Foundations of Medical Physics

and

Radiation Protection

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Chapter - 1

Introduction to Medical Physics

By the year 2008, medical physics had evolved into a distinctly unique and immensely vital branch of applied physics that specifically centers around the numerous applications of knowledge and methods that arise from the natural sciences, particularly physics and mathematics, as they pertain to the practice of medicine in a variety of diverse contexts. This significant discipline consistently operates under the expert direction and knowledgeable guidance of extensively qualified medical personnel who are not only well-versed in various intricate aspects of health care provision but also devoted to significantly advancing the quality of patient care through their diverse expertise. The collective personnel comprises esteemed professionals such as accomplished professors of nuclear medicine, who integrate their profound academic expertise into clinical environments with considerable practical applications; highly-skilled radiologists, who exhibit exceptional proficiency in interpreting complex medical imaging results to facilitate and ensure accurate diagnoses; seasoned radiotherapists, who specialize in the effective therapeutic treatment of patients through the precise and cautious use of advanced radiation therapies; knowledgeable nuclear pharmacists, who fulfill a critical function in meticulously preparing and dispensing radioactive materials that are vital for both crucial diagnostic and therapeutic purposes while ensuring strict adherence to safety protocols; compassionate nursing graduates, who diligently deliver essential patient care with meticulous attention to detail, skill, and empathy; along with numerous other qualified individuals who contribute their diverse and invaluable expertise to the medical field, which in turn enhances the overall effectiveness of healthcare delivery for all involved. In more recent documents and discussions that have taken place within the scientific and medical communities, the innovative field of medical engineering has begun to be mentioned more frequently in conjunction with this vital area of study, underscoring its increasing significance and relevance in the ever-evolving landscape of modern medicine and patient care strategies. A proficient medical physicist, therefore, represents a highly trained and educated professional who possesses a robust and comprehensive academic and practical background in the multifaceted realm of physics, and who plays an indispensable and critical role in ensuring the safe and effective medical care of patients by integrating innovative methodologies into various clinical practices and procedures. This proficient professional is actively involved not only in the maintenance, calibration, and management of intricate and sophisticated medical equipment but is also strategically positioned at the forefront of the pioneering development of innovative new medical technologies that are specifically tailored to improve patient outcomes dramatically and considerably. By enhancing essential medical practices through the rigorous, detailed, and meticulous application of physics within healthcare, medical physicists make substantial contributions that ultimately promote better health and overall well-being for individuals across diverse healthcare settings, continually striving to optimize treatment efficacy and improve quality of life for all patients while adapting to the ever-changing dynamics of technology and medical science in this modern age [1, 2, 3, 4, 5, 6, 7, 8].

The competencies of the medical physicist are described in great detail by various esteemed organizations that are dedicated to the pursuit of excellence in the realm of healthcare. These comprehensive definitions not only underscore the significant role that the medical physicist plays, being a vital and integral component of the professional health team, but they also delineate an essential and specialized area within the larger and broader field of medical physics: clinical physics. In addition to the critical domain of clinical physics, there exist several other important fields of expertise for the medical physicist to consider and explore, including the academically demanding domain of academic physics. This encompasses not just teaching but also vital educational roles, which are crucial for the dissemination of knowledge as well as the thorough training of future professionals in the field of medical physics. Additionally, research and development initiatives are integral components of the profession, as they actively push the boundaries of scientific inquiry while simultaneously encouraging innovation and advancement within the ever-evolving field. The industrial sector represents yet another key area where cutting-edge technology and essential medical equipment are developed and manufactured, making significant contributions to the ongoing advancement of health technologies that benefit patient care. Moreover, the essential area of radiation protection stands as a fundamental necessity for ensuring that effective safety protocols are strictly followed and adhered to throughout all medical practices involving radiation. The wide array of services that medical physicists provide encompasses a multitude of important, specialized tasks, including but not limited to the meticulous acquisition, interpretation, and thorough analysis of extensive medical data, as well as imaging studies that are critical for informing treatment decisions. They bear the significant responsibility of adapting various advanced methods and sophisticated instruments utilized in the practice of medical physics, which allows for achieving the best possible outcomes, both diagnostic and therapeutic, that are effective, efficient, and safety-focused for all involved patients. This complex yet essential process is executed with paramount attention to minimizing radiation exposure to patients and to all individuals who may be present during the procedure. Simultaneously, the medical physicist is tasked with making certain that an excellent quality of the image is consistently maintained throughout the entirety of the diagnostic or therapeutic procedure, thereby promoting accurate assessments and successful interventions. Furthermore, the medical physicist is closely integrated with a variety of diverse areas of expertise, which include but are not limited to fundamental topics such as magnetism, various types of radiation, the critical principles of radiation protection, advanced mathematics for intricate problem-solving, relevant engineering practices, and the life sciences, all of which provide the foundational knowledge that underpins much of the vital work performed in this specialized and critical field. In addition to this extensive expertise, detailed job descriptions specifically for clinical medical physicists have been meticulously established to clearly delineate the precise responsibilities and expectations for professionals working within this essential specialty. Such clear delineation is absolutely critical for maintaining high standards in healthcare delivery and ensuring the highest quality of care possible for patients. These comprehensive job descriptions serve as invaluable tools for guiding the training, continuous development, and practical application of medical physicists as they navigate the essential and dynamic roles they play in rapidly evolving healthcare environments, thereby promoting safe, efficient, and effective care for all patients who rely on these specialized and necessary services [9, 10, 11, 12].

1.1 Definition and scope

Medical physics and radiation protection as a professional field have experienced remarkable evolution and significant advancement throughout the past century. This evolution signifies the emergence of a complex and multidisciplinary integration of various scientific, medical, and engineering principles, leading to profound improvements in the usage of medical technology. In essence, this ongoing progression supports the safe, responsible, and cost-effective utilization of radiation in both the treatment and the diagnosis of a diverse range of diseases and injuries that critically impact human health and wellbeing. Furthermore, this field plays a crucial role in the continuous assurance of safety and protection for patients, healthcare workers, and the general public against the potential hazards linked to radiation exposure, whether this exposure occurs accidentally, as a result of a mishap, or due to unforeseen circumstances. As recognized technical disciplines, the activities and responsibilities undertaken by medical physicists, health physicists, and a variety of other professionals holding related titles encompass the meticulous management, precise monitoring, and careful removal of some or potentially all sources of ionizing radiation. The central focus and ultimate goal of these activities are to decrease or even completely eliminate the potential for exposure of individuals to harmful radiation, which can have long-lasting and sometimes detrimental consequences for health. The combined fields of expertise are typically comprised of specialists whose focus areas include radiation oncology physics, diagnostic imaging physics, nuclear medicine physics, and health physics. In addition, these fields involve dedicated therapists and skilled technicians who collaborate closely towards achieving common objectives and shared goals within the healthcare setting. These specialized professionals possess extensive skills and in-depth knowledge that empower them to ensure that the radiation doses administered are meticulously and accurately aligned with the medical needs of their patients. They undergo rigorous and comprehensive training to make certain that these radiation doses are in compliance with the established regulations and guidelines within the field, thereby ensuring that safety levels are never surpassed. Additionally, the work conducted by these specialists is essential in maintaining the delicate balance between utilizing radiation for indispensable medical purposes and safeguarding individuals from unnecessary or excessive exposure. This balance underscores the vital importance of their role in modern healthcare practices, particularly in initiatives aimed at enhancing patient safety. Moreover, the ongoing challenges presented by rapid technological advancements necessitate constant vigilance, proactive decision-making, and unwavering dedication from these professionals. This reinforces the essential nature of their contributions to health, safety, and wellness in various medical environments, allowing for quality patient care and improved health outcomes. As the field continues to advance, the need for collaboration among various specialties will remain paramount in addressing the evolving needs and complexities of healthcare [13, 14, 15, 16, 17, 18, 19, 20].

Medical physicists hold an incredibly important position in the realm of healthcare, primarily focusing on ensuring the safe and effective operation of radiotherapy equipment along with a variety of diagnostic imaging devices.

Their contributions are vital in delivering high-quality care in clinical environments where patients are often exposed to radiation, albeit typically in incidental amounts. Colleagues within the clinical setting highly appreciate the direct application of leadership skills that medical physicists display, recognizing this characteristic as an invaluable quality that significantly enhances the quality of patient care. As the field of medical technology shifts and expands at an unprecedented pace, the responsibilities assigned to medical physicists are also continuously evolving. It becomes increasingly necessary for them to remain current with a continually growing selection of sophisticated technologies that fall under their area of expertise. In the fields of radiology and radiation oncology, medical physicists typically engage with numerous diagnostic instruments, including but not limited to X-ray, fluoroscopy, computed tomography (CT), bone densitometry, mammography, and ultrasound techniques. Furthermore, they are actively involved with advanced imaging modalities, such as magnetic resonance imaging (MRI), planar X-ray, computerized radiography, and X-ray computed tomographic (CT) imaging, ensuring that a wide spectrum of imaging is covered. In addition to this, medical physicists are also engaged with various forms of tomographic imaging and therapeutic radiologic procedures, encompassing methods like brachytherapy. Central to their function is therapy planning that involves an assortment of imaging techniques like X-ray, fluoroscopic, computerized radiographic, along with X-ray computed tomographic verification processes, which are integral to ensuring effective treatment plans. Medical physicists are tasked with overseeing both the installation and operational aspects of medical accelerators that produce ionizing radiation for treatment purposes, whether for inpatient or outpatient cases. Their responsibilities frequently overlap with the management of older systems, while simultaneously integrating X-ray methods that, although they might not always be classified in this way, are commonly employed in substantial teaching hospitals. They often serve as a crucial link between biomedical engineering and clinical engineering, fostering collaboration to guarantee the smooth and efficient delivery of medical physics services for both inpatient and outpatient environments. Moreover, the role of the medical physicist extends beyond technical responsibilities; it encompasses providing essential leadership in numerous diagnostic and therapeutic situations, thereby reinforcing the vital and integral role they occupy within the healthcare system and its framework [21, 22, 23, 24, 25, 26, 27, 28, 29, 30].

1.2 Historical development

It was an extraordinarily extensive and remarkable journey that spanned a considerable number of centuries, beginning with several captivating suggestions put forth in ancient Greece regarding the intriguing idea that light travels from the eye to the object that one perceives or is attempting to observe. This lengthy and complex journey ultimately culminated in the groundbreaking and transformative discovery of regular image formation, which was achieved through the intricate and detailed application of lenses alongside the fundamental properties of light itself that govern the way we see and understand our surroundings. It represents a long-standing, rich, and multifaceted traditional tale that originated from the philosophical schools of thought in Greece, featuring the substantial and pivotal contributions of eminent philosophers and scientists who dedicated their lives to the profound understanding of light, all the way through to the Islamic period, and then onward into the flourishing era of European humanism and enlightenment. This expansive and intricate timeline reflects the gradual yet thorough clarification of complex image problems within the evolving and dynamic field of optics. This vital clarification process encompassed the precise definition and rigorous proof of essential properties that govern light behavior, such as the straightforward and straight-line propagation of light across space, the principles of reflection that allow us to see our own images appear in mirrors, and the intriguing phenomenon of refraction, which causes light to bend as it passes through different mediums, such as glass or water, altering our perception of them. The journey eventually culminated in a seminal work that provided a complete and comprehensive geometric description, illustrating the formation of images created by both refracting lenses as well as by mirrors, showcasing the intricate interplay of light and surfaces. All of this significant and groundbreaking effort took place within an atmosphere that was rich in theosophical and philosophical discussions, fueled by a profound interest in tackling various intricate and challenging optics problems despite the fact that they were often far removed from having any direct practical applications in the realm of everyday life. Such a unique and intellectually stimulating backdrop created a compelling context in which various thinkers could deeply engage with theoretical questions about the very nature of light and the fundamental processes of vision itself, fostering a continuous and dynamic exchange of innovative ideas that would shape and revolutionize the future of optical science significantly for generations to come [31, 32, 33, 34, 35, 36, 37, 38].

The most renowned and spectacular use of mirrors, along with the complex and intricate process of image formation that occurs with mirrors, can be primarily attributed to the brilliant and profoundly influential mind of Archimedes of Syracuse, a figure whose lasting legacy has profoundly influenced and shaped various fields of study throughout history. Archimedes was not only an influential figure in the realms of mathematics, proving and demonstrating extraordinary skills in geometry and calculus with remarkable precision, but he also made noteworthy and significant contributions to the expansive fields of physics and engineering that have echoed through the corridors of time and profoundly shaped our understanding of the natural world. His groundbreaking and monumental work took place before the middle of the third century B.C., during a period when scientific understanding was still very much in its infancy, and the foundational underpinnings of many key scientific principles were yet to be laid out comprehensively. Entrusted with an ambitious and innovative project of great significance, Archimedes aimed to design and create mirrors that could effectively focus the intense rays of sunlight emanating from the brilliant sun onto enemy ships that were strategically positioned nearby, eyeing to sabotage and destroy their fleet. The ultimate goal of this undertaking was to set these ships ablaze and lead to a decisive victory in an important conflict. This remarkable and innovative undertaking not only illustrated his extraordinary grasp of optics, a vital branch of modern physics, but also demonstrated his deep understanding of the intricate and dynamic behavior of light, as well as the fundamental principles governing its complex phenomena of reflection and refraction. Through extensive experimentation, meticulous study, and relentless pursuit of knowledge, Archimedes successfully devised and meticulously crafted these specially shaped mirrors, which were ingeniously designed to direct a substantial amount of intense solar radiation precisely to the exact location where the enemy ships were anchored, creating a strikingly effective weapon. The intense and concentrated focus of sunlight upon these wooden vessels resulted in the wooden components of the ships heating up rapidly and efficiently, causing them to reach their auto-ignition temperature in a very short span of time, leading to catastrophic outcomes for the enemy forces. Consequently, this process initiated fierce and uncontrollable fires that swiftly intensified and rapidly spread across the ships, ultimately leading to their total and complete destruction, much to the dismay and horror of their crews and the strategic planners behind the enemy fleet. This astonishing and monumental accomplishment not only showcased Archimedes' remarkable technological prowess and inventiveness but also reflected the profound ingenuity, creativity, and inquisitive nature that characterized ancient Greek science. This scientific legacy laid down the foundational principles and philosophies for future generations of scientists, scholars, and thinkers who have since continued to explore the natural world and seek to understand its many complexities in an effort to push forward human knowledge.

Archimedes' innovative use of mirrors serves as a powerful testament to the incredible power of human creativity and intellect in overcoming the various challenges of life, while simultaneously pushing the boundaries of scientific inquiry and understanding as we know it today [39, 40, 41, 42, 43, 44, 45].

Chapter - 2

Basic Principles of Radiation Physics

The awareness that our immense and vast universe exposes us to a myriad of varied forms of natural radiation has been acknowledged and recognized since prehistoric times, a fascinating era when ancient humans roamed freely and exuberantly across the Earth. In those early and formative eras, people began to keenly observe, notice, and fundamentally understand the potentially harmful and adverse effects that arose from exposure to various types of ionizing radiation, which emanated from a multitude of diverse sources found abundantly in nature. This radiation also stemmed from naturally occurring radioactive elements that are present in our flora, particularly within commonly consumed vegetables and fruits, such as roots, tubers, and leafy greens. This early yet vital awareness laid the essential groundwork for what would ultimately evolve into a more formalized scientific discipline, specifically dedicated to comprehensively understanding and effectively managing the wide-ranging implications of radiation exposure. The formal beginning of this pivotal and significant discipline, which is known as the thorough study of ionizing radiation and its myriad practical applications, occurred in France at the very onset of the 19th century, synthesized and advanced meticulously by the pioneering founders of radiology. These trailblazers actively sought to explore the profound implications of radiation for varied medical purposes with genuine curiosity. As the field underwent significant progress and continuous evolution, it became increasingly clear that acquiring a comprehensive understanding of the fundamental procedures inherent to radiation physics, alongside grasping the necessary principles of protection for medical teams, was not only important but absolutely essential for optimal practice. This crucial knowledge entails a keen and detailed understanding of the various natural radiation sources that exist all around us in our environment, often unnoticed. Additionally, it encompasses the important and crucial ability to effectively distinguish between the different types of radiation that are necessary for effective medical diagnosis and treatment, as opposed to the critical protective measures that are required to guard against the potentially harmful effects of radiation exposure that can occur within the medical environment. Thus, it is now well understood and broadly accepted that medical personnel, to some extent, are obligated to be regularly exposed to certain modalities that utilize ionizing radiation alongside other varied forms of radiation as an integral part of their professional practice. These exposures are essential and vital for them to effectively perform their diverse and critical professional duties in various health care settings, ensuring accurate diagnoses and effective treatments. However, as a vital safeguard in this regard, several comprehensive recommendations have been thoughtfully adopted by specific government organizations and regulatory bodies to ensure the protection of individuals who are subjected to ionizing radiation due to various work-related reasons. These comprehensive and thorough guidelines are absolutely crucial for maintaining the health and safety of professionals working in environments where they may frequently encounter such radiation exposure, ensuring that their ongoing practice remains safe for both them and their patients, thereby fostering a safer medical community overall [46, 47, 48, 49, 50, 51, 52, 53, 54, 20].

The application of essential knowledge that is pertinent to the expansive and intricate field of medicine, specifically aimed at a diverse array of medical professionals who are engaged in various related practices, is referred to as radiation physics. This important and vital discipline, when it is combined with the requisite and contemporary methods of radiation protection that must be consistently implemented in the workplace, highlights the medical industry as one particularly critical area in which this specialized knowledge is profoundly relevant and significantly applied. The primary objective of this paper is to elucidate the fundamental legal concepts that serve as the foundational framework for the comprehensive application of radiation physics within the medical profession and the broader healthcare sector. In the forthcoming second section, we will seek to thoroughly clarify, elaborate on, and explain the basic principles of radiation physics along with the essential aspects of radiation protection that should be universally understood, meticulously learned, and diligently adhered to by all professionals who are operating in this highly specialized field. The fundamental nature of radiation physics encompasses a variety of intricate principles and applications that are absolutely indispensable for ensuring safe practice and delivering effective patient care. Following this introductory discussion, we will delve into an informative and detailed examination of how ionizing radiation is effectively utilized within the complex realm of medical physics, while also discussing its broader implications for clinical settings, healthcare processes, and the potential impacts on patient outcomes. In this analysis, we will explore various techniques and methodologies that are adopted in the medical field, which involve the use of ionizing radiation, while emphasizing its pivotal role in both diagnostics and treatment protocols that are administered in modern healthcare systems. This text ultimately concludes with an insightful analysis regarding the potentially serious and detrimental consequences of exposure to radiation, and it outlines various critical protection measures that should be diligently undertaken to effectively ensure the safety and well-being of both healthcare providers and patients alike in the dynamic and constantly evolving context of medical practices. The exploration of this complex and significant topic will aim to foster a more profound understanding of both the advantages and risks associated with radiation in the medical horizon, ensuring that professionals are thoroughly well-equipped to navigate this essential and critical aspect of contemporary healthcare [13, 55, 56, 57, 20].

2.1 Atomic and nuclear structure

The model of the atom was first proposed during the early stages of the 20th century, specifically in the transformative and dynamic years from 1900 to 1910. This initial proposition was a culmination of a series of groundbreaking and meticulously detailed experiments that rigorously examined the scattering patterns of alpha particles, particularly as they interacted with the incredibly dense nuclei of gold atoms. Observers who conducted these critical and revealing experiments noted with profound interest the striking observation that a considerable majority of the alpha particles passed through the gold foil without exhibiting any significant deviation at all. This remarkable finding led them to arrive at the monumental conclusion that atoms are predominantly composed of vast empty spaces rather than being made up entirely of solid matter, challenging previously held beliefs about atomic structure. In the year 1913, an exhilarating and pioneering quantum model of the atom was introduced, marking an extraordinarily significant advancement in the ever-evolving and revolutionary field of atomic theory. This groundbreaking theory is carefully constructed upon two primary postulates, both of which were absolutely critical and indispensable in shaping our comprehensive and nuanced understanding of atomic structure and behavior. The first postulate conveys a profound concept known as the quantization of angular momentum: this significant principle explains that an electron can only orbit the nucleus at distinct, specific energy levels that are quantized and discrete, rather than being able to occupy any arbitrary energy level. The second key and equally important postulate clearly states that a single photon is emitted every single time an electron makes a transition from a higher energy level to a lower energy level. This specific emission of energy corresponds to a unique frequency, with the energy of the photon being directly connected and intrinsically tied to this very frequency. It is vitally important to note and recognize that any photon can only possess the specific frequency that is directly associated with that transition; no other frequency can occur or be allowed within the established framework of atomic interactions. These unique frequencies are distinctive to each atom and contribute tremendously to the formation of its discrete line spectrum, which ultimately serves as a crucial and defining identifying characteristic for each chemical element found in the periodic table. Furthermore, the isotopes of any given element share the same number of protons that are situated within the nucleus; however, they can and often do vary in the total number of neutrons present within the atomic structure. This variance in neutron count leads to the existence of different isotopes for a particular element, each of which can exhibit varying and distinct physical properties that can be experimentally observed through various meticulous studies. The combined total of protons and neutrons that are present in the nucleus is commonly referred to as the nucleon number. Each specific isotope of a given element is denoted in a clear and systematic manner by using the element's name, followed by the number of protons it contains and the nucleon number associated with it. This systematic naming convention plays a vital and crucial role in helping to clearly distinguish between the various isotopes, providing a sharper and clearer understanding of atomic composition and behavior, essential knowledge and insight for anyone studying chemistry or adjacent scientific fields. This understanding enhances our grasp of complex phenomena observed in both theoretical research and practical applications in the natural sciences [58, 59, 60, 61, 62, 63, 64, 65, 66].

The size and shape of the nucleus found within an atom can be effectively evaluated and determined through a variety of sophisticated scattering experiments that involve various types of particles being methodically directed at the nucleus. While it is duly noted that the value of the radius can indeed vary depending on the specific energy of the scattering particle utilized in these complex experimental setups, the overall shape of the nucleus consistently retains a spherical form across different evaluations and detailed measurements. From these comprehensive experiments that employ advanced techniques and methodologies, it was discovered that the average nuclear radius is approximately one femtometer, which is a precise measurement that is commonly utilized in the field of nuclear physics and related disciplines. Additionally, it has been firmly established that the density of the nucleus remains remarkably constant, regardless of the specific type of nucleons that are inherent within it. Some particular nuclei exhibit a distinct excess of protons or neutrons when compared to other isotopes within the periodic table.

These specific types of nuclei typically tend to stabilize themselves by undergoing various processes such as emitting a positron or by attracting an electron from the outer shells of the atomic substructure, thereby resulting in a change in the nuclear configuration. The energy that is emitted during these significant and noteworthy nuclear processes is specifically known as positron emission energy, which plays a crucial role in our deepening understanding of nuclear stability and the various kinds of reactions that can occur. In the second scenario mentioned above, the nucleus can undergo numerous transformations that lead it into an excited state reflecting a new and distinct configuration of nucleons. These important transitions are frequently observed and interpreted as characteristic X-rays within the energy spectrum of the atom, thereby contributing valuable and insightful data to the field of spectroscopy. This also adds to numerous nuclear studies that seek to deepen and enhance our comprehension of atomic behavior, interactions, and the fundamental principles governing nuclear phenomena [67, 68, 69, 70, 71, 72, 73].

2.2 Radioactive decay

This is the detailed and systematic process by which a nucleus undergoes a transition to a notably different state, which occurs as a result of the emission of a photon that carries away energy from the nucleus. The newly attained state that the nucleus reaches after this transition could potentially be the ground state, indicating that in this specific scenario, it emits a high-energy gamma-ray following the transition. On the other hand, it might alternatively represent one of the various excited states that the nucleus could occupy. In situations where the nucleus transitions to an excited state, the process may result in several different types of particles being emitted. These emissions can include an internal conversion electron, which is involved in the intricate process known as internal conversion, or a standard, traditional conversion electron. Alternatively, it could result in the emission of an Auger projectile, which plays a significant role in the energy exchange processes that accompany nuclear transformations. The overall result of this multifaceted and complex interaction is precisely the generation of a daughter nucleus, which possesses its own distinct, unique gamma-ray spectrum. This spectrum can be meticulously analyzed to uncover and understand the various properties of the resulting nucleus. Furthermore, this daughter nucleus tends to exhibit different and notable physical characteristics when compared to the original parent nucleus from which it has undergone transformation. These characteristics include an altered atomic number and mass, leading to its own distinct set of nuclear properties that differentiate it from the precursor nucleus. It is also essential to highlight that the phenomenon of radioactive decay is fundamentally a stochastic, or inherently random, process, characterized by a fundamental lack of predictable patterns in individual occurrences of decay events. The only factors that truly govern whether the decay will ultimately occur within a given timeframe are the average number of decays that take place within a specific time interval, alongside the unique specific activity of the radioactive material. Additionally, the total population of decay nuclei that are present and available for decay at any given moment also plays a crucial role. The specific activity, a key metric in this context, is defined clearly as the activity at a specific given time \(t \), denoted by \(A(t) \). This specific activity is calculated by taking the number of decays occurring above a chosen arbitrary time interval, typically set at 1 second, and dividing this number by the total number of nuclei that are actively undergoing the decay process during that interval. The number of decays that occur over any designated timeframe closely adheres to an exponential distribution pattern. This pattern ultimately reflects the inherent randomness of the radioactive decay process. In essence, the probability that a radioactive source will have experienced a specific number of decayed events within a clearly defined time interval can be mathematically represented by a particular mathematical expression. This expression effectively captures the essence and nature of the decay process, highlighting its underlying statistical properties and ensuring that a much deeper understanding can be derived from closely observing such fascinating phenomena [74, 75, 76, 77, 78, 79, 80].

Chapter - 3

Interaction of Radiation with Matter

3.1 Fundamental interactions

The intricate and myriad interaction of radiation with matter stands as an area of fundamental and profound significance, exerting a substantial impact within the expansive and ever-evolving realm of scientific inquiry. This dynamic and multifaceted investigation encompasses a plethora of complex relationships that intricately involve both electromagnetic forces and nuclear phenomena. These fundamental forces serve a crucial role in shaping the behavior of a diverse multitude of elements and compounds contained within and among atoms. Moreover, this includes a broader range of contexts that encompasses the varied interactions between multiple types of molecules. Such intricate interactions extend far beyond mere theoretical frameworks; they truly embody the very core and essence of scientific exploration and endeavor in a rich and varied landscape. Researchers from across an impressive and extensive spectrum of scientific disciplines have committed substantial efforts, time, and a vast wealth of resources to the profound and demanding task of developing highly detailed theoretical frameworks and rigorous experimental methodologies. Their aim has consistently been to gain deeper insights into how and why these fundamental forces exhibit particular and distinct behaviors in a variety of specific contexts, both qualitatively and quantitatively. It is absolutely essential to highlight that these behaviors manifest across a broad spectrum of ever-varying conditions and diverse circumstances; thus, the journey of discovery remains endlessly captivating and continuously evolving. While numerous complex interactions of critical importance to physicists and materials scientists are undeniably significant to the wide-ranging field of medical physics, it is worth noting that only a finite number of distinctly different types of interactions emerge as primary concerns for either crucial diagnostic techniques or essential therapeutic applications serving modern medicine. The specialized and distinctly rapidly advancing field of medical physics adeptly harnesses well-established physical principles and employs highly advanced techniques in a meticulous and systematic manner, effectively addressing both fundamental and pressing problems that are prevalent in the intricate realms of biology and medicine.

This vibrant and multidisciplinary field plays an integral and indispensable role, contributing significantly to the academic research process, which functions effectively within various clinical and healthcare settings. Such diverse contributions not only enhance our understanding but also pave the way for pioneering and groundbreaking advancements that can greatly improve patient care and elevate medical outcomes to unprecedented levels. This ultimately reveals the intricate synergy between basic research and applied science in the critical context of health and illness in our society today. The ongoing and dynamic dialogue between theoretical explorations and practical applications continually shapes and influences the future landscape of both medicine and science alike, fostering an environment ripe for innovation and discovery [81, 82, 83, 84, 85, 86, 87, 88, 89, 90].

The first type of interaction that occurs is the direct ionization of an atom, which can happen through either a charged particle or by means of electromagnetic radiation, such as photons or beta particles. These interactions are notably significant and undeniably play a crucial role in various physical processes. However, the effects resulting from the production of secondary particles, which stem from such an interaction, are generally considered inconsequential when viewed within the broader context of the radiation protection regime that is commonly applied in practice. As a result of this perspective, these types of interactions, categorized as direct ionization, are often referred to as exceedingly simple and straightforward. They are seen as lacking in complexity when compared to other phenomena encountered in the field. The second broad class of interactions, on the other hand, is directly related to the electromagnetic forces that exist between charged particles. These charged particles include not only electrons and protons but also other charged nuclei that may be present. Unlike the more apparent direct ionization interactions that one might first consider, the forces at play here, along with the potential secondary particles that can arise from these subtle electromagnetic interactions, are characterized by a much less noticeable and far subtler nature. Despite being less noticeable, these subtle interactions can lead to the intricate formation of electrically charged atomic fragments as well as neutral atomic excitations. Both of these phenomena hold considerable practical importance in various applications ranging from radiation therapy to materials science and beyond. Although it is true that the nature and extent of the secondary particle production within living tissue is often viewed as inconsequential in many medical physics applications—largely due to the exceedingly small overall impact—it remains a fact that charged secondary atomic fragments generally exhibit small ranges. These ranges are typically on the order of about 1 μm or even less, which is minuscule indeed. Within this minuscule range, the energies of these particles can significantly influence the electrically inverse square law forces that act powerfully between atomic electrical charges. This interaction thereby affects processes at the quantum level, making it crucial to consider. It is also noteworthy that the electric charges of certain atomic particles including loosely bound orbital electrons and tightly bound nucleus protons are quantized multiples of a single elementary charge. This essential quantization forms a foundational principle that has allowed electromagnetic theory to account very accurately for all observable experimental consequences which arise from these quantized atomic interactions. This ongoing exploration leads to a deeper understanding of the fundamental nature of matter and energy, illuminating the intricate dance of atoms and subatomic particles that constitute the building blocks of the universe [91, 92, 93, 94, 95, 96, 97, 98].

3.2 Attenuation and absorption

In numerous medical applications spanning a wide array of healthcare contexts, a central concern that health professionals confront with great seriousness is the fact that radiation not only passes through but also interacts significantly and meaningfully with the patient's body during various medical procedures. This interaction gives rise to a multitude of important considerations that focus on both safety concerns and efficacy in the effective delivery of medical services to patients. Technologies such as X-ray radiography and computed tomography (CT) scanning are designed to create detailed and nuanced images that are fundamentally based on the intricate quantity of radiation that successfully reaches and interacts with different parts of the patient's complex anatomy. In the crucial context of radiation therapy, which stands as a vital and irreplaceable aspect of cancer treatment utilized in various clinical settings, the primary aim remains to meticulously and carefully control and adjust the precise amount of radiation that a patient receives. This goal remains critically important even in the presence of scattered beams, mixed tissue composition, and numerous variations in patient anatomy that may occur due to inherent individual differences among diverse patient populations. Given this vital concern, one of the most critical areas of focus within the expansive realms of medical physics and engineering is the thorough and rigorous study of the attenuation and absorption characteristics of radiation as it interacts with various types of human tissue. Comprehending the fundamental principles that govern how radiation diminishes and decreases in intensity as it travels through a range of biological substances is essential not only for effective production but also for the accurate interpretation and innovative application of imaging technologies and therapeutic procedures across diverse medical settings. This wealth of specialized knowledge not only significantly enhances the overall quality of patient care but also plays a crucial role in aiding the minimization of potential risks linked to radiation exposure for patients. By ensuring that patients receive optimal therapeutic outcomes while effectively safeguarding their health and well-being throughout the intricate and often complex processes involved in their care, healthcare providers can achieve a considerably higher standard of care in the treatment and diagnosis of a wide array of challenging medical conditions. This, in turn, ultimately leads to improved patient outcomes and satisfaction levels, promoting a safer and more effective healthcare environment for everyone involved [99, 100, 101, 102, 103, 104, 105, 106, 107, 108].

Consider a beam of monoenergetic photons that are traveling steadily in the z direction through a slab of material characterized by a specific thickness denoted as dz along the z axis. This particular slab possesses a certain density represented by the variable ρ, and it contains a defined number of electrons per unit volume, which is labeled as N. Each distinct incident photon within this beam has the potential to experience one of three unique fates during its interaction with the material: it may either pass through with minimal interaction, thereby continuing its journey unimpeded, be completely absorbed by the material itself leading to a total loss of its energy, or undergo scattering which may redirect it without complete absorption, thus altering its trajectory. The likelihood, or probability, for each of these three types of possible interactions occurring within the material is methodically quantified as μρdz for minimal interaction, σTρdz for absorption, and σCρdz for scattering, respectively. This nuanced representation allows for a clearer understanding of the photon behavior within the material. The comprehensive probability for a photon to interact in any manner at all is succinctly represented by the sum of these three events occurring: minimal interaction, complete absorption, and scattering. These calculated probabilities therefore provide us with valuable information pertaining to the different types of attenuation phenomena in play. These phenomena are crucial for understanding, predicting, and quantifying the behavior of photons interacting with various types of material and environments. Since the expectation value of a specific probability is commonly understood to reflect its mean value, this becomes particularly significant when it comes to practical applications. The attenuation of the expected value of a quantity that is directly related to attenuation and energy loss is essential, and this quantity is widely recognized as the 'half-value layer.' The half-value layer concept is particularly advantageous across a range of contexts, such as determining doses of radiation, evaluating dose rates over time, and effectively managing the reduction of radiation exposure to workers and individuals situated in proximity to sources of radiation. This understanding informs strategic approaches to safety and exposure reduction practices. Furthermore, when we denote N as the initial number of photons encountered within the material, and z as a numeric representation of a specific number of half-value layers traversed, the relationship expressed illustrates that N/2 corresponds to the reduced number of photons present after absorption has taken place, while N/4 represents the expected number of photons remaining after one additional half-value layer has been traversed. This understanding of photon behavior in relation to half-value layers is crucial and indispensable for effectively assessing, managing, and mitigating radiation exposure in practical situations encountered across a variety of scientific, medical, and industrial applications and contexts. Such insights bolster safety protocols, enhance operational standards, and promote healthier environments by allowing for better planning and control regarding exposure to radiation sources for all individuals involved in processes where radiation is a factor [109, 110, 111, 112, 113, 114, 115, 116, 117].

3.3 Scattering

In the intricate phenomenon of scattering, a primary photon that possesses a specific kinetic energy level finds itself interacting and colliding with an atom, an event which subsequently leads to the intricate generation of two or more secondary photons. Each of these resultant secondary photons, in turn, possesses lower energy than the original photon that initiated the vibrant interaction. The energy that was originally held by the primary photon is either effectively transferred into the form of energy of one of the newly created secondary photons, which by necessity has to be of lower energy, or it may manifest as a completely new photon that is emitted from the engaging interaction process. In addition to this significant transfer of energy, the kinetic energy associated with the recoiling atom that has been struck during the collision also plays a crucial and pivotal role in this dynamic exchange of energy among the particles involved. The likelihood or probability of each of these different processes occurring is determined by a variety of essential factors, including the crucial initial kinetic energy of the primary photon, the precise angle at which the scattering takes place, and the specific atomic structure and unique characteristics of the atom involved in this profound interaction. Among the various reactions and interactions that can take place in this complex context, our primary interest lies firmly in delving deeper into the well-studied Compton and Rayleigh types of interactions. This focus is primarily due to their significant role and relevance in the specialized field of photon dosimetry, where accurately measuring and understanding the doses of radiation is absolutely critical for a wide array of applications in both medical and scientific research. Understanding these intricate interactions better not only helps in developing more effective and robust radiation safety measures but also enhances and broadens our overall knowledge of the fundamental physics principles that meticulously govern these interactions and phenomena within the natural world. By doing so, we can appreciate the delicate balance and complex interplay that define the behavior of photons when they engage with matter on such a fundamental level [118, 119, 120, 121].

Generally, the probability of occurrence of a certain process within collision processes is fundamentally determined by the cross section of each individual reaction that takes place, which can vary significantly depending on a myriad of factors that are both intrinsic and extrinsic to the material in question. This concept can be illustrated effectively by employing a relatable analogy involving a sheet of paper, which serves to represent the atoms of the material we are discussing in greater detail and with more clarity. In this analogy, the act of throwing a stone at the paper symbolizes the scattered primary photon that collides with a fixed object, while, in this scenario, the fixed object directly represents the atomic cell of the material being analyzed for its various properties. This particular scenario elegantly illustrates how, when the throwing stone impacts the sheet, it can be deflected or absorbed in an array of numerous complex ways by the intricate and often unpredictable atomic structure of the material, which may consist of various elements, compounds, and bonds that contribute to its overall behavior. Consequently, the probability that the throwing stone is deflected in a specific manner by this fixed object will have a direct and profound influence on how we characterize and interpret the various properties observed in this object, leading to a deeper understanding of its unique characteristics under differing conditions. In this context, the product of the number of scattering centers present in the material and the overall probability of all scattering events occurring together is referred to as the mass attenuation coefficient, which is a key parameter in this discussion. This significant and vital coefficient reflects the cumulative effects of all the scattering events and interactions that take place within the material at a microscopic level, and it will provide reliable and essential information, especially when the probability of the scattering process, which is known to dominate the absorption processes of the primary photon beam, shifts significantly under varying experimental conditions. Understanding these intricate and often complex relationships is not merely an academic exercise; it is crucial for accurately modeling the complex behavior of different materials as they interact with various radiation sources, shedding light on how these materials respond dynamically under diverse conditions and circumstances. This profound understanding not only enhances our knowledge of the fundamental principles governing particle interactions at the atomic and subatomic levels but also has important implications for various applications in fields like materials science, nuclear physics, and radiation therapy, impacting everything from the development of innovative new materials to advancements in cutting-edge medical technologies and essential safety regulations that protect individuals working in or around these materials [122, 123, 124, 125, 126, 127, 128, 129, 130].

Chapter - 4

Radiation Detection and Measurement

Radiation detection, along with the meticulous and precise determination of the levels of ionizing radiation that exists in a multitude of environments, holds profound significance and critical relevance across all domains of radiation protection. This essential area of study encompasses various important aspects, such as the comprehensive assessment of medical radiation exposure, which can substantially influence patient outcomes and safety methodologies. Medical physicists, who are highly trained and experienced professionals specializing in the practical application of physical principles within a healthcare framework, routinely engage in the extensive utilization of diverse and sophisticated radiation detection methodologies to support their clinical responsibilities. They thereby fulfill their paramount obligations to patient safety and quality care in the healthcare system. A thorough and comprehensive understanding of the strengths, weaknesses, and inherent limitations of the various types of available radiation detectors, in conjunction with the fundamental physical processes governing their proper and effective application, is integral to the successful execution of their complex tasks in varied environments. The selection process and operational procedures associated with a particular radiation detector are influenced directly by the specific properties of the radiation being measured, along with the precise way the detector itself reacts, responds, and interacts with that particular radiation source. It is crucial to acknowledge that there does not exist a singular radiation detector capable of fulfilling all the diverse and complex detection requirements frequently encountered in real-world practice today. Instead, the unique characteristics and nuanced specifications of a specific application typically dictate the choice of a particular detector design, along with the corresponding detection system that will ultimately be employed in the specific environment concerned. Every radiation detector possesses its own distinct set of advantages and disadvantages, which necessitate careful consideration while making selections for practical use and implementation in various diverse scenarios. A thorough understanding of the specific characteristics of the radiation that is to be studied forms a vital framework for determining the essential qualities that a radiation detector must embody to provide acceptable sensitivity levels and achieve satisfactory performance outcomes. More often than not, the design of an effective radiation detection system necessitates a careful compromise among conflicting needs and requirements that are of paramount importance. These often include the heightened demand for elevated sensitivity to detect even the faintest levels of radiation, minimized physical dimensions for practical use and portability, high low-energy efficiency to respond accurately to a broad spectrum of energy levels, and a linear or quasi-linear response throughout an extensive dynamic range of measurement applications. The accumulated and expansive knowledge surrounding the detection of ionizing radiation, along with the associated processes involved in accurately measuring radiation levels, has evolved tremendously since the inception of these critical studies in the latter part of the 19th century. This evolution has expanded systematically over the decades to encompass a rich and diverse array of physical principles that intersect with multiple specialized fields. These include atomic and nuclear physics, spectral analysis, high-energy physics, and numerous other relevant disciplines, all contributing to a broader and richer understanding of radiation phenomena. Such interdisciplinary integration ensures the continued advancement, refinement, and enhancement of techniques and devices aimed at paving the way toward greater radiation detection and measurement capabilities. This collective progress plays a crucial role in improving both safety measures and scientific inquiry in various settings, ultimately enhancing our knowledge and capacity to address radiation-related challenges effectively [131, 132, 133, 134, 135, 136, 137].

4.1 Types of detectors

The detectors that are employed in the highly specialized and critically significant field of nuclear medicine can in fact be broadly categorized into two fundamental and absolutely essential categories: imaging detectors and dose detectors. The imaging detectors are specifically engineered and finely optimized for a diverse and varied array of applications, including but not limited to planar organ scanning and advanced gamma-camera imaging techniques, which facilitate the comprehensive acquisition of detailed insights, analytical information, and critical understanding into the precise functioning and operational status of various organs within the extraordinarily complex human body. On the other hand, dose detectors play an indispensable and pivotal role in the precise measurement and meticulous calibration of the amount of radiation exposure that patients are subjected to during various critical diagnostic procedures, thereby ensuring utmost safety, efficacy, and protection. It is of paramount significance and importance for these detectors to exhibit an extraordinary degree of selectivity, which entails that they should be fully competent and highly capable of discerning and effectively differentiating between the specific types of ionizing radiation that may be present in a given and specific environment, and they must also possess a remarkably high capacity to accurately capture, record, and analyze the intricate physical characteristics that are inherently associated with the different forms of ionizing radiation. In general, there exists a comprehensive and overarching expectation for these sophisticated and highly specialized detectors to demonstrate an exceptionally high sensitivity level, thus ensuring that they can efficiently detect faint signals that might otherwise go completely unnoticed, while simultaneously incorporating minimum energy thresholds to facilitate a thorough and comprehensive study of the objects of interest that are presently being examined in the medical context. The primary function of the imaging detector is to accurately and reliably record the spatial position of the ionizing radiation that is emitted by the subject or patient being examined during the entire imaging process. To effectively and adeptly accomplish this essential and critical task, the scanning detector systematically captures pertinent data and presents a real virtual image by diligently collecting this important information in a sequential manner, which ultimately results in a comprehensive and detailed representation of the detected radiation patterns and distributions throughout the human body. The detection matrix is intricately linked to an input device, such as a keyboard, along with a sophisticated display system, which function harmoniously together to maintain, manage, and visualize the images that have been obtained through the complex and intricate scanning process. The accumulated set of images is skillfully projected to visually produce an impressive and informative series of virtual images, greatly allowing medical professionals, specialists, and healthcare providers to analyze, interpret, and make informed decisions based on the rich data effectively and efficiently. Typically, the sophisticated and intricate equipment used in these advanced processes showcases the image that has been acquired by displaying the numerical values generated by the specific detector that has been designated to operate within that particular examination room. However, if all the detected points in a specific room are interconnected systematically, they can reveal a significant and critical point within the transverse plane of the human body, where the intensity of the radiating section that is directed towards the collimator is ultimately gathered and transmitted to the detector for thorough in-depth analysis. By utilizing this pertinent and vital information, it becomes possible to construct a detailed and accurate virtual image that represents a surface from which the radiation that has been emitted by the organ reaches the collimator for effective processing and evaluation. A scintillation camera serves as a notable and exemplary illustration of this specific type of detector that is utilized in the expansive field of nuclear medicine, showcasing the advanced technology, sophisticated methodologies, and innovative methods that are employed in modern and contemporary diagnostic practices, ensuring enhanced medical care, better outcomes, and significantly improved patient safety as a whole [138, 139, 140, 133, 141, 142, 143, 144, 145].

4.2 Dosimetry

Exposure pertains to the quantity of ionization that is induced by X or γ rays for every individual unit of mass present within a specific medium, and the unit that is used to quantify this exposure is referred to as the roentgen. The intricate phenomenon of ionization occurs chiefly as an outcome of interactions enabled through the photoelectric effect, which is indeed a vital process in the domain of radiation physics that significantly contributes to our understanding of how various forms of radiation transact with matter. In the practice of measuring the exposure of a beam of ionizing particles, one utilizes an ionization chamber that possesses a defined volume denoted as V. The detection wall of such a chamber is located at a particular distance R from the source of radiation, thereby enabling a complete description of the chamber being exposed to a radiation field characterized by an intensity denoted as Φ/x. Within this context, Φ serves as the symbol for the number of ionizations that occur per unit of time, serving as a reflection of the intensity of the incident radiation, while x indicates the spatial distance from the relevant point of consideration to the detection wall. Following this foundational understanding, the unit of exposure is intricately defined in close correlation with the count of ionizations that are produced within a selected area of air, wherein the liberated electrons effectively cease their motion within the same volume of the measuring chamber. By employing straightforward geometric considerations alongside fundamental physical principles, the total number of ionizations anticipated to occur at a designated distance x can be articulated mathematically as $N = 2xn/Ve$. In this formula, V signifies the overall volume of the chamber, while e represents the average energy required to successfully dislodge an electron from the atomic structure of air. This nuance underscores the complex interplay that exists between energy levels and ionization processes. Such understanding is fundamentally essential for scientists and engineers alike, particularly within specialized fields such as medical imaging, radiation therapy, and the stringent safety regulations that govern exposure to ionizing radiation. Gaining a deeper comprehension of these principles is not merely beneficial but utterly crucial for the precise measurement and subsequent analysis of exposure to ionizing radiation across various professional disciplines. This acquires greater significance when it is apparent that ensuring safety and strict adherence to established health standards are paramount in all of these fields of practice [146, 147, 148, 149, 150, 151, 152].

Ionizing radiation that is present in the atmosphere holds immense significance as it plays a crucial role in the generation of a considerable number of electron-ion pairs. This intricate and fundamental process is notably influenced by various pivotal factors, including the distance that the radiation travels as it propagates through the air, and the total energy lost throughout the entirety of its journey through different mediums. The intricate relationship between these elements strongly suggests that the quantity of ionizations generated for each unit mass of air serves as an effective and reliable method for characterizing the level of exposure an individual receives from the incoming radiation beam. In accordance with a widely accepted definition in scientific discourse, the unit known as the roentgen is particularly defined as an important and relevant measure of exposure, specifically created in the atmosphere by X-rays or gamma rays. This remarkable phenomenon occurs when a volume of air measuring 1 cm^3, which is equivalently weighing 1 gram, undergoes an ionization process that leads to the generation of an amount of electrical charge due to the movement and migration of a single positive charge. In a range of diverse scenarios where radiation travels through the air and successfully achieves ionization of a certain number of n particles, it effectively deposits a defined amount of energy, which can be represented as u, within a specific volume of air that has a determined density, denoted by m. The exposure can therefore be mathematically represented by the formula $(n/u) - 2/m$, which provides a quantitative understanding. This essential and significant relation indicates clearly that the level of exposure experienced is primarily dependent on the specific type of radiation that is under consideration in a given context. This dependency arises mainly due to the average energy, u, that the various particles tend to lose while they generate these critical and consequential ionization events. As we carefully consider the impact of varying air density, it can also be expressed in a different form, where we denote $m = 2/V$, leading us to understand that the exposure can also be comprehensively defined in terms of n and u by investigating the product of n, multiplied by the ratio of the air's density in relation to the average energy that radiation dissipates while it traverses through the specified volume. This nuanced and detailed understanding significantly enhances our comprehension of how ionizing radiation interacts with the various elements present in the atmosphere, which ultimately affects the ionization rates along with the exposure levels experienced under different situations and scenarios. By engaging in this expanded understanding, we vastly enhance our ability to appreciate the complexities involved in radiation exposure, helping to inform safety measures, regulatory compliance, and scientific exploration in the burgeoning field of radiological science and safety protocols [147, 153, 154, 155, 156, 157, 158].

Chapter - 5

Biological Effects of Radiation

Radiation protection undeniably represents a crucial and foundational component of the extensive and diverse range of medical practices and procedures that utilize radiation in numerous forms and applications. The various and diverse exposure conditions that are often encountered in a multitude of medical settings significantly underscore the need for a comprehensive and meticulously detailed understanding, paired with a full and nuanced appreciation of the principles that underpin and support the effective implementation of robust and comprehensive radiation protection measures across these many differing medical practices. The standards for medical radiation protection are systematically established and clearly delineated based on authoritative recommendations that are carefully coordinated through the united efforts of several international organizations that have dedicated themselves to health and safety. These organizations work tirelessly to assure that all guidelines and protocols are adhered to with precision and conscientious diligence, reflecting a commitment to the highest standards of safety and care. These extensively established standards are specifically designed to ensure that radiation exposure is minimized to the absolute lowest extent possible while being managed effectively and appropriately in all pertinent situations and circumstances. The dose limitations articulated in these comprehensive and systematically structured standards specifically pertain to various stakeholders including individual professional radiation workers, the general public, and the patients who are receiving various treatment methodologies that involve exposure to radiation. Additionally, this framework importantly addresses the vital and significant aspect of the perinatal dose limit, which is particularly relevant to the embryo or fetus during those highly vulnerable and critical stages of development. The protection of these delicate and sensitive populations is of the utmost importance, as even minimal exposure to radiation can possibly lead to significant and deleterious health consequences that could materialize later in life and potentially affect their overall development. Moreover, the concept of a radiation worker is thoughtfully expanded beyond merely those individuals who are formally required to work regularly and consistently with ionizing radiation; it also encompasses those workers who may not necessarily be mandated to handle radiation sources on a daily basis but who might still be potentially exposed to such radiation within their varied and diverse work environments. This broader and more inclusive definition recognizes the reality that various professions may inadvertently incorporate incidental and uncontrolled exposure to radiation; therefore, effective safety measures should be unreservedly and rigorously in place to protect all individuals who might be affected by exposure in any manner. By ensuring a wide net of comprehensive protection, the overall safety of the community and the healthcare environment itself is enhanced significantly, underscoring the critical importance of collective responsibility in the maintenance of health and safety standards across all sectors. Furthermore, it is paramount to conduct regular training and updates for all pertinent personnel, ensuring that the latest information and technologies regarding radiation safety measures are effectively communicated, implemented, and integrated into everyday practices. This ongoing commitment to education and vigilance plays a pivotal role in safeguarding not only the workers involved but also the patients receiving care, as well as the broader public, all of whom deserve protection in this crucial aspect of healthcare and safety. Ultimately, the principles of radiation protection are essential for fostering a robust culture of safety, where the risks associated with radiation exposure are continually assessed and systematically mitigated through proactive strategies, ongoing community engagement, and a steadfast dedication to public health and safety standards. The commitment to these principles reflects a wider understanding that, while utilizing radiation can be fundamental to medical advancements, the safety and protection of everyone involved must always remain a top priority [159, 160, 138, 161, 162, 11, 163, 164, 165, 166].

The comprehensive and multifaceted theory of radiation protection encompasses a multitude of critical and essential aspects that relate not only to the safeguarding of radiation workers and the general public but also to the specific procedures that involve suitable intervention measures. Notably, the nuanced protection of pregnant workers stands out as an area of particular concern. This intricate and complex framework is firmly established on extensive, thorough, and meticulous analysis concerning the various biological effects that can be imposed by ionizing radiation on living organisms. Furthermore, the theory utilizes an extensive array of epidemiological data, which is meticulously complemented by experimental information obtained from laboratory animals, as well as cultured cells in controlled environments. This combination significantly enhances our understanding of the wide-ranging implications and potential risks associated with radiation exposure. A thorough and detailed knowledge of the specific biological endpoints that may arise directly as a consequence of ionizing radiation, as well as a solid and comprehensive grasp of the specific terms and quantities that are essential to accurately measure and quantify these various effects, remains a foundational concern in not only medical practices but also in the evolving fields of diagnostic imaging and radiation therapy. Recently, a significant report has surfaced in the scientific literature, which has highlighted a concerning reduction in birth weight among babies born to mothers who had undergone medical radiodiagnostic examinations during their pregnancy period. This particular and alarming finding could potentially represent one of the very initial indications emerging from human studies that concern a collateral damaging potential effect of radiation exposure, particularly in relation to crucial developmental and growth parameters for infants. While the data collected and analyzed thus far may not yet be viewed as definitive or conclusive evidence, the biological mechanisms that predispose individuals to the manifestation of this concerning effect are already well cataloged, documented, and understood within the scientific community at large. Additionally, the observation of the absence of a definitive threshold for detectable genetic effects of radiation in the descendants of individuals who were exposed to low dose levels provides robust support for the prevailing and widely accepted hypothesis. This suggests that there does not exist any observable threshold for genetic effects of ionizing radiation. This is especially relevant in relation to the natural incidence of genetic mutations that occur and accumulate over time within populations, raising further questions about the long-term implications of radiation exposure on genetic stability and overall public health [163, 167, 168, 169, 170, 11, 171, 172, 173, 174].

5.1 Deterministic effects

The deterministic effects that are associated with radiation exposure are manifold and encompass a wide variety of serious issues that can arise directly as a consequence of such exposure. These serious health issues include, but are not limited to, radiation burns, the hematopoietic syndrome, gastrointestinal syndrome, and the neurovascular syndrome. Such significant health conditions manifest as a direct and noteworthy result of the damage inflicted upon specific populations of cells within the human body. Among these populations are critical cellular components, such as conventional stem cells, which play an essential and irreplaceable role in the vital process of regenerating and producing all vital blood cells needed for survival.

Furthermore, intestinal crypt cells are indispensable for maintaining the overall integrity and functionality of the gastrointestinal tract, ensuring that it operates effectively and efficiently under normal and stressful conditions. In addition to these critical cell types, microvascular endothelial cells are equally crucial as they ensure the proper and robust functionality of the body’s complex vascular system, which is fundamental for sustaining overall health and wellness across multiple bodily systems and organs. A deterministic effect will only begin to manifest itself if a particular threshold of radiation dose is exceeded, which leads to significant physiological consequences that can be quite severe and, in some cases, even life-threatening. This specific dose threshold is typically measured in several grays (Gy), and it is important to note that as the radiation dose increases, the value of this threshold dose tends to decrease considerably over time. As this threshold dose decreases in value, the severity of the symptoms experienced by the affected individual tends to increase correspondingly, thereby creating a complex and multifaceted relationship between the exposure to radiation and the perceived health impacts that may rightly ensue. The relationship that exists between the dose of radiation administered and the resultant health effects is typically characterized by what is referred to as a step-function type of response, clearly indicating that there is a specific threshold of the radiation dose at which cellular damage begins to become significant. This is often followed by a different threshold level beyond which the damage becomes clinically apparent and starts to manifest as observable symptoms in patients who have unfortunately been affected by such exposure. In relevant literature focusing on the intricate and crucial field of radiation biology, these specific effects are often referred to as threshold effects due to their distinctive and defining nature. Deterministic effects have been thoroughly documented in individuals who have regrettably experienced unintended accidental exposure to penetrating radiation, especially in clinical and research settings. This documented evidence is particularly evident in extreme scenarios such as nuclear accidents or serious radiological incidents, where established safety protocols unfortunately fail to adequately protect individuals from potential harm. The onset of symptoms associated with these serious effects typically becomes apparent relatively soon after exposure has occurred, leading to increased concern for affected individuals. The timeline for the manifestation of symptoms can range from merely a few days to several weeks or even longer following radiation exposure. This situation highlights the urgency and seriousness of obtaining prompt medical attention in the event of such radiation exposures, as the health risks can evolve rapidly and unexpectedly with serious implications. Early intervention is critical for effectively managing and mitigating these dangerous consequences and thereby improving the chances of recovery for those who have been adversely affected by deterministic effects stemming from their exposure to radiation, as it can significantly influence their treatment outcomes and overall health trajectory moving forward [175, 20, 176, 177, 151, 178, 179, 180, 181].

In the situation where there exists penetrating whole-body exposure to radiation doses that exceed 2 Gy, the symptoms that are associated with such exposure tend to manifest in a progression that encompasses three distinct stages.

Stage 1: The early initial stage is known to commence within a timeframe of only a few minutes to several hours following the exposure, and it can continue to persist for as long as several days. During these initial crucial minutes, or within a few hours, after a person absorbs a whole-body dose of radiation that surpasses the critical threshold of 2 Gy, the subjective symptoms that may arise could encompass a variety of physical reactions, which typically include nausea, vomiting, and diarrhea. Specifically concerning the gastrointestinal syndrome that correlates with doses exceeding 6 Gy, the symptoms that are experienced become markedly more severe and alarming, presenting with pronounced vomiting, relentless diarrhea, significant dehydration, and notable electrolyte imbalances that are already manifesting within mere hours following exposure. These intense and distressing symptoms may then diminish temporarily, fading away only to reappear later after a latency period of several days or potentially even weeks, eventually posing a significant and substantial risk of mortality for the affected individual.

Stage 2: The latent period that occurs in the aftermath of the initial symptoms is heavily influenced by the amount of radiation that has been absorbed by the individual receiving the dose. In general terms, the greater the dose of radiation absorbed by an individual, the shorter the overall duration of the latent period tends to be. This specific period can lead to a temporary phase of recovery during which the individual may appear to be entirely symptom-free, creating a deceptive sense of security that can be misleading, as one might falsely believe they are out of danger.

Stage 3: The final and often later second stage emerges with grave and severe symptoms, which may unfold after a duration that can exceed the length of the erstwhile latent period, persisting for several days, several weeks, or potentially even months afterward. For certain sensitive tissues within the body, specifically focusing on bone marrow and other radiosensitive tissues found within, an individual who has received a dose that remains below a critical threshold may find that they can recover from the initial symptoms that were experienced. However, the symptoms that are induced by radiation which become apparent after a clearly defined latent period are also prevalent in other vital and crucial cells, including those found in the brain, spinal cord, eyes, lungs, and heart. In these unfortunate scenarios, recovery may not be a viable possibility for the individual, and death could potentially occur within several days to just a few weeks following the exposure to intense and damaging radiation [182, 175, 183, 184, 185, 178, 186, 187, 188, 189].

5.2 Stochastic effects

Radiation protection is fundamentally rooted in the essential and well-recognized principle of keeping the exposure for any individual as low as is reasonably achievable, which is commonly abbreviated to the acronym ALARA. This guiding principle necessitates the meticulous and thoughtful establishment of dose limits that are specifically tailored for workers who operate within the radiation field, thereby ensuring their safety and well-being on a daily basis. Furthermore, it encompasses the careful designation and assignment of various reference levels that apply to the general public at large, which reflects a broader responsibility to protect all individuals, regardless of their occupation, from the potential dangers associated with radiation exposure. This comprehensive approach indicates a commitment not only to the workforce but also to the community as a whole. It is crucial to recognize that no particular detriment or negative health effect is generally known to manifest below these established protective levels, thereby underscoring the importance of adhering steadfastly to these vital safety measures at all times. However, it is of great significance to mention that when radiation exposure exceeds these pre-established safety levels, various health effects may indeed manifest in a manner that is proportionately correlated with the extent and degree of exposure incurred by the individual experiencing it. The severity and overall impact of such health effects, which may be experienced by a group of individuals exposed to radiation, will generally tend to increase in a direct correlation with the exposure levels faced by each individual within that same group. Deterministic effects, which are particularly concerning and critical in the context of various radiation exposure scenarios, have a clearly defined threshold; only those individuals who are exposed to doses that surpass this critical threshold are deemed to be at increased risk for these more severe and adverse health impacts. This reinforces the need for continuous education and training in radiation safety among those who work in radiation-related fields. Therefore, great care must be taken to ensure that all safety protocols and procedures are followed diligently and rigorously, not only to protect against undue exposure but also to minimize the risk of adverse and detrimental health outcomes that could arise from radiation incidents. Compliance with safety standards, regular monitoring, and assessments are essential components of effective radiation protection strategies. The complexity of radiation safety necessitates a collective effort that involves not only the individuals who are directly exposed to radiation but also the organizations that govern, regulate, and oversee radiation practices. In this context, collaboration among regulatory bodies, industry stakeholders, and safety professionals is critically important. Implementing robust safety culture within organizations enhances the overall effectiveness of radiation protection measures and fosters an environment where safety is prioritized. Moreover, public awareness campaigns aimed at educating the general populace about the perils of radiation exposure and the significance of safety standards can play a pivotal role in achieving widespread understanding and compliance. Effective radiation protection strategies must be viewed as dynamic systems that require periodic reviews, updates, and improvements to address emerging technologies and practices that may influence exposure levels. Therefore, it is essential to stay informed about advancements in radiation research, changing regulations, and best practices in safety management to ensure that protective measures remain relevant and effective. In essence, the paradigm of radiation protection is not static; it evolves alongside our understanding of radiation science, health effects, and advances in protective technologies, thereby enabling a comprehensive and proactive approach to safeguarding the health of individuals and communities alike [190, 191, 192, 22, 9, 193, 194, 195, 196].

On the other hand, exposure to radiation can lead to a wide variety of non-specific, detrimental damages to the DNA strands that are present within living cells, and this type of genetic damage may unfortunately persist throughout the entire lifespan of the affected cell, often leading to serious long-term consequences. This persistent genetic damage can result in the manifestation of what are known as 'stochastic' effects, which tend to arise in a random manner and without any specific predictability. The likelihood of these stochastic effects occurring tends to markedly increase as the radiation dose administered escalates. Stochastic effects encompass a broad and concerning range of serious health issues, including radiation-induced cancers, which are particularly alarming, as well as genetic damage that has the potential to be passed down to the offspring of individuals who have experienced various forms of radiation exposure in one capacity or another. Furthermore, in addition to these significant and alarming risks, even low doses of radiation can potentially lead to these detrimental and harmful effects over time. Although the actual probability of experiencing such effects is relatively low at these lower doses, it is still widely accepted within the scientific community that there exists no dose level that can guarantee an absolute absence of risk associated with radiation exposure. This concept is fundamentally based on a linear dose-response relationship that effectively models the cancer risk associated with radiation exposure in a nuanced manner and delves deeply into examining its correspondence with various possible underlying biological mechanisms. These underlying mechanisms can include multiple phenomena such as cell death as a direct result of the exposure, along with radiation-induced increases in mutation rates, which can occur in either one or both copies of a specific gene that resides within individual cells themselves. To develop a better understanding of this intricate relationship, data collected from comprehensive studies involving animals, extensive cellular research, and sophisticated mathematical modeling were utilized to quantitatively assess both a multiplicative and an additive model concerning the complex association between the radiation dose and both the excess relative risk as well as the excess absolute risk of developing cancer stemming from that radiation exposure. As an essential part of the dosimetry process, the tissue dose equivalent refers specifically to the exact amount of radiation energy that is deposited per unit mass within a particular type of tissue or organ inside the human body. This important metric plays a critical role in establishing regulatory dose limits, evaluating the efficacy of operational health physics procedures that are specifically designed to keep the effective dose equivalent for workers well within recognized safe limits, and in assessing the validity of dose-response models through meticulous epidemiological data analysis conducted over numerous cases. Both risk assessment and radiation absorption based on solid epidemiological evidence are considered crucial and foundational aspects of this field, and furthermore, the protection of patients and healthcare workers during the entire intricate process of cancer diagnosis and treatment stands as an essential obligation of every qualified medical physicist who is involved in these significant and often critical endeavors [197, 198, 199, 200, 201, 202, 203, 204, 205].

Chapter - 6

Radiation Protection Principles

In contrast to the traditional practices that are usually associated with classical radiology, the intriguing field of nuclear medicine entails the precise and meticulous administration of carefully measured activities derived from various radioactive sources directly into the human body in an exceptionally controlled and systematic manner. This intricate and multifaceted process serves both crucial diagnostic and therapeutic objectives, showcasing effectively its remarkable versatility, effectiveness, and potential applications within the realm of contemporary medical practices. This fundamental distinction not only highlights but also underscores the innovative and unique approach that nuclear medicine embodies, which relies heavily on the systematic use of specialized radiopharmaceuticals that are explicitly designed to interact with distinct biological processes occurring within the body in a highly targeted way. Moreover, in response to the unique and specific needs of individual patients and the healthcare system at large, a following section of this comprehensive discussion will be committed specifically to thoroughly exploring the fundamental principles of radiation protection that are absolutely essential in this specialized field of medicine. This in-depth exploration is crucial since it necessitates a comprehensive understanding of essential concepts in both radiation physics and dosimetry, which play an integral role in promoting patient care while ensuring safety in everyday practice. It is of the utmost importance for practitioners and professionals who operate within this ever-evolving and dynamic field of nuclear medicine to be thoroughly well-versed in these foundational elements, as they are vital to ensuring both safety and effectiveness in the utilization of radioactive materials during various complex and nuanced medical procedures. Each careful step taken in the application of these principles serves not only to enhance patient outcomes significantly but also to minimize potential risks associated with exposure to radioactive materials. By adhering diligently to these established guidelines and protocols, healthcare providers can promote a safer environment for patients while maximizing the therapeutic benefits of nuclear medicine, thereby ensuring that all practices align impeccably with the high and exacting standards of safety that patients indeed deserve and expect [206, 141, 207, 208, 209, 210, 211, 212].

To ensure that ionizing radiation is employed with a minimal degree of radiation risk, particularly for humans and living organisms, a specific and comprehensive regulation that governs the use and radioprotection of ionizing radiation sources has been meticulously and carefully developed over an extended period. This diligent and systematic process has led to the establishment of a well-defined and coherent framework, systematically designed with the sole aim of safeguarding health and minimizing harmful exposure to radiation. Within this crucial and vital context, there are three fundamental principles that are inherent and essential in almost every radioprotection law that is established: the principle of justification, the principle of optimization, and, naturally, the principle of dose limit, all of which play a critical and indispensable role in enhancing safety protocols. The justification principle stipulates that any practice which involves the use of radioactive sources must only be carried out when the potential benefits significantly outweigh the radiation risks that are incurred through their use. This principle not only emphasizes the critical responsibility of those who are in charge of applying radioactive sources responsibly and competently, but it also involves patients or their guardians, who must provide informed consent while fully understanding the prospective risks and benefits associated with the use of such sources. This comprehensive process ensures a meticulous and thoughtful consideration as well as a thorough assessment of the potential outcomes, thereby reinforcing the paramount importance of safety, ethical standards, and well-being in the application of ionizing radiation in medical practices. This vigilant and cautious approach is equally vital in other relevant fields, industries, and applications where such advanced technology is utilized appropriately and judiciously for the benefit of society. The ongoing evolution of regulations reflects a deep and unwavering commitment to effective radioprotection strategies, which are designed to protect both workers and the public from unnecessary exposure, while also promoting advancements that can lead to better health outcomes with minimal risk. By adhering to these foundational principles, society can ensure that the use of ionizing radiation remains a safe and effective tool in various applications, fostering trust and confidence among those who rely on these practices for health and safety [190, 213, 214, 215, 216, 217, 218, 219, 151, 220].

The principle of optimization signifies that any procedure, operation, or practice which incorporates the use of ionizing radiation must be carried out in such a manner that the resulting doses of radiation exposure consistently remain well below the established and formally recognized dose limits that have been meticulously put in place by relevant authorities and regulatory bodies. This criterion is crucial in ensuring that the radiological protections afforded to both medical staff and patients are not only effective in nature but also rigorously enforced throughout all applicable scenarios across various healthcare settings. Ultimately, the governing principle of limiting the dose dictates that a person's exposure during an X-ray examination, for instance, must not exceed specific and measurable thresholds that have been clearly delineated by regulatory authorities based on substantial evidence and thorough risk assessment practices. These established thresholds can vary significantly and markedly, depending on whether the exposure is classified as occupational, which refers specifically to those individuals who work diligently within the radiological field and deal directly with the equipment, or pertains to the general public, a category that includes patients and any individuals who may be exposed incidentally and without intent to the radiation sources that are in use. It is indeed important to note that if the law were not designed with effective enforcement mechanisms, it should nonetheless include clear definitions, understandable regulations, and stringent guidelines that will enable its application to be both practical and comprehensible when it is enforced across a variety of settings in healthcare environments. Such precise definitions of the various protective measures are vital concepts that form the foundation of any substantially modern discourse related to the practice of radiation therapy and its associated protocols and safety measures. This relevance extends well beyond the strict confines of therapeutic contexts, encompassing broader considerations surrounding dose curves, risk assessment models, and comprehensive radiation exposure management strategies that are imperative in today's healthcare landscape. These definitions serve as essential guidelines that aid in navigating the often complex intricacies involved in ensuring safety, compliance, and adherence to rigorous regulatory standards that are essential within the field. They work collectively to create an environment in which the use of radiation is maximized for the direct benefit of patients while effectively minimizing potential risks to health and overall safety across all relevant scenarios encountered in the medical field [221, 222, 223, 9, 11, 224, 225, 226, 227].

6.1 ALARA concept

The ALARA concept has firmly established itself as the essential and indispensable foundation of modern radiation protection practices and methodologies. This vital principle is decidedly rooted in two fundamental tenets that have been widely recognized and accepted across various sectors and industries as the compelling justification for implementing and enforcing effective radiation protection measures. The first principle emphasizes the critical necessity of keeping radiation exposure as low as is reasonably achievable, thereby ensuring the utmost protection of public health and the environment from potential hazards. This crucial directive mandates that all possible steps and actions should be vigorously pursued to minimize exposure, taking into account both individual circumstances and broader environmental considerations. It serves as a crucial reminder that the responsibility for maintaining safety lies not only with regulatory bodies but also with every individual and organization involved in activities that could result in radiation exposure. Meanwhile, the second principle takes into account significant economic and social factors that can greatly impact the overall approach to ensuring comprehensive radiation safety, health, and the well-being of communities at large. This principle clearly recognizes that economic constraints and social implications can sometimes present obstacles to implementing the most stringent safety measures effectively. Therefore, it allows for a pragmatic approach that efficiently balances the imperative for safety with the realistic challenges of cost and resource allocation. By strategically integrating these two tenets, organizations ranging from healthcare facilities to nuclear energy plants can effectively establish a robust framework that not only adheres to rigorous safety standards but also adequately meets the diverse needs of society in real-world scenarios. Consequently, the thoughtful integration of these two tenets serves as a comprehensive guide for implementing effective and sustainable strategies in radiation protection, allowing for a balanced consideration of health risks alongside societal needs. It provides a meticulously structured method for thoroughly evaluating multiple radiation exposure scenarios, ensuring that both immediate health concerns and long-term environmental impacts are diligently taken into account as part of the decision-making process. This holistic approach is absolutely crucial for promoting a sustainable and safe environment that prioritizes both safety and economic viability in the face of pervasive radiation-related challenges that may arise in various contexts. Ultimately, the ALARA principle advocates passionately for a shared and collective commitment to fostering a culture of safety, where every stakeholder plays a vital and indispensable role in the collaborative effort to protect both human health and the environment from the potentially harmful and detrimental effects of radiation exposure. In doing so, it emphasizes the importance of collaboration, vigilance, and education in enhancing the effectiveness of radiation protection practices worldwide, thereby contributing to a healthier and more secure future for all [190, 228, 229, 230, 231, 232, 213, 54].

ALARA is often regarded as the golden rule of radiation protection in a variety of contexts and scenarios, underscoring its vital importance across numerous fields. This principle is widely recognized as a fundamental guiding concept one that is indispensable for effectively managing and mitigating risks associated with radiation exposure. It functions seamlessly in all types of circumstances, particularly when critical decisions must be made under pressure, especially in cases where there is a pressing need to modify or change exposure conditions in a timely manner. ALARA encompasses an extensive array of factors, including staff exposure, public exposure, and exposure resulting from planned situations, in addition to exposure that occurs from existing conditions that may pose risks. This crucial principle is rigorously and consistently applied in both normal operational contexts and emergency occupational situations, steadfastly ensuring that comprehensive safety measures are upheld while managing and minimizing exposure risks to all individuals involved and affected. By steadfastly adhering to the ALARA principle, organizations can greatly enhance the safety of their operations while simultaneously minimizing the potential hazards related to radiation exposure. Moreover, this principle fosters a culture of continuous evaluation and enhancement of practices and protocols to assure that radiation exposure is consistently kept to an absolute minimum. This commitment promotes a firm culture of safety and accountability, reinforcing the organization's dedication to safeguarding not only employees and the general public but also the surrounding environment in which these activities are carried out. Ultimately, this reflects a holistic and comprehensive approach to radiation protection that seeks to benefit society as a whole, ensuring the wellbeing of current and future generations [233, 191, 234, 235, 236, 237, 238, 239, 240].

The fundamental objective of ALARA, articulated specifically in the critical context of operational radiation protection, is to ensure that doses to individuals, as well as to various populations and communities, are kept as low as reasonably achievable at all times, all without compromising safety considerations that are paramount. This significant principle involves careful and detailed consideration of numerous social, economic, and environmental factors that come into play, factoring in the varying levels of exposure that individuals may encounter in their unique circumstances and the different risks associated with known, probable, and even speculative situations that may arise. Additionally, it is of utmost importance to recognize the inherent variability of human responses to these distinct forms of radiation exposure, which must be duly acknowledged, alongside the natural background levels of radiation that are invariably present in our environment. These natural background levels can fluctuate significantly based on geographical location, altitude, and local sources of radiation, and thus understanding them is essential for effective and robust radiation protection. This comprehensive and thorough approach inherently provides an elastic and highly adaptable interpretation of the ALARA concept, allowing for a nuanced and context-sensitive understanding of its broad implications in various scenarios, whether in public health or industrial applications. The allowable flexibility embedded within this framework permits the effective and appropriate implementation of the ALARA principle in alignment with the specific social, economic, organizational, and technical conditions that vary widely within different countries and across diverse regulatory landscapes. Consequently, ALARA is designed to be universally applicable across a diverse range of circumstances, making it inherently action-oriented in its design and execution. Furthermore, it is strategically aimed at fostering a gradual and continuous reduction of radiation doses over time to protect public health and safety in a meaningful way. This ongoing endeavor can sometimes be significantly facilitated by a self-management approach in specific situations, particularly where relevant stakeholders, including organizations and individuals, are actively encouraged to take ownership of their radiation protection measures and responsibilities. This empowerment ensures that the doses remain consistently low and are fully compliant with the overarching safety goals that have been established by regulatory bodies and health organizations alike. By promoting a culture of safety and responsibility, ALARA not only aims to achieve compliance but also to instill a deep-rooted respect for safety among all practitioners involved in radiation practices across various sectors and industries, ensuring that these principles are integrated into daily operations and standard procedures [195, 190, 193, 196, 22, 9, 192, 241, 213, 242].

6.2 Shielding design

All barriers are meticulously engineered to possess more than adequate shielding capabilities, ensuring they can not only support their own intrinsic weight but also withstand any additional forces that may arise during their diverse operational contexts. The following enumeration serves as a key reference for the multitude of loading parameters employed in the comprehensive evaluation of shielding requirements, which are absolutely essential to uphold the overall integrity and effectiveness of the barriers. The structural loads that are imposed on these barriers will be systematically calculated employing the precise methods carefully delineated in the manual specifically designed for Structural Steel Buildings. In relation to the methodical assessment of roof live loads or any other horizontal loads, these will be approached at the discrete and detailed level whenever applicable, utilizing the designated and relevant building codes alongside the prevailing snow load standards that govern current construction practices. It is crucial to note that an asterisk is routinely employed to denote any appurtenances located conveniently on the roof, which could encompass HVAC units, ventilation systems, and other essential equipment that are necessary for maintaining optimal operational functionality. Furthermore, when considering seismic impacts, we will assess not just the structure itself, but also any mechanical or electrical elevator equipment thoroughly integrated within the overarching design framework of the building. Additionally, we will take into extended consideration seismic influences related to file storage, which includes file loading and/or the configuration of file cabinets, as well as any storage irregularities or peculiarities that may significantly affect overall load calculations, thereby impacting structural safety and integrity. The potential impacts of wind will also be thoroughly analyzed, with due diligence to the effects that emerge on structures, mechanical areas, and other crucial locations that are adjacent to streets or open spaces. Moreover, the wind loading will be meticulously evaluated regarding penthouses, whether they are occupied or unoccupied, in addition to assessing the broader implications for any solar equipment that may be installed on the premises, thereby ensuring a comprehensive understanding of all forces at play in the environment [243, 136, 124, 244, 245, 246, 247, 248, 249].

The facility must be comprehensively and adequately shielded in a thorough manner to effectively control, mitigate, and limit the potential doses of harmful radiation that employees may encounter while they are diligently engaged in their work outside of the specifically designated shielded and controlled areas that are designed with their safety as the utmost priority. The appropriate and necessary degree of shielding required for such an environment will depend significantly and critically on various factors, particularly on the specific dose rate that is produced in the work area where radiation may be present, which is a crucial factor in determining the overall safety and well-being of all personnel involved. In general, it is widely observed and understood that the higher the dose rate emitted in a given area, the thicker and more robust the walls of the radiation shielding must be constructed in order to ensure maximum safety, protection, and assurance for all involved personnel. Health Physics professionals, who have specialized knowledge and expertise in the meticulous study of radiation and its potentially harmful effects on human health, can effectively provide comprehensive shielding requirements by employing either the modern approach or the more traditional method of evaluation for effective and reliable shielding design. With the modern approach employed, the dose rate that is precisely measured outside the shielded control area, in combination with the frequency of use of that area, will fundamentally determine the crucial and necessary design criteria that are essential for effective shielding to protect all employees from potential radiation exposure. On the contrary, for the more traditional approach, both the frequency of use and the occupancy factor play critical and foundational roles in establishing the design criteria that are indeed needed for the development of appropriate shielding that is efficient and safe. The detailed design criteria outlined in this document have been carefully developed, structured, and scrutinized based on a more liberal and flexible use factor to ensure the maximum safety and effectiveness for all individuals who may potentially be exposed to radiation during their work duties. It is absolutely essential to meticulously design a wall or a roof/ceiling barrier that incorporates the correct shielding factor, which is tailored specifically for the unique task it is intended to shield against while effectively utilizing either one of the two approaches that have been described above. Furthermore, it is of utmost importance to ensure that this crucial barrier is not only structurally sound and well-constructed but also reliable enough to withstand the normal operating conditions that may occur in the facility, and additionally any abnormal situations that may arise unexpectedly and require immediate and urgent attention. These abnormal situations might include seismic loading and other dynamic forces, which can put additional and significant stress on structural integrity, as well as conditions like extreme wind speeds of 90 mph, which is based on the geometrically basic wind speed determined by local codes and regulations, to provide an additional layer of safety and security for all employees who work diligently within the facility on a daily basis. Ensuring these considerations can significantly enhance the safety and integrity of the facility in the face of a variety of challenging and unpredictable conditions [244, 250, 129, 124, 251, 252, 253, 254, 255].

Evaluate the wall that is situated directly in the line of sight of the High Voltage Line (HVL) for the specific lead thickness that is required to provide adequate and effective radiation protection. It is absolutely essential to determine the necessary thickness of lead shielding based on not only the HVL but also the presence of other potential sources of gamma radiation that may be contributing to the overall exposure experienced in the vicinity. In this particular scenario, it is crucial to consistently choose the greater of these two critical measurements when assessing lead thickness to ensure optimum safety and full compliance with established regulations. The following data extensively outlines the specific extent of areas that require robust shielding for a particular radiation source currently under consideration. On the alternate table, it clearly specifies that the gamma dose measured at a distance of six feet behind glass shielding is fundamentally based on the presence of substantial thick lead material that has been integrated meticulously into the surrounding wall. Moreover, it also emphasizes that the gamma dose at a distance of twenty feet from the wall is an important factor that must be noted for the comprehensive overall evaluation of radiation safety. High-Z materials, especially those that contain electrons in the K-shell, are well-known for their exceptional ability to preferentially attenuate x-rays effectively and efficiently, thus playing a vital role in the overall design and execution of appropriate radiation shielding. To ensure accuracy in reducing the occupancy classification during the detailed evaluation process, the necessary calculations must thoroughly account for buildup factors that significantly influence radiation exposure. The buildup factor itself is defined as the ratio of the exposure that is measured at a specific barrier thickness in relation to the exposure that is measured at a barrier thickness that is one-quarter of the mean free path, making it a critical element in the thoughtful design of effective shielding solutions. This entire process requires careful diligence and a systematic approach to ensure that all safety protocols and recommendations are meticulously followed for the protection of individuals who may be exposed to radiation in various contexts [256, 257, 258, 259, 260, 261, 262, 263, 264].

Chapter - 7

Medical Imaging Techniques

In recent years, the dynamic and rapidly advancing field of nuclear medicine has made remarkable strides and has firmly established itself as an absolutely indispensable and invaluable tool in the ever-evolving realm of diagnostic medicine. In Belgium alone, an impressive number of approximately 25,000 examinations are performed annually, which remarkably highlights the growing reliance on this advanced and specialized field of healthcare services. Nuclear medicine encompasses a wide array of diverse and significant applications, which not only include critical areas such as emergency care and thorough pre-operative investigations but also extend to the precise and accurate diagnosis of various diseases in significant medical specialties, including cardiology, neurology, and nephrology. This innovative and cutting-edge technique, which utilizes radioactive isotopes efficiently, has long been effectively harnessed in a variety of important medical treatments and interventions. Among these isotopes, strontium-89 and strontium-90 have been particularly remarkable for their notable therapeutic effects in the treatment of prostate cancer, demonstrating the unique and considerable capabilities of this specialized medical discipline. Similarly, the well-known and widely recognized use of radioactive iodine and phosphorus for treating malignant disorders of the thyroid has further solidified the pivotal and critical role of nuclear medicine in providing comprehensive and effective patient care and management. The distinctions between the realms of nuclear medicine and conventional medical physics are fundamental, profound, and indeed quite significant: radioactive substances, specifically designed as radiopharmaceuticals, are carefully introduced into the patient's body for either diagnostic or therapeutic purposes; nuclear medicine specifically maintains only those particular radiopharmaceuticals that exhibit precise molecular specificity for the organ or area under investigation; and it employs technologically advanced and complex imaging devices to accurately display the highly intricate functional anatomy of the patient. Through these exceptional and innovative means, nuclear medicine continues to advance and evolve, providing vital information and promising treatment options that significantly enhance patient outcomes and overall healthcare experiences in a remarkable way. The ongoing development and continuous integration of nuclear medicine into the mainstream medical practices further underscores its importance in modern medicine as well as the continuous quest for improved diagnostic and therapeutic solutions for patients in need, ensuring that those requiring such specialized care receive the most effective and state-of-the-art treatments available today [265, 266, 267, 268, 269, 270, 271, 272, 273].

Thirty years ago, the doses that were involved in nuclear medicine examinations underwent considerable variation, with values generally ranging between 2 x 10^10 decays per minute (DPM) for diagnostic doses and reaching as high as 2 x 10^12 DPM for curative doses associated with each examination performed. During that specific period, traditional methodologies dominated the field, providing a foundation for the practices of the time, which were largely based on empirical knowledge and established guidelines that had been developed over decades of research. However, everything underwent a remarkable transformation with the groundbreaking discovery and subsequent implementation of advanced gamma camera tomoscintigraphy. This revolutionary technology, when complemented by scintigraphic cameras that were equipped with specialized capture sectors, allowed for significant refinements in the standard dosages that were utilized across various procedures. Consequently, the dosages employed in a wide range of nuclear medicine examinations witnessed a notable reduction, aligning more closely with a refined and more controlled dosage range of 5 x 10^10 to 2 x 10^12 DPM, paving the way for more effective and safer medical practices. In more recent times, the innovative development of Anger cameras has played a crucial role in further contributing to an impressive and substantial reduction in these dosages, now managing to bring the administered doses down to a more manageable and notably safer range ranging from 5 x 10^9 DPM to 2 x 10^11 DPM. This remarkable advancement in dose reduction is of immense importance, as it not only enhances patient safety but also significantly enriches the overall understanding of the evolution of nuclear medicine practices over the decades. This ongoing evolution helps to elucidate, at least in part, why nuclear medicine has ultimately transformed and firmly established itself as a recognized and crucial subspecialty within the broader domain of medical imaging, reflecting the continuous improvement in technology and methodology that underpins the discipline. Moreover, within various circles of the medical community, a strong perspective exists that emphasizes the utmost significance of possessing extensive knowledge in the principles of nuclear physics. Such expertise is deemed essential for the methodologies that are effectively employed within this fascinating field of study, setting the groundwork for quality assurance and patient safety practices that are foundational to the discipline. This deep understanding of nuclear physics is critical for the precise synthesis, careful marking, and meticulous extraction of various radioactive isotopes from different biological mediums, which are specifically designed to tag organic molecules of interest for further analysis. Through these dynamic and intricate examinations, it becomes abundantly clear that it is possible to closely scrutinize the functional and metabolic activity occurring within diverse biological structures. This advanced capability leads to significant contributions that are not only original and innovative but are also highly relevant in the realm of modern medical diagnostics, thereby expanding the horizons of what can be achieved through targeted nuclear imaging techniques. The ongoing advancements underscore the transformative impact of nuclear medicine in enhancing patient care, improving treatment outcomes, and ultimately contributing to a more refined approach to diagnosis and therapy. The commitment to developing and implementing state-of-the-art technology continues to reshape both the practice and the understanding of nuclear medicine, ensuring that the field remains at the cutting edge of medical science. These strides forward promise not only to improve current practices but also to open new avenues for research and application in the years to come, thereby enhancing the overall quality and efficacy of healthcare delivery [274, 151, 275, 276, 277, 278, 279].

7.1 X-ray imaging

The physicist who specializes in the development and continuous refinement of medical imaging equipment plays a particularly critical and indispensable role in ensuring that these highly complex and intricate devices are not only optimally designed to meet the highest standards but also are operated safely and efficiently in order to produce the highest possible quality of diagnostic radiographic images for clinical and investigative use. This expert physicist must possess a comprehensive and thorough understanding of how each component of the sophisticated imaging equipment functions as well as the vital, overarching role it plays in the elaborate multistep process of accurate medical diagnosis and assessment. This extensive knowledge is essential for effectively fulfilling these important professional responsibilities in an accurate and timely manner, which is crucial in healthcare settings. Various types of advanced medical imaging equipment are readily available on the market today, which include versatile general-use X-ray systems that can perform a myriad of essential diagnostic functions, as well as specially designed X-ray systems that are aimed specifically at addressing particular applications within the expansive medical field. In addition, other advanced imaging technologies encompass advanced fluoroscopy systems that facilitate real-time imaging of internal structures for dynamic studies, mammographic devices that are specifically engineered for high-resolution breast imaging, and dental intraoral imaging systems designed for capturing detailed high-resolution images of teeth and their structures. Moreover, there are specialized dental panoramic and cephalometric imaging systems that are used extensively for evaluating various dental and skeletal issues, thereby enhancing orthodontic practices and other dental procedures. Additionally, state-of-the-art CT systems offer comprehensive cross-sectional imaging of the body, while bone densitometry systems provide crucial and timely assessments of bone health and density, which are vital in diagnosing osteoporosis and other related conditions. Regardless of the specific type of X-ray imaging equipment being utilized in a clinical setting, it is of utmost importance for the physicist and the medical staff to be thoroughly informed about the intricate complex biophysical interactions that exist between radiation exposure and various human tissues. A profound and deep understanding of these interactions is crucial, particularly with respect to how they influence the accumulation of detected X-rays when diagnosing various diseases and medical conditions that may arise within patients. This knowledge is particularly critical when setting the different parameters of the imaging examination, including but not limited to the type and energy of radiation employed, the precise radiation dose administered to patients, the exposure time necessary for sufficiently capturing the images, the specific field of view that requires detailed analysis to obtain diagnostic clarity, the speed at which images are captured during the procedure, and the implementation of special filters that may be essential to enhance the overall quality of the images produced for diagnostic purposes, thereby ensuring the best possible outcomes for patient care and treatment [55, 1, 280, 4, 16, 213, 281, 282].

7.2 Computed Tomography (CT)

Computed Tomography (CT) represents a truly significant and transformative advance in the expansive field of medical imaging as well as the everyday practice of diagnosis and assessment. The ingenious and highly effective use of X-rays for capturing meticulously detailed images of incredibly thin slices through the intricate and complex human body is seamlessly integrated with cutting-edge digital computer technology and sophisticated image reconstruction techniques. These significant advancements enable the provision of high-contrast three-dimensional images that are invaluable in contemporary medicine, revolutionizing the way practitioners visualize and interpret health conditions. This groundbreaking imaging technique has made a remarkable impact on clinical practice and the medical field at large, significantly enhancing diagnostic capabilities and has been embraced without reservation by both medical professionals and patients alike, who widely appreciate its potential for accurate and timely diagnosis. Moreover, the widespread integration of CT imaging into routine medical assessments allows healthcare providers to make quicker decisions, thereby facilitating better patient management and treatment options. Nevertheless, the rapid pace of technological advances has resulted in a scenario wherein the radiation dose received by patients, particularly in pediatric imaging as well as in certain specialized types of adult examinations, can sometimes exceed the doses used in conventional imaging practices by a substantial and concerning margin, which also raises serious safety concerns that must be tackled with diligence and care. It is crucial to recognize, acknowledge, and understand that it is entirely possible to ensure that both the patient dose and the diagnostic capability are optimized simultaneously by using clearly defined principles and guidelines that experts in the field have established over time, promoting a balance between effective imaging and minimal exposure to radiation. This chapter thoroughly outlines the historical origin of computed tomography and provides a comprehensive and detailed description of the underlying physics and technology that support this innovative imaging technique. Additionally, it addresses common misconceptions surrounding CT imaging, which can often lead to misunderstandings about its risks and benefits, offering clarifications and elucidating pertinent facts, and discusses critically important methods for optimization that can enhance safety and efficacy in its practical use. Properly implemented strategies will ensure that the advantages significantly outweigh the risks involved while maximizing the value of the diagnostic process. As a result, both healthcare providers and patients can engage more confidently with this indispensable tool in modern medicine, ensuring that CT remains a cornerstone in the diagnostic toolkit employed across various medical specialties [213, 283, 284, 285, 286, 287, 288].

CT examination represents a significant and highly instrumental medical usage of X-ray imaging, remarkable in its extensive ability to provide detailed and valuable insights into the incredibly complex workings of the human body. This substantial growth in popularity is largely due to the intrinsic and remarkable capability of detecting differences in X-ray attenuation between various tissues, a phenomenon that can sometimes reach an impressive magnitude of up to 1% in its level of precision and accuracy. The absorption characteristics of the diverse body tissues and organs stand in stark and notable contrast to those of air, as well as to other tissue components, thereby allowing for considerable contrast to be recorded and analyzed effectively, ensuring great clarity in the images produced. One of the major attractions of CT imaging lies in its unique possibility to acquire ultra-thin slices of the body, enabling the generation of highly detailed two-dimensional images or even sophisticated three-dimensional diagnostic images that can be extremely beneficial and useful for thorough medical assessments and evaluations. In traditional radiographic imaging, the information concerning the depth of the absorbing structures does not provide substantial benefits for most forms of analyses, limiting its effectiveness. However, CT technology possesses an exceedingly unique and powerful ability to produce high-resolution digital cross-sectional images from any desired distribution location inside the body, which fundamentally enhances overall diagnostic accuracy and detail. The clinical applications of these cross-sectional slices are vast and extensive, encompassing detailed visualization throughout the entire body, detection of lesions that involve particularly challenging anatomical superimposition, thorough assessment of tumor staging, comprehensive evaluation of processes related to muscles and soft tissues, and the detection of various abnormalities specifically in the head, brain, and skull, all achieved through the adoption of remarkably efficient non-invasive procedures. The advent of CT has efficiently revolutionized not only the manner of obtaining intricate images but also the way interpreting X-ray absorption amplitude variation across multiple detecting locations within the body is undertaken, providing an especially significant benefit for examining intricate and complex structures found within the brain and spine. Furthermore, CT imaging continues to stand as an integral and essential tool for healthcare providers and professionals across various medical disciplines, fundamentally enhancing both diagnosis and treatment planning through its advanced and sophisticated imaging capabilities. This technological advancement ensures that medical teams are equipped with the most refined tools to accurately assess and address a multitude of health conditions, thereby making it an invaluable asset in modern medical diagnostics and care strategies. As technology advances further and new methodologies are developed, the role of CT imaging is likely to expand even more, allowing for even greater precision in identifying diverse health issues and crafting effective, individualized treatment strategies tailored to specific patient needs. The growing reliance on such advanced imaging techniques highlights the ongoing necessity of continuous developments in methodologies and applications within the ever-evolving realm of diagnostic medicine [289, 290, 291, 292, 293, 294, 295, 296, 297].

Chapter - 8

Radiation Therapy

Radiation therapy is a specialized and significant medical treatment that utilizes high-energy, ionizing radiation with the primary goal of effectively targeting and killing cancer cells. This innovative treatment method is essential for the management of a wide variety of different types of malignancies and occupies a crucial role in the field of oncology. However, it is important to emphasize that this powerful and highly targeted therapy can also inadvertently cause damage to normal, healthy cells that are located in proximity to the treated area. This duality of action presents a significant consideration for both patients and their healthcare providers alike. Furthermore, this treatment modality induces substantial, profound, and often significant changes within the physical and chemical properties of the cellular components, which include essential subatomic particles such as photons, electrons, protons, and neutrons. To enhance the overall effectiveness and maximize the desired outcomes of radiation therapy, it is generally recommended that this treatment be utilized in conjunction with other complementary treatment strategies like surgery, chemotherapy, or biological therapy. This collaborative, integrative, and multimodal approach often proves beneficial in effectively reducing the size of a tumor or, in some fortunate cases, achieving successful and complete removal of the tumor altogether. Patients who are undergoing radiation therapy may experience a range of side effects related to the treatment process. One of the most prevalent and common side effects encountered is weakness and fatigue. This fatigue can be alarmingly extreme and debilitating, to the extent that it severely hinders a patient's ability to engage in their everyday daily activities, thus drastically diminishing their overall quality of life from day to day. Moreover, when patients are exposed to radiation, many normal skin cells residing in the vicinity of the treatment area may absorb a significant amount of high-energy radiation, which can subsequently lead to pronounced inflammation of the skin. Symptoms such as redness, itching, rashes, and in some circumstances, even peeling skin can manifest within a few weeks following the treatment, particularly in the localized area that was subjected to irradiation. The duration of these alterations can persist for several weeks, and they may necessitate ongoing intervention and support from the specialized healthcare team. This team focuses on effectively managing these adverse effects to promote the patient's overall well-being and quality of life. A dedicated and well-coordinated radiation therapy team plays an instrumental role in the organization and administration of radiation treatment that is tailored specifically to each patient's individual condition and unique needs. Generally, this multidisciplinary team encompasses a radiation oncologist, a radiation physicist, a radiation therapist, and a nurse who diligently oversees the patient's care throughout the entire treatment process. Furthermore, this team may also enlist the vital expertise of additional professionals, such as a social worker who can provide essential psychological support, a dietitian to ensure proper nutrition during the treatment course, a radiologist, and other specialists who can contribute to comprehensive patient care and recovery strategies. When determining the necessity for radiation therapy, several critical factors are meticulously considered. These factors include the specific type of cancer being treated and its particular stage, the potential risk of the cancer spreading to other areas of the body, the additional treatments that are planned to complement the radiation therapy, the overall health and medical history of the patient, the patient's personal preferences and wishes regarding their treatment journey, and the anticipated side effects of radiation therapy, particularly those that affect normal bodily cells in the area being irradiated. Careful consideration of all these factors is vital for tailoring the most appropriate and individualized treatment plan for each patient, ensuring the best possible outcomes throughout their cancer care journey, and improving their chances for successful recovery and overall well-being [298, 299, 300, 182, 301, 302, 303, 304, 305, 306].

8.1 External beam therapy

Overview: Radiation therapy utilizing external beams of X-rays, gamma rays, or electrons is an essential component of cancer treatment, playing a crucial role in healthcare, specifically responsible for nearly half of all curative cancer treatments delivered across North America today. In recent years, there have been remarkable technological advancements within this field, coupled with the increasing sophistication of treatment planning systems that now offer a vast array of possibilities for precise target dose delivery. These advancements encompass innovative techniques such as 3D conformal therapy and intensity-modulated therapeutics, both of which significantly enhance our capability to target tumors with greater efficacy and accuracy. Nonetheless, the successful implementation of these advanced techniques necessitates rigorous quality assurance measures, as well as comprehensive radiation protection procedures that are continuously evolving and becoming more sophisticated. When medical practitioners are confronted with the important decision of which specific radiation therapy modality to recommend to a patient, they are compelled to conduct a meticulous assessment of various critical factors, weighing the potential benefits against any possible risks. This thorough evaluation process encompasses analyzing the advantages concerning the decreased probability of recurrence for malignant diseases, in relation to the potential risks associated with the likelihood of developing secondary malignancies that can stem from the particular treatment under consideration. The emergence of particle therapy is particularly noteworthy, as it has demonstrated the potential to lead to a significant reduction in the late effects that are often related to traditional radiation methods. Consequently, this innovative approach holds the promise of substantially impacting the persistent challenges associated with radiation-induced secondary malignancies in patients undergoing treatment, thereby improving overall treatment outcomes and patient quality of life [299, 307, 308, 309, 310].

Radiation shaping

Homogeneous irradiation of the target volume is not just essential; it is critical in ensuring that the target area receives adequate treatment while effectively sparing the surrounding normal tissues. These normal tissues typically possess the remarkable capacity to endure relatively large doses of radiation that carry considerable biological significance. This outcome is undeniably the primary objective of radiation therapy, which is designed to maximize therapeutic efficacy while concurrently minimizing adverse and unintended effects. In the ever-evolving and rapidly advancing field of teletherapy, this highly desired result can be achieved through two distinct and scientifically sound approaches.

The first approach involves the sophisticated and meticulous modulation of the intensity of individual radiation beams that precisely and accurately target the tumor from various calculated angles. This careful modulation ensures that the radiation doses are not only meticulously delivered but also evenly distributed from different, discrete directions, leading to a well-distributed dose across the tumor itself. The second approach employs a beam composed of particles that maintain the same energy level, such as electrons or photons. This method is significant because it substantially contributes to a proportional increase in the sparing of normal tissues surrounding the tumor. This beneficial phenomenon ultimately leads to what is commonly referred to as therapeutic gain, a crucial factor in successful treatments.

The application of these two strategies allows for a more refined and effective focus on the malignant cells that are the target of the therapy while simultaneously safeguarding the adjacent healthy tissues from excessive radiation exposure. From a practical perspective, common sense considerations strongly suggest that when the greater number of field directions utilized is increased, or when the larger therapeutic gain achieved is realized, the more effective the resulting profiles of dose distribution will be in the targeted area. By enhancing the dosage modulation and carefully considering the beam composition, one can achieve an optimal overlap of radiation doses that are precisely tailored to circumvent and protect non-cancerous cells.

This impressive and carefully managed outcome not only leads to a significant reduction in the severity of complications that are associated with normal tissue damage but also plays a crucial role in minimizing the risk of developing radiation-induced secondary cancers in patients who are undergoing treatment. Ultimately, by advancing and refining radiation shaping techniques and methodologies, radiation therapy can continue to evolve, providing more effective cancer control while simultaneously prioritizing patient safety and overall health. This ensures a future that may see improved and more favorable outcomes for countless individuals diagnosed with cancer. Thus, the continued improvement and diligent refinement of these methods remain vital for the ongoing battle against malignancies and represent a significant aspect of contemporary therapeutic radiation practices, highlighting the importance of innovation in this crucial field [311, 299, 312, 313].

8.2 Brachytherapy

Brachytherapy represents an innovative and highly specialized approach to treating various medical conditions, particularly cancers, through the precise placement of radioactive material either inside or immediately adjacent to the affected area. This targeted technique aims to deliver radiation exclusively to the cells that necessitate intervention, which effectively minimizes the likelihood of harming the surrounding healthy tissues that do not require treatment. The method is built on two primary types of radioactive sources: temporary and permanent.

The temporary source consists of a controlled, small amount of highly radioactive material that is meticulously positioned during the treatment session and is designed to be removed afterward. The duration for which this material is left in place may range from just a few minutes to several days, guided by a customized treatment plan devised by the dedicated healthcare team based on the patient's unique situation and requirements. In contrast, the permanent sources are often represented as tiny, non-radioactive seeds that are intentionally left within the patient's body. These seeds do not present any health risks to others, even if they inadvertently remain in the patient's body for extended durations.

This meticulously developed technique is routinely employed and has proven to be highly effective, particularly in the treatment of prostate cancer, making it one of the most prevalent applications within the field of oncology. To guarantee the absolute safety of both medical staff and patients throughout these procedures, reflective shields are sometimes utilized to shield healthcare professionals from unnecessary radiation exposure that could arise during treatment. In the context of low dose rate (LDR) brachytherapy, treatments are commonly administered over one or two days. Alternatively, high dose rate (HDR) brachytherapy involves the delivery of radiation in carefully calculated fractions and is often extended over several weeks to maximize patient outcomes and effectiveness.

After patients complete their treatment course, it is typically recommended that they minimize direct contact with pregnant women and young children for a specified duration. This precautionary measure is taken to further reduce the potential risk of radiation exposure during their recovery phase post-treatment, highlighting the commitment to patient safety and thorough care in brachytherapy practices. Through this precise and responsible application of brachytherapy, patients can benefit from a targeted treatment that prioritizes their well-being while effectively tackling cancerous cells [314, 315, 316, 317, 318].

Seeds that are employed in a wide variety of specialized brachytherapy treatment procedures generally measure between about 1 mm and 10 mm in length, while typically possessing a diameter that hovers around 0.75 mm. These small yet incredibly essential seeds are meticulously crafted from resilient and durable materials, including stainless steel, silver, or titanium. Within them, there exists precisely embedded internal radioactivity that aids in facilitating targeted and effective treatment strategies for patients. When considering High-Dose Rate (HDR) brachytherapy treatments, the radionuclide that is most frequently utilized within the medical field is Iridium-192. This particular radioisotope boasts a half-life of approximately 73.8 days, which plays an essential role in influencing its widespread usage and numerous applications in the realm of brachytherapy. Due to its unique decay characteristics, Iridium-192 is regarded as relatively safe for the medical personnel who find themselves in proximity to it. This safety is ensured since it is always securely shielded within the controlled and secure confines of the treatment room, which in turn significantly minimizes any potential exposure risk to those present. In addition to Iridium-192, there exists another radioactive source known as Cobalt-60 that is also utilized in various brachytherapy procedures; however, its application necessitates a uniquely designed after loading technique due to its distinct physical properties and unique radiation characteristics. For all types of treatment procedures involving Cobalt-60, the implementation of a remote after loader becomes absolutely vital to ensure not only the safety of the medical personnel but also the overall efficiency and efficacy of handling the radioactive material involved in the treatments. The half-life of Cobalt-60 is relatively lengthy, which can pose significant challenges during the process of source replacement. This extended duration that is required for replacing Cobalt-60 sources may lead to the unfortunate scenario where a brachytherapy machine is rendered unavailable for patient treatments over quite an extended period, potentially disrupting the continuity of care for the patients needing treatment. Furthermore, the financial implications that are tied to the replacement of a Cobalt-60 source are notably substantial and significant. The overall costs associated with this process are considered to be quite high, especially when taking into consideration the various medical budget constraints and financial limitations that often accompany healthcare operations. Moreover, medical facilities that make the decision to incorporate Cobalt-60 into their treatment protocols must also construct treatment rooms with notably thicker walls. This added requirement is essential for providing adequate shielding necessary to ensure the safety of not just the personnel but also the patients being treated. The complexity that accompanies this additional construction requirement does not merely contribute to the overall financial burden but also serves to increase the difficulty involved in setting up such specialized treatment rooms. As a consequence of these various constraints and specific requirements associated with the use of Cobalt-60, it is relatively uncommon for new medical facilities or specialized units to opt for the use of Cobalt-60 in their brachytherapy procedures as a primary choice for treatment. Instead, the general preference among healthcare providers tends to lean significantly towards isotopes that enable more efficient use and enhanced management within clinical settings. This ultimately makes the treatments smoother, safer, and potentially more financially viable in the long term, benefiting both patients and healthcare systems alike [319, 320, 321, 322, 323, 324].

Chapter - 9

Quality Assurance and Quality Control

In the field of radiotherapy, the principles of Quality Control and Quality Assurance (QC/QA) constitute a comprehensive and multi-faceted approach that encompasses a thorough calibration, performance validation, and a series of safety inspections pertaining to both clinical and processing equipment, as well as all the various and complex procedures utilized in the delivery of effective radiotherapy. The central objectives of QC/QA within the radiotherapy discipline focus on guaranteeing the safe and precise administration of ionizing radiation to patients undergoing treatment and ensuring that reliable and accurate dose assessment methodologies are rigorously in place. In addition to these critical aims, it is important to note that this robust quality management is exceptionally vital during the commissioning phase of radiotherapy equipment, which typically involves establishing optimal operating conditions and meticulously implementing standardized procedures that are derived from a diverse and rich array of guidelines and protocols that exist within a fully functioning radiotherapy department. The myriad components of QC/QA are generally governed by a series of stringent regulations that are enforced by governmental authorities, particularly as adherence to stringent radiation safety standards has increasingly become a prerequisite for nations that are adopting and advancing radiation therapy practices; a significant and practical consideration stemming from this regulatory requirement is the enhancement of patient safety during clinical treatment. This enhancement is achieved through the strategic integration of multiple redundant safety systems that are thoughtfully designed to protect patients throughout their treatment experience, ensuring that they receive the safest and most effective therapeutic interventions possible [325, 326, 327, 328, 329].

QC/QA programs can significantly differ due to a variety of factors including variations in the regulations imposed by governing bodies, as well as the specific equipment, tools, and technologies that are utilized in each facility setting. However, it is imperative that these programs are comprehensively developed in collaboration with many relevant professional bodies, stakeholders, and regulatory organizations to ensure uniformity and compliance across the board. Guidelines for QA/QC procedures are established and endorsed by various entities and stakeholders actively participating in the field, reinforcing the overall quality assurance framework. Therefore, it is essential that such guidelines and recommendations be diligently followed and rigorously implemented to ensure the utmost treatment efficacy, quality, and safety for patients receiving care. It is the primary responsibility of the local medical physicist to not only create but also oversee and implement a safe, comprehensive QC/QA program that aligns with the highest industry standards. Additionally, the medical physicist must effectively communicate the established guidelines and protocols to all involved professionals, staff, and other relevant personnel to foster an environment of compliance and safety. Any failure to adequately follow the recommended safety procedures, as well as the guidelines established through sound operational practice, may unfortunately lead to serious injury, negative outcomes, or adverse events for patients and staff alike. Adhering strictly to these protocols and guidelines is crucial in maintaining high standards of care, ensuring quality service delivery, and ultimately protecting patient safety in all healthcare environments [330, 331, 332, 333, 334, 335, 336].

9.1 Equipment calibration

Generally, this information could indeed constitute a significant and substantial part of the commissioning process that is traditionally undertaken when establishing the operation of a new or replacement unit within the hospital or medical practice. This essential process is not limited in scope to any one particular domain and also applies at any point in time when there are legitimate and substantive concerns regarding the accuracy and overall quality of data that is crucial for effective and safe medical practice. Such accuracy and precision are particularly vital to establish seamless traceability to the International System of Units (SI) for various critical medical situations where such high levels of precision are both required and expected to ensure optimal patient safety and treatment efficacy. Calibration should thoroughly take into account the necessity and importance of producing a highly quantitative image of the absorbed dose distribution, which is paramount in the highly specialized field of medical imaging and radiation therapy. Digital techniques for ion chamber calibrations have been available since the early 1980s and have truly revolutionized and transformed the field, facilitating a multitude of gamma-ray energies to be utilized in the measurements, thereby improving diagnostic capabilities and overall imaging performance. Calibration of ion chambers under a narrow-energy beam provides the best possible direct comparison of chamber response against the absorbed dose, yet it possesses the notable disadvantage of not being truly representative of the majority of areas within dosimetry. This is especially relevant as it pertains to the intricate complexities of diagnostic radiology, where conditions can vary widely. Furthermore, calibration performed in standard or quality x-ray beams that are typically utilized at national and secondary standards laboratories also fails to be representative of the real-world scenarios encountered in the diverse practices of diagnostic radiology across various institutions. The realization that the interaction of photon radiation with the tissues is fundamentally determined by the total field of view in a conventional x-ray exposure, and that the absorbed dose image is generated correspondingly as a direct result, indicates a significant understanding. It shows that the most effective calibration method should ensure that the chamber field of view is irradiated uniformly during the calibration measurement process, free from any unavoidable biases. Such a comprehensive and systematic approach would significantly enhance the validity, reliability, and applicability of the calibration results in actual clinical settings. This leads to much better outcomes for patients undergoing treatment or diagnostic procedures that involve the use of ionizing radiation, thus positively impacting their overall healthcare experience and recovery processes [337, 338, 339, 226, 340, 341, 216].

9.2 QA procedures

In the United States, alongside a multitude of other countries spread across the globe, a comprehensive and diverse array of quality assurance (QA) procedures has steadily gained significant recognition as not just an option, but as the standard of care within radiation therapy facilities that are dedicated to providing effective and precise treatment for patients. A wealth of meticulously developed QA charts and thorough lists of evaluations are now readily accessible to assist medical personnel in efficiently and effectively carrying out these vital assessments that are crucial for patient safety and care. Equipment manufacturers, along with the providers of the required and sophisticated computer software, typically offer essential and well-structured QA tests that are specifically designed for their devices, which is absolutely critical in ensuring optimal performance levels and steadfast adherence to safety standards that protect patients. The radiotherapy treatment planning system comprises a diverse range of components, each of which can be evaluated individually for both its efficacy and accuracy, thereby fostering a holistic understanding of the system's performance. Beyond the routine verification processes that focus on the light field and the protruding beam, it becomes exceedingly important to conduct a meticulous and comprehensive examination of the multileaf collimator, particularly when dealing with irregular and complex field shapes, so as to ensure that targeting remains precise and reliably correct, thereby maximizing treatment effectiveness. Additionally, it is of utmost importance that the manufacturer supplies an extensive and detailed list of various supplementary tests and acceptable tolerances that are necessary to maintain the highest possible levels of patient care and regulatory compliance, ensuring that all procedures meet the required health standards. This rigorous process guarantees that every single facet of radiation therapy is meticulously aligned with established safety protocols and rigorous quality standards, which is crucial for safeguarding the well-being of patients and achieving optimal therapeutic outcomes in clinical practices. Thoroughly adhering to these quality assurance protocols not only enhances the overall treatment process but also fosters trust, confidence, and reassurance among patients receiving radiation therapy, ensuring they feel supported throughout their treatment journey [342, 327, 343, 344, 345, 346, 347, 348].

Numerous comprehensive and rigorous tests have been proposed and suggested by various groups of dedicated professionals and workers who are deeply committed to the medical field and its most vital aspects. These tests have been meticulously implemented in extensive and thorough radiotherapy treatment programs that seek to enhance the quality of care provided to patients. It is essential that these tests not only effectively address several critical aspects, including coordinating support for the operating system, but also ensure that all integrated and associated hardware functions properly and efficiently. Simultaneously, it is of utmost importance that the radiation therapy scheduler is able to operate smoothly and without complications, allowing for seamless patient management and treatment scheduling. Furthermore, the configuration of the hardware devices must be sufficiently addressed, taking into consideration the intricate and sometimes convoluted nature of network addressing tasks that can often be quite complex and challenging to navigate.

To maintain the integrity and accuracy of vital physician data, it is imperative that an independent, well-trained team is tasked with conducting thorough and meticulous checks on patient demographic information. This thorough review process includes, but is not limited to, specific therapist instructions, detailed simulation history, and all relevant treatment data that could significantly impact patient care and outcomes. In a similar vein, established and well-documented procedures should be put in place for the meticulous and careful checking of data related to physicists, dosimetrists, and all indispensable equipment involved in radiation therapy, including all associated machines and devices that are utilized during treatment.

Quality Assurance (QA) documents hold a vital role in this process, as they maintain comprehensive descriptions of every procedure, outline the necessary tolerance levels that need to be adhered to, and present detailed check-in and check-out procedures that are relevant to the different personnel and locations involved in the critical process of radiotherapy. It is crucial that all these extensive and intricate procedures are not only thoroughly established but are also meticulously documented before any installation of radiotherapy systems or equipment can take place. This careful documentation is essential to guarantee a seamless integration and optimal functionality of all systems in place, ultimately ensuring the highest standard of care for patients undergoing complex treatment protocols. This ongoing commitment to excellence in both testing and documentation reflects the dedication of the medical community toward improving and maintaining patient safety and the efficiency of radiation therapy practices [349, 328, 327, 350, 325, 351, 352, 326, 329].

Conclusion

Today medical physics integrates the application of physics in medicine for the purpose of treatment, diagnosis, and prevention. Medical physics departments maintain the quality of performance, consulates regarding the choice of instruments for hospitals and practitioners, and, additionally, engage in translational research with direct practical benefit for patients. With the continuous acceleration of technological progress in the world, the need for dedicated professionals is very high. The investigation of the history of medical physics reveals recurrent but accidental production of radiation-induced accidents. Therefore, adding more material is no motivate to avoid such occurrences. The motivation to have the first preliminary safety analysis on some public concerns such as the treatment of ionizing radiation in the Occupational control is allied to a project developed by the Structural Mechanics Division of the Institute of Aeronautic Technology. The job of providing safety analysis results for the use of ionizing radiation was an initial response of the Group of research associated with the project to public demand, hoping to collaborate with the generation of new basic knowledge to the benefit of the advancement in the Security chain and not only satisfactory but also surmounting the demands of neighboring compounds, both medical and industrial, for the use of ionizing radiation.

References

1. S. Cui, H. H. Tseng, J. Pakela, and R. K. Ten Haken, "Introduction to machine and deep learning for medical physicists," Medical Physics, 2020. nih.gov
2. A. Morega, M. Morega, and A. Dobre, "Computational Modeling in Biomedical Engineering and Medical Physics," 2020. [HTML]
3. H. Yan, Z. Hu, P. Huang, K. Men, Y. Zhang, and L. H. Wang, "The status of medical physics in radiotherapy in China," Physica Medica, 2021. physicamedica.com
4. M. Avanzo, A. Trianni, F. Botta, C. Talamonti, and M. Stasi, "Artificial intelligence and the medical physicist: welcome to the machine," Applied Sciences, 2021. mdpi.com
5. D. Sarrut, T. Baudier, D. Borys, A. Etxebeste, "The OpenGATE ecosystem for Monte Carlo simulation in medical physics," Physics in Medicine, 2022. nih.gov
6. L. Manco, N. Maffei, S. Strolin, S. Vichi, and L. Bottazzi, "Basic of machine learning and deep learning in imaging for medical physicists," Physica Medica, 2021. physicamedica.com
7. N.C. Knutson, J.A. Kavanaugh, and H.H. Li, "Radiation oncology physics coverage during the COVID-19 pandemic: Successes and lessons learned," Medical Physics, 2021. nih.gov
8. D. C. Luximon, T. Ritter, E. Fields, and J. Neylon, "Development and interinstitutional validation of an automatic vertebral-body misalignment error detector for cone-beam CT-guided radiotherapy," Medical, 2022. escholarship.org
9. N. Frane and A. Bitterman, "Radiation safety and protection," 2020. europepmc.org
10. W. R. Widmer and D. E. Thrall, "Radiation protection and physics of diagnostic radiology," in Thrall's Textbook of Veterinary, 2024. [HTML]
11. C. Clement, W. Ruehm, and J. Harrison, "Keeping the ICRP recommendations fit for purpose," … of Radiological …, 2021. iop.org
12. Y. Mekdad, A. Aris, L. Babun, A. El Fergougui, and M. Conti, "A survey

on security and privacy issues of UAVs," Computer Networks, Elsevier, 2023. sciencedirect.com

13. M. Endo, "History of medical physics," Radiological Physics and Technology, 2021. [HTML]
14. J. Boice Jr, L. T. Dauer, and K. R. Kase, "Evolution of radiation protection for medical workers," The British Journal of …, 2020. nih.gov
15. H. Do Huh and S. Kim, "History of radiation therapy technology," Progress in Medical Physics, 2020. koreamed.org
16. J. Malone, "X-rays for medical imaging: Radiation protection, governance and ethics over 125 years," Physica Medica, 2020. physicamedica.com
17. N. Rammohan, J. W. Randall, and P. Yadav, "History of technological advancements towards MR-Linac: the future of image-guided radiotherapy," Journal of Clinical Medicine, 2022. mdpi.com
18. C. Fiorino, R. Jeraj, C. H. Clark, and C. Garibaldi, "Grand challenges for medical physics in radiation oncology," Radiotherapy and Oncology, Elsevier, 2020. thegreenjournal.com
19. A. G. Chmielewski, "Radiation technologies: The future is today," Radiation Physics and Chemistry, 2023. sciencedirect.com
20. R. Najjar, "Radiology's ionising radiation paradox: weighing the indispensable against the detrimental in medical imaging," Cureus, 2023. nih.gov
21. N. Gambo and M. Shehu, "The Role of Diagnostic Medical Physics in Medicine: An Overview," Sahel Journal of Life Sciences, 2024. fudutsinma.edu.ng
22. M. B. A. Jacqueline Kim Mylan, "Safety and Protection in Radiation Therapy," assets.asimcme.com, . asimcme.com
23. K. H. Ng, N. M. Ung, and R. Hill, "Problems and Solutions in Medical Physics: Radiotherapy Physics," 2022. [HTML]
24. C. Garibaldi, M. Essers, B. Heijmen, J. Bertholet, "The 3rd ESTRO-EFOMP core curriculum for medical physics experts in radiotherapy," Radiotherapy and ..., Elsevier, 2022. thegreenjournal.com
25. P. Xia, B. J. Sintay, V. C. Colussi, C. Chuang, "Medical Physics Practice Guideline (MPPG) 11. a: Plan and chart review in external beam radiotherapy and brachytherapy," in *Medical Physics*, 2021. wiley.com

26. A. Darafsheh, H. Lavvafi, and R. Taleei, "Mitigating disruptions, and scalability of radiation oncology physics work during the COVID-19 pandemic," … clinical medical physics, 2020. wiley.com

27. N. Tohyama, H. Okamoto, K. Shimomura, "A national survey on the medical physics workload of external beam radiotherapy in Japan," Journal of Radiation, 2023. oup.com

28. N. Hayashi, M. Okumura, M. Nakamura, "Current status of the educational environment to acquire and maintain the professional skills of radiotherapy technology and medical physics specialists in Japan: a …," Radiological Physics, Springer, 2023. [HTML]

29. E. Ford, L. Conroy, L. Dong, and L. F. de Los Santos, "Strategies for effective physics plan and chart review in radiation therapy: Report of AAPM Task Group 275," Medical Physics, 2020. nih.gov

30. I. Buzurovic, J. H. Mott, and J. Perez-Catalayud, "Medical physics and planning in skin radiotherapy and brachytherapy," in Non-melanoma Skin, 2023. [HTML]

31. N. Lawtoo, "Black mirrors: Reflecting (on) hypermimesis," Philosophy Today, 2021. academia.edu

32. H. Hartono, S. Suparto, and A. Hassan, "Language: a 'mirror'of the culture and its application English language teaching," Linguistics and Culture Review, 2021. lingcure.org

33. N. Klein, "Doppelganger: A trip into the mirror world," 2024. [HTML]

34. S. Gao, K. Yang, H. Shi, and K. Wang, "Review on panoramic imaging and its applications in scene understanding," IEEE Transactions on, 2022. [PDF]

35. J. de la Fuente Prieto, P. Lacasa, "Approaching metaverses: Mixed reality interfaces in youth media platforms," New Techno Humanities, Elsevier, 2022. sciencedirect.com

36. B. Busch, "The body image: Taking an evaluative stance towards semiotic resources," International Journal of Multilingualism, 2021. tandfonline.com

37. U. Sarı, E. Duygu, F. Şen, and T. Kırındı, "The Effects of STEM education on scientific process skills and STEM awareness in simulation based ınquiry learning environment," Journal of Turkish Science Education, 2020. tused.org

38. K. M. Hampson, R. Turcotte, D. T. Miller, "Adaptive optics for high-resolution imaging," Nature Reviews, 2021. nih.gov

39. E. Hall, "Engineering: Archimedes of Syracuse," 2020. gresham.ac.uk
40. F. Joseph, "Ancient High Tech: The Astonishing Scientific Achievements of Early Civilizations," 2020. [HTML]
41. T. M. Lardinois, R. L. Hollenbach III, and S. Garner, "Concentrating solar power and thermal energy storage system technologies and case studies," *The Sustainable Power*, Elsevier, 2025. [HTML]
42. B. A. A. Yousef, A. Radwan, and A. G. Olabi, "Development of solar thermal energy systems," in Energy-Volume 1: Solar, 2023, Elsevier. [HTML]
43. B. McDonald, "The Future Is Now: Solving the Climate Crisis with Today's Technologies," 2024. [HTML]
44. M. V. R. MALLARI, "THE AEROGRAMME PROJECT," phil.airwarfare.center, . airwarfare.center
45. E. J. Gago and S. E. Berrizbeitia, "The Coming of Age of Solar and Wind Power," Springer, . [HTML]
46. S. Akram and Y. S. Chowdhury, "Radiation exposure of medical imaging," 2020. europepmc.org
47. L. Bastiani, F. Paolicchi, and L. Faggioni, "Patient perceptions and knowledge of ionizing radiation from medical imaging," JAMA Network, 2021. jamanetwork.com
48. A. Ribeiro, O. Husson, N. Drey, I. Murray, and K. May, "Ionising radiation exposure from medical imaging–A review of Patient's (un) awareness," Radiography, 2020. sciencedirect.com
49. H. M. Shi, Z. C. Sun, and F. H. Ju, "Recommendations for reducing exposure to medical X-ray irradiation," Medicine International, 2022. spandidos-publications.com
50. A. Ploussi, E. P. Efstathopoulos, and E. Brountzos, "The importance of radiation protection education and training for medical professionals of all specialties," … and Interventional Radiology, 2021. [HTML]
51. C. J. Martin, J. D. Harrison, and M. M. Rehani, "Effective dose from radiation exposure in medicine: past, present, and future," Physica Medica, 2020. physicamedica.com
52. M. Marengo, C. J. Martin, S. Rubow, and T. Sera, "Radiation safety and accidental radiation exposures in nuclear medicine," in Nuclear Medicine, Elsevier, 2022. academia.edu

53. X. Xu, Y. Xie, H. Li, X. Wang, S. Shi, and Z. Yang, "Awareness and preparedness level of medical workers for radiation and nuclear emergency response," *Frontiers in Public Health*, 2024. frontiersin.org

54. O. A. Al Khudairi, R. S. A. Alasiri, "Radiation In Diagnostic Imaging: An In-Depth Examination," Journal of Survey, 2023. sifisheriessciences.com

55. T. Beyer, D. L. Bailey, U. J. Birk, I. Buvat, and C. Catana, "Medical Physics and imaging–A timely perspective," in Physics, 2021. frontiersin.org

56. S. L. Kitson, "Modern Medical Imaging and Radiation Therapy," Cyber Security Big Data AI. Open Med Science, 2024. openmedscience.com

57. L. M. Chong, D. J. H. Tng, L. L. Y. Tan, M. L. K. Chua, "Recent advances in radiation therapy and photodynamic therapy," Applied Physics, 2021. [HTML]

58. M. A. Villena, O. Kaya, and U. Schwingenschlögl, "Density functional theory and molecular dynamics simulations for resistive switching research," Materials Science and ..., 2024. [HTML]

59. D. Saumon, S. Blouin, and P. E. Tremblay, "Current challenges in the physics of white dwarf stars," Physics Reports, 2022. sciencedirect.com

60. J. Zheng, Z. Ju, B. Zhang, J. Nai, T. Liu, and Y. Liu, "Lithium ion diffusion mechanism on the inorganic components of the solid–electrolyte interphase," Journal of Materials, 2021. [HTML]

61. Y. Yuan, D. S. Kim, J. Zhou, D. J. Chang, and F. Zhu, "Three-dimensional atomic packing in amorphous solids with liquid-like structure," Nature Materials, 2022. osti.gov

62. Z. Fan, B. Xing, and P. Cao, "Predicting path-dependent diffusion barrier spectra in vast compositional space of multi-principal element alloys via convolutional neural networks," Acta Materialia, 2022. sciencedirect.com

63. R. P. Thedford, F. Yu, W. R. T. Tait, and K. Shastri, "The Promise of Soft-Matter-Enabled Quantum Materials," Advanced, 2023. wiley.com

64. M. Wuttig, C. F. Schön, J. Lötfering, and P. Golub, "Revisiting the nature of chemical bonding in chalcogenides to explain and design their properties," Advanced, 2023. wiley.com

65. A. M. El-Khawaga, A. Zidan, "Preparation methods of different nanomaterials for various potential applications: A review," Journal of Molecular, Elsevier, 2023. [HTML]

66. I. Mosquera-Lois, S. R. Kavanagh, and A. Walsh, "Identifying the ground state structures of point defects in solids," npj Computational, 2023. nature.com
67. N. Schunck and D. Regnier, "Theory of nuclear fission," Progress in Particle and Nuclear Physics, 2022. sciencedirect.com
68. C. Fu, G. Zhang, and Y. Ma, "New opportunities for nuclear and atomic physics on the femto-to nanometer scale with ultra-high-intensity lasers," Matter and Radiation at Extremes, 2022. aip.org
69. N. and 2024, "Imaging shapes of atomic nuclei in high-energy nuclear collisions," nature.com, . nature.com
70. XT. Ji, S.Y. Luo, Y.H. Huang, K. Zhu, and J. Zhu, "A novel 4D resolution imaging method for low and medium atomic number objects at the centimeter scale by coincidence detection technique of cosmic-ray muon and …," Nuclear Science and …, 2022. researchgate.net
71. S. Gautam, A. Venneti, S. Banik, and B. K. Agrawal, "Re-visiting the role of short-range correlations on neutron-star properties," Nuclear Physics A, 2024. sciencedirect.com
72. G. Giacalone, "Beyond axial symmetry: high-energy collisions unveil the ground-state shape of 238U," Nuclear Science and Techniques, 2024. springer.com
73. R. A. Dunlap, "An introduction to the physics of nuclei and particles," 2023. [HTML]
74. J. V. Kratz, "Nuclear and radiochemistry: Fundamentals and applications," 2022. [HTML]
75. A. Algora, J. L. Tain, B. Rubio, and M. Fallot, "Beta-decay studies for applied and basic nuclear physics," The European Physical, Springer, 2021. springer.com
76. M. Agostini, G. Benato, J. A. Detwiler, and J. Menéndez, "Toward the discovery of matter creation with neutrinoless decay," Reviews of Modern Physics, 2023. aps.org
77. F. Cappuzzello, H. Lenske, M. Cavallaro, C. Agodi, "Shedding light on nuclear aspects of neutrinoless double beta decay by heavy-ion double charge exchange reactions," in Particle and Nuclear, Elsevier, 2023. [HTML]
78. V. Mannalatha, S. Mishra, and A. Pathak, "A comprehensive review of

quantum random number generators: Concepts, classification and the origin of randomness," Quantum Information Processing, 2023. [PDF]

79. D. Gambacurta, M. Grasso, and J. Engel, "Gamow-Teller Strength in and with the Charge-Exchange Subtracted Second Random-Phase Approximation," Physical Review Letters, 2020. [PDF]
80. M. Laubenstein and I. Lawson, "Low background radiation detection techniques and mitigation of radioactive backgrounds," Frontiers in Physics, 2020. frontiersin.org
81. F. Battiston, G. Cencetti, I. Iacopini, V. Latora, M. Lucas, et al., "Networks beyond pairwise interactions: Structure and dynamics," Physics Reports, 2020. sciencedirect.com
82. R. D. Benford and S. A. Hunt, "Interactional Dynamics in Public Problems Marketplaces: M ovements and the Counterframing and Reframing of Public Problems," Challenges and choices, 2024. [HTML]
83. V. Caputo, "Anthropology's silent 'others': A consideration of some conceptual and methodological issues for the study of youth and children's cultures," Youth cultures, 2022. [HTML]
84. G. Berg, D. Rybakova, D. Fischer, T. Cernava, "Microbiome definition re-visited: old concepts and new challenges," Microbiome, Springer, 2020. springer.com
85. ATD Perera and P Kamalaruban, "Applications of reinforcement learning in energy systems," Renewable and Sustainable Energy, Elsevier, 2021. sciencedirect.com
86. Z. Xi, W. Chen, X. Guo, W. He, Y. Ding, and B. Hong, "The rise and potential of large language model based agents: A survey," *arXiv preprint arXiv*, 2023. github.io
87. S. Khan, M. Naushad, M. Govarthanan, and J. Iqbal, "Emerging contaminants of high concern for the environment: Current trends and future research," Environmental, Elsevier, 2022. [HTML]
88. S. Qin, W. Xiao, C. Zhou, Q. Pu, X. Deng, and L. Lan, "Pseudomonas aeruginosa: pathogenesis, virulence factors, antibiotic resistance, interaction with host, technology advances and emerging therapeutics," Signal Transduction and..., 2022. nature.com
89. Y. K. Dwivedi, L. Hughes, A. M. Baabdullah, et al., "Metaverse beyond the hype: Multidisciplinary perspectives on emerging challenges, opportunities, and agenda for research, practice and policy," International Journal of ..., 2022. sciencedirect.com

90. F. Battiston, E. Amico, A. Barrat, G. Bianconi, et al., "The physics of higher-order interactions in complex systems," Nature Physics, 2021. [PDF]

91. G. R. D. Prabhu, E. R. Williams, and M. Wilm, "Mass spectrometry using electrospray ionization," Nature Reviews Methods, 2023. [HTML]

92. G. C. Hofheins, Z. Ulibarri, and E. M. Petro, "Electrospray Secondary Ion Mass Spectrometry Diagnostic–Design and Preliminary Results," in … Conference, Toulouse, France, 2024. researchgate.net

93. A. Prasad, N. V. Salim, and M. Mozetič, "Time-of-flight secondary ion mass spectrometric analysis of polymer surfaces: A review," Journal of Applied, 2022. wiley.com

94. JN Audinot, P Philipp, O De Castro, "Highest resolution chemical imaging based on secondary ion mass spectrometry performed on the helium ion microscope," *Reports on Progress*, 2021. [HTML]

95. A. Priebe and J. Michler, "Review of recent advances in gas-assisted focused ion beam time-of-flight secondary ion mass spectrometry (FIB-TOF-SIMS)," Materials, 2023. mdpi.com

96. H. Bosco, L. Hamann, N. Kneip, M. Raiwa, and M. Weiss, "New horizons in microparticle forensics: Actinide imaging and detection of 238Pu and 242mAm in hot particles," Science, 2021. science.org

97. M. Zhou, C. Lantz, K. A. Brown, Y. Ge, and L. Paša-Tolić, "Higher-order structural characterisation of native proteins and complexes by top-down mass spectrometry," Chemical, 2020. rsc.org

98. E. Largy, A. Konig, A. Ghosh, and D. Ghosh, "Mass spectrometry of nucleic acid noncovalent complexes," Chemical, 2021. hal.science

99. S. McBride, E. Sherman, C.J. Tsai, and S. Baxi, "Randomized phase II trial of nivolumab with stereotactic body radiotherapy versus nivolumab alone in metastatic head and neck squamous cell carcinoma," Journal of Clinical, 2021. nih.gov

100. S. Corbacioglu et al., "Total body irradiation or chemotherapy conditioning in childhood ALL: a multinational, randomized, noninferiority phase III study," Journal of Clinical, 2021. ascopubs.org

101. L. L. Tang, R. Guo, N. Zhang, B. Deng, L. Chen, and Z. B. Cheng, "Effect of radiotherapy alone vs radiotherapy with concurrent chemoradiotherapy on survival without disease relapse in patients with low-risk nasopharyngeal …," Jama, 2022. jamanetwork.com

102. J. Nuszkiewicz, A. Woźniak, "Ionizing radiation as a source of oxidative stress—the protective role of melatonin and vitamin D," International Journal of ..., 2020. mdpi.com

103. H. Wilhalme, D. A. Low, K. Sheng, and S. Sharma, "Magnetic resonance imaging–guided vs computed tomography–guided stereotactic body radiotherapy for prostate cancer: the MIRAGE randomized clinical trial," JAMA, 2023. jamanetwork.com

104. NA Wijetunga, E. Pentsova, S. Wolden, et al., "Randomized phase II trial of proton craniospinal irradiation versus photon involved-field radiotherapy for patients with solid tumor leptomeningeal metastasis," Journal of Clinical, 2022. nih.gov

105. AU Kishan, Y. Sun, H. Hartman, T. M. Pisansky, "Androgen deprivation therapy use and duration with definitive radiotherapy for localised prostate cancer: an individual patient data meta-analysis," The Lancet, 2022. [HTML]

106. Z. Zhang, X. Liu, D. Chen, and J. Yu, "Radiotherapy combined with immunotherapy: the dawn of cancer treatment," Signal Transduction and Targeted, 2022. nature.com

107. S. Mumtaz, J. N. Rana, E. H. Choi, and I. Han, "Microwave radiation and the brain: Mechanisms, current status, and future prospects," International Journal of Molecular, 2022. mdpi.com

108. Y. Wu, Y. Song, R. Wang, and T. Wang, "Molecular mechanisms of tumor resistance to radiotherapy," Molecular Cancer, 2023. springer.com

109. P. Tandon, D. Prakash, S. C. Kheruka, and N. N. Bhat, "Radiation Hazard Evaluation and Control in Nuclear Medicine," Radiation Safety Guide for ..., Springer, 2022. [HTML]

110. G. B. SOLOMON, K. Diyor, K. Kuvondik, and D. Federico, "Characterization of X-ray beam for Half and Quarter Value Layers," 2024. researchsquare.com

111. M. Talbi, M. Khalis, R. Sebihi, and O. Nhila, "Analysis of Half-Value Layer and Average Glandular Dose for Mammography Using Gate," Moscow University, 2021. [HTML]

112. M. Kamislioglu, "… investigation into gamma radiation shielding parameters of the (Al: Si) and (Al+ Na): Si-doped international simple glasses (ISG) used in nuclear waste management …," Journal of Materials Science: Materials in Electronics, 2021. [HTML]

113. L. Jönsson, "Staff Radiation Protection," in Handbook of Nuclear Medicine and Molecular …, 2022. [HTML]

114. A. N. Nandakumar, "Radiation protection," Nuclear fuel cycle, 2023. [HTML]

115. D. E. Kwon, D. H. Han, J. O. Kim, and K. H. Jung, "Multi-layered structures for lightweight providing shielding from unintended radiation exposure for pediatric patients," Radiation Physics and …, Elsevier, 2023. [HTML]

116. C. Yamauchi-Kawaura, E. Maki, and K. Fujii, "Measurement of Half-Value Layer in Computed Tomography Scanners Using Luminescence of Polyethersulfone Resin by X-Ray Irradiation," Radiation Protection, 2021. [HTML]

117. K. Ono and Y. Asada, "Optimal conversion coefficient from easily measurable dose to effective dose with consideration to radiation quality for posterior–anterior chest radiography," Biomedical Physics & Engineering Express, 2023. [HTML]

118. S. Malerz, F. Trinter, U. Hergenhahn, A. Ghrist, "Low-energy constraints on photoelectron spectra measured from liquid water and aqueous solutions," Physical Chemistry, 2021. rsc.org

119. T. O'Shea, M. Giannotti, and I. G. Irastorza, "Prospects on the detection of solar dark photons by the International Axion Observatory," … of Cosmology and …, 2024. [PDF]

120. E. P. Hartouni, A. S. Moore, A. J. Crilly, and B. D. Appelbe, "Evidence for suprathermal ion distribution in burning plasmas," Nature Physics, 2023. osti.gov

121. A. Berlin, G. Krnjaic, and E. Pinetti, "Reviving MeV-GeV indirect detection with inelastic dark matter," Physical Review D, 2024. aps.org

122. K. Ono, "A comprehensive report on ultrasonic attenuation of engineering materials, including metals, ceramics, polymers, fiber-reinforced composites, wood, and rocks," Applied Sciences, 2020. mdpi.com

123. DŞ Baykal, HO Tekin, and RBÇ Mutlu, "An investigation on radiation shielding properties of borosilicate glass systems," International Journal of …, 2021. dergipark.org.tr

124. A. M. Onaizi, M. Amran, W. Tang, and N. Betoush, "Radiation-shielding concrete: A review of materials, performance, and the impact of radiation on concrete properties," *Journal of Building*, 2024. sciencedirect.com

125. Q. Thijssen, J. A. Carroll, F. Feist, and A. Beil, "Beyond absorption maxima: the impact of wavelength-resolved photochemistry on materials science," Materials, 2024. [HTML]

126. M. Elsafi, M. F. Alrashedi, M. I. Sayyed, and I. F. Al-Hamarneh, "The potentials of egyptian and indian granites for protection of ionizing radiation," Materials, 2021. mdpi.com

127. S. Takeya, S. Muromachi, and A. Yoneyama, "X-ray imaging of clathrate hydrates as gas storage materials: absorption contrast of low-density and low-absorption materials using energy-dependent X-ray computed …," Energy & Fuels, 2022. [HTML]

128. S. Sim, D. Jeon, D. H. Kim, W. S. Yum, and S. Yoon, "Incorporation of copper slag in cement brick production as a radiation shielding material," Applied Radiation and …, 2021. [HTML]

129. E. Mansouri, A. Mesbahi, and R. Malekzadeh, "Shielding characteristics of nanocomposites for protection against X-and gamma rays in medical applications: effect of particle size, photon energy and nano-particle …," Radiation and …, 2020. researchgate.net

130. Q. Li, R. Zhong, X. Xiao, J. Liao, and X. Liao, "Lightweight and flexible Bi@ Bi-La natural leather composites with superb X-ray radiation shielding performance and low secondary radiation," ACS Applied Materials & Interfaces, 2020. [HTML]

131. W. R. Widmer and D. E. Thrall, "Radiation protection and physics of diagnostic radiology," in *Thrall's Textbook of Veterinary*, 2024. [HTML]

132. A. Karmakar, J. Wang, J. Prinzie, V. De Smedt et al., "A review of semiconductor based ionising radiation sensors used in Harsh radiation environments and their applications," Radiation, 2021. mdpi.com

133. L. Marques, A. Vale, and P. Vaz, "State-of-the-art mobile radiation detection systems for different scenarios," Sensors, 2021. mdpi.com

134. W. Rühm, C. Clement, D. Cool, and D. Laurier, "Summary of the 2021 ICRP workshop on the future of radiological protection," in *Journal of Radiological Protection*, 2022. iop.org

135. H. M. H. Zakaly, S. A. M. Issa, H. A. Saudi, "Decoding the role of bismuth oxide in advancing structural, thermal, and nuclear properties of -Nb2O5 glass systems," Radiation Physics and ..., 2024. [HTML]

136. B. Kanagaraj, N. Anand, and A. D. Andrushia, "Recent developments of

radiation shielding concrete in nuclear and radioactive waste storage facilities–a state of the art review," Construction and Building, 2023. researchgate.net

137. M. K. Hossain, G. A. Raihan, M. A. Akbar, "Current applications and future potential of rare earth oxides in sustainable nuclear, radiation, and energy devices: a review," ACS Applied, 2022. [HTML]

138. F. A. Mettler Jr, M. Mahesh, and M. Bhargavan-Chatfield, "Patient exposure from radiologic and nuclear medicine procedures in the United States: procedure volume and effective dose for the period 2006–2016," Radiology, 2020. rsna.org

139. H. Hricak, M. Abdel-Wahab, R. Atun, and M. M. Lette, "Medical imaging and nuclear medicine: a Lancet Oncology Commission," The Lancet, 2021. [HTML]

140. G. Verfaillie, C. Franck, A. De Crop, L. Beels, and Y. D'Asseler, "A systematic review and meta-analysis on the radiation dose of computed tomography in hybrid nuclear medicine imaging," *EJNMMI Physics*, 2023. springer.com

141. JF Gomes Marin, RF Nunes, AM Coutinho, "Theranostics in nuclear medicine: emerging and re-emerging integrated imaging and therapies in the era of precision oncology," Radiographics, 2020. rsna.org

142. K. Johnsson, J. Brynolfsson, H. Sahlstedt, "… performance of aPROMISE: automated anatomic contextualization, detection, and quantification of DCFPyL (PSMA) imaging for standardized reporting," … of Nuclear Medicine …, Springer, 2022. springer.com

143. N. Tsoulfanidis and S. Landsberger, "Measurement and detection of radiation," 2021. [HTML]

144. D. Jiang, X. Chen, Z. You, H. Wang, X. Zhang, and X. Li, "Comparison of Ga-FAPI-04 and -FDG for the detection of primary and metastatic lesions in patients with gastric cancer: a bicentric retrospective study," in *Journal of Nuclear Medicine*, Springer, 2022. [HTML]

145. Y. He, I. Hadar, and M. G. Kanatzidis, "Detecting ionizing radiation using halide perovskite semiconductors processed through solution and alternative methods," Nature photonics, 2022. osti.gov

146. H. G. Erenstein, D. Browne, S. Curtin, and R. S. Dwyer, "The validity and reliability of the exposure index as a metric for estimating the radiation dose to the patient," Radiography, 2020. sciencedirect.com

147. B. L. Mulherin, C. T. W. Width, and W. Level, "History, Physiology, Modality Options, and Safety for Diagnostic Imaging of the Oral Cavity," Veterinary Oral, 2023. divisionmedica.es
148. Q. B. Carroll, "Radiography in the Digital Age: Physics-exposure-radiation biology," 2023. [HTML]
149. H. Cao, "Accuracy of radiostereometric analysis using a motorized Roentgen system in a pilot study for clinical simulation," Medical Engineering & Physics, 2023. [HTML]
150. G. B. Saha, "Radiation Units, Exposure, and Absorbed Dose," in *Radiation Safety in Nuclear Medicine: A Practical …*, Springer, 2023. [HTML]
151. Y. Wei and S. A. Dewji, "A comprehensive review of dose limits, triage systems and measurement tools for consequence management of nuclear and radiological emergencies," Radiation Physics and Chemistry, 2024. [HTML]
152. R. Siasendeka, "Evaluation of factors affecting the exposure indicator of computed radiography and how it relates to radiation organ dose at a second level hospital in Zambia," 2023. cput.ac.za
153. W. R. Widmer and D. E. Thrall, "Radiation protection and physics of diagnostic radiology," in Thrall's Textbook of Veterinary, 2024. [HTML]
154. A. Pathak, "Radioactivity and Its Units," Tools and Techniques in Radiation Biophysics, 2023. [HTML]
155. M. D. Sakhil, "Study of the Effect of Radiology X-ray and its Risks on Human," International Journal of Scientific Trends, 2022. scientifictrends.org
156. S. Dhanekar and K. Rangra, "Wearable dosimeters for medical and defence applications: A state of the art review," Advanced Materials Technologies, 2021. [HTML]
157. K. Y. Cheung, "Apparatus that separated radiotherapy from radiology," Hong Kong Medical Journal, 2021. hkmj.org
158. K. Bouzegzi and A. Frahi-Amroun, "The system of radiation protection quantities used for occupational exposures to external sources: short history and critical review," Radiation Protection Dosimetry, 2022. researchgate.net
159. E. Obrador, R. Salvador, J. I. Villaescusa, J. M. Soriano, "Radioprotection

and radiomitigation: from the bench to clinical practice," Biomedicines, 2020. mdpi.com

160. H. Murshed, "Fundamentals of radiation oncology: physical, biological, and clinical aspects," 2024. [HTML]

161. N. W. Jenkins, J. M. Parrish, and E. D. Sheha, "Intraoperative risks of radiation exposure for the surgeon and patient," *Journal of Translational Medicine*, 2021. nih.gov

162. M. Smith, E. Yanko, and M. Huynh, "X-ray therapy safety and awareness education for medical trainees and attending physicians," Canadian Urological, 2022. nih.gov

163. M. Belli and M. A. Tabocchini, "Ionizing radiation-induced epigenetic modifications and their relevance to radiation protection," International journal of molecular sciences, 2020. mdpi.com

164. L. T. Dauer, A. Bouville, and R. E. Toohey, "Dosimetry and uncertainty approaches for the million-worker study of radiation workers and veterans: overview of the recommendations in NCRP Report No. 178," in Low-Dose Radiation, 2024. [HTML]

165. B. Alshahrani, I. O. Olarinoye, and C. Mutuwong, "Amorphous alloys with high Fe content for radiation shielding applications," Radiation Physics and ..., Elsevier, 2021. [HTML]

166. M. S. Al-Buriahi, "Radiation shielding performance of a borate-based glass system doped with bismuth oxide," Radiation Physics and Chemistry, 2023. [HTML]

167. S. Furukawa, A. Nagamatsu, and M. Nenoi, "Space radiation biology for 'Living in Space'," BioMed Research, 2020. wiley.com

168. W. R. Widmer and D. E. Thrall, "Radiation protection and physics of diagnostic radiology," in Thrall's Textbook of Veterinary, 2024. [HTML]

169. C. C. Ban, M. A. Khalaf, M. Ramli, N. M. Ahmed, "Modern heavyweight concrete shielding: Principles, industrial applications and future challenges; review," *Journal of Building*, Elsevier, 2021. [HTML]

170. M. Kamislioglu, "Research on the effects of bismuth borate glass system on nuclear radiation shielding parameters," Results in Physics, 2021. sciencedirect.com

171. M. S. Al-Buriahi, T. A. Taha, M. A. Alothman, and H. Donya, "Influence of WO3 incorporation on synthesis, optical, elastic and radiation

shielding properties of borosilicate glass system," *The European Physical*, 2021. researchgate.net

172. A. A. Friedl, K. M. Prise, and K. T. Butterworth, "Radiobiology of the FLASH effect," Medical, 2022. wiley.com

173. MHA Mhareb, Y Slimani, YS Alajerami, MI Sayyed, "Structural and radiation shielding properties of BaTiO3 ceramic with different concentrations of Bismuth and Ytterbium," Ceramics, 2020. sciencedirect.com

174. M. S. Al-Buriahi, Z. A. Alrowaili, C. Eke, J. S. Alzahrani, "Optical and radiation shielding studies on tellurite glass system containing ZnO and Na2O," Optik, Elsevier, 2022. [HTML]

175. S. Mohan and V. Chopra, "Biological effects of radiation," Radiation dosimetry phosphors, 2022. [HTML]

176. A. E. Waltar, A. J. Gonzalez, and L. E. Feinendegen, "Why low-level radiation exposure should not be feared," Health Physics, 2023. jick.net

177. W. Rühm, J. Breckow, G. Dietze, A. Friedl, "Dose limits for occupational exposure to ionising radiation and genotoxic carcinogens: a German perspective," Radiation and ..., Springer, 2020. [HTML]

178. N. Bhat, U. Yadav, and R. K. Chaurasia, "Biological Effects of Radiation," in *Radiation Environment*, vol. 2, Dose, 2024, Springer. [HTML]

179. M. Alvandi, R. N. Javid, and Z. Shaghaghi, "An In-depth Analysis of the Adverse Effects of Ionizing Radiation Exposure on Cardiac Catheterization Staffs," Current, 2024. umsha.ac.ir

180. U. Uğrak, Y. Uzkar, İ. Düzen, and T. Acar, "Evaluation of Procedure Doses and Staff Attitudes in Interventional Cardiology in Terms of Radiation Safety," Archives of the ..., 2024. [HTML]

181. E. Seeram, "Dose Optimization: A Major Principle of Optimization," in *Dose Optimization in Digital Radiography and ...*, Springer, 2023. [HTML]

182. J. Talapko, D. Talapko, D. Katalinić, I. Kotris, and I. Erić, "Health Effects of Ionizing Radiation on the Human Body," Medicina, 2024. mdpi.com

183. A. L. DiCarlo, A. C. Bandremer, "Cutaneous radiation injuries: models, assessment and treatments," Radiation, 2020. allenpress.com

184. N. V. Gorbunov and J. G. Kiang, "Brain damage and patterns of

neurovascular disorder after ionizing irradiation. Complications in radiotherapy and radiation combined injury," Radiation research, 2021. allenpress.com

185. P. Arnautou, G. Garnier, J. Maillot, and J. Konopacki, "Management of acute radiation syndrome," Transfusion Clinique et ..., 2024. [HTML]

186. M. Al-Qabandi and J. Alshammary, "Ionizing radiation: biologic effects and essential cell biology," The Pathophysiologic Basis of Nuclear, Springer, 2022. [HTML]

187. L. Strigari, S. Strolin, and A. G. Morganti, "Dose-effects models for space radiobiology: an overview on dose-effect relationships," Frontiers in Public Health, 2021. frontiersin.org

188. M. T. Chew, E. Daar, and M. U. Khandaker, "Low radiation dose to treat pneumonia and other inflammations," The British Journal of, 2021. nih.gov

189. M. Lenarczyk, A. Kronenberg, M. Mäder, R. Komorowski, "Exposure to multiple ion beams, broadly representative of galactic cosmic rays, causes perivascular cardiac fibrosis in mature male rats," Plos One, 2023. plos.org

190. P. A. Bryant, "Radiation Protection Optimisation in New Nuclear Build: Challenges in the Application of the'As Low As Reasonably Achievable'(ALARA) Principle," 2021. surrey.ac.uk

191. R. Bhanot, Z. B. M. Hameed, M. Shah, and P. Juliebø-Jones, "ALARA in urology: steps to minimise radiation exposure during all parts of the endourological journey," *Current Urology*, Springer, 2022. springer.com

192. P. A. Bryant, "Communicating radiation risk: the role of public engagement in reaching ALARA," Journal of Radiological Protection, 2021. iop.org

193. P. A. Oakley and D. E. Harrison, "Death of the ALARA radiation protection principle as used in the medical sector," Dose-Response, 2020. sagepub.com

194. S. Andresz, J. Morgan, and C. Nuccetelli, "Application of the ALARA principle for radon at work: feedback from the European ALARA network," in *Journal of Radiological Protection*, 2022. [HTML]

195. N. N. S. Marzuki, M. Hassan, and S. A. Othman, "ALARA Concept in Radiation Protection and Application in Radioiodine Treatment-A Short Review," iscientific.org, . iscientific.org

196. B. B. Joseph and S. George, "The road to radiation safety and ALARA: A review," Int. J. Maxillofac Imaging, 2020. semanticscholar.org
197. G. T. Duarte, P. Y. Volkova, F. Fiengo Perez, and N. Horemans, "Chronic ionizing radiation of plants: An evolutionary factor from direct damage to non-target effects," Plants, 2023. mdpi.com
198. K. Lumniczky, N. Impens, G. Armengol, and S. Candéias, "Low dose ionizing radiation effects on the immune system," Environment, Elsevier, 2021. sciencedirect.com
199. M. Arroyo-Hernández, F. Maldonado, et al., "Radiation-induced lung injury: current evidence," BMC Pulmonary, Springer, 2021. springer.com
200. S. A. Hamouda, N. K. Alshawish, and Y. K. Abdalla, "Ultraviolet Radiation: Health Risks and Benefits," Saudi Journal of ..., 2022. saudijournals.com
201. A. Terfort and M. Zharnikov, "Electron-Irradiation Promoted Exchange Reaction as a Tool for Surface Engineering and Chemical Lithography," Advanced Materials Interfaces, 2021. wiley.com
202. M. Röösli, S. Dongus, H. Jalilian, and M. Feychting, "The effects of radiofrequency electromagnetic fields exposure on tinnitus, migraine and non-specific symptoms in the general and working population: A …," Environment, Elsevier, 2021. sciencedirect.com
203. R. Prasad, N. K. Jain, J. Conde, and R. Srivastava, "Localized nanotheranostics: recent developments in cancer nanomedicine," Materials Today Advances, 2020. sciencedirect.com
204. K. Zheng, X. Zhu, S. Guo, and X. Zhang, "Gamma-ray-responsive drug delivery systems for radiation protection," Chemical Engineering Journal, 2023. [HTML]
205. D. Leszczynski, "Review of the scientific evidence on the individual sensitivity to electromagnetic fields (EHS)," Reviews on environmental health, 2022. degruyter.com
206. W. A. Weber, J. Czernin, C. J. Anderson, et al., "The future of nuclear medicine, molecular imaging, and theranostics," *Journal of Nuclear Medicine*, 2020, Society of Nuclear Medicine. snmjournals.org
207. G. Sgouros, L. Bodei, and M. R. McDevitt, "Radiopharmaceutical therapy in cancer: clinical advances and challenges," *Nature Reviews Drug Discovery*, 2020. nature.com
208. M. V. Kovalchuk, S. M. Deyev, and K. A. Sergunova, "Targeted Nuclear

Medicine. Achievements, Challenges and Prospects," Nanobiotechnology Reports, 2023. springer.com

209.J. P. O'Malley and H. A. Ziessman, "Nuclear Medicine and Molecular Imaging: The Requisites E-Book: Nuclear Medicine and Molecular Imaging: The Requisites E-Book," 2020. [HTML]

210.G. Crișan, N. S. Moldovean-Cioroianu, "Radiopharmaceuticals for PET and SPECT imaging: a literature review over the last decade," International Journal of ..., 2022. mdpi.com

211.A. Abubakr, A. I. Othman, and T. M. Ewedah, "The applications of radioisotopes in modern medicine: a review of diagnostic, therapeutic, and research advancements," ERU Research Journal, 2024. ekb.eg

212.C. D. Kaur, K. K. Mishra, A. Sahu, and R. Panik, "Theranostics: New era in nuclear medicine and radiopharmaceuticals," Medical, 2020. intechopen.com

213.S. S. Dudhe, G. Mishra, P. Parihar, and D. Nimodia, "Radiation dose optimization in radiology: a comprehensive review of safeguarding patients and preserving image fidelity," Cureus, 2024. nih.gov

214.M. Joshi, D. K. Aswal, and A. Chandra, "Radiation Protection Policies: Safeguarding Health and the Environment," in *Handbook on Radiation Environment*, Springer, 2024. [HTML]

215.B. M. Moores, "On the justification of justification in radiation protection-legal and sociological considerations," Radiography, 2021. [HTML]

216.J. D. Harrison, M. Balonov, F. Bochud, "ICRP publication 147: use of dose quantities in radiological protection," Annals of the…, 2021. sagepub.com

217.N. E. Martinez and F. Zölzer, "Review of ethical values across the ICRP's system of radiological protection," Journal of Radiological Protection, 2024. iop.org

218.UC Okonkwo, CC Ohagwu, and ME Aronu, "Ionizing radiation protection and the linear No-threshold controversy: Extent of support or counter to the prevailing paradigm," Journal of ..., 2022. [HTML]

219.J. S. Wieder and T. Schneider, "The three R's of reasonable in radiological protection: relationships, rationale, and resources," Journal of Radiological Protection, 2022. [HTML]

220. A. N. Nandakumar, "11.1 Part I Basic Principles of Radiation Protection," Nuclear Fuel Cycle, . [HTML]

221. S. Demaria, C. Guha, J. Schoenfeld, Z. Morris, "Radiation dose and fraction in immunotherapy: one-size regimen does not fit all settings, so how does one choose?," for immunotherapy of, 2021. nih.gov

222. A. F. Mikhailova and O. L. Tashlykov, "The ways of implementation of the optimization principle in the personnel radiological protection," Physics of Atomic Nuclei, 2020. [HTML]

223. F. Romano, C. Bailat, P. G. Jorge, M. L. F. Lerch, "Ultra-high dose rate dosimetry: challenges and opportunities for FLASH radiation therapy," Medical, 2022. wiley.com

224. M. Shavers, E. Semones, L. Tomi, and J. Chen, "Space agency-specific standards for crew dose and risk assessment of ionising radiation exposures for the International Space Station," … für Medizinische Physik, 2024, Elsevier. sciencedirect.com

225. E. Atlı, S. A. Uyanık, U. Öğüşlü, and H. Ç. Cenkeri, "Radiation doses from head, neck, chest and abdominal CT examinations: an institutional dose report," Diagnostic and ..., 2020. nih.gov

226. M. Weber, M. Lam, C. Chiesa, and M. Konijnenberg, "EANM procedure guideline for the treatment of liver cancer and liver metastases with intra-arterial radioactive compounds," European Journal of ..., 2022. springer.com

227. J. Groen, "FLASH optimisation in clinical IMPT treatment planning," 2020. tudelft.nl

228. J. Dawson and S. Haulon, "Radiation Stewardship: Radiation Exposure, Protection and Safety in Contemporary Endovascular Practice," in *Mechanisms of Vascular Disease: A Textbook for …*, Springer, 2020. [HTML]

229. S. ROESLER, "Occupational radiation protection in the operation of accelerators at CERN," eu-alara.net, . eu-alara.net

230. N. A. F. Buhari, N. E. M. Rizal, and S. A. Othman, "Radiation Protection Program in Nuclear Industry-A Short Review," iscientific.org, . iscientific.org

231. K. A. Alturkistani, "Evaluation of radiation dose reduction strategies in pediatric radiology," sjr-publishing.com, . sjr-publishing.com

232. A. Chandra and S. Anand, "Socio-economic Implications of Radiation Protection Policies," in Handbook on Radiation Environment, vol. 1, Springer, 2024. [HTML]

233. C. Granata, C. Sofia, M. Francavilla, and M. Kardos, "Let's talk about radiation dose and radiation protection in children," Pediatric, Springer, 2024. [HTML]

234. R. Velshi, "(Un) stated assumptions: values, ethics, and the System of Radiological Protection," Annals of the ICRP, 2023. sagepub.com

235. M. K. Pise, M. S. Tivaskar, and M. A. Luharia, "Assessment Of Radiation Dose In Digital Radiography System-A Review Article," Journal of ..., 2022. pnrjournal.com

236. J. R. James, T. M. Martin, and Y. Liang, "Radiation Exposure and Protection," in *Image Guided Interventions of the Spine*, Springer, 2021. [HTML]

237. I.N. Wijma, R.F. Casal, G.Z. Cheng, P.F. Einsiedel, A. Fantin, et al., "Radiation Principles, Protection, and Reporting for Interventional Pulmonology: A World Association of Bronchology and Interventional Pulmonology White Paper," Respiration, 2024. karger.com

238. P. S. Sarkar, "Safety, regulations, metrology and standards in neutron imaging," Neutron imaging: basics, . [HTML]

239. L. N. H. M. Kamal, S. A. Othman, and N. A. Elias, "Controversies and Safety in Radiotherapy-A Short Review," researchgate.net, . researchgate.net

240. G. S. Johal, R. Masoomi, and J. Sweeny, "Basics of Radiation Safety," in *Practical Manual of Interventional*, Springer, 2021. [HTML]

241. S. I. Baker and S. Kamboj, "Applying ALARA principles in the design of new radiological facilities," Health Physics, 2022. osti.gov

242. A. Schiska, "Teaching radiography students the ALARA principle," Radiologic technology, 2021. [HTML]

243. A. Pai, C. R. Kini, and S. Shenoy, "Development of materials and structures for shielding applications against Blast and Ballistic impact: A Detailed Review," Thin-Walled Structures, 2022. [HTML]

244. Y. Wu and Z. Wang, "Progress in ionizing radiation shielding materials," Advanced Engineering Materials, 2024. [HTML]

245. R. Thandavamoorthy and Y. Devarajan, "Study on the nuclear shield

behaviors of basalt/carbon fibers reinforced PbO blended epoxy matrix composite–A novel material for thermal insulation …," Nuclear Engineering and Technology, 2024. sciencedirect.com

246. M. S. Alauddin, N. A. Abdul Hayei, M. A. Sabarudin, "Barrier membrane in regenerative therapy: a narrative review," Membranes, 2022. mdpi.com

247. C. Liu, M. Han, J. Lin, W. Liu et al., "Wood biomass-derived carbon for high-performance electromagnetic wave absorbing and shielding," Carbon, 2023. [HTML]

248. S. Gong, X. Sheng, X. Li, M. Sheng, and H. Wu, "… multi-source driven thermal management, electromagnetic interference shielding, and fire safety performance, inspired by a “brick–mortar” sandwich structure," Advanced Functional, 2022. [HTML]

249. J. Liu, M. Y. Yu, Z. Z. Yu, and V. Nicolosi, "Design and advanced manufacturing of electromagnetic interference shielding materials," Materials Today, 2023. sciencedirect.com

250. S. C. Kim, "Analysis of shielding performance of radiation-shielding materials according to particle size and clustering effects," Applied Sciences, 2021. mdpi.com

251. C. V. More, Z. Alsayed, M. S. Badawi, and A. A. Thabet, "Polymeric composite materials for radiation shielding: a review," Environmental Chemistry, Springer, 2021. springer.com

252. G. Tyagi, A. Singhal, S. Routroy, and D. Bhunia, "Radiation Shielding Concrete with alternate constituents: An approach to address multiple hazards," *Journal of hazardous*, 2021. [HTML]

253. M. S. Al-Buriahi, C. Eke, and S. Alomairy, "Radiation attenuation properties of some commercial polymers for advanced shielding applications at low energies," Polymers for ..., 2021. [HTML]

254. S. Yasmin, M. U. Khandaker, D. A. Bradley, "The efficacy of various thicknesses of float glasses for protection of gamma-radiation," Radiation Physics and ..., Elsevier, 2022. [HTML]

255. M. A. Al-Rajhi, H. Idriss, and A. A. S. Alaamer, "Gamma/neutron radiation shielding, structural and physical characteristics of iron slag nanopowder," Applied Radiation and ..., 2021. [HTML]

256. R. N. Ihsani, P. L. Gareso, and D. Tahir, "An overview of gamma radiation shielding: Enhancements through polymer-lead (Pb) composite materials," Radiation Physics and Chemistry, 2024. [HTML]

257. M. S. Mansy, Y. F. Lasheen, M. M. E. Breky, and Y. Selim, "Experimental and theoretical investigation of Pb–Sb alloys as a gamma-radiation shielding material," Radiation Physics and …, 2021. [HTML]

258. M. Almurayshid, Y. Alssalim, F. Aksouh, and R. Almsalam, "Development of new lead-free composite materials as potential radiation shields," Materials, 2021. mdpi.com

259. M. Saad, H. AlMohiy, A. A. Alshihri, and M. Alelyani, "Microstructural modifications, elastic properties and radiation attenuation performance of ZnO nano-sized particles-reinforced Pb-based alloys for radiation shielding," Radiation Effects and ..., 2023. [HTML]

260. H. Özdoğan, Y. A. Üncü, F. Akman, H. Polat et al., "Investigation of Gamma Ray Shielding Characteristics of Binary Composites Containing Polyester Resin and Lead Oxide," Polymers, 2024. mdpi.com

261. S. A. Habeeb, "Studying the High Loading of Lead-Rubber Nanocomposites as Gamma Radiations Shielding.," 2024. [HTML]

262. O. Kilicoglu, C. V. More, F. Akman, K. Dilsiz, and H. Oğul, "Micro Pb filled polymer composites: Theoretical, experimental and simulation results for γ-ray shielding performance," Radiation Physics and ..., 2022. [HTML]

263. H. M. Qadr, "Calculation of gamma-ray attenuation parameters for aluminium, iron, zirconium and tungsten," Вопросы атомной науки и техники, 2020. nbuv.gov.ua

264. A. M. Abdalla, T. I. Al-Naggar, A. M. Bashiri, "Radiation shielding performance for local granites," Progress in Nuclear, Elsevier, 2022. [HTML]

265. N. Mario, A. Kolmayer, G. Turquet, and M. Medeiros, "Study on Sustainable and Resilient Supply of Medical Radioisotopes in the EU," 2022. europa.eu

266. E. Radiopharmacy, "Meeting abstracts from the 21st European Symposium on Radiopharmacy and Radiopharmaceuticals," Nucl. Med, 2023. springer.com

267. M. Bosch de Basea Gomez, I. Thierry-Chef, and R. Harbron, "Risk of hematological malignancies from CT radiation exposure in children, adolescents and young adults," Nature Medicine, 2023. nature.com

268. J. Van Dyck, "Exploring Models to Address Belgium's Defense Personnel Shortages in the Current Geopolitical Landscape," 2024. researchgate.net

269. D. Nevens, I. Kindts, N. Defourny, and L. Boesmans, "The financial impact of SBRT for oligometastatic disease: A population-level analysis in Belgium," Radiotherapy and Oncology, 2020. ugent.be

270. S. Bayart, "Towards efficient evaluation of lead aprons," 2021. ugent.be

271. V. Peri, "Implementing nuclear non-proliferation in Finland: Regulatory control, international cooperation and the Comprehensive Nuclear-Test-Ban Treaty: Annual report 2022," 2023. julkari.fi

272. C. B. Hess, J. Parkes, G. O. Janssens, and C. Lin, "Global pediatric radiation therapy in resource-limited settings," *Pediatric Blood &*, 2021. [HTML]

273. DH Ballard, KR Burton, N Lakomkin, S Kim, P Rajiah, "The role of imaging in health screening: screening for specific conditions," Academic Radiology, Elsevier, 2021. nih.gov

274. N. Dainiak and J. Albanese, "Assessment and clinical management of internal contamination," Journal of Radiological Protection, 2022. [HTML]

275. Y. K. Dewaraja, D. M. Mirando, A. B. Peterson, "A pipeline for automated voxel dosimetry: application in patients with multi-SPECT/CT imaging after 177Lu-peptide receptor radionuclide therapy," in *Journal of Nuclear Medicine*, Soc Nuclear Med, 2022. snmjournals.org

276. J. Blakkisrud, A. B. Peterson, S. J. Wildermann, "SPECT/CT Image-Derived Absorbed Dose to Red Marrow Correlates with Hematologic Toxicity in Patients Treated with Lu-DOTATATE," *J. Nucl. Med.*, 2024. snmjournals.org

277. B. Serencsits, B. P. Chu, and N. Pandit-Taskar, "Radiation safety considerations and clinical advantages of α-emitting therapy radionuclides," in ... of Nuclear Medicine ..., Soc Nuclear Med, 2022. snmjournals.org

278. K. Eseonu, U. Oduoza, and P. Robinson, "Bone scintigraphy with SPECT/CT in paediatric patients with neck and back pain in comparison with other imaging modalities: the experience of a tertiary paediatric …," Nuclear Medicine, 2024. [HTML]

279. P. Tandon, D. Prakash, S. C. Kheruka, and N. N. Bhat, "Radiation Safety Considerations During Radiopharmaceutical Preparation," in *Guide for Nuclear Medicine*, Springer, 2022. [HTML]

280. S. Hussain, I. Mubeen, and N. Ullah, "Modern diagnostic imaging

technique applications and risk factors in the medical field: a review," BioMed Research, 2022. wiley.com

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

282. 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

283. V. Grégoire, M. Guckenberger, "Image guidance in radiation therapy for better cure of cancer," Molecular, 2020. wiley.com

284. J. Andersson, "Dosimetric quantities and effective dose in medical imaging: a summary for medical doctors," European Society of Radiology (ESR) - … into imaging, Springer, 2021. springer.com

285. M. Unterrainer, C. Eze, H. Ilhan, and S. Marschner, "Recent advances of PET imaging in clinical radiation oncology," Radiation, Springer, 2020. springer.com

286. C. Brower and M. M. Rehani, "Radiation risk issues in recurrent imaging," The British journal of radiology, 2021. nih.gov

287. I. A. Tsalafoutas, M. H. Kharita, H. Al-Naemi, and M. K. Kalra, "Radiation dose monitoring in computed tomography: status, options and limitations," Physica Medica, 2020. physicamedica.com

288. K. D. Abalo, E. Rage, K. Leuraud, D. B. Richardson, "Early life ionizing radiation exposure and cancer risks: systematic review and meta-analysis," Radiology, Springer, 2021. hal.science

289. EL Irede, OR Aworinde, and OK Lekan, "Medical imaging: A Critical Review on X-ray Imaging for the Detection of Infection," Biomedical Materials & ..., Springer, 2024. researchgate.net

290. A. Moussaid, N. Zrira, I. Benmiloud, and Z. Farahat, "On the implementation of a post-pandemic deep learning algorithm based on a hybrid ct-scan/x-ray images classification applied to pneumonia categories," Healthcare, 2023. mdpi.com

291. W. Lan, X. Hui, B. Nicolaï, P. Verboven, and J. Qin, "… and chemical heterogeneity of fruit and vegetables using advanced imaging techniques: fundamentals, instrumental aspects, applications and future perspectives," Critical Reviews in …, 2024. google.com

292. Y. H. Bhosale and K. S. Patnaik, "Bio-medical imaging (X-ray, CT,

ultrasound, ECG), genome sequences applications of deep neural network and machine learning in diagnosis, detection …," Multimedia Tools and Applications, 2023. springer.com

293. A. K. Mondal, "COVID-19 prognosis using limited chest X-ray images," Applied Soft Computing, 2022. nih.gov

294. B. Hou, Q. Chen, L. Yi, P. Sellin, and H. T. Sun, "Materials innovation and electrical engineering in X-ray detection," Nature Reviews, 2024. [HTML]

295. F. Toia, M. Cajozzo, F. Rosatti, S. Di Lorenzo, and G. Rinaldi, "Effectiveness of clinical and instrumental follow-up for cutaneous melanoma," Surgical Oncology, Elsevier, 2022. [HTML]

296. D. González-Mancebo, A. I. Becerro, and C. Caro, "Nanoparticulated Bimodal Contrast Agent for Ultra-High-Field Magnetic Resonance Imaging and Spectral X-ray Computed Tomography," Inorganic, 2024. acs.org

297. A. Sarmadi, Z. S. Razavi, A. J. van Wijnen, and M. Soltani, "Comparative analysis of vision transformers and convolutional neural networks in osteoporosis detection from X-ray images," Scientific Reports, 2024. nature.com

298. G. G. Dhakad, G. D. Patil, and A. C. Nikum, "Review on Radiation Therapy on Cancer," Research Journal of ..., 2022. rjppd.org

299. E. M. Zeman, E. C. Schreiber, and J. E. Tepper, "Basics of radiation therapy," Abeloff's clinical oncology, 2020. practiceupdate.net

300. Y. F. Ali, F. A. Cucinotta, L. Ning-Ang, and G. Zhou, "Cancer risk of low dose ionizing radiation," Frontiers in Physics, 2020. frontiersin.org

301. J. Winiecki, "Principles of radiation therapy," Physical Sciences Reviews, 2022. degruyter.com

302. M. G. Ronga, M. Cavallone, A. Patriarca, A. M. Leite, and P. Loap, "Back to the future: very high-energy electrons (VHEEs) and their potential application in radiation therapy," *Cancers*, 2021. mdpi.com

303. J. Zhang, J. Si, L. Gan, R. Zhou, and M. Guo, "Harnessing the targeting potential of differential radiobiological effects of photon versus particle radiation for cancer treatment," Journal of Cellular, 2021. [HTML]

304. N. Karmaker, K. M. Maraz, and F. Islam, "Fundamental characteristics and application of radiation," GSC Advanced, 2021. gsconlinepress.com

305. E. Boopathi, R. B. Den, and C. Thangavel, "Innate Immune System in the Context of Radiation Therapy for Cancer," Cancers, 2023. mdpi.com

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

307. K. Wang and J. E. Tepper, "Radiation therapy-associated toxicity: Etiology, management, and prevention," CA: a cancer journal for clinicians, 2021. wiley.com

308. A. Saini, M. Kumar, S. Bhatt, and V. Saini, "Cancer causes and treatments," *Int. J. Pharm. Sci. Res.*, 2020. researchgate.net

309. E. F. Gillespie, J. C. Yang, N. J. Mathis, and C. B. Marine, "Prophylactic radiation therapy versus standard of care for patients with high-risk asymptomatic bone metastases: a multicenter, randomized phase II clinical trial," *Journal of Clinical Oncology*, 2024. [HTML]

310. V. Yazbeck, E. Alesi, J. Myers, and M. H. Hackney, "An overview of chemotoxicity and radiation toxicity in cancer therapy," Advances in Cancer, Elsevier, 2022. [HTML]

311. R. J. Griffin, M. M. Ahmed, B. Amendola, and O. Belyakov, "Understanding high-dose, ultra-high dose rate, and spatially fractionated radiation therapy," in *… of Radiation Oncology …*, Elsevier, 2020. iupui.edu

312. J. A. Vargo, V. Moiseenko, J. Grimm, J. Caudell, "Head and neck tumor control probability: radiation dose–volume effects in stereotactic body radiation therapy for locally recurrent previously-irradiated head and neck …," … of Radiation Oncology …, Elsevier, 2021. redjournal.org

313. G. Ferini, V. Valenti, A. Tripoli, S. I. Illari, L. Molino, and S. Parisi, "Lattice or oxygen-guided radiotherapy: what if they converge? Possible future directions in the era of immunotherapy," Cancers, 2021. mdpi.com

314. D. Berger, S. Van Dyk, L. Beaulieu, T. Major et al., "Modern tools for modern brachytherapy," Clinical Oncology, 2023. sciencedirect.com

315. P. Pathak, J. J. Thomas, A. Baghwala, C. Li, and B. S. Teh, "Personalized Brachytherapy: Applications and Future Directions," *Cancers*, 2024. mdpi.com

316. S. Banerjee, S. Goyal, S. Mishra, and D. Gupta, "Artificial intelligence in brachytherapy: a summary of recent developments," The British Journal of ..., 2021. nih.gov

317. S. Cozzi, M. Augugliaro, P. Ciammella, A. Botti, and V. Trojani, "The role of interstitial brachytherapy for breast cancer treatment: an overview of indications, applications, and technical notes," Cancers, 2022. mdpi.com

318. N. F. Z. M. Khairi and N. F. Roszaini, "Principles and Techniques in Handling Brachytherapy-A Short Review," *Journal of Advanced*, 2023. uthm.edu.my
319. T. Y. Gebremariam, G. Geraily, and A. G. Arero, "Efficacy of Nanoparticles in dose enhancement with high dose rate of Iridium-192 and Cobalt-60 radionuclide sources in the Treatment of Cancer: A systematic review," Journal of Cancer, 2023. lww.com
320. M. Abtahi, S. Gholami, and H. H. Jassim, "High dose rate 192Ir versus high dose rate 60Co brachytherapy: an overview of systematic reviews of clinical responses of gynecological cancers from 1984 to 2020," Biomedical Physics & …, 2021. [HTML]
321. J. Tamihardja, S. Weick, P. Lutyj, and M. Zimmermann, "Comparing Iridium-192 with Cobalt-60 sources in high-dose-rate brachytherapy boost for localized prostate cancer," Acta, 2022. tandfonline.com
322. MH Sadeghi, S Sina, and A Meigooni, "A comparison of treatment duration for Cobalt-60 and Iridium-192 sources with different activities in HDR brachytherapy using tandem-ovoid applicator," Iranian Journal of Medical, 2021. researchgate.net
323. Y. Roussakis and G. Anagnostopoulos, "Physical and dosimetric aspects of the iridium-knife," Frontiers in Oncology, 2021. frontiersin.org
324. R. Radha, S. M. Lawrence, and P. R. Babu, "HDR Brachytherapy in Cervical Cancers with Co 60 Source: A Single Institution Experience," Int. J. Acad. Med., 2024. academicmed.org
325. IJ Das, SL Dawes, MM Dominello, B Kavanagh, "Quality and safety considerations in stereotactic radiosurgery and stereotactic body radiation therapy: An ASTRO safety white paper update," Practical Radiation, Elsevier, 2022. [HTML]
326. Q. Xiao and G. Li, "Application and challenges of statistical process control in radiation therapy quality assurance," *International Journal of Radiation Oncology* Biology …, 2024. [HTML]
327. L. Vandewinckele, M. Claessens, and A. Dinkla, "Overview of artificial intelligence-based applications in radiotherapy: Recommendations for implementation and quality assurance," Radiotherapy and ..., Elsevier, 2020. sciencedirect.com
328. P. J. Lewis, L. E. Court, Y. Lievens, and A. Aggarwal, "Structure and processes of existing practice in radiotherapy peer review: a systematic review of the literature," Clinical Oncology, 2021. sciencedirect.com

329. D. Schmitt, O. Blanck, T. Gauer, M. K. Fix, "… requirements for stereotactic radiotherapy: Expert review group consensus from the DGMP Working Group for Physics and Technology in Stereotactic Radiotherapy," Strahlentherapie und ..., 2020. springer.com

330. R. Alrae, "Quality Tools, Technologies, and Techniques: Enhancing Product and Service Excellence," 2024. intechopen.com

331. M. Mubarak, "Quality Assurance in Histopathology Laboratories," Journal of Clinical and Translational Pathology, 2023. xiahepublishing.com

332. J. Kinkorová, "Education for future biobankers-the state-of-the-art and outlook," Epma Journal, 2021. springer.com

333. M. Z. Jeddi, N. B. Hopf, H. Louro, S. Viegas, and K. S. Galea, "Developing human biomonitoring as a 21st century toolbox within the European exposure science strategy 2020–2030," Environment, 2022. sciencedirect.com

334. S. Sader, I. Husti, and M. Daroczi, "A review of quality 4.0: Definitions, features, technologies, applications, and challenges," Total Quality Management & Business, 2022. [HTML]

335. A. Ogunshe, "Restructuring assessments and monitoring of quality assurance, policy implementations and international cohesion in post-21st century higher education," Lagos/Paris/Washington 2023, . chea.org

336. A. J. Kwarteng, "Ensuring quality in higher education institutions: going beyond quality assurance system," International Journal of Productivity and ..., 2022. [HTML]

337. J. Renaud, H. Palmans, and A. Sarfehnia, "Absorbed dose calorimetry," in Medicine & Biology, 2020. [HTML]

338. M. Esposito, E. Villaggi, S. Bresciani, S. Cilla, "Estimating dose delivery accuracy in stereotactic body radiation therapy: a review of in-vivo measurement methods," Radiotherapy and…, Elsevier, 2020. quotidianosanita.it

339. K. Sjögreen Gleisner, N. Chouin, P. M. Gabina, "EANM dosimetry committee recommendations for dosimetry of 177Lu-labelled somatostatin-receptor-and PSMA-targeting ligands," in … and Molecular Imaging, Springer, 2022. springer.com

340. C. Chiesa, K. Sjogreen-Gleisner, S. Walrand, L. Strigari, "Committee series on standard operational procedures: A unified methodology for

99m Tc-MAA pre-and 90 Y peri-therapy dosimetry in liver radioembolization with 90," EJNMMI Physics, 2021. springer.com

341. D. E. Whittier, S. K. Boyd, A. J. Burghardt, and J. Paccou, "Guidelines for the assessment of bone density and microarchitecture in vivo using high-resolution peripheral quantitative computed tomography," Osteoporosis, Springer, 2020. nih.gov

342. A. Balekundri and V. Mannur, "Quality control of the traditional herbs and herbal products: a review," Future Journal of Pharmaceutical Sciences, 2020. springer.com

343. C. K. Glide-Hurst, E. S. Paulson, K. McGee, "Task group 284 report: magnetic resonance imaging simulation in radiotherapy: considerations for clinical implementation, optimization, and quality assurance," Medical Physics, 2021. nih.gov

344. A. Haleem, M. Javaid, R. P. Singh, and R. Suman, "Medical 4.0 technologies for healthcare: Features, capabilities, and applications," Internet of Things and Cyber, Elsevier, 2022. sciencedirect.com

345. E. Coleman, A. E. Radix, W. P. Bouman, "Standards of care for the health of transgender and gender diverse people, version 8," … journal of transgender …, 2022. tandfonline.com

346. Y. Baribeau, A. Sharkey, O. Chaudhary, and S. Krumm, "Handheld point-of-care ultrasound probes: the new generation of POCUS," Journal of Cardiothoracic, Elsevier, 2020. nih.gov

347. C. S. Lai, Y. Jia, Z. Dong, D. Wang, Y. Tao, and Q. H. Lai, "A review of technical standards for smart cities," Clean, 2020. mdpi.com

348. N. Kumar, R. Salehiyan, V. Chauke, and O. J. Botlhoko, "Top-down synthesis of graphene: A comprehensive review," FlatChem, Elsevier, 2021. [HTML]

349. T. Kron, C. Fox, and M. A. Ebert, "Quality management in radiotherapy treatment delivery," … and radiation oncology, 2022. [HTML]

350. M. Amurao, D. A. Gress, M. A. Keenan, "Quality management, quality assurance, and quality control in medical physics," Journal of Applied, 2023. wiley.com

351. G. Hildebrandt, A. Stachs, B. Gerber, J. Potenberg, "Central review of radiation therapy planning among patients with breast-conserving surgery: results from a quality assurance process integrated into the INSEMA trial," … of Radiation Oncology …, 2020. redjournal.org

352. M. Claessens, C. S. Oria, C. L. Brouwer, B. P. Ziemer, "Quality assurance for AI-based applications in radiation therapy," in Radiation Oncology, 2022, Elsevier. sciencedirect.com