T. S. Hong, *et al.*, "NRG Oncology Liver Proton SBRT and Hypofractionated Radiation Therapy: Current Treatment Technical Assessment and Practice Patterns," Cancers, 2025. mdpi.com

126. A. J. Frankart, J. C. Breneman, and L. E. Pater, "Radiation therapy in the treatment of head and neck rhabdomyosarcoma," Cancers, 2021. mdpi.com

127. M. G. Herman, "Book Review," 2006. ncbi.nlm.nih.gov

128. J. A. Nickoloff, L. Taylor, N. Sharma, "Exploiting DNA repair pathways for tumor sensitization, mitigation of resistance, and normal tissue protection in radiotherapy," *Cancer Drug*, vol. 2021. nih.gov

129. J. A. Nickoloff, "Targeting replication stress response pathways to enhance genotoxic chemo-and radiotherapy," Molecules, 2022. mdpi.com

130. M. Valceski, E. Engels, S. Vogel, J. Paino, D. Potter, "A novel approach to double-strand DNA break analysis through γ-H2AX confocal image quantification and bio-dosimetry," *Scientific Reports*, 2024. nature.com

131. C. Liu, Y. Zheng, and L. Sanche, "Damage Induced to DNA and Its Constituents by 0–3 eV UV Photoelectrons†," Photochemistry and Photobiology, 2022. wiley.com

132. A. B. Bukhari, G. K. Chan, and A. M. Gamper, "Targeting the DNA damage response for cancer therapy by inhibiting the kinase Wee1," Frontiers in Oncology, 2022. frontiersin.org

133. K. Czajkowski, M. Herbet, M. Murias, "Senolytics: charting a new course or enhancing existing anti-tumor therapies?", Cellular Oncology, 2025. springer.com

134. Y. Zhao, X. Ye, Z. Xiong, A. Ihsan, I. Ares, and M. Martínez, "Cancer metabolism: the role of ROS in DNA damage and induction of apoptosis in cancer cells," Metabolites, vol. 13, no. 4, 2023. mdpi.com
135. D. Jurkovicova, C. M. Neophytou, A. Č. Gašparović, *et al.*, "DNA damage response in cancer therapy and resistance: challenges and opportunities," *International Journal of …*, 2022. mdpi.com
136. FJ Groelly, M. Fawkes, RA Dagg, AN Blackford, "Targeting DNA damage response pathways in cancer," Reviews Cancer, vol. 2023. google.com
137. R. Huang and P. K. Zhou, "DNA damage repair: historical perspectives, mechanistic pathways and clinical translation for targeted cancer therapy," Signal transduction and targeted therapy, 2021. nature.com
138. W. Yu, Y. Tu, Z. Long, J. Liu, D. Kong, "Reactive oxygen species bridge the gap between chronic inflammation and tumor development," *Journal of Cellular Physiology*, vol. 2022. wiley.com
139. S. P. Lee, "Book Review," 2002. ncbi.nlm.nih.gov
140. B. McEvoy, A. Maksimovic, D. Howell, P. Reppert, "Comparative effectiveness of X-rays, gamma rays and electron beams to inactivate microorganisms at different dose rates in industrial sterilization of medical …," Radiation Physics and …, 2023. sciencedirect.com
141. JGJ Lftta, ANAA Zahra, AHJ Ashour, "X-Rays and Their Uses on The Human Body," in Clinical and Medical, 2024. visionpublisher.info
142. M. Malinowski, "Using X-ray technology to sterilize medical devices," *American Journal of Biomedical Science & …*, 2021. researchgate.net
143. N. Chaudhary and G. Kumar, "Mutagenic radiations: X-rays, ionizing particles, and ultraviolet," in *… and genetics in plant mutation breeding*, 2023 [HTML]
144. H. M. Saleh and A. I. Hassan, "Introductory Chapter: Exploring the Multifaceted Applications of Gamma Rays in Science and Technology," Gamma Rays-Current Insights, 2024. intechopen.com
145. C. Collins, "Radiation Therapy Medical Physics Review – Delivery, Interactions, Safety, Feasibility, and Head to Head Comparisons of the Leading Radiation Therapy Techniques," 2017 [PDF]
146. A. Carlos-Reyes and M. A. Muñiz-Lino, "Biological adaptations of

tumor cells to radiation therapy," *Frontiers in Oncology*, vol. 2021. frontiersin.org

147. E. Boopathi, R. B. Den, and C. Thangavel, "Innate immune system in the context of radiation therapy for cancer," Cancers, 2023. mdpi.com

148. G. G. Dhakad, G. D. Patil, A. C. Nikum, "Review on radiation therapy on cancer," Research Journal of…, vol. 2022. rjppd.org

149. M. Al-Qabandi and J. Alshammary, "Ionizing radiation: biologic effects and essential cell biology," in *The pathophysiologic basis of nuclear …*, Springer, 2022 [HTML]

150. S. Anand, T. A. Chan, T. Hasan, and E. V. Maytin, "Current prospects for treatment of solid tumors via photodynamic, photothermal, or ionizing radiation therapies combined with immune checkpoint inhibition (a …," Pharmaceuticals, 2021. mdpi.com

151. S. V. Mathan, M. Rajput, and R. P. Singh, "Chemotherapy and radiation therapy for cancer," Understanding cancer, 2022 [HTML]

152. M. Hamad Al Darmaki, "Achievable accuracy of radiation dose measurement for linear accelerators using different protocols," 2016 [PDF]

153. G. Neyman, J. P. Seuntjens, A. S. Shiu, and others, "Recommendations on the practice of calibration, dosimetry, and quality assurance for gamma stereotactic radiosurgery: Report of AAPM Task Group 178," *Medical Physics*, vol. 2021, Wiley Online Library. wiley.com

154. D. W. O. Rogers, "Minimum phantom size for megavoltage photon beam reference dosimetry," Medical Physics, 2024. wiley.com

155. W. Häger, V. Kaveckyte, and H. Benmakhlouf, "Experimental investigation of TRS-483 reference dosimetry correction factors for Leksell Gamma Knife® Icon™ beams," Medical Physics, 2021. wiley.com

156. W. Hager, V. Kaveckyte, and H. Benmakhlouf, "Experimental investigation of TRS-483 reference dosimetry correction factors for Leksell Gamma Knife (R) Icon (TM) beams," Medical physics (Lancaster), 2021. diva-portal.org

157. A. C. Shiau, S. M. Hsu, P. Y. Huang, C. P. Chen, and Y. T. Huang, "Dosimetry audits in Taiwan radiotherapy departments," BJR| Open, 2021. oup.com

158. T. Şahmaran and C. Yılmaz Koca, "Evaluation of dosimetric parameters after electron gun and ion pump replacement in linear accelerator device and comparison of results by gATE/Geant4 simulation," *Radiation Effects and Defects in Solids*, vol. 2023, Taylor & Francis. researchgate.net

159. J. Niemelä, "Novel dosimetry methods for small photon fields in external beam radiation therapy," utupub.fi, utupub.fi

160. K. Gulabivala and Y. L. Ng, "Factors that affect the outcomes of root canal treatment and retreatment A reframing of the principles," International Endodontic Journal, 2023. wiley.com

161. S. S. Poh, Y. L. Soong, K. Sommat, and C. M. Lim, "Retreatment in locally recurrent nasopharyngeal carcinoma: Current status and perspectives," *Cancer*, vol. 2021. nih.gov

162. J. F. Brochado Martins *et al.*, "Outcome of selective root canal retreatment A retrospective study," *International Endodontic Journal*, vol. 2023, Wiley Online Library. wiley.com

163. S. Moughal and F. I. Islim, “Long-term safety and efficacy of Woven Endobridge in the treatment of wide-neck intracranial aneurysms and risk factors associated with re-bleeding and re-treatment,” *Interventional*, 2024. nih.gov

164. W. A. McDougald and J. G. Mannheim, "Understanding the importance of quality control and quality assurance in preclinical PET/CT imaging," EJNMMI physics, 2022. springer.com

165. M. Mambrini, L. Mecozzi, E. Ferrini, L. Leo, D. Bernardi, *et al.*, "The importance of routine quality control for reproducible pulmonary measurements by in vivo micro-CT," *Scientific Reports*, 2022. nature.com

166. J. Papp, "Quality Management in the Imaging Sciences-E-Book: Quality Management in the Imaging Sciences-E-Book," 2023 [HTML]

167. R. H. Helle and H. G. Lemu, "A case study on use of 3D scanning for reverse engineering and quality control," Materials Today: Proceedings, 2021. sciencedirect.com

168. W. Sun, C. Ge, Y. Shi, X. He, L. Xiao, and Y. Liu, "Evaluation of a Monte Carlo based EPID system for patient-specific IMRT and VMAT quality assurance," Journal of Applied ..., 2025. wiley.com

169. D. Misokefalou and P. Papoutsidakis, "Non-destructive testing for

quality control in automotive industry," Int. J. Eng. Appl. Sci., vol. 2022. academia.edu

170. K. B. Beć, J. Grabska, and C. W. Huck, "Miniaturized NIR spectroscopy in food analysis and quality control: Promises, challenges, and perspectives," Foods, 2022. mdpi.com

171. R. Agrawal, A. Kumar, M. K. A. Mohammed, and S. Singh, "Biomaterial types, properties, medical applications, and other factors: a recent review," 2023. ncbi.nlm.nih.gov

172. S. Todros, M. Todesco, and A. Bagno, "Biomaterials and their biomedical applications: from replacement to regeneration," Processes, 2021. mdpi.com

173. R. Whitaker, B. Hernaez-Estrada, R. M. Hernandez, "Immunomodulatory biomaterials for tissue repair," *Chemical*, vol. 2021, ACS Publications [HTML]

174. D. Cao and J. Ding, "Recent advances in regenerative biomaterials," Regenerative Biomaterials, 2022. oup.com

175. M. M. Farag, "Recent trends on biomaterials for tissue regeneration applications," Journal of Materials Science, 2023. springer.com

176. A. Bharadwaj, "An overview on biomaterials and its applications in medical science," IOP Conference Series: Materials Science and Engineering, vol. 2021, 2021. iop.org

177. X. Deng, M. Gould, and M. A. Ali, "A review of current advancements for wound healing: Biomaterial applications and medical devices," *J. Biomed. Mater. Res. Part B: Appl. Biomater.*, vol. 110, no. 3, pp. 789-802, 2022. wiley.com

178. A. C. Pedro, O. G. Paniz, I. A. A. Fernandes, D. G. Bortolini, "The importance of antioxidant biomaterials in human health and technological innovation: a review," Antioxidants, 2022. mdpi.com

179. F. Ekinci, T. Asuroglu, and K. Acici, "Monte Carlo Simulation of TRIM Algorithm in Ceramic Biomaterial in Proton Therapy," 2023. ncbi.nlm.nih.gov

180. M. Devar, "Core Concepts of Biomechanics," 2025 [HTML]

181. M. Y. Akbarova and A. A. Tursunaliyev, "Biomechanics in the human body," Экономика и социум, 2024. cyberleninka.ru

182. S. Y. Rabbany, D. M. Rooney, and N. Merna, "Fundamentals of Biomechanics," Springer, [HTML]

183. W. F. Reed, "Biophysics: physical processes underlying the living state," 2025 [HTML]

184. P. Sharma, "Qualitative analysis in biomechanics: A review study," ENCYCLOPAEDIA OF BIOMECHANICS, 2022. wisdompress.co.in

185. R. F. Zernicke, S. P. Broglio, and W. C. Whiting, "Biomechanics of Injury," 2023 [HTML]

186. S. A. Einstein, A. E. Rubinstein, P. Svolos, *et al.*, "Medical Physics in Global Health Radiology," in *Applications*, 2025, Springer [HTML]

187. C. Garibaldi, M. Essers, B. Heijmen, J. Bertholet, *et al.*, "The 3rd ESTRO-EFOMP core curriculum for medical physics experts in radiotherapy," *Radiotherapy and Oncology*, vol. 2022, Elsevier. thegreenjournal.com

188. C. Chiesa, L. Strigari, M. Pacilio, E. Richetta, V. Cannata, "… and the Italian law N. 101/2020. Position paper and recommendations by the Italian National Associations of Medical Physics (AIFM) and Nuclear Medicine …," Physica Medica, vol. 83, pp. 1-8, 2021. sciencedirect.com

189. K. Zhang, H. Y. Zhou, D. T. Baptista-Hon, Y. Gao, and X. Liu, "Concepts and applications of digital twins in healthcare and medicine," Patterns, vol. 4, no. 1, 2024. cell.com

190. A. Payne, R. Chopra, N. Ellens, and L. Chen, "AAPM Task Group 241: A medical physicist's guide to MRI-guided focused ultrasound body systems," *Medical Physics*, vol. 2021, Wiley Online Library. wiley.com

191. S. Bhat and A. Kumar, "Biomaterials and bioengineering tomorrow's healthcare," 2013. ncbi.nlm.nih.gov

192. F. D. Al-Shalawi, A. H. Mohamed Ariff, D. W. Jung, *et al.*, "Biomaterials as implants in the orthopedic field for regenerative medicine: metal versus synthetic polymers," Polymers, 2023. mdpi.com

193. P. Trucillo, "Biomaterials for drug delivery and human applications," Materials, 2024. mdpi.com

194. R. Davis, A. Singh, M. J. Jackson, and R. T. Coelho, "A comprehensive review on metallic implant biomaterials and their subtractive manufacturing," *International Journal of …*, vol. XX, no. YY, pp. ZZ-ZZ, 2022. springer.com

195. R. Agrawal, S. Singh, K. K. Saxena, "A role of biomaterials in tissue

engineering and drug encapsulation," *Journal of Engineering*, vol. 2023 [HTML]

196. J. N. Kizhakkedathu and E. M. Conway, "Biomaterial and cellular implants: foreign surfaces where immunity and coagulation meet," Blood, vol. 2022. sciencedirect.com

197. H. M. Khan, X. Liao, B. A. Sheikh, Y. Wang, Z. Su, "Smart biomaterials and their potential applications in tissue engineering," *Journal of Materials*, 2022. researchgate.net

198. W. G. Mengesha, "Cutting-edge physics driven advancements in medical industry," American Journal of Modern Physics, 2024. researchgate.net

199. L. Ghimire and E. Waller, "The Future of Health Physics: Trends, Challenges, and Innovation," Health Physics, 2025 [HTML]

200. Q. Gao, F. Xiong, J. Fu, S. Deng, J. Wang, and S. Li, "Intelligent Biomaterials in Diagnostic Systems," in *Intelligent Biomaterials*, 2025, Springer [HTML]

201. R. Assmann, D. Caldwell, G. Cerullo, *et al.*, "Physics for health," in *Physics for Society*, 2024. europhysicsnews.org

202. P. K. Prabhakar, "Biomedical Research Developments for Improved Healthcare," 2024 [HTML]

203. J. Lambert Cause, "Unraveling the contact force impact on the complex multi-wavelength PPG signal morphology at different vascular depths. Lambert Cause, Joan; Sole Morillo …," 2022. vub.be

204. E. T Curtis, "Monitoring of mesenchymal based constructs using magnetic resonance elastography," 2011 [PDF]

205. C. Y. Lin and J. H. Kang, "Mechanical properties of compact bone defined by the stress-strain curve measured using uniaxial tensile test: a concise review and practical guide," Materials, 2021. mdpi.com

206. Y. Li, J. Q. Chen, J. H. Yang, J. S. Liu *et al.*, "Determination of shale macroscale modulus based on microscale measurement: A case study concerning multiscale mechanical characteristics," Petroleum Science, 2022. sciencedirect.com

207. S. Huysveld, J. Dewulf, S. De Meester, and others, "Addressing the complex challenge of understanding and quantifying substitutability for recycled plastics," Resources, 2021. sciencedirect.com

208. P. Royer, D. Noël, and S. Le Floc'h, "Cartilage biomechanics: From the basic facts to the challenges of tissue engineering," *… Research Part A*, vol. 2023, Wiley Online Library. wiley.com

209. Y. Wang, L. Li, D. Hofmann, J. E. Andrade *et al.*, "Structured fabrics with tunable mechanical properties," Nature, 2021 [HTML]

210. L. Kong, F. Hadavimoghaddam, C. Li, K. Liu, B. Liu, and others, "AFM vs. Nanoindentation: Nanomechanical properties of organic-rich Shale," *Marine and Petroleum Geology*, vol. 2021, Elsevier [HTML]

211. T. D'Antino and M. A. Pisani, "Tensile and compressive behavior of thermoset and thermoplastic GFRP bars," Construction and Building Materials, 2023 [HTML]

212. C. Andreou, R. Weissleder, and M. F. Kircher, "Multiplexed imaging in oncology," Nature Biomedical Engineering, 2022. semi.ac.cn

213. Y. Zhang, T. Zu, R. Liu, and J. Zhou, "Acquisition sequences and reconstruction methods for fast chemical exchange saturation transfer imaging," NMR in Biomedicine, 2023 [HTML]

214. L. A. Rivera-Rivera, T. Vikner, L. Eisenmenger, and others, "Four-dimensional flow MRI for quantitative assessment of cerebrospinal fluid dynamics: Status and opportunities," NMR in Biomedicine, 2024. wiley.com

215. S. Gallo-Bernal, M. A. Bedoya, M. S. Gee, and C. Jaimes, "Pediatric magnetic resonance imaging: faster is better," Pediatric Radiology, 2023 [HTML]

216. M. K. Manhard, J. Stockmann, C. Liao, "…-inversion multi-echo spin and gradient echo echo planar imaging sequence with low image distortion for rapid quantitative parameter mapping and synthetic image …," *Magnetic*, vol. 2021, Wiley Online Library. nih.gov

217. M. K. Kramer and A. M. Cerjanic, "Fast, motion-robust MR elastography with distributed, generalized encoding," *Magnetic Resonance in Medicine*, vol. 2025, Wiley Online Library [HTML]

218. M. W. Haskell, J. F. Nielsen, and D. C. Noll, "Off-resonance artifact correction for MRI: A review," NMR in Biomedicine, 2023. wiley.com

219. E. A. Margolis, N. E. Friend, M. W. Rolle, E. Alsberg, "Manufacturing the multiscale vascular hierarchy: progress toward solving the grand challenge of tissue engineering," Trends in…, vol. 2023, no. 2023. sciencedirect.com

220. C. O'Connor, E. Brady, Y. Zheng, E. Moore, "Engineering the multiscale complexity of vascular networks," *Nature Reviews*, vol. 2022. nih.gov

221. C. D. Devillard and C. A. Marquette, "Vascular tissue engineering: challenges and requirements for an ideal large scale blood vessel," *Frontiers in Bioengineering and Biotechnology*, vol. 2021. frontiersin.org

222. S. Cho, D. E. Discher, K. W. Leong, G. Vunjak-Novakovic, "Challenges and opportunities for the next generation of cardiovascular tissue engineering," *Nature*, vol. 2022. nih.gov

223. P. Gupta and B. B. Mandal, "Tissue-engineered vascular grafts: emerging trends and technologies," Advanced Functional Materials, 2021 [HTML]

224. D. S. Masson-Meyers and L. Tayebi, "Vascularization strategies in tissue engineering approaches for soft tissue repair," *Journal of Engineering and Regenerative Medicine*, vol. 2021, Wiley Online Library. nih.gov

225. A. Joshi, S. Choudhury, S. B. Gugulothu, "Strategies to promote vascularization in 3D printed tissue scaffolds: trends and challenges," ACS Publications, 2022 [HTML]

226. B. B. J. Leal, N. Wakabayashi, K. Oyama, and others, "Vascular tissue engineering: polymers and methodologies for small caliber vascular grafts," in *Cardiovascular*, 2021. frontiersin.org

227. H. S. Viswanath, "Bioprocess scale-up and scale-down: Bulk production," Concepts & applications, wisdompress.co.in

228. A. F. M. de Mello and L. P. de Souza Vandenberghe, "Strategies and engineering aspects on the scale-up of bioreactors for different bioprocesses," Systems Microbiology, vol. 2024, Springer. researchgate.net

229. S. Ganeshan, S. H. Kim, and V. Vujanovic, "Scaling-up production of plant endophytes in bioreactors: concepts, challenges and perspectives," Bioresources and Bioprocessing, 2021. springer.com

230. G. Abdi, R. Tendulkar, C. Thatte, S. Mishra, "Scaling up nature's chemistry: a guide to industrial production of valuable metabolites," Advances in ..., vol. 2024, Springer [HTML]

231. M. Anuradha and S. Balasubramanya, "Commercialization of In Vitro

Secondary Metabolite Production: Challenges and Opportunities," In Vitro Production of ..., 2025. Springer [HTML]

232. V. Choudhary, "Strategies for Biotech Companies to Scale Up Commercially through Effective Project and Risk Management," BULLET: Jurnal Multidisiplin Ilmu, 2022 [HTML]

233. A. M. Elazzazy, M. N. Baeshen, K. M. Alasmi, S. I. Alqurashi, *et al*., "Where Biology Meets Engineering: Scaling up microbial nutraceuticals to bridge nutrition, therapeutics, and global impact," Microorganisms, 2025. mdpi.com

234. S. Parveen, K. Krishnakumar, and S. K. Sahoo, "New Era in Health Care: Tissue Engineering," 2006. ncbi.nlm.nih.gov

235. N. Ashammakhi, A. GhavamiNejad, R. Tutar, "Highlights on advancing frontiers in tissue engineering," Tissue Engineering, vol. XX, no. YY, pp. ZZ-ZZ, 2022. nih.gov

236. R. Bhole, H. Kapare, P. Karwa, "Revolutionizing Healthcare: Unveiling The Power Of Regenerative Medicine And Tissue Engineering," Bulletin of Pharmaceutical, 2025. ekb.eg

237. Z. Akhtar, "Exploring biomedical engineering (BME): Advances within accelerated computing and regenerative medicine for a computational and medical science …," J. Emerg. Med. OA, 2024. academia.edu

238. Z. B. Akhtar and A. D. Gupta, "Advancements within molecular engineering for regenerative medicine and biomedical applications: an investigation analysis towards a computing retrospective," in *Journal of Electronics, Electromedical Engineering, and …*, 2024. jeeemi.org

239. E. Sheikhbahei and A. A. Ari, "Harnessing the power of emerging digital technologies for improved sustainability and productivity in biomedical engineering and neuroscience," Scientific Hypotheses, 2024. scientifichypotheses.org

240. C. Wang, T. He, H. Zhou, Z. Zhang *et al*., "Artificial intelligence enhanced sensors-enabling technologies to next-generation healthcare and biomedical platform," Bioelectronic Medicine, 2023. springer.com

241. S. Krishnan, "Biomedical signal analysis for connected healthcare," 2021 [HTML]

242. G. Bocchetta, G. Fiori, S. A. Sciuto, and A. Scorza, "Performance of smart materials-based instrumentation for force measurements in biomedical applications: A methodological review," Actuators, 2023. mdpi.com

243. A. M. Upadhyaya, M. K. Hasan, S. Abdel-Khalek, *et al.*, "A comprehensive review on the optical micro-electromechanical sensors for the biomedical application," *Frontiers in Public Health*, 2021. frontiersin.org

244. M. A. Ali, C. Hu, E. A. Yttri, and R. Panat, "Recent advances in 3D printing of biomedical sensing devices," Advanced functional materials, 2022. nih.gov

245. F. J. Jaime, A. Muñoz, F. Rodríguez-Gómez, "Strengthening privacy and data security in biomedical microelectromechanical systems by IoT communication security and protection in smart healthcare," Sensors, 2023. mdpi.com

246. M. Deliorman and D. S. Ali, "Next-generation microfluidics for biomedical research and healthcare applications," *Biomedical Engineering*, 2023. sagepub.com

247. Y. Su, S. Huang, H. Liu, Y. Chen, Y. Du, and Y. Wang, "PPG-Hear: A Practical Eavesdropping Attack with Photoplethysmography Sensors," Mobile, Wearable and …, 2024 [HTML]

248. R. A. Powsner, M. R. Palmer, and E. R. Powsner, "Essentials of nuclear medicine physics, instrumentation, and radiation biology," 2021 [HTML]

249. M. A. S. Sherer, P. J. Visconti, E. R. Ritenour, and K. W. Haynes, "Radiation Protection in Medical Radiography-E-Book: Radiation Protection in Medical Radiography-E-Book," 2021 [HTML]

250. J. W. Burmeister, N. C. Busse, A. J. Cetnar, *et al.*, "Academic program recommendations for graduate degrees in medical physics: AAPM Report No. 365 (Revision of Report No. 197)," *Medical Physics*, vol. 2022. nih.gov

251. H. K. K. Mostafa, "Different cells of the human body: categories and morphological characters," Journal of Microscopy and Ultrastructure, 2022. lww.com

252. L. Sun, J. Wu, Y. Xu, and Y. Zhang, "A federated learning and blockchain framework for physiological signal classification based on continual learning," Information Sciences, 2023 [HTML]

253. C. G. Jung and R. F. C. Hull, "Psychological Factors Determining Human Behaviour 1," Collected works of CG Jung, 2023 [HTML]

254. M. Zhang, Y. Ma, X. Ye, N. Zhang, and L. Pan, "TRP (transient receptor potential) ion channel family: structures, biological functions

and therapeutic interventions for diseases," Signal Transduction and Targeted Therapy, vol. 8, no. 1, 2023. nature.com

255. S. Latif, M. Jahangeer, D. M. Razia, M. Ashiq, A. Ghaffar, "Dopamine in Parkinson's disease," Clinica Chimica Acta, vol. 2021, Elsevier. researchgate.net

256. Y. Zhu, H. Zhang, B. Liu, and J. Dou, "Exploring Cutting-Edge Developments in Deep Learning for Biomedical Signal Processing," International Journal of …, 2024 [HTML]

257. A. M. Alqudah and Z. Moussavi, "A Review of Deep Learning for Biomedical Signals: Current Applications, Advancements, Future Prospects, Interpretation, and Challenges.," Computers, . researchgate.net

258. A. K. Lenka and L. Das, "Machine Vision and Biomedical Signal and Image Processing," in *… and Computer Vision: Models and Biomedical …*, Springer, 2025 [HTML]

259. R. R. Kumar and R. Priyadarshi, "Denoising and segmentation in medical image analysis: A comprehensive review on machine learning and deep learning approaches," Multimedia Tools and Applications, 2025 [HTML]

260. A. C. Yadav, M. H. Kolekar, D. B. Patil, and M. K. Zope, "Image informatics for clinical and preclinical biomedical analysis," in *… for information retrieval*, Elsevier, 2025 [HTML]

261. C. Ding and C. Wu, "Self-Supervised Learning for Biomedical Signal Processing: A Systematic Review on ECG and PPG Signals," medRxiv, 2024. medrxiv.org

262. Y. Wang, L. Liu, and C. Wang, "Trends in using deep learning algorithms in biomedical prediction systems," Frontiers in Neuroscience, 2023. frontiersin.org

263. R. Martinek, M. Ládrová, M. Šidiková, R. Jaroš *et al.*, "Advanced bioelectrical signal processing methods: Past, present and future approach - Part I: Cardiac signals," 2021 [PDF]

264. M. Boyer, L. Bouyer, J. S. Roy, and A. Campeau-Lecours, "Reducing noise, artifacts and interference in single-channel EMG signals: a review," Sensors, 2023. mdpi.com

265. D. Goyal, C. Mongia, and S. Sehgal, "Applications of digital signal

processing in monitoring machining processes and rotary components: A review," IEEE Sensors Journal, 2021 [HTML]

266. G. Ramesh, J. Logeshwaran, and J. Gowri, "The management and reduction of digital noise in video image processing by using transmission based noise elimination," *ICTACT Journal on Image and Video Processing*, vol. 2022. ictactjournals.in

267. W. Wei, Y. Shang, Y. Peng, and R. Cong, "Research progress of noise in high-speed cutting machining," Sensors, 2022. mdpi.com

268. PM Tripathi, A. Kumar, R. Komaragiri, "A review on computational methods for denoising and detecting ECG signals to detect cardiovascular diseases," *Journal of Computational Methods*, vol. 2022, Springer [HTML]

269. N. T. Bui and G. Byun, "The comparison features of ECG signal with different sampling frequencies and filter methods for real-time measurement," Symmetry, 2021. mdpi.com

270. A. K. Yetisen, J. Leonardo Martinez-Hurtado, B. Ünal, A. Khademhosseini *et al.*, "Wearables in Medicine," 2018. ncbi.nlm.nih.gov

271. K. Guk, G. Han, J. Lim, K. Jeong *et al.*, "Evolution of Wearable Devices with Real-Time Disease Monitoring for Personalized Healthcare," 2019. ncbi.nlm.nih.gov

272. S. Nur, "The role of digital health technologies and sensors in revolutionizing wearable health monitoring systems," *International Journal of Innovative Research in …*, 2024. academia.edu

273. M. U. Tariq, "Advanced wearable medical devices and their role in transformative remote health monitoring," in *... approaches to patient literacy and healthcare*, 2024. researchgate.net

274. SS Alegavi, B. Nemade, V. Bharadi, and S. Gupta, "Revolutionizing Healthcare through Health Monitoring Applications with Wearable Biomedical Devices," *International Journal of …*, 2023. academia.edu

275. S. M. A. Iqbal, I. Mahgoub, E. Du, M. A. Leavitt, *et al.*, "Advances in healthcare wearable devices," NPJ Flexible Electronics, 2021. nature.com

276. EP Adeghe, CA Okolo, OT Ojeyinka, "A review of wearable technology in healthcare: Monitoring patient health and enhancing outcomes," OARJ of Multidisciplinary Research, 2024. researchgate.net

277. E. Escobar-Linero, L. Muñoz-Saavedra, F. Luna-Perejón, "Wearable health devices for diagnosis support: evolution and future tendencies," Sensors, vol. 2023. mdpi.com

278. M. S. Linet, P. B. Davis, and J. A. Brink, "The need for a broad-based introduction to radiation science within US medical schools' educational curriculum," Radiology, 2021. rsna.org

279. C. Borrás and M. G. Stabin, "Radiotheranostics-a Primer for Medical Physicists I: Physics, Chemistry, Biology and Clinical Applications," 2024 [HTML]

280. R. Salazar-Peña and M. A. Pedroza-Toscano, "Project-based learning for an online course of simulation engineering: From bioreactor to epidemiological modeling," *Education for Chemical Engineers*, vol. 2023, Elsevier [HTML]

281. T. Weissmann, L. Deloch, M. Grohmann, *et al*., "German radiation oncology's next generation: a web-based survey of young biologists, medical physicists, and physicians from problems to solutions," Strahlentherapie und Onkologie, vol. 2024, Springer. springer.com

282. Y. Tsekhmister, "Medical informatics and biophysics in medical universities of European countries: A systematic review and meta-analysis.," Electronic Journal of General Medicine, 2024. ejgm.co.uk

283. M. Abdelouahed, D. Yateem, C. Amzil, I. Aribi, "Integrating artificial intelligence into public health education and healthcare: insights from the COVID-19 and monkeypox crises for future pandemic readiness," Frontiers in …, 2025. frontiersin.org

284. J. P. Williams, M. S. Anscher, M. Vazquez, "Radiation biology workforce in the United States," *Medical Physics*, vol. 49, no. 1, pp. 1-10, 2022. wiley.com

285. M. S. H. AlHarshan, "The Implementation of Quality Management Systems in Laboratory, Nursing, Radiology and Their Impact on Patient Care and Safety," Saudi J Med Pharm Sci, 2023. saudijournals.com

286. M. Chau, "Enhancing safety culture in radiology: Key practices and recommendations for sustainable excellence," Radiography, 2024. sciencedirect.com

287. J. Papp, "Quality Management in the Imaging Sciences-E-Book: Quality Management in the Imaging Sciences-E-Book," 2023 [HTML]

288. SS Dudhe, G. Mishra, P. Parihar, D. Nimodia, A. Kumari, "Radiation

dose optimization in radiology: a comprehensive review of safeguarding patients and preserving image fidelity," Cureus, 2024. cureus.com

289. M. Vyas and D. Tafti, "Nuclear Medicine Quality Assurance," StatPearls [Internet], 2025. nih.gov

290. C. Malamateniou, K. M. Knapp, M. Pergola, N. Woznitza, "Artificial intelligence in radiography: where are we now and what does the future hold?" Radiography, vol. 27, no. 1, pp. 9-16, 2021. city.ac.uk

291. B. Al Qassabi, R. AlSukaiti, S. Alajmi, "Improving Turnaround Times and Operational Efficiency in Radiology Services: Quality Improvement Study in Oman," Pacific Journal of ..., 2025. nih.gov

292. J. Papp, "Quality Management in the Imaging Sciences-E-Book: Quality Management in the Imaging Sciences-E-Book," 2023 [HTML]

293. M. O. Adelodun and E. C. Anyanwu, "Environmental and patient safety: Advances in radiological techniques to reduce radiation exposure," Int J Front Med Surg Res, 2024. researchgate.net

294. M. G. Kawooya, H. N. Kisembo, D. Remedios, "An Africa point of view on quality and safety in imaging," in *Insights into Imaging*, vol. 13, no. 1, 2022. springer.com

295. M. Adelodun and E. Anyanwu, "Comprehensive risk management and safety strategies in radiation use in medical imaging," Int J Front Med Surg Res, 2024. researchgate.net

296. M. C. Kelvin-Agwu, M. O. Adelodun, G. T. Igwama, "The Impact of Regular Maintenance on the Longevity and Performance of Radiology Equipment," Unpublished, 2024. researchgate.net

297. Y. Tadavarthi, V. Makeeva, W. Wagstaff, *et al.*, "Overview of noninterpretive artificial intelligence models for safety, quality, workflow, and education applications in radiology practice," *Radiology: Artificial Intelligence*, 2022. rsna.org

298. M. Amurao, D. A. Gress, M. A. Keenan, "Quality management, quality assurance, and quality control in medical physics," *Journal of Applied Physics*, vol. 2023, Wiley Online Library. wiley.com

299. J. Papp, "Quality Management in the Imaging Sciences-E-Book: Quality Management in the Imaging Sciences-E-Book," 2023 [HTML]

300. C. K. Glide-Hurst, E. S. Paulson, K. McGee, *et al.*, "Task group 284 report: magnetic resonance imaging simulation in radiotherapy:

considerations for clinical implementation, optimization, and quality assurance," *Medical Physics*, vol. 48, no. 1, pp. 1-20, 2021. wiley.com

301. 김동욱, "Radiotherapy Risk Estimation Based on Expert Group Survey," 2019 [PDF]
302. R. Lonceint, F. Bodéré, and B. Geffroy, "Risk Management Through an “Activity Contradictions” Lens: Exposure to Low Doses of Radiation in Nuclear Medicine," 2019. ncbi.nlm.nih.gov
303. M. Abdel-Wahab, S. S. Gondhowiardjo, A. A. Rosa, *et al*., "Global radiotherapy: current status and future directions white paper," *JCO Global Oncology*, vol. 7, pp. 1-15, 2021. ascopubs.org
304. R. A. Chandra, F. K. Keane, F. E. M. Voncken, and C. R. Thomas, "Contemporary radiotherapy: present and future," The Lancet, 2021. apricusbiopharm.com
305. J. S. Mayadev, G. Ke, U. Mahantshetty, M. D. Pereira, *et al*., "Global challenges of radiotherapy for the treatment of locally advanced cervical cancer," *International Journal of …*, vol. 2022, Elsevier. sciencedirect.com
306. D. A. Jaffray, F. Knaul, M. Baumann, and M. Gospodarowicz, "Harnessing progress in radiotherapy for global cancer control," Nature cancer, 2023 [HTML]
307. P. Maitre, R. Krishnatry, S. Chopra, *et al*., "Modern radiotherapy technology: obstacles and opportunities to access in low-and middle-income countries," JCO Global Oncology, vol. 2022. ascopubs.org
308. S. N. C. Elmore, A. Polo, J. M. Bourque, Y. Pynda, *et al*., "Radiotherapy resources in Africa: an International Atomic Energy Agency update and analysis of projected needs," *The Lancet*, 2021. nih.gov
309. M. Abdel-Wahab, F. Giammarile, M. Carrara, *et al*., "Radiotherapy and theranostics: a lancet oncology commission," The Lancet, 2024. ox.ac.uk
310. G. S. Ibbott, A. Chougule, J. Damilakis, S. Tabakov *et al*., "Medical physicist certification and training program accreditation," 2022. ncbi.nlm.nih.gov
311. M. Al-Raeei, "Shaping the future of cancer treatment: The commitment of medical physicists," AIP Advances, 2024. aip.org

312. W. D. Newhauser, D. A. Gress, M. D. Mills, *et al.*, "Medical physics workforce in the United States," *Medical Physics*, 2023. nih.gov

313. F. Zanca, I. Hernandez-Giron, M. Avanzo, G. Guidi, "Expanding the medical physicist curricular and professional programme to include Artificial Intelligence," Physica Medica, vol. 2021, Elsevier. physicamedica.com

314. L. G. Marcu, N. L. Abbott, A. Appelt, S. Chauvie, A. Gasnier, *et al.*, "The role of medical physicists in clinical trials across Europe," Physica Medica, vol. 2022, Elsevier. physicamedica.com

315. G. S. Ibbott, A. Chougule, J. Damilakis, S. Tabakov, "Medical physicist certification and training program accreditation," *Health and Technology*, vol. 12, no. 1, pp. 1-10, 2022. springer.com

316. A. J. J. Maas, A. A. Lammertsma, S. Agius, C. Bert, B. Byrne, *et al.*, "Education, training and registration of Medical Physics Experts across Europe," Physica Medica, vol. 2021, Elsevier. physicamedica.com

317. B. W. Pogue and A. P. Niver, "Analysis of the institutional free market in accredited medical physics graduate programs," *Journal of Applied Clinical Medical Physics*, 2025. wiley.com

318. R. Hill, C. Barbagallo, and C. Baldock, "In Australia professional registration for qualified medical physicists should be mandated through the Australian Health Practitioner Regulation Agency (AHPRA)," in *Biomedical Engineering and Engineering Sciences in Medicine*, 2024. springer.com

319. R. Alfredo Siochi, P. Balter, C. D. Bloch, H. S. Bushe *et al.*, "Information technology resource management in radiation oncology," 2009. ncbi.nlm.nih.gov

320. R. Beckers, Z. Kwade, and F. Zanca, "The EU medical device regulation: Implications for artificial intelligence-based medical device software in medical physics," Physica Medica, 2021. physicamedica.com

321. R. F. Fisher, K. E. Applegate, L. K. Berkowitz, *et al.*, "AAPM medical physics practice guideline 12. a: fluoroscopy dose management," *Medical Physics*, vol. 49, no. 1, pp. 1-10, 2022. wiley.com

322. D. Sarrut, A. Etxebeste, E. Munoz, N. Krah, "Artificial intelligence for Monte Carlo simulation in medical physics," Frontiers in Physics, 2021. frontiersin.org

323. Q. Chen, Y. Rong, J. W. Burmeister, E. H. Chao, "AAPM Task Group Report 306: quality control and assurance for tomotherapy: an update to Task Group Report 148," *Medical Physics*, vol. 50, no. 5, pp. 1-12, 2023. wiley.com

324. I. J. Das, P. Francescon, J. M. Moran, A. Ahnesjö, and others, "Report of AAPM Task Group 155: megavoltage photon beam dosimetry in small fields and non-equilibrium conditions," *Medical Physics*, vol. 48, no. 4, pp. 1-30, 2021. wiley.com

325. E. T. Elmas and M. A. Cinibulak, "Fundamental Scientific and Technical Issues related with the “Hip Replacement Design and Biomechanical Analysis”," Matsci Nano J, 2025. scholarspublishers.org

326. S. Tabakov, "e-Learning development in medical physics and engineering," 2008. ncbi.nlm.nih.gov

327. M. Woo and K. H. Ng, "Real-time teleteaching in medical physics," 2008. ncbi.nlm.nih.gov

328. K. Gouripur, "The impact of artificial intelligence on healthcare: A revolution in progress," The North and West London Journal of General, 2024. tnwljgp.org

329. P. Jeyaraj and T. Narayanan, "Role of artificial intelligence in enhancing healthcare delivery," *International Journal of Innovative Science and Engineering*, 2023. ijisme.org

330. S. A. Alowais, S. S. Alghamdi, N. Alsuhebany, *et al.*, "Revolutionizing healthcare: the role of artificial intelligence in clinical practice," BMC Medical, vol. 2023, Springer. springer.com

331. D. B. Olawade, A. C. David-Olawade, O. Z. Wada, *et al.*, "Artificial intelligence in healthcare delivery: Prospects and pitfalls," Journal of Medicine, vol. 2024, Elsevier. sciencedirect.com

332. H. Arabi and H. Zaidi, "Applications of artificial intelligence and deep learning in molecular imaging and radiotherapy," 2020. ncbi.nlm.nih.gov

333. M. Koenigkam Santos, J. Raniery Ferreira Júnior, D. Tadao Wada, A. Priscilla Magalhães Tenório *et al.*, "Artificial intelligence, machine learning, computer-aided diagnosis, and radiomics: advances in imaging towards to precision medicine," 2019. ncbi.nlm.nih.gov

334. J. Oyeniyi and P. Oluwaseyi, "Emerging trends in AI-powered medical imaging: enhancing diagnostic accuracy and treatment decisions," *International Journal of Enhanced …*, 2024. researchgate.net

335. S. Hassan, "Artificial Intelligence in Diagnostic Imaging: Enhancing Patient Care Through Advanced Algorithms and Data Integration," 2025. preprints.org

336. M. S. Hamad, M. H. Aldeeb, M. M. Almzainy, and S. J. Albadrasawi, "Harnessing Artificial Intelligence to Enhance Medical Image Analysis," 2024. philarchive.org

337. J. Meyer-Szary, M. Souza Luis, S. Mikulski, A. Patel *et al.*, "The Role of 3D Printing in Planning Complex Medical Procedures and Training of Medical Professionals Cross-Sectional Multispecialty Review," 2022. ncbi.nlm.nih.gov

338. Z. Sun, "Insights into 3D printing in medical applications," 2019 [PDF]

339. T. Mateti, S. Jain, L. A. Shruthi, A. Laha, and G. Thakur, "An overview of the advances in the 3D printing technology," in *3D Printing Technology for …*, 2023, Elsevier [HTML]

340. E. Peed and N. Lee, "3D printing, history of," Encyclopedia of Computer Graphics and Games, 2024 [HTML]

341. A. Colly, C. Marquette, J. M. Frances, and E. J. Courtial, "Classification of the emerging freeform three-dimensional printing techniques," MRS Bulletin, 2023. hal.science

342. L. Savvides, "A History of 3D Printing: Three Waves of Development," 3D Printing Cultures, [HTML]

343. S. Shaikh, "History and Evolution of 3D Printing," in *3D Printing in Prosthetics and Orthotics: Innovations*, 2024, Springer [HTML]

344. V. R. Talanki, Q. Peng, S. B. Shamir, "Three-dimensional printed anatomic models derived from magnetic resonance imaging data: current state and image acquisition recommendations for appropriate …," Journal of Magnetic Resonance Imaging, vol. 2022, Wiley Online Library. nih.gov

345. A. Leontiou, S. Georgopoulos, V. K. Karabagias, "Three-dimensional printing applications in food industry," 2023. mdpi.com

346. J. Anthony Seibert, A. P. Blatnica, J. B. Clements, P. H. Halvorsen *et al.*, "AAPM medical physics practice guideline 7.a.: Supervision of medical physicist assistants," 2019. ncbi.nlm.nih.gov

347. G. Frija, I. Blažić, D. P. Frush, M. Hierath, M. Kawooya, "How to improve access to medical imaging in low-and middle-income countries?" The Lancet, 2021. thelancet.com

348. M. Hu, J. Zhang, L. Matkovic, T. Liu, "Reinforcement learning in medical image analysis: Concepts, applications, challenges, and future directions," Clinical Medical Physics, 2023. wiley.com

349. F. Romano, C. Bailat, P. G. Jorge, M. L. F. Lerch, *et al*., "Ultra-high dose rate dosimetry: challenges and opportunities for FLASH radiation therapy," *Medical Physics*, vol. 49, no. 12, pp. 1-12, 2022. wiley.com

350. E. Bezak, C. Borrás, F. Hasford, N. Karmaker, "Science diplomacy in medical physics–an international perspective," Health and Technology, vol. 2023, Springer. springer.com

351. J. A. Nye, J. P. Dugas, W. D. Erwin, D. P. Gierga, *et al*., "AAPM Task Group No. 249. B Essentials and guidelines for clinical medical physics residency training program," *Medical Physics*, vol. 52, no. 1, pp. 1-10, 2025. wiley.com

352. S. P. McCullough, H. Alkhatib, K. J. Antes, *et al*., "AAPM Medical Physics Practice Guideline 2. b.: commissioning and quality assurance of X-ray-Based image-guided radiotherapy systems," *Medical Physics*, vol. 48, no. 1, pp. 1-15, 2021. wiley.com

353. J. Bertholet, H. Al Hallaq, I. Toma-Dasu, *et al*., "Medical Physics Training and Education: Learning from the Past and Looking to the Future," *Biology Physics*, 2023 [HTML]

354. J. Zhang, C. L. Brunnquell, T. J. Andrews, R. H. Behrman, "Updating the American Association of Physicists in Medicine (AAPM) Diagnostic Radiology Resident Physics Curriculum: Strategies, Content, and Dissemination," Academic Radiology, vol. 2025, Elsevier [HTML]

355. K. R. G. Hendrickson, T. Juang, A. Rodrigues, and J. W. Burmeister, "Ethical violations and discriminatory behavior in the MedPhys Match," 2017. ncbi.nlm.nih.gov

356. M. Akdeniz, B. Yardımcı, and E. Kavukcu, "Ethical considerations at the end-of-life care," SAGE open medicine, 2021. sagepub.com

357. S. McLennan, A. Fiske, D. Tigard, R. Müller, "Embedded ethics: a proposal for integrating ethics into the development of medical AI," *Journal of Medical Ethics*, vol. 2022, pp. 1-10, Springer, 2022. springer.com

358. Y. Zhang, M. Wu, G. Y. Tian, G. Zhang *et al*., "Ethics and privacy of artificial intelligence: Understandings from bibliometrics," Knowledge-Based Systems, 2021. uts.edu.au

359. C. Huang, Z. Zhang, B. Mao, and X. Yao, "An overview of artificial intelligence ethics," IEEE Transactions on …, 2022. ieee.org
360. M. A. S. Sherer, P. J. Visconti, E. R. Ritenour, and K. W. Haynes, "Radiation Protection in Medical Radiography-E-Book: Radiation Protection in Medical Radiography-E-Book," 2021 [HTML]
361. M. N. Sharmin, H. Reza, I. Kaes, P. Mosharaf, "Specialized Radiotherapy for Female Cancer Patients with Pregnancy: Best Practices for Medical Physicists," Journal of Cancer, 2025. scirp.org
362. K. Sathiya and K. Ramachandran, "Impacts of Radiation on Human Health: A Narrative Review," J Radiol Med Imaging, 2024. meddocsonline.org
363. A. Torresin, S. Evans, D. Lizio, L. Pierotti *et al.*, "Practical recommendations for the application of DE 59/2013," 2019 [PDF]
364. J. B. Smilowitz, I. J. Das, V. Feygelman, B. A. Fraass *et al.*, "AAPM Medical Physics Practice Guideline 5.a.: Commissioning and QA of Treatment Planning Dose Calculations Megavoltage Photon and Electron Beams," 2015. ncbi.nlm.nih.gov
365. I. C. R. P. PUBLICATION 154, "Optimisation of Radiological Protection in Digital Radiology Techniques for Medical Imaging," Annals of the ICRP, 2023. sagepub.com
366. K. Chida, What are useful methods to reduce occupational radiation exposure among radiological medical workers, especially for interventional radiology personnel? Radiological Physics and Technology, 2022 [HTML]
367. C. Candela-Juan, O. Ciraj-Bjelac, M. S. Merce, J. Dabin, "Use of out-of-field contact shielding on patients in medical imaging: a review of current guidelines, recommendations and legislative documents," Physica Medica, vol. 83, pp. 1-10, 2021. physicamedica.com
368. Z. Bárdyová and M. Horváthová, "The importance of public health in radiology and radiation protection," *Journal of Public Health*, vol. 2021, 2021. sagepub.com
369. M. Endo, "History of medical physics," Radiological Physics and Technology, 2021 [HTML]
370. S. Tabakov, F. Milano, M. S. Stoeva, P. Sprawls, and S. Tipnis, *Encyclopaedia of Medical Physics: Two Volume Set*, Taylor & Francis, 2021 [HTML]

371. T. M. Deserno (né Lehmann), H. Handels, K. H. Maier-Hein (né Fritzsche), S. Mersmann *et al.*, "Viewpoints on Medical Image Processing: From Science to Application," 2013. ncbi.nlm.nih.gov

372. S. Alzola-Aldamizetxebarria, L. Fernández-Méndez, D. Padro, J. Ruíz-Cabello *et al.*, "A Comprehensive Introduction to Magnetic Resonance Imaging Relaxometry and Contrast Agents," 2022. ncbi.nlm.nih.gov

373. S. Penninckx, E. Pariset, E. Cekanaviciute, *et al.*, "Quantification of radiation-induced DNA double strand break repair foci to evaluate and predict biological responses to ionizing radiation," NAR, 2021. oup.com

374. G. van de Kamp, T. Heemskerk, R. Kanaar, "DNA double strand break repair pathways in response to different types of ionizing radiation," Frontiers in..., vol. 2021. frontiersin.org

375. A. Bushmanov, N. Vorobyeva, D. Molodtsova, *et al.*, "Utilization of DNA double-strand breaks for biodosimetry of ionizing radiation exposure," Environmental…, vol. 2022, Elsevier. sciencedirect.com

376. D. Valente, M. P. Gentileschi, A. Guerrisi, V. Bruzzaniti, *et al.*, "Factors to consider for the correct use of γH2AX in the evaluation of DNA double-strand breaks damage caused by ionizing radiation," Cancers, vol. 14, no. 3, 2022. mdpi.com

377. C. Y. Li, "Non-canonical roles of apoptotic and DNA double-strand break repair factors in mediating cellular response to ionizing radiation," International journal of radiation biology, 2023. nih.gov

378. G. C. Pereira, M. Traughber, and R. F. Muzic, "The Role of Imaging in Radiation Therapy Planning: Past, Present, and Future," 2014. ncbi.nlm.nih.gov

379. K. Koka, A. Verma, B. S Dwarakanath, and R. V L Papineni, "Technological Advancements in External Beam Radiation Therapy (EBRT): An Indispensable Tool for Cancer Treatment," 2022. ncbi.nlm.nih.gov

380. C. Seidel, S. Heider, P. Hau, A. Glasow, S. Dietzsch, *et al.*, "Radiotherapy in medulloblastoma evolution of treatment, current concepts and future perspectives," Cancers, vol. 13, no. 2, 2021. mdpi.com

381. 김용배 and 서창옥, "Evolution of Radiotherapy: High-precision Radiotherapy," 2008 [PDF]

382. R. García-Figueiras, S. Baleato-González, A. Luna, "How imaging advances are defining the future of precision radiation therapy," Radiographics, 2024. rsna.org

383. D. Jin, D. Guo, J. Ge, X. Ye *et al.*, "Towards automated organs at risk and target volumes contouring: Defining precision radiation therapy in the modern era," Journal of the National Cancer Center, 2022. sciencedirect.com

384. T. Voglhuber, K. A. Eitz, M. Oechsner, M. M. E. Vogel, "Analysis of using high-precision radiotherapy in the treatment of liver metastases regarding toxicity and survival," BMC Cancer, vol. 21, 2021. springer.com

385. Y. Cheng, Y. Shang, S. Zhang, and S. Fan, "The interplay between RNA m6A modification and radiation biology of cancerous and non-cancerous tissues: a narrative review," Cancer Biology & Medicine, 2024. cancerbiomed.org

386. X. Xiong, L. W. Zheng, Y. Ding, Y. F. Chen, Y. W. Cai, *et al*., "Breast cancer: pathogenesis and treatments," Signal Transduction and…, 2025. nature.com

387. M. Schäfer, G. Hildenbrand, and M. Hausmann, "Impact of gold nanoparticles and ionizing radiation on whole chromatin organization as detected by single-molecule localization microscopy," *International Journal of …*, 2024. mdpi.com

388. E. Russ, C. M. Davis, J. E. Slaven, D. T. Bradfield, and R. G. Selwyn, "Comparison of the medical uses and cellular effects of high and low linear energy transfer radiation," Toxics, vol. 10, no. 4, 2022. mdpi.com

389. D. Srinivasan and R. Subbarayan, "A comprehensive overview of radiation therapy impacts of various cancer treatments and pivotal role in the immune system," *Wiley Online Library*, 2024 [HTML]

390. T. Paunesku, A. Stevanović, J. Popović, "Effects of low dose and low dose rate low linear energy transfer radiation on animals–review of recent studies relevant for carcinogenesis," *International Journal of …*, vol. 2021, Taylor & Francis. tandfonline.com

391. M. Martellini, M. Sarotto, and P. Ferrari, "Simulation of the nIORT® Treatment by Fast Neutrons of Severe Brain Cancers (as GBM) and Comparison with Standard IORT Techniques Adopting X-rays and …," Cancer Sci Res, 2025. scivisionpub.com