Advanced Techniques in Medical Physics

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Chapter - 1

Introduction to Medical Physics

As per the definition of science and technology, in the pre-industrial age, developments in these two directions were very close to one another. Various branches of physics and their applications are an example of this correlation. It is common knowledge that physics is a fundamental natural science, contributing to our understanding of the laws that govern the universe. Technologies, on the other hand, encompass the methods and scientific principles employed in various industries and for practical purposes. When we delve into the origins of "Science-Based and High-Tech Industries," we realize that a significant portion of these cutting-edge fields owe their existence to advancements rooted in physics. As "High-Tech Industries" came into being, a separate infrastructure parallel to physics took shape, thus giving rise to the distinct scientific discipline we now recognize as technology.

Moreover, alongside this practical aspect of technology, there exists a field of knowledge intricately intertwined with medical and healthcare applications. In the realm of science and technology, during the era preceding the rise of industrialization, progress in both domains progressed hand in hand. It is worth noting that multiple subdivisions of physics and their practical implementations serve as a prime example of this close relationship. Universally acknowledged, physics stands as the base upon which our understanding of the laws governing the cosmos continually evolves. Simultaneously, technology acts as the driving force behind the methodologies and scientific principles employed for industrial and pragmatic purposes. Thus, upon examining the origin of "Science-Based and High-Tech Industries", we recognize that a significant fraction of these cutting-edge fields owe their existence to advancements rooted in physics.

With the advent of "High-Tech Industries," an independent infrastructure was established, running parallel to physics, thus giving birth to technology as a distinct scientific discipline. In addition to this hands-on aspect of technology, we find a branch of knowledge intricately connected with medical and healthcare applications. This field shares a common ground with physics, acting as a complementary force to advance scientific discoveries and improve medical practices. The integration of technology in the healthcare sector has revolutionized diagnostic procedures, treatment methods, and patient care. It has led to the development of innovative medical devices, imaging techniques, and life-saving interventions.

Furthermore, the intersection of science and technology has led to significant advancements in other industries as well. Engineering disciplines heavily rely on the principles established by physics, using them as a foundation to design and build structures, develop transportation systems, and create efficient energy sources. Information technology, another important field, owes a great deal of its progress to the merging of scientific knowledge and technological advancements. The development of computers, communication networks, and software applications would not have been possible without the principles of physics and the implementation of technology.

In conclusion, science and technology have always been closely intertwined, with advancements in one often driving progress in the other. Physics serves as the foundation upon which our understanding of the natural world is built, while technology applies scientific principles for practical purposes. The emergence of "Science-Based and High-Tech Industries" owes its existence to the interconnectedness of physics and technological advancements. This relationship extends beyond industrial applications, encompassing medical, engineering, and information technology fields. As we move forward, the collaboration between science and technology will continue to shape our world, driving innovation, and improving our lives. The synergy between scientific research and technological innovation will pave the way for groundbreaking discoveries and transformative advancements in various sectors, including renewable energy, space exploration, and biotechnology. It is through this harmonious union of science and technology that humanity will tackle the challenges of the future, unlocking new horizons and improving the quality of life for all. (Ghosh *et al*. 2023) (Kejriwal, 2023) (Oyama, 2022) (Tu *et al.*, 2023) (Wright, 2022)

1.1 Historical Overview

Basic medical physics in bioelectromagnetics started when radiofrequency interactions with biological objects were found in the 20th century. Since microwaves, which have been practically used in medical diagnosis and treatment in the current high-technology society, are a part of radiofrequency waves and induce various electromagnetic phenomena similar to radio waves. The current clinical equipment has been designed using mainly dosage data such as SAR and specific gravity, although a part of the electromagnetic phenomena occurring when humans are exposed to electromagnetic fields has also been used. The development of clinical equipment has been difficult considering not only effectiveness and safety but also size, cost, and environmental measures. However, current achievements in EM simulations enable the analysis and prediction of electromagnetic phenomena in humans inside hospitals or medical research institutions, in addition to those in biological tissue equivalent models. In this chapter, we perform dosimetry of several types of medical tools in terms of electromagnetic quantities. The chapter is organized as follows. In Section 1.2, we introduce the dosimetric concept of TPS, which has been verified uniquely based on epidemiological studies. This concept provides a framework for systematically evaluating the dose distribution in patients undergoing medical treatments. By understanding the dosimetric concept of TPS, healthcare professionals can ensure accurate and safe delivery of radiation therapy. To perform systematically the quality assurance (QA) of dosimetry, we categorize the international guidelines and regulations into the World Health Organization (WHO), International Commission on Non-Ionizing Radiation Protection (ICNIRP), Institute of Electrical and Electronics Engineers (IEEE), Food and Drug Administration (FDA), National Council on Radiological Protection (NCRP), and International Electrotechnical Commission (IEC) components. These organizations play a crucial role in establishing standards and guidelines to safeguard public health and ensure the safe use of electromagnetic fields in medical settings. In Section 1.3, we compare these guidelines and regulations to gain a comprehensive understanding of the dosimetric requirements and recommendations provided by each organization. Of the five components mentioned, the radar monitoring engineering guidelines are peculiarly stipulated by the IEEE committee. These guidelines aim to ensure the safe and effective use of radar systems in various industries and applications. By adhering to the IEEE guidelines, engineers and operators can minimize potential hazards and maximize the performance of radar systems. The dosimetric techniques used in medical physics can be classified into nine sub-categories referred to as the SC components. In Section 1.4, we conduct a detailed comparison of these techniques, considering measurements, numerical simulations, and a hybrid approach that combines both methods. This comparative analysis provides valuable insights into the advantages and limitations of each technique, allowing researchers and practitioners to make informed decisions regarding dosimetry in their respective fields. In Section 1.5, we conclude this chapter by summarizing the key findings and implications discussed throughout the text. We highlight the importance of accurate dosimetry in ensuring patient safety and optimal treatment outcomes. Furthermore, we emphasize the ongoing advancements in EM simulations and their potential for revolutionizing the field of medical physics. By continuously refining and expanding our understanding of bioelectromagnetics, we can further enhance the development of clinical equipment while prioritizing efficacy, safety, size, cost-effectiveness, and environmental sustainability.

In recent years, the field of medical physics has seen significant advancements in the understanding and application of bioelectromagnetics. These advancements have been driven by the discovery of radiofrequency interactions with biological objects, which sparked the study of basic medical physics in this area. The utilization of microwaves, a subset of radiofrequency waves, in medical diagnosis and treatment has become commonplace in today's high-technology society. These microwaves induce various electromagnetic phenomena that are similar to those observed with traditional radio waves.

While the design of clinical equipment has primarily relied on dosage data such as the Specific Absorption Rate (SAR) and specific gravity, the understanding of the electromagnetic phenomena experienced by humans when exposed to electromagnetic fields has also played a crucial role. However, the development of clinical equipment has been a challenging task, as it requires considerations beyond just effectiveness and safety. Factors such as size, cost, and environmental impact must also be taken into account.

Fortunately, advancements in electromagnetic (EM) simulations have provided researchers and medical professionals with invaluable tools for analyzing and predicting electromagnetic phenomena. These simulations have extended their reach beyond biological tissue equivalent models to include realistic human scenarios within hospitals and medical research institutions. Through the systematic dosimetry of various medical tools, electromagnetic quantities can be accurately evaluated, leading to improved treatment outcomes and patient safety.

Within the realm of dosimetry, the dosimetric concept of Treatment Planning Systems (TPS) has emerged as a vital framework. Based on unique epidemiological studies, TPS allows for the systematic evaluation of dose distributions in patients undergoing medical treatments. By understanding the dosimetric concept of TPS, healthcare professionals can ensure the precise and safe delivery of radiation therapy.

To ensure the quality assurance (QA) of dosimetry, it is essential to refer to international guidelines and regulations established by prominent organizations. These include the World Health Organization (WHO), the International Commission on Non-Ionizing Radiation Protection (ICNIRP), the Institute of Electrical and Electronics Engineers (IEEE), the Food and Drug Administration (FDA), the National Council on Radiological Protection (NCRP), and the International Electrotechnical Commission (IEC). Each of these organizations plays a pivotal role in setting standards and guidelines that safeguard public health and promote the safe use of electromagnetic fields in medical settings.

Within the scope of these guidelines and regulations, the IEEE committee has uniquely stipulated radar monitoring engineering guidelines. These guidelines are specifically designed to ensure the safe and effective usage of radar systems across various industries and applications. By adhering to these guidelines, engineers and operators can minimize potential hazards and optimize radar systems' overall performance.

In the field of medical physics, dosimetric techniques can be classified into nine distinct sub-categories known as the SC components. These techniques encompass a broad spectrum, including measurements, numerical simulations, and hybrid approaches that combine both methods. Through a comprehensive comparison of these techniques in Section 1.4, researchers and practitioners gain valuable insights into their advantages and limitations. This knowledge empowers individuals to make informed decisions regarding dosimetry in their respective fields.

Finally, in Section 1.5, we conclude this chapter by summarizing the key findings and implications discussed throughout the text. We emphasize the crucial importance of accurate dosimetry in ensuring patient safety and achieving optimal treatment outcomes. Furthermore, we underscore the ongoing advancements in EM simulations and their potential to revolutionize the field of medical physics. By continuously expanding our understanding of bioelectromagnetics and refining our techniques, we can further enhance the development of clinical equipment. This enhancement must prioritize efficacy, safety, size, cost-effectiveness, and environmental sustainability to meet the demands of a rapidly evolving healthcare landscape. (Pall, 2022) (Kreindel and Mulholland 2021) (Pophof *et al.* 2023) (Endo, 2021) (Omer, 2021) (Beyer *et al.* 2021) (Liu *et al.*, 2024) (Cloutier *et al.*, 2021) (Raković 2021) (Rubik & Brown, 2021)

1.2 Role and Importance in Healthcare

The practice of medical physics involves extensive scientific research, development, application, and evaluation of a vast array of physical and engineering methodologies for the prevention, diagnosis, and treatment of a diverse range of human diseases. It is worth noting that this specialized field attracts a multitude of highly qualified professionals who hold master's or doctoral degrees with specializations in one or more specific areas of medical physics. These experts are deeply committed to their craft as they diligently work for esteemed medical organizations that are predominantly affiliated with renowned hospitals. Remarkably, these dedicated professionals are known to serve their field diligently, either as exceptional researchers, visionary developers, or invaluable consultants for industry manufacturers. It is essential to emphasize that the field of medical physics is broad in nature and encompasses several sub-specializations, which may include the highly crucial therapeutic medical physics, diagnostic medical physics, medical imaging physics, radiation protection, nuclear medicine, and many more. Undoubtedly, medical physics plays an integral role in society due to its immense significance in safeguarding the health and general well-being of the population. The continued progression towards improved and equitable access to three fundamental components becomes increasingly reliant on the prowess of medical physics. First and foremost, the reliance on accurate, reliable, and swift communication of vital medical data necessitates the seamless integration of dependable information technology systems. Medical physicists collaborate with experts in computer science to develop and implement robust electronic health records, imaging software, and data analytics tools. This, in turn, facilitates prompt and precise diagnoses along with timely treatments, therefore effectively ensuring the seamless progression of medical care. Moreover, the constant pursuit of advanced diagnostics is of paramount importance, as it demands innovative solutions that strike a delicate balance between accuracy, minimally invasive procedures, cost-effectiveness, and widespread availability. Medical physicists work with radiologists, pathologists, and other healthcare professionals to develop cutting-edge imaging techniques, such as magnetic resonance imaging (MRI), computed tomography (CT), and ultrasound, that can accurately detect and characterize various diseases. The ultimate goal is to provide the population with access to diagnostic tools that not only yield highly accurate results but also minimize discomfort and reduce financial burdens. The field of medical physics also stands as a crucial pillar in fitting therapy to individual patients, tailoring treatments in a manner that maximizes the likelihood of success while emphasizing the importance of delivering these treatments as expeditiously and safely as possible. Medical physicists collaborate with radiation oncologists, surgeons, and other specialists to develop and refine treatment techniques, including external beam radiation therapy, brachytherapy, and proton therapy. They utilize advanced imaging technologies, such as positron emission tomography (PET) and single-photon emission computed tomography (SPECT), to accurately map the target area and guide the delivery of radiation. Additionally, medical physicists play a key role in ensuring the safe and effective use of medical radiation, utilizing shielding and quality assurance techniques to protect patients, healthcare professionals, and the general public from unnecessary exposure. The necessity to navigate these challenges necessitates the unwavering commitment to the development, evaluation, dissemination, and effective utilization of the various new and multidisciplinary resources that have emerged due to the tremendous advances in related fields. As medical physics continues to evolve, there is a growing emphasis on collaboration and interdisciplinary research. Medical physicists are increasingly collaborating with experts in biology, chemistry, materials science, and other fields to develop novel therapies and imaging techniques. For example, the integration of nanotechnology and targeted drug delivery systems holds great promise for improving the effectiveness of chemotherapy while reducing side effects. Furthermore, medical physicists are exploring the potential of artificial intelligence (AI) and machine learning (ML) algorithms to analyze complex medical data, identify patterns, and optimize treatment plans. It is of utmost importance to acknowledge the significant interplay between clinical medicine and medical physics, as the latter science progressively influences an ever-growing array of domains within clinical diagnosis and therapy. The dynamic nature of this interaction is profoundly impacting the medical landscape and is rapidly reshaping the approaches utilized in healthcare settings. Subsequently, it becomes crucial for the medical physics community to remain at the forefront of scientific advancements and continuously adapt to the emerging trends to ensure optimal patient care. As is the case with any dynamic field, the next generation of medical physicists are faced with a myriad of challenges that stem from the escalating demand for new, avant-garde technologies. The ever-expanding horizons of medical physics necessitate the relentless pursuit of innovative breakthroughs and advancements that hold the promise of revolutionizing healthcare as we know it. The integration of artificial intelligence and machine learning algorithms in medical physics research and clinical practice has opened up new avenues for precision medicine, patient-specific treatment planning, and real-time image-guided interventions. Additionally, the advent of nanomedicine, which involves the use of nanotechnology in medical applications, holds great promise for targeted drug delivery, early disease detection, and non-invasive therapies. Furthermore, the field of medical robotics is rapidly evolving, with the development of sophisticated robotic systems that can assist in surgical procedures, rehabilitation therapies, and prosthetics. The utilization of Virtual Reality (VR) and Augmented Reality (AR) technologies in medical physics is also gaining traction, allowing for immersive simulations, training, and enhanced visualization during surgical interventions. Moreover, the growing importance of personalized medicine in healthcare has created new opportunities for medical physicists to contribute to the development and implementation of tailored treatment strategies based on an individual's genetic makeup, lifestyle factors, and specific disease characteristics. Advances in genomics and molecular imaging have enabled a deeper understanding of disease mechanisms, paving the way for targeted therapies and personalized interventions. Additionally, the use of medical physics in radiation therapy continues to evolve, with innovations in image-guided radiation therapy, adaptive treatment planning, and proton therapy. These advancements offer improved precision, better disease control, and reduced side effects for cancer patients. The field of medical physics is also playing a critical role in developing novel imaging techniques, such as functional magnetic resonance imaging (fMRI), diffusion tensor imaging (DTI), and positron emission tomography (PET), which allow for the non-invasive assessment of brain function, connectivity, and metabolism. These techniques have significant implications in the diagnosis, treatment, and monitoring of neurological disorders, such as Alzheimer's disease, Parkinson's disease, and stroke. Moreover, the integration of medical physics in nuclear medicine has revolutionized the field, enabling more accurate diagnoses and targeted treatments for various conditions, including cardiovascular diseases, endocrine disorders, and cancer. The development of new radiotracers, imaging agents, and hybrid imaging technologies has enhanced the sensitivity, specificity, and therapeutic capabilities of nuclear medicine, leading to improved patient outcomes and quality of life. In conclusion, the field of medical physics is continuously evolving and expanding, driven by technological advancements and the increasing demand for personalized, precise, and efficient healthcare solutions. With its multidisciplinary approach and wide-ranging applications, medical physics holds the potential to revolutionize diagnosis, treatment, and patient care across various medical specialties. The future of medical physics will undoubtedly be shaped by ongoing research, innovation, and collaboration, as we strive to improve the health and well-being of individuals and communities worldwide. (McCarthy *et al.* 2021) (Zanca *et al.* 2021) (Panayides *et al.* 2020) (Diaz *et al.* 2021)

(Whig *et al*. 2023) (Pramanik *et al*. 2020) (Avanzo *et al*. 2021) (Saw & Ng, 2022) (Ehwerhemuepha *et al*. 2020) (Aiello *et al*. 2021)

Chapter - 2

Advanced Imaging Techniques

High-resolution images of the body can now be acquired without the need for surgical intervention, which represents a significant advancement in healthcare. This groundbreaking development allows for the diagnosis of many medical conditions based solely on these images, eliminating the need for complex and costly exploratory and interventional procedures that were previously the norm. Furthermore, the quality of these images can often be enhanced by the introduction of contrast media containing iodine, a substance that strongly absorbs X-rays. This enhancement is particularly beneficial in improving the visibility and clarity of the images. Additionally, advancements in reconstruction algorithms have allowed for a reduction in the acquisition time of images. An example of such algorithms is iterative reconstruction, which accurately models the physical behavior of X-rays with proper Poisson noise statistics. This approach contributes to shorter acquisition times and increased efficiency in medical imaging. Another way to improve acquisition time is by increasing the number of X-ray photons and detectors or by selectively scanning only a specific area of the body where a suspected medical condition is present. This focused approach is especially relevant in imaging techniques like positron emission tomography (PET) and computed tomography with X-ray cone beam: single photon emission tomography, which are both nuclear medicine imaging techniques with relatively low spatial resolution. Despite the limited spatial resolution, these techniques provide valuable information about the distribution of radiopharmaceuticals labeled with isotopes that have an affinity for tumors. In clinical practice, the selection of the optimal image or patient-specific acquisition strategy often considers the patient's dose as the primary factor. This may require double exposure in certain cases, such as therapeutic monitoring or trauma care. It is worth noting, however, that nuclear magnetic resonance imaging (MRI) has emerged as a leading noninvasive technique for detecting and monitoring diseases by generating detailed images of internal organs and tissues. Moreover, the utilization of core facility high-field-spec hyperpolarizing gas techniques has significantly expanded our understanding of blood flow and lymph node function. These state-of-the-art techniques, employed in healthcare, have proven to be highly valuable. Notably, pediatric patients can now benefit from screen-quality images that can be obtained using low-cost noncontrast agents as required. Furthermore, the availability of high-field care, specifically at 7 T or 11.1 T, in combination with advanced RF and gradient coil technology, has revolutionized clinical settings in certain healthcare facilities. These advancements enable the performance of site-specific multi-nuclear imaging and spectroscopy, which hold tremendous promise in the analysis and understanding of various diseases. Another crucial aspect to consider is the quantification of the effects of physical or pharmacological therapies on tumor interactivity within the body. This can be accomplished through the use of techniques such as positron emission tomography (PET) and computed tomography (PET-CT) with advanced reconstruction algorithms. Additionally, low-dose multi-detector-row computed tomography (MDCT) can also be employed to determine the dose distributions of radiopharmaceuticals used in imaging. Integration of modern PET-CT images with those obtained through other techniques, such as four-dimensional cone-beam PDCT (four-dimensional computed tomography with X-ray cone beam) or contrast-enhanced hybrid systems like one PE-PET system with an integrated MRI-PET/x-ray CT prototype scanner, is vital to ensure comprehensive and accurate medical imaging. These integrated approaches contribute to a more holistic understanding of diseases and enable healthcare professionals to provide more targeted and personalized treatment plans. In conclusion, the advancements in high-resolution imaging technology, reconstruction algorithms, contrast media, and integrated imaging techniques have revolutionized the field of medical imaging. These developments have enabled noninvasive diagnosis, enhanced image quality, reduced acquisition times, and a more comprehensive understanding of diseases. With the continued progress in healthcare, the future of medical imaging holds great promise for further advancements and improved patient care. Medical imaging is an extraordinarily important aspect of modern healthcare. With ongoing advancements in technology, researchers and clinicians are uncovering new and exciting ways to acquire detailed images of the human body, aiding in the diagnosis and treatment of various medical conditions. One major breakthrough has been the ability to obtain high-resolution images without the need for surgical intervention. This revolutionary achievement has transformed healthcare by providing a noninvasive means of visualizing internal structures, significantly reducing the need for invasive procedures that were once considered routine. These images have the potential to reveal crucial information about a patient's health, enabling doctors to make accurate diagnoses and develop appropriate treatment plans. To further enhance the quality of these images, contrast media containing iodine can be introduced. This substance has the remarkable ability to absorb X-rays, resulting in clearer and more detailed images. This enhancement technique has proven to be highly beneficial in improving the visibility of various medical conditions. Another area of advancement in medical imaging technology is the development of reconstruction algorithms. These algorithms have allowed for a significant reduction in image acquisition time. One example of such an algorithm is iterative reconstruction, which accurately models the physical behavior of X-rays, taking into account proper Poisson noise statistics. By implementing this approach, medical professionals can obtain images more efficiently, leading to faster diagnoses and improved patient outcomes. Additionally, increasing the number of X-ray photons and detectors or selectively scanning specific areas of the body where medical conditions are suspected can further reduce acquisition time. This targeted approach is particularly relevant in nuclear medicine imaging techniques such as positron emission tomography (PET) and computed tomography with X-ray cone beam: single photon emission tomography. While these techniques may have relatively low spatial resolution, they offer valuable information about the distribution of radiopharmaceuticals labeled with isotopes that have an affinity for tumors. Thus, they play a crucial role in diagnosing and monitoring various cancer types. When choosing the optimal imaging strategy for a patient, healthcare professionals often consider the patient's dose as a primary factor. In certain cases, such as therapeutic monitoring or trauma care, double exposure can be necessary. However, it is important to note that nuclear magnetic resonance imaging (MRI) has emerged as a leading noninvasive technique for detecting and monitoring diseases. By generating detailed images of internal organs and tissues, MRI provides invaluable insights into the body's condition. In recent years, core facility high-field-spec hyperpolarizing gas techniques have significantly expanded our understanding of blood flow and lymph node function. These cutting-edge techniques are revolutionizing healthcare and contributing to advancements in patient care. Furthermore, pediatric patients can now benefit from screen-quality images obtained using low-cost noncontrast agents, making medical imaging more accessible to a broader population. The availability of high-field care, particularly at 7 T or 11.1 T, in combination with advanced radiofrequency and gradient coil technology, has brought about a paradigm shift in clinical settings. These innovations allow for site-specific multi-nuclear imaging and spectroscopy, facilitating the analysis and understanding of various diseases. Another crucial aspect of medical imaging is quantifying the effects of physical or pharmacological therapies on tumor interactivity within the body. Techniques like positron emission tomography (PET) and computed tomography (PET-CT) with advanced reconstruction algorithms are instrumental in achieving this. Additionally, low-dose multi-detector-row computed tomography (MDCT) can be used to determine the dose distributions of radiopharmaceuticals used in imaging. Integrating modern PET-CT images with other imaging techniques, such as four-dimensional cone-beam PDCT (four-dimensional computed tomography with X-ray cone beam) or contrast-enhanced hybrid systems, ensures comprehensive and accurate medical imaging. For example, one integrated system combines PE-PET with an MRI-PET/x-ray CT prototype scanner, maximizing the benefit of multiple imaging modalities. This multi-modal approach allows healthcare professionals to gain a more comprehensive understanding of diseases, ultimately leading to more targeted and personalized treatment plans for patients. In summary, the field of medical imaging has undergone a remarkable transformation due to advancements in high-resolution imaging technology, reconstruction algorithms, contrast media, and integrated imaging techniques. These developments have revolutionized healthcare by enabling noninvasive diagnoses, improving image quality, reducing acquisition times, and enhancing our understanding of diseases. As healthcare continues to progress, we can undoubtedly expect further advancements in medical imaging, bolstering patient care and revolutionizing the way we approach disease diagnosis and treatment. (Mondal *et al.* 2020) (Han *et al.* 2020) (Kohler *et al.* 2021) (Hansen *et al.* 2020) (Chen *et al.* 2023) (Laghari & Yin, 2022) (Barberio *et al.* 2021) (Catalano & Wortsman, 2020) (Davidson *et al.* 2021) (Shalom *et al.*, 2020)

2.1 Computed Tomography (CT)

X-rays are absorbed to different degrees by different parts of the human body. By providing a beam of X-rays rotating about the human body at different angles, a cross-section of the body can be viewed. This innovative imaging technique revolutionizes medical diagnosis by allowing doctors to obtain detailed information about a patient's internal structure and identify potential areas of concern. A computed tomography (CT) scanner takes this process even further, surpassing the capabilities of a standard X-ray image. By emitting a series of X-ray beams at various angles, it can produce a precise and comprehensive slice in any part of the body. The power of the CT scanner lies in its ability to reconstruct multiple individual slices into a complete three-dimensional picture, providing medical professionals with an in-depth understanding of the body's internal workings. This three-dimensional representation not only enhances the accuracy of diagnosing injuries but also reveals valuable insights into their root causes. For instance, in the case of trauma, such as a fracture or injury resulting from an accident, the CT scanner can be instrumental in pinpointing the exact origin and nature of the damage, aiding physicians in formulating appropriate treatment plans. Additionally, the utilization of a CT scanner plays an essential role in the early detection and monitoring of cancerous tissue. By examining the body's internal structures in minute detail, this remarkable imaging technology enables medical experts to identify any anomalous growths or abnormalities with greater precision. The enhanced visualization capabilities allow for the detection of even the tiniest malignancies, which can prove crucial in determining the appropriate course of action and potentially saving lives. In recent advancements, a groundbreaking variation of the CT scanner has emerged, utilizing a conventional X-ray source in conjunction with a diffraction grating. This innovative technique improves the overall resolution of the images produced while substantially reducing the radiation dose administered to patients during the process. By gaining access to three-dimensional images of anatomical structures and achieving unparalleled visualization of soft tissue with remarkable contrast, this new type of CT scanner pushes the boundaries of medical imaging technology. Moreover, it opens up possibilities for further advancements in diagnosing and treating various medical conditions. However, it is important to acknowledge the potential risks associated with certain medical investigations that involve exposing patients to high levels of ionizing radiation. These risks, including an increased likelihood of developing cancer and potential lifespan shortening, underline the necessity for optimal radiation management and responsible medical practices. Procedures such as coronary angiography, which involves injecting radioactive iodine through a catheter in the patient's blood vessel, and CT imaging carry inherent risks due to their utilization of ionizing radiation. Furthermore, in order to maintain the highest standards of safety, monitoring radiation source distributions is imperative to ensure radiation exposure remains as low as reasonably achievable (ALARA). In this pursuit, two radiation imaging techniques, PET (positron emission tomography) and SPECT (single-photon emission computed tomography), have proven to be invaluable. These methods offer effective localization of radiation sources within the body, enabling medical professionals to precisely identify and manage potential hazards. In summary, the advancements in X-ray and CT scanning technologies have revolutionized the field of medical imaging. From providing detailed cross-sectional views to constructing three-dimensional representations, these imaging techniques offer invaluable insights into the human body's inner workings. They have opened up new possibilities for accurately diagnosing and monitoring various conditions, ultimately enhancing patient care and overall well-being. While the benefits of these technologies are immense, it is crucial to exercise caution and adhere to stringent safety protocols to minimize the risks associated with ionizing radiation exposure. With continued advancements, the field of medical imaging holds tremendous potential in diagnosing, monitoring, and treating various conditions, ultimately enhancing patient care and overall well-being. The integration of artificial intelligence and machine learning algorithms into these imaging systems can further improve accuracy and efficiency, making medical imaging an even more powerful tool in healthcare. The future of medical imaging is bright, with ongoing research and development aiming to bring even more sophisticated and accessible imaging techniques to healthcare professionals around the world. By harnessing the full potential of these advanced imaging technologies, medical professionals can continue to save lives, improve diagnoses, and provide the highest standard of care to patients. The advancement of medical imaging technologies has been a game-changer in the healthcare industry. It has brought about a revolutionary change in how medical professionals diagnose and treat various conditions, allowing for better patient care and overall well-being. The introduction of X-rays and their ability to penetrate the human body, albeit to different degrees, has paved the way for a more comprehensive understanding of our internal structure. By rotating an X-ray beam around the body at various angles, doctors can now obtain a cross-sectional view that gives them vital insights into potential problem areas. The introduction of computed tomography (CT) scanning took this process even further, surpassing the capabilities of a standard X-ray image. By emitting multiple X-ray beams at different angles, a CT scanner can produce a precise and comprehensive slice of any part of the body. This ability to reconstruct multiple slices into a complete three-dimensional picture provides medical professionals with a deep understanding of the body's inner workings. Not only does this enhance the accuracy of diagnosing injuries, but it also offers valuable insights into the root causes of various conditions. In cases of trauma resulting from accidents or fractures, the CT scanner has proven invaluable in pinpointing the exact location and nature of the damage. This information aids physicians in formulating appropriate treatment plans and ensures better outcomes for patients. The utilization of a CT scanner plays a vital role in the early detection and monitoring of cancerous tissue as well. By examining the body's internal structures in minute detail, medical experts can identify anomalous growths or abnormalities with greater precision. The enhanced visualization capabilities enable the detection of even the smallest malignancies, which is critical in determining the most effective course of action and potentially saving lives. Recent advancements in CT scanning technology have led to the emergence of a groundbreaking variation that combines a conventional X-ray source with a diffraction grating. This innovative technique substantially improves the overall resolution of the images produced while reducing the radiation dose administered to patients. The result is three-dimensional images of anatomical structures with exceptional visualization of soft tissue, providing remarkable contrast. This new type of CT scanner sets new benchmarks in medical imaging technology, offering incredible potential for diagnosing and treating various medical conditions. However, it is essential to acknowledge the potential risks associated with medical investigations that expose patients to high levels of ionizing radiation. Increased cancer risks and potential lifespan shortening emphasize the need for optimal radiation management and responsible medical practices. Procedures such as coronary angiography, which involves injecting radioactive iodine through a catheter in the patient's blood vessel, and CT imaging inherently carry risks due to their utilization of ionizing radiation. To maintain the highest safety standards, monitoring radiation source distributions is crucial to ensure radiation exposure remains as low as reasonably achievable (ALARA). In this pursuit, two radiation imaging techniques, PET (positron emission tomography) and SPECT (single-photon emission computed tomography), have proven invaluable. These methods efficiently localize radiation sources within the body, enabling medical professionals to precisely identify and manage potential hazards. In conclusion, the advancements in X-ray and CT scanning technologies have revolutionized medical imaging. These techniques provide detailed cross-sectional views and construct three-dimensional representations, offering valuable insights into the inner workings of the human body. They have significantly improved the accuracy of diagnosing and monitoring various conditions, ultimately enhancing patient care and overall well-being. However, it is crucial to exercise caution and adhere to stringent safety protocols to minimize the risks associated with ionizing radiation exposure. Continued advancements in the field of medical imaging, along with the integration of artificial intelligence and machine learning algorithms, have the potential to further improve accuracy and efficiency, making medical imaging a more powerful tool in healthcare. Ongoing research and development aim to bring even more sophisticated and accessible imaging techniques to healthcare professionals worldwide. Fully harnessing the potential of advanced imaging technologies allows medical professionals to save lives, improve diagnoses, and provide the highest standard of care to patients. The future of medical imaging is bright, holding tremendous potential for the healthcare industry.

(Luan *et al.*, 2021) (Prabhu *et al*. 2020) (Bras *et al*. 2021) (Poirier *et al*. 2020) (Li *et al*. 2020) (Oakley & Harrison, 2020) (Jamal *et al.*, 2020)

2.2 Magnetic Resonance Imaging (MRI)

The magnetic resonance imaging (MRI), which is a key component of the broader MRI field, entails the use of a cylindrical-shaped MRI machine to scan the human body. Utilizing a powerful magnetic field, this machine generates a multitude of highly detailed and precise images of the patient's anatomy. Notably, this technique is completely non-invasive, ensuring the absence of any exposure to ionizing radiation. Consequently, it proves to be especially valuable in the diagnosis of conditions affecting the central nervous system and musculoskeletal system. At present, MRI stands as the definitive imaging modality given its ability to offer comprehensive physiological and anatomical insights within a single study. The wide array of image contrast available allows for the visualization of diverse tissues including bones, gastrointestinal and genitourinary tracts, liver, spleen, kidneys, heart, and even coronary arteries. Moreover, advanced functional MRI techniques such as blood oxygen level-dependent MRI (BOLD-MRI fMRI) and diffusion tensor imaging (DTI) have revolutionized our understanding of the intricate patterns underlying brain structure and function. These cutting-edge methods are frequently leveraged to assess compromised tissues, detect myocardial infarctions, characterize tumors, and evaluate strokes. Additionally, MRI plays a crucial role in the assessment of congenital malformations, cardiac function, and the confirmation of hepatic and renal masses, among other significant clinical scenarios. Despite its cost and time-consuming nature, typically lasting between 30 to 60 minutes, MRI examinations are indispensable in surgical interventions. Surgeons rely heavily on the detailed anatomical information furnished by MRI to effectively plan their operations. Consequently, the demand for MRI remains consistently high, particularly in the field of Orthopedics. In this realm, requests for MRI scans are frequent in patients presenting with herniated discs, various arthropathies, suspected injuries, damaged ligaments, meniscus-related issues, as well as tumors affecting either the central or peripheral systems. This wide range of uses demonstrates the versatility and importance of MRI in modern healthcare. As technology continues to advance, the capabilities of MRI machines will likely expand, further enhancing its diagnostic and therapeutic potential. With its non-invasive nature and ability to provide detailed imaging, MRI will undoubtedly continue to play a crucial role in the medical field for years to come. (Weiskopf *et al*. 2021) (Anzia *et al*. 2021) (Dawood *et al*. 2022) (Morgan *et al*. 2021) (Evans *et al*. 2020)

2.3 Positron Emission Tomography (PET)

Positron emission tomography (PET) is a highly advanced and sophisticated nuclear medical imaging modality that plays a crucial role in imaging the functional processes of internal organs. This state-of-the-art technology has revolutionized the field of medical diagnostics by enabling the detection of gamma rays emitted by positron-emitting radionuclides that are introduced into the body through biologically active compounds. In PET, commonly used tracers include fluorine-18 and carbon-11, which are carefully injected into the patient to circulate within molecules of biological interest, allowing for unparalleled insights into the inner workings of the human body. The primary objective of PET is to conduct dynamic quantitative studies of the distribution, or kinetics, of positron-emitting tracers in laboratory animals and humans alike. As a result, PET has found extensive applications in the comprehensive study and assessment of brain, heart, and tumor physiology and functionality. By leveraging the fundamental physical principle of positron-electron annihilation, PET facilitates the emission of two nearly back-to-back photons, each possessing an energy of 511 kilo-electron volts (keV). These photons travel along a straight line, and by precisely detecting and analyzing their trajectories, the line of response (LOR) for the interaction can be determined. By further utilizing time correlation of the two detected gammas, the spatial position of the annihilation event can be deduced. This remarkable capability of pinpointing the annihilation occurrence allows for the visualization of the radiotracer distribution with exceptional sensitivity. The core component of a PET tomograph's functionality lies in its ability to reconstruct the emission distribution of the radiotracer. By employing a technique similar to that of transmission computed tomography, the PET system facilitates the acquisition of numerous angular projections of the radiotracer's displacement distribution. To transform this acquired data back into the original emission distribution, sophisticated algorithms are employed. These algorithms primarily rely on solving a mathematical problem known as Maximum Likelihood Expectation Maximization, which forms the backbone of the PET tomograph's processing capabilities. In the realm of clinical applications, the Positron Emission Mammograph clinical instrument known as the PEM Flex Solo II constitutes a significant advancement in data acquisition techniques. This cutting-edge technology enables superior spatial resolution, typically ranging from 2 to 3 millimeters, rendering it highly suitable for precision imaging. Additionally, with a sensitivity in the order of hundreds of counts per second and per milliliter of patient tissue, the PEM Flex Solo II allows for clinical utilization with only a fraction of the injected radiopharmaceutical, underscoring its groundbreaking efficiency and patientfriendly approach. With its remarkable capabilities and constant scientific advancements, PET continues to revolutionize medical imaging, providing invaluable insights into the complexities of the human body and contributing to the advancement of healthcare worldwide. As the field of positron emission tomography (PET) continues to evolve, its significant impact on medical diagnostics and healthcare becomes increasingly evident. This highly advanced and sophisticated nuclear medical imaging modality has paved the way for a deeper understanding of the functional processes occurring within internal organs. By harnessing the power of positron-emitting radionuclides and gamma ray detection techniques, pet allows for unprecedented insights into the intricate workings of the human body. Utilizing carefully selected tracers such as fluorine-18 and carbon-11, PET enables the visualization and study of biological molecules of interest. These tracers, injected into patients, circulate through the body and emit gamma rays that are detected by highly sensitive equipment. This detection process, based on the fundamental physical principle of positron-electron annihilation, involves the emission of two photons with an energy of 511 kilo-electron volts (keV). Through precise trajectory analysis, the line of response (LOR) for the interaction can be determined, shedding light on the spatial position of the annihilation event and allowing for the visualization of radiotracer distribution with exceptional sensitivity. The distribution of the radiotracer is not the only piece of the puzzle. PET's capabilities extend to dynamic quantitative studies of positron-emitting tracers in both animals and humans. This ability has made PET a valuable tool in comprehensively studying and assessing brain, heart, and tumor physiology and functionality. By leveraging time correlation of the detected gammas, PET unveils the mysteries of biological processes, contributing to scientific advancements and better healthcare outcomes. At the heart of a PET tomograph lies its ability to reconstruct the emission distribution of the radiotracer. Similar to transmission computed tomography, PET systems acquire numerous angular projections of the radiotracer's displacement distribution. Advanced algorithms, such as the well-known Maximum Likelihood Expectation Maximization, are employed to transform this acquired data back into the original emission distribution. These algorithms serve as the backbone of PET tomographs' processing capabilities, ensuring accurate and detailed imaging results. In the domain of clinical applications, the Positron Emission Mammograph known as the PEM Flex Solo II represents a significant leap in data acquisition techniques. This cutting-edge clinical instrument offers superior spatial resolution, ranging from 2 to 3 millimeters, making it highly suitable for precision imaging. What sets the PEM Flex Solo II apart is its exceptional sensitivity, capable of capturing hundreds of counts per second and per milliliter of patient tissue. This remarkable sensitivity enables clinical utilization of the instrument with only a fraction of the injected radiopharmaceutical, minimizing patient discomfort and contributing to the efficiency of healthcare delivery. PET's transformative capabilities and continuous scientific advancements have positioned it as a cornerstone of medical imaging. Its unparalleled ability to provide invaluable insights into the complexities of the human body has revolutionized healthcare practices worldwide. With each new breakthrough, PET takes us further along the path of understanding and treating diseases, ultimately improving the well-being of individuals and advancing healthcare as a whole. (Cervenka *et al.*, 2022) (Zhang *et al.*, 2020) (Zaidi & El Naqa, 2021) (Ghosh *et al.* 2022) (Wang *et al.* 2023) (Rong *et al.* 2023) (Pérez-Medina *et al.* 2020) (Van *et al.* 2021) (Iking *et al.* 2021) (Takamura & Kakuta, 2021)

2.4 Ultrasound Imaging

For a significant period of time, the diagnostic imaging of human organs for assessing pathological status was constrained to specialized methods such as X-ray imaging, angiography, computed tomography and magnetic resonance imaging. However, the ultrasound imaging technique as we know it today came into routine use by the early seventies, marking a crucial turning point in medical examinations. It is universally acknowledged as the fastest growing among all the imaging modalities employed for diagnostic non-invasive examinations. The widespread and enthusiastic reception of ultrasound imaging can be attributed to its exceptional performance characteristics and the absence of the adverse effects associated with ionizing radiation, which are inherent in the use of X-rays. These qualities, coupled with the relative simplicity of the equipment and the cost-effectiveness of the imaging stages, have positioned the ultrasound technique as the preferred method for routine examinations. The echoes generated during an ultrasonic pulse-echo experiment are significantly lower in intensity compared to those obtained through other modalities that share the same size and anatomical features (e.g., ECG with the heart). Consequently, ultrasonic imaging can be utilized as frequently as necessary without posing any risk to the patient. Moreover, the performance characteristics of ultrasound imaging make it ideal for low-tech medical settings. The fundamental principles underlying ultrasound imaging are rooted in the effects observed when an ultrasound pulse is transmitted through a medium and subsequently reflected from a boundary or dispersed within it. The resulting image is formed by capturing the echoes, and further processing of these echoes yields valuable information about their relative strength at specific times following the reception of the echo. Synchronization displays for the transmitted pulses are employed to ensure that the path traversed to the desired depth of the echoes represents echoes that have passed through adjacent volumes of the medium. Sonographic techniques primarily rely on backscatter echoes rather than transcription-type echoes in order to obtain detailed information about the structures and functions of the tissue, organs, and body. These techniques have become the gold standard and represent the most significant applications of ultrasound in the field of medical imaging. Furthermore, the scattering characteristics of specific ultrasonic waves serve as the basis for methods that have emerged in the last decade or so, to a certain extent, enabling the acquisition of three-dimensional images of tissue boundaries. These three-dimensional representations are obtained, for example, by employing image scanning surfaces. Additionally, quantitative information can be derived from echoes; ultrasonic pulse attenuation is influenced by the morphological and physiological features of the inhomogeneous structures of the examined tissues. In most cases, water, blood, or fat act as the primary scatterers within the inhomogeneous distribution encountered. Highly sophisticated algorithms have been developed and integrated into equipment to extract comprehensive tissue properties related to pathological conditions that go beyond the description of tissue shape, size, and texture. Despite the fact that imaging with arrayed transducers remains the recognized standard technique, the continuous advancement of digitizing techniques and their sustained development over the past five decades have paved the way for significant progress in establishing the pulse backscatter capabilities of the hydrophone. These capabilities have been meticulously evaluated and extensively investigated using numerous biological subjects, with a predominant focus on perfused organs or tissues. The Huygens principle, a fundamental principle in science, forms the bedrock of scientific interpretation in ultrasound imaging. It provides the most essential conceptual foundation for understanding and accurately predicting ultrasonic propagation within the human body, offering a theoretical basis that would be otherwise unattainable. The remarkable advancement in medical technology has ushered in a significant revolution in the field of diagnostic imaging. Previously, the options for examining the pathological conditions of human organs were limited to specialized techniques such as X-ray imaging, angiography, computed tomography, and magnetic resonance imaging. However, the emergence of ultrasound imaging in the early seventies brought a revolutionary change in the landscape of medical examinations. This non-invasive and rapidly evolving modality soon outperformed all other techniques in terms of growth rate and popularity. One of the key factors contributing to the widespread acceptance of ultrasound imaging is its unique set of performance characteristics. Unlike X-rays, ultrasound does not involve ionizing radiation, eliminating associated health risks. Additionally, the equipment used in ultrasound imaging is relatively simple and cost-effective, making it an ideal choice for routine examinations. Furthermore, the echoes generated during an ultrasonic pulse-echo experiment have significantly lower intensity compared to other modalities. This enables frequent use of ultrasound imaging without posing any danger to the patient, as well as making it the preferred imaging technique in low-tech medical settings. The principles underlying ultrasound imaging are based on the interactions between ultrasound pulses and the medium through which they travel. When these pulses encounter a boundary or disperse within the medium, echoes are produced. By capturing and analyzing these echoes, an image is formed, and further processing can determine the relative strength of the echoes at specific times. Synchronization displays are used to ensure that the echoes originated from adjacent volumes of the medium, representing the depth of interest. Sounding techniques utilizing backscatter echoes have become the standard for obtaining structural and functional information about tissues, organs, and the human body. In recent years, advancements in ultrasound technology have even enabled the creation of three-dimensional images of tissue boundaries. These breakthroughs have been achieved by leveraging the scattering characteristics of specific ultrasonic waves. By studying the reflected waves from tissue surfaces, three-dimensional representations can be obtained. Furthermore, quantitative information can be derived from the echoes. Ultrasonic pulse attenuation, for instance, depends on the morphological and physiological features of the examined tissues' inhomogeneous structures. Water, blood, or fat often act as the primary scatterers in such cases at high frequencies. Sophisticated algorithms have been developed to extract comprehensive tissue properties related to pathological conditions. These algorithms are implemented in ultrasound imaging equipment, allowing for a more in-depth analysis beyond just the shape, size, and texture of tissues. While arrayed transducers remain the standard technique for ultrasound imaging, continual advancements in digitizing techniques over the past five decades have greatly contributed to unlocking the pulse backscatter capabilities of hydrophones. Numerous biological subjects, especially perfused organs or tissues, have undergone evaluation and investigation, pushing the boundaries of ultrasound capabilities to new heights. The Huygens principle serves as the cornerstone of scientific interpretation in ultrasound imaging. It provides a theoretical basis that is essential for understanding and predicting the propagation of ultrasonic waves within the human body. Without this principle, the advancements and achievements in ultrasonic diagnostics would lack the necessary foundation for further progress. In conclusion, ultrasound imaging has revolutionized the field of medical examinations, offering a non-invasive and rapidly evolving modality for assessing pathological conditions in human organs. Its exceptional performance characteristics and the absence of ionizing radiation have made it the preferred method for routine examinations. With the ability to generate detailed images through the capture and analysis of echoes, ultrasound imaging provides valuable information about tissue structures and functions. Recent advancements have even made it possible to obtain three-dimensional representations of tissue boundaries. Furthermore, quantitative information can be derived from echoes, allowing for a comprehensive analysis of tissue properties related to pathological conditions. The continuous advancement of digitizing techniques has played a crucial role in expanding the capabilities of ultrasound imaging, particularly in relation to pulse backscatter. By adhering to the fundamental principles, such as the Huygens principle, ultrasound imaging has achieved remarkable progress and continues to pave the way for further advancements in diagnostic imaging. (Akram & Chowdhury, 2020) (Omer, 2021) (Miller *et al*. 2020) (Lacerda *et al*. 2021) (Luan *et al*., 2021) (Xu *et al*. 2021) (Garcia-Sayan *et al*. 2024) (Cuttler, 2020) (Ouyang *et al*., 2022)

Chapter - 3

Radiation Therapy

In the early days of linear accelerator-based radiation therapy, simple two-dimensional (2D) beams were used to treat cancers and noncancerous radiosensitive conditions by ablating end-organ function. The conventional enlarging and re-forming non-IMRT photon and electron fields added relatively little dose to underdose or partly blanketed skin, which was being forced to tolerate a radical underdose. The use of conventional therapy was necessarily limited by an unavoidably narrow therapeutic ratio. This was almost inevitable, given the nature of TRT, which must always aim to optimize radiation dose to the target and minimize dose to normal tissue. It is also potentially damaging but is not permitted to fail the treatment by exceeding its presumed limits of tolerance. Radiation therapy is one of the established branches of medical physics. The technological advances in the field of computing capability, 3D imaging, and engineering have brought groundbreaking changes to the patterns of medical physics services provided to patients and their radiation oncology caregivers during the short history of cancer treatment involving charged particle- or photon-based field therapy. These include the challenge of close-quarters collaboration with engineers dedicated to patient safety, such as those involved in the LINAC HEAD project, the development of HM technology, and the study pipeline in phase diagnostics for close-functional tissue dosimetry in support of intra-fractional motion management and the means to improve the precision of interventions in cases of advanced cancer and risky dose delivery. Additionally, new developments have emerged in the field, including innovative techniques like intensity-modulated radiation therapy (IMRT), which has revolutionized cancer treatment by allowing for more precise delivery of radiation to the target area while sparing surrounding healthy tissue. This advancement in technology has greatly expanded the possibilities of radiation therapy, enabling oncologists to provide more tailored and effective treatment plans for their patients. Furthermore, recent research has focused on the use of proton therapy, a form of radiation therapy that utilizes protons instead of photons or electrons. Proton therapy offers distinct advantages over traditional radiation therapy, as it can deliver radiation with greater precision and a more targeted dose distribution, reducing the risk of damage to nearby organs and tissues. The use of proton therapy is particularly beneficial for pediatric patients, as it minimizes the long-term side effects associated with radiation treatment in developing bodies. With ongoing advancements in medical physics and radiation therapy techniques, the field continues to evolve, offering new possibilities and improved outcomes for cancer patients. The expansion of linear accelerator-based radiation therapy has not only improved treatment options but also provided significant enhancements to patient care and safety. The integration of computer technology, 3D imaging, and engineering has revolutionized the field of medical physics, allowing for more accurate and efficient treatment planning processes. The collaboration between radiation oncology caregivers and engineers dedicated to patient safety, as seen in projects like the LINAC HEAD project, has further enhanced the quality of care provided to patients. One area of advancement in radiation therapy is the development of HM (??) technology. This technology has paved the way for close-functional tissue dosimetry, which plays a crucial role in managing intra-fractional motion and ensuring precise interventions in cases of advanced cancer and risky dose delivery. By monitoring tissue doses in real-time, HM technology enables radiation oncologists to make necessary adjustments and improve treatment outcomes. Furthermore, the field has witnessed a shift towards innovative techniques like intensity-modulated radiation therapy (IMRT). IMRT has revolutionized cancer treatment by offering a more precise delivery of radiation to the target area while sparing healthy surrounding tissue. This has significantly reduced the risk of collateral damage and allowed for more personalized and effective treatment plans. The ability to tailor radiation doses to individual patients has led to improved outcomes and better overall quality of life. Proton therapy, another significant development in radiation therapy, has gained prominence in recent years. By utilizing protons instead of traditional photons or electrons, proton therapy offers distinct advantages. Protons can be precisely targeted, allowing for a more focused dose distribution and minimizing the risk of damage to nearby organs and tissues. This targeted approach is especially beneficial for pediatric patients, as it reduces the long-term side effects associated with radiation treatment in developing bodies. As medical physics and radiation therapy techniques continue to advance, the field holds immense potential for further improvement. Ongoing research and development aim to enhance treatment precision, minimize side effects, and improve overall patient outcomes. The future of radiation therapy holds promise, with continued advancements paving the way for personalized, effective, and safer treatment options for individuals battling cancer. In recent years, there has been significant progress in the field of radiotherapy. The early days of linear accelerator-based radiation therapy were characterized by the use of simple two-dimensional (2D) beams to treat cancers and noncancerous radiosensitive conditions. However, these treatments had limitations in terms of dose delivery and precision. With advancements in technology and medical physics, the field has witnessed groundbreaking changes in the way radiation therapy is delivered to patients. One major development is the use of intensity-modulated radiation therapy (IMRT), which has revolutionized cancer treatment. IMRT allows for more precise delivery of radiation to the target area while sparing healthy tissue, resulting in improved treatment outcomes and reduced side effects. Additionally, proton therapy has emerged as an innovative technique in radiation therapy. Proton therapy utilizes protons instead of traditional photons or electrons, offering distinct advantages in terms of dose distribution and minimizing damage to surrounding organs and tissues. This targeted approach is particularly beneficial for pediatric patients, as it reduces long-term side effects. The integration of computer technology, 3D imaging, and engineering has also played a significant role in advancing radiation therapy. These advancements have improved treatment planning processes and allowed for more accurate and efficient delivery of radiation. Collaborations between radiation oncology caregivers and engineers dedicated to patient safety have further enhanced patient care and safety. For example, projects like the LINAC HEAD project have focused on ensuring patient safety through close-quarter collaboration. In recent times, the development of HM technology has paved the way for close-functional tissue dosimetry. This technology allows for real-time monitoring of tissue doses, enabling radiation oncologists to make necessary adjustments and improve treatment outcomes. The field of radiation therapy continues to evolve, offering new possibilities and improved outcomes for cancer patients. Ongoing research and development aim to enhance treatment precision, minimize side effects, and improve overall patient outcomes. With continued advancements in medical physics and radiation therapy techniques, the future of radiation therapy looks promising. Personalized and effective treatment options will continue to be developed, providing hope for individuals battling cancer and improving their quality of life. (Das *et al*., 2020) (Fiorino *et al*. 2020) (Grégoire *et al*. 2020) (Koka *et al*. 2022) (Do Huh & Kim, 2020) (Kawamura *et al*. 2024) (Bazan *et al*. 2020)

3.1 External Beam Radiation Therapy

Advanced techniques of medical physics in IGRT (Image-Guided Radiation Therapy) and radiation therapy of gynecological and rectal cancer have significantly evolved over time. With the emergence of external beam radiation therapy as a key technique in accurately targeting and treating tumors, the field has witnessed substantial progress. However, one of the major challenges that healthcare professionals face is the potential movement of tumors during treatment caused by factors such as respiration, nearby organs, and the patient's positioning. To address this challenge, extensive research and development have been conducted to devise predictive methods that can continually track and predict the position of tumors during radiation therapy. These methods involve the evaluation and monitoring of dynamic effects, respiratory cycle, cardiac rhythm, and changes in rectal and bladder filling. By continuously assessing these parameters, healthcare professionals can adapt the treatment plan accordingly and ensure the optimal targeting of tumors. There are two main classes of predictive methods used in IGRT and radiation therapy. The first class, as mentioned earlier, is image-guided radiation therapy (IGRT). In this approach, the tumor is precisely targeted using advanced imaging techniques immediately prior to the radiation treatment. This allows for accurate localization of the tumor, enhancing the effectiveness of the therapy and minimizing the potential damage to surrounding healthy tissues. The second class of predictive methods is known as motion management. This approach involves quantifying tumor motion and implementing additional strategies to ensure accurate targeting during treatment. While IGRT-based motion management techniques are considered reactive, they still provide reliable precision. However, it is important to acknowledge that the precision of the second class of techniques may vary due to variations in the speed of markers and tumors. Healthcare professionals need to carefully consider these variations and adapt their strategies accordingly to achieve optimal outcomes. A specific area of advancement in IGRT is markerless image-guided radiation therapy of lung tumors. Surgical interventions may not be feasible for lung cancer patients, making radiation therapy a crucial component of their treatment plan. In such cases, healthcare professionals perform the percutaneous implantation of a metal clip within the tumor. This enables the execution of an x-ray digital CBCT (Cone Beam Computed Tomography) in an axial and isocentric manner. Additionally, two fluoroscopic x-rays are taken per field pair in a dual arrow mode. By continuously screening and monitoring the tumor's movements, valuable insights can be gained into its behavior during different phases, including attacks, systolic, and diastolic stages. While attacks and dyspnea have been successfully positioned and managed using these techniques, it is worth noting that certain limitations exist. Specifically, gating techniques have shown some limitations due to the intrinsic error of multipurpose medical scanning imagers. However, healthcare professionals are actively researching and developing new strategies to overcome these limitations and further enhance the precision of IGRT for lung tumors. The advancements in medical physics have significantly improved the field of IGRT and radiation therapy, playing a crucial role in the precise and effective treatment of gynecological and rectal cancer, as well as lung tumors. The continuous evolution of these techniques and the interdisciplinary collaboration among experts in the field continue to revolutionize patient care, enabling more personalized and targeted treatment approaches. Through ongoing research and development, healthcare professionals strive to further refine and optimize IGRT and radiation therapy, ultimately improving patient outcomes and quality of life. The future holds great promise for the field of medical physics and its applications in IGRT and radiation therapy. (Kurz *et al*. 2020) (Rammohan *et al*., 2022) (Ravindran, 2022) (Luh *et al*. 2020) (Endo, 2021)

3.2 Brachytherapy

The American Society of Radiologic Technologists defines brachytherapy as a highly effective and versatile treatment option that involves the implantation of radioactive sources near or within a tumor. This innovative approach revolutionizes the field of radiation oncology by precisely delivering radiation to tumors while sparing healthy tissues, thereby offering patients improved treatment outcomes and reduced side effects. Brachytherapy is a remarkable form of treatment that can be used alone or as a boost alongside other therapies such as external beam therapy. By effectively killing tumor cells, it plays a crucial role in the fight against various types of cancers. The technique utilizes catheters, seeds, or other small devices to precisely place and control the radioactive sources. This careful management of dose distribution achieves greater isodose conformality, minimizing the impact on surrounding normal tissues and ultimately limiting both acute and late side effects. Additionally, it reduces the risk of secondary malignancies, which is a significant benefit for patients. One type of brachytherapy is Low-Dose Rate (LDR) brachytherapy, which involves the implantation of radioactive sources for a few minutes or permanently. This approach allows for the delivery of radiation therapy at a low and constant dose rate until the prescribed dose is reached. With strategically designed heterogeneous implants, needles with sources are positioned throughout the tumor while sparing the surrounding normal tissues. This technique ensures optimal treatment outcomes, making it particularly effective for addressing prostate cancer. Permanent prostate implants are a testament to the success and precision of LDR brachytherapy in treating this specific type of cancer. In contrast, High-Dose Rate (HDR) brachytherapy takes a different approach. It utilizes specially-designed devices to deliver a high dose rate in fractions, preventing normal tissues from undergoing repair during the inter-fraction intervals. This sophisticated technique maximizes the impact on tumor cells while minimizing the impact on healthy tissues. It exemplifies the efficiency and advancements seen in modern brachytherapy techniques. The versatility of brachytherapy extends to a wide range of tumor sites, including the prostate, breast, cervix, skin, and head and neck. It continues to evolve and advance, with ongoing research and development efforts aimed at improving treatment outcomes and enhancing the quality of life for patients. Exciting approaches like image-guided brachytherapy and intensity-modulated brachytherapy are being explored, offering enhanced precision and customization of treatment plans. These cutting-edge technologies have the potential to further revolutionize the field of brachytherapy, paving the way for even more effective and targeted cancer treatments. In conclusion, brachytherapy is a highly effective and versatile treatment option that holds great promise in the field of radiation oncology. Its ability to precisely target tumors while minimizing damage to healthy tissues has made it an invaluable tool in the fight against cancer. As advancements in technology and research continue to push the boundaries of brachytherapy, the future looks bright for this groundbreaking treatment modality. The field is constantly growing and evolving, with new techniques and approaches continuously being developed to further enhance the effectiveness of brachytherapy and improve patient outcomes. By continually pushing the boundaries of innovation and research, brachytherapy is poised to remain at the forefront of cancer treatment, shaping the future of radiation oncology in profound ways.

3.3 Proton Therapy

Proton therapy represents the single most advanced and cutting-edge technology available for cancer treatments in terms of physical constraints. It allows for much more precise and conformal dose distributions to the tumors, ensuring a much better preservation of the surrounding healthy tissues. This remarkable capability stems from the unique physical properties of protons. Unlike other radiation therapies, protons deposit their energy in living tissues in a gradual manner, leading to a peak value known as the Bragg peak at the end of their range. Following the Bragg peak, there is a rapid decrease in energy deposition until it reaches zero. This energy release around the Bragg peak is now commonly referred to as the spread-out Bragg peak (SOBP). Achieving the SOBP is made possible by precisely modulating the energy of protons and the number of extraction foils in a synchronized fashion. Once these parameters are fixed, the entire proton confinement problem is simplified to being one-dimensional within the treatment target. Thus, only a limited number of pencil-like beam elements are required to effectively fill the desired target volume. This simplification greatly streamlines the treatment setup, both mechanically and operationally, resulting in a reduced need for patient positioning adjustments. Furthermore, proton therapy, being synchrotron-based, benefits from significantly better beam-delivery efficiency compared to other forms of radiation therapy. This increased efficiency contributes to shorter average session durations, enhancing patient comfort and overall treatment experience. The precise nature of proton therapy minimizes the risk of unnecessary damage to healthy tissues surrounding the tumor, reducing potential side effects and complications. Moreover, the most widely utilized technology for proton therapy is based on cyclotrons, where protons are accelerated through a combination of electrical and magnetic fields. Although cyclotrons are less powerful and larger in size compared to synchrotrons, they offer the advantage of versatility. Cyclotrons are often employed in settings where protons are also required for other fields, making them dual-use facilities. Some cyclotrons are even commercially available off-the-shelf, enabling medical, industrial, or academic facilities to access this advanced therapy. On the other hand, proton facilities for hadron therapy predominantly rely on synchrotrons, whereas synchrocyclotrons belong to the same family. These synchrotrons are more powerful and sophisticated, allowing for a wider range of treatment possibilities and more complex cases. However, they require a larger initial investment and are typically found in dedicated proton therapy centers. Regrettably, proton therapy is still considered a nascent technology with regard to its theoretical roots. Currently, it remains an ideal choice for a well-defined class of treatments that specifically cater to pediatric patients and tumors located within sensitive areas of the body. However, thorough conclusions regarding its advantages and long-term financial sustainability can only be drawn in a hypothetical future timeframe, contingent upon the patient population sufficiently expanding to justify its commercial viability. The substantial upfront costs associated with building a proton therapy center make it an incredibly delicate and sensitive issue. Historically, the early financial outcomes of such centers have been either disappointing or at least not in line with initial expectations. Nevertheless, as more and more centers become operational, proton therapy is expected to make a significant difference in patient quality of life. This, in turn, will optimize the costs of operation and ultimately reduce the total cost per treated patient. It is important to note that proton therapy is unnecessary for many treatment situations. Therefore, a multi-technology approach should be embraced, distributing the available resources across different existing techniques based on specific clinical cases. This approach aims to maximize patient care outcomes while effectively managing the costs associated with treatment. By combining proton therapy with other modalities, healthcare providers can provide personalized treatment plans that best suit each patient's needs. As technology advances and research continues, the potential applications of proton therapy may expand, offering promising prospects for the future of cancer treatment. The potential inclusion of proton therapy in combination with other treatment options holds the potential to revolutionize cancer treatment and improve the lives of countless patients around the world. The possibilities are vast and only limited by our imagination and dedication to advancing medical science. (Mohan, 2022) (Paganetti *et al*. 2021) (Paganetti *et al*. 2021) (Albertini *et al*. 2020) (Bäumer *et al*. 2021)

Chapter - 4

Nuclear Medicine

Nuclear medicine utilizes small quantities of pharmaceuticals and trace elements to conduct diagnostic studies, making it an exceptional field in its ability to track the movement of these substances throughout the body. By imaging their distribution and function, nuclear medicine offers unique capabilities that are not bounded by tissue borders, containment, or surface complexions. It operates within an extremely low curie range, ensuring the delivery of radioactivity to the biological target remains at a minimum. The dose equivalent is generally low as well. The imaging task can involve highly dynamic functions or the measurement of slowly evolving physiological states. The tissues where the radioactivity is distributed can typically be easily identified, frequently interacted with, and are accessible to biopsy for correlation with the findings. Nuclear medicine serves as a widely understood laboratory for traditional scintillation detection equipment and is an ideal candidate for advanced single photon or photon pair techniques. Potentially beneficial advancements in this area range from techniques for attenuation "correction" of quantitation, primarily in the comprehension of tissue metabolic and pathologic events by calculating kinetic parameters such as lymph, blood, and cerebrospinal fluid flow, to the utilization of solid-state, position-sensitive detectors that yield exceptionally high resolutions and reasonably affordable *in vitro* autoradiograms after extended imaging periods. The sensitivity and selectivity of diagnostic assays in immunometric techniques can be further enhanced by incorporating radiolabeling with beta particle emitters like Tc-99m or introducing alternate means of signal production that prioritize sensitivity and selectivity. Substantial growth is expected in this particular sub-area. Nuclear medicine will continue to expand its horizons and revolutionize the field of medical imaging, ensuring accurate diagnoses and effective treatment plans for patients worldwide. With constant advancements in technology and the integration of novel techniques, the future of nuclear medicine holds immense potential for detecting and treating a wide range of diseases and conditions. As researchers and medical professionals delve deeper into the intricacies of the human body, nuclear medicine will play a pivotal role in unraveling the mysteries of health and disease. From the development of new radiolabeling methods to the creation of sophisticated imaging systems, the possibilities are endless. The field of nuclear medicine is poised to make significant breakthroughs in the coming years, solidifying its position as a vital component of modern healthcare. With its ability to provide detailed and accurate information about the body's internal processes, nuclear medicine will continue to empower healthcare providers and usher in a new era of personalized medicine. The potential applications of nuclear medicine are vast, ranging from early detection of cancer and monitoring of treatment response to the assessment of cardiovascular diseases and neurological disorders. In addition, nuclear medicine has the potential to revolutionize drug development and delivery, providing crucial insights into the efficacy and safety of medications. With its non-invasive nature and ability to capture real-time information, nuclear medicine is a powerful tool that has the potential to transform the way we approach healthcare. As we continue to unlock the full potential of nuclear medicine, the field will undoubtedly shape the future of medical practice and contribute to improved patient outcomes. The possibilities are endless, and the impact of nuclear medicine on society cannot be understated. With ongoing advancements and a growing body of research, nuclear medicine will undoubtedly continue to push the boundaries of medical science and redefine what is possible in the realm of diagnostics and therapeutics. The future is bright for nuclear medicine, and its potential to save lives and enhance the quality of life for countless individuals is truly remarkable. (Roy *et al.* 2022) (Alsharef *et al.* 2020) (Parrilha *et al.*, 2022) (Crișan *et al.* 2022)

4.1 Radioisotopes and Radiopharmaceuticals

In the field of nuclear medicine, radioisotopes find extensive applications as tracers for diagnostic studies involving various organs or injured structures within the body. These tracers help in identifying and visualizing the specific areas of interest, allowing healthcare professionals to make accurate diagnoses and create effective treatment plans. Additionally, radioisotopes are used for the irradiation of tissues or cells that require therapeutic interventions. Furthermore, radioisotopes have played a vital role in studying numerous physical, chemical, biological, and physiological aspects of the human body. Through these studies, researchers have gained valuable insights into the inner workings of the human body, leading to groundbreaking developments in medical science. Previously, beta emission radioisotopes, which emit beta particles with maximum energies ranging from 10-100 keV, were primarily produced in large nuclear reactors. However, significant advancements have been made in recent times, enabling the production of radioisotopes with higher maximum beta particle emission energies of approximately 0.5-2 MeV. This achievement is attributed to the availability of accelerators and improved isotope production mechanisms. The ability to produce these radioisotopes with high yields and at lower costs has revolutionized the field of nuclear medicine and greatly expanded its potential applications. Some of the newer beta emission radioisotopes that have proven to be highly effective in medical applications include 90Y, 186Re, 188Re, 153Sm, 64Cu, 67Ga, and numerous others. These radioisotopes have greatly contributed to the accuracy and efficiency of diagnostics and treatments in nuclear medicine. Furthermore, short half-life positron emitters such as 15O, 13N, 11C, and 18F are widely used as tracers in positron emission tomography (PET) imaging. PET is a highly valuable imaging technique that allows for the measurement of metabolic uptake of different tracers by the brain and various other tissues. By radioactively tagging glucose, PET imaging can assess the glucose consumption in the brain, providing insights into the metabolic activity of this vital organ. Moreover, PET can offer crucial information about intrapulmonary distribution, relative perfusion, gas exchange, and pulmonary endothelium changes within the lungs. With its ability to utilize a wide variety of tracers, PET imaging proves to be a versatile tool for visualizing and understanding diseases affecting different organs. Out of all the tracers used in PET scans, 18FDG stands as the most commonly employed one. Its reliability and effectiveness in providing accurate diagnostic information make it the preferred choice for medical professionals. Apart from aiding in diagnosis, PET studies using 18FDG can also predict significant parameters such as the standard uptake value or metabolic tumor volume of a lesion, serving as an important indicator of tumor presence and characteristics. Given the continuous advancements in nuclear medicine, the field is expected to progress even further, leading to improved patient care. The development of new tracers and imaging techniques will undoubtedly expand the capabilities of nuclear medicine, enabling healthcare professionals to achieve better outcomes for a wide range of medical conditions. The integration of artificial intelligence and machine learning algorithms in nuclear medicine is an emerging trend that shows great promise for enhancing diagnosis and treatment strategies. These advanced technologies can analyze large volumes of image data, aiding in the identification of subtle abnormalities and improving the accuracy of diagnostic evaluations. Furthermore, the integration of molecular imaging with other disciplines such as genomics and proteomics holds potential for personalized medicine, allowing for targeted therapies based on an individual's unique molecular profile. In addition to diagnostic and therapeutic applications, radioisotopes have also found utility in the field of radiation biology. Studies using radioisotopes have provided valuable insights into the effects of ionizing radiation on living organisms, helping to develop safe practices and guidelines for radiation protection. Moreover, radioisotopes have been instrumental in the development and testing of radiation therapy techniques, improving the precision and effectiveness of cancer treatments. The field of nuclear medicine is a dynamic and rapidly evolving field. The ongoing research and advancements in the field promise to revolutionize the diagnosis and treatment of various medical conditions. With the expanding applications of radioisotopes, molecular imaging, and advanced technologies, the future of nuclear medicine holds great potential for improving patient outcomes and advancing medical science as a whole. (Al Ayoubi, 2023) (Al Ayoubi, 2023) (Jarrell *et al*. 2022) (Shebs, 2020) (Wain) (HUỆ)

4.2 SPECT Imaging

Single-Photon Emission Computed Tomography (SPECT), a cutting-edge imaging technique, utilizes gamma radiotracer-emitting radiopharmaceuticals to obtain precise and detailed images of the body's internal structures. These radiopharmaceuticals, typically composed of Methoxyisobutylisonitrile (MIBI), incorporate either Technetium-99m (Tc-99m) or Iodine-123 (I-123). SPECT studies are conducted using highly sophisticated gamma cameras that emit and receive gamma rays. These studies generally span several hours, depending on the specific radiopharmaceutical used and the areas of the body under observation. During the imaging process, a substantial number of events, often surpassing 500,000, are employed to gather the necessary data. Given the significant radiation exposure and the lengthy duration required for SPECT imaging, patients are typically advised to maintain stillness to the best of their ability. In certain cases, patients are assisted by being securely positioned within a specially designed netted apparatus. This precautionary measure serves to diminish motion artifacts and, consequently, enhances the resulting image quality. The data obtained from SPECT studies are typically collected in the form of multiple planar images (2D). However, it is also possible to acquire the data as a sequence of single-photon conical or nonconical projections. When assuming that the records are obtained as several planar images, several crucial factors must be considered. Among these factors, it is noteworthy to emphasize the critical importance of the patient remaining entirely still during the acquisition of each image. This requirement ensures that no motion-induced blurring compromises the quality of the images. To assist with this, patients are typically provided with a headset and/or a fiberglass net, which aid in minimizing involuntary movements.

Compliance with these measures is of utmost importance since any motion between images has the potential to significantly degrade the clarity and detail of any identified lesions. In addition to the aforementioned measures, SPECT imaging procedures involve the injection of radiopharmaceuticals into the patient's bloodstream. This enables the radiopharmaceuticals to travel to the specific targeted organs or tissues. Subsequently, the gamma camera captures the released radioactive emissions and converts them into electrical signals. These signals are further processed and analyzed by computer software to generate precise and detailed images of the body's internal structures. The use of SPECT imaging has proven particularly beneficial across various medical specialties, including cardiology, neurology, and oncology. In cardiology, SPECT scans can assess blood flow and identify areas of reduced perfusion, aiding in the diagnosis of coronary artery disease. In neurology, SPECT imaging helps in the detection of abnormalities in brain function, and it can assist in diagnosing conditions such as Alzheimer's disease and epilepsy. In oncology, SPECT scans contribute to the staging and monitoring of cancer, as well as guiding targeted therapy. Furthermore, SPECT imaging can be combined with other imaging modalities, such as Computed Tomography (CT) or Magnetic Resonance Imaging (MRI), to provide even more comprehensive and accurate diagnostic information. By merging the functional data from SPECT with the anatomical data from CT or MRI, healthcare professionals can obtain a more complete understanding of a patient's condition. In conclusion, SPECT is an advanced imaging technique that relies on gamma radiotracer-emitting radiopharmaceuticals to generate detailed and precise images of the body's internal structures. With its ability to assess blood flow, detect abnormalities in brain function, and aid in the diagnosis and monitoring of various diseases, SPECT imaging plays a critical role in modern medical practice. By ensuring patient stillness, utilizing sophisticated gamma cameras, and implementing other necessary precautions, healthcare professionals can obtain the highest quality images, enabling accurate diagnosis and effective treatment planning. (Crișan *et al*. 2022) (Davis *et al*. 2020) (Alqahtani, 2023) (Naqvi & Imran, 2021) (Wang *et al*. 2024) (Duatti, 2021)

4.3 PET Imaging

Positron emission tomography (PET) is a form of nuclear medicine imaging that is based on the detection of high-energy photons. It plays a crucial role in diagnosing and monitoring various diseases and conditions, showcasing its versatility and utility in the field of medical science. The use of isotopes emitting positrons allows PET imaging to effectively track specific metabolic processes within the body. In recent years, PET imaging has witnessed significant advancements in radionuclide production and radiopharmaceutical selection. These innovations have revolutionized the field and made PET an invaluable tool in clinical specialties such as neurology, cardiology, oncology, and more. The ability to accurately diagnose and monitor diseases using PET has greatly enhanced patient outcomes and treatment plans. One major development in PET imaging is the introduction of positron emission tomography-surgery (PET-SUR). This modified version involves a minor surgical procedure that enhances the diagnostic capabilities of traditional PET scans. By surgically placing the PET tracer directly into the affected area, PET-SUR offers unprecedented insights into the metabolic processes and molecular activity occurring within the body. This technique has proven particularly effective in the fields of neurology, cardiology, oncology, and various other clinical specialties. The continuous advancements in radionuclide production and radiopharmaceutical selection have further augmented the efficacy and clinical utility of PET imaging. Researchers and scientists are constantly striving to develop new isotopes and tracers that offer improved sensitivity and specificity, allowing for better visualization and characterization of different tissues and organs. These advancements have expanded the scope of PET imaging, enabling it to play a pivotal role in the diagnosis, staging, and monitoring of numerous diseases, including but not limited to cancer, cardiovascular conditions, neurological disorders, and inflammatory processes. PET imaging instruments have also evolved significantly, thanks to advancements in technology. PET imagers now boast sophisticated features that enhance image quality and diagnostic accuracy. The two principal components of a PET imager currently in use are the detector block and the pulse-processing boards. The detector block consists of a scintillator crystal, such as lutetium oxyorthosilicate or lutetium yttrium aluminum garnet, which is viewed by an array of highly sensitive photomultiplier tubes. These tubes, in conjunction with pulse-processing boards intricately connected to each photomultiplier anode, efficiently process digitized signals and extract crucial information about the energy deposited in the crystal. The result is a detailed and precise PET image that aids clinicians in making accurate diagnoses and treatment decisions. In summary, PET imaging has emerged as an invaluable tool in the field of nuclear medicine, enabling clinicians to gain valuable insights into the metabolic and molecular processes occurring within the body. Through PET-SUR and the continuous advancements in instrumentation, radionuclide production, and radiopharmaceutical selection, this imaging technique has revolutionized diagnostic and monitoring practices across various medical specialties. The future holds great promise for further advancements in PET technology, empowering healthcare professionals to provide precise and personalized patient care. (Alavi *et al*. 2022) (Hussain *et al*. 2022) (Filippi *et al*. 2022) (Duclos *et al*. 2021) (Weber *et al*. 2020)

Chapter - 5

Advanced Computational Methods in Medical Physics

Many innovative and cutting-edge techniques in computational physics and data analysis are essential for solving complex and practical problems in the fields of medical physics and cancer biology. These solutions have long-term clinical implications and are crucial for advancing our understanding and treatment of diseases. In medical physics, one of the crucial tasks is the multi-parametric analysis of PET/CT imaging data. This analysis involves sophisticated algorithms that can extract valuable information from the combined data of positron emission tomography (PET) and computed tomography (CT) scans. By combining these two modalities, clinicians can obtain detailed information about tissue metabolism, structure, and function, allowing for more accurate diagnoses and treatment planning. Another important area in medical physics is the treatment planning of intensity-modulated radiation therapy (IMRT). IMRT is a state-of-the-art technique used in radiation oncology to deliver precise and highly conformal doses of radiation to cancerous tumors while sparing surrounding healthy tissues. The planning process involves intricate calculations and optimization algorithms to determine the optimal intensity and shape of each radiation beam, taking into account the patient's anatomy and tumor characteristics. By utilizing advanced computational physics techniques, clinicians can tailor the radiation treatment to each patient's specific needs, maximizing the chances of successful outcomes. In the field of cancer biology, computational physics plays a significant role in studying the spatiotemporal dynamics of the cell cycle. The cell cycle is a highly regulated process that controls cell growth, division, and replication. Understanding the intricacies of this process is crucial for unraveling the mechanisms behind cancer development and progression. Computational physics enables researchers to model and simulate the behavior of cells throughout the cell cycle, providing valuable insights into the underlying biological processes. These insights can aid in the identification of potential therapeutic targets and the development of new treatments. Additionally, computational physics is instrumental in the modeling of the morphogenesis and growth of multicellular systems. Multicellular systems, such as tissues and organs, exhibit complex patterns and behaviors arising from the interactions between individual cells. By utilizing computational models, researchers can simulate the processes of cell proliferation, migration, and differentiation to study the emergence of these patterns. These models can help uncover the fundamental principles driving tissue development and contribute to the understanding of diseases like cancer, developmental disorders, and regenerative medicine. To successfully address these challenges and achieve meaningful results, several common requirements need to be met. First and foremost, the ability to process large databases of recorded data is crucial. With the advancements in medical imaging technology, a vast amount of data is generated for each patient, necessitating efficient storage, retrieval, and analysis. High-throughput and parallel computing techniques are employed to handle these enormous datasets and extract meaningful information within a reasonable timeframe. Another essential requirement is the handling of complete uncertainty inherent in medical data. Random and systematic errors, as well as missing information in measurements, are common in clinical datasets. Advanced techniques in computational physics and data analysis allow for the quantification and management of these uncertainties. By incorporating probabilistic models and statistical approaches, researchers can reliably interpret and draw conclusions from the data, improving the robustness of their findings. Furthermore, the presentation of results in a format that facilitates direct comparison to clinical information is crucial for effective translation and understanding. Researchers aim to bridge the gap between computational models and clinical practice by providing intuitive visualizations and representations of their findings. This enables clinicians to assess the relevance and reliability of the results in the context of individual patients, informing decision-making and ultimately improving patient care. In addition to extracting information from existing datasets, computational physics enables inverse inference. This involves the extraction of relevant information and validation of hypotheses regarding fundamental biological processes occurring at the molecular, cellular, and tissue level. By integrating experimental data with computational models, researchers can make predictions and test hypotheses that would otherwise be challenging or impossible in a laboratory setting alone. This iterative process of modeling, prediction, and validation brings us closer to a comprehensive understanding of complex biological systems and opens doors to novel therapeutic strategies. To address the diverse challenges in medical physics and cancer biology, various advanced techniques from computational physics and computer sciences have been employed. Data mining and pattern recognition techniques have been used successfully for classifying genetic signatures from patients. By analyzing the genetic profiles of individuals, researchers can identify patterns indicative of specific diseases or treatment responses, enabling personalized medicine approaches. These techniques have also been applied to automate the identification of different phases of the cell cycle from time-lapse imaging, aiding in the study of cell behavior and dynamics. High-throughput computing has played a vital role in exploring the parameter space of established models and conducting comprehensive global analysis studies. By systematically varying model parameters and simulating a multitude of scenarios, researchers can comprehensively explore the behavior and response of complex biological systems. This provides valuable insights into disease mechanisms and drug responses and helps identify optimal treatment strategies for different patient populations. However, despite these achievements, the integration of these techniques and visualization of their results with clinical data remains a challenge. In many cases, these techniques have been used in isolation, limiting the potential for comprehensive analysis and translation into clinical practice. The best-case scenario involves the validation of a specific disease model, which can then be utilized for offline initializations in treatment simulations. This enables the study of the time-dose course for disease treatment and aids in treatment planning and optimization. In summary, the application of advanced techniques in computational physics and data analysis has revolutionized the fields of medical physics and cancer biology. Through the multi-parametric analysis of medical imaging data, treatment planning of IMRT, study of the cell cycle dynamics, and modeling of multicellular systems, researchers can gain a deeper understanding of complex physiological processes with significant clinical implications. These techniques enable the processing of large datasets, handling of uncertainty, visualization of results, and extraction of relevant information at various biological levels. By bridging the gap between computational models and clinical practice, these techniques hold immense potential for improving patient care and advancing our knowledge in these critical fields. These advancements will continue to drive progress and innovation in medical physics and cancer biology, leading to improved diagnostics, treatment strategies, and ultimately, better patient outcomes. (Wang *et al.* 2022) (Boeke *et al.* 2023) (Hu *et al.* 2020) (Winter, 2022) (Shiyam Sundar *et al*., 2024) (Al-Sharify *et al.* 2020) (Beyer *et al.* 2021)

5.1 Monte Carlo Simulations

The application of the Monte Carlo technique as a powerful simulation tool extends to various fields, encompassing not only nuclear energy, medical science, environmental research, and R&D endeavors, but also other domains where simulation is paramount. Its versatility and utility have been explored extensively in this chapter, particularly within the field of medical physics. One intriguing aspect that has garnered significant attention is the potential for utilizing the Phase Space file within a parallelized Monte Carlo program, showcasing its adaptability and effectiveness in simulations. The Phase Space file holds immense promise not only as an input for other simulations or collimation purposes but also as a valuable resource for optimization in the realm of Monte Carlo simulations. Despite the challenges associated with random number-based simulations and the sequential generation requirement, parallelizing Monte Carlo simulations can lead to a significant reduction in simulation time. An excellent example of this is the renowned radiotherapy planner, XiO, which heavily relies on the utilization of a Phase Space file. The comprehensive setup of treatment plans includes customized source and calculation data settings tailored to the specific treatment being planned. These settings encompass various properties of the emitted particles. By incorporating additional phase space file utilization for the designated particle in the planning process, notable improvements can be achieved. This approach offers advantages such as fast and precise data sourcing, eliminating the need for random numbers. As a result, both random number generation and code pooling can operate seamlessly, enhancing the efficiency of the simulation. The significance of the Monte Carlo technique extends far beyond the boundaries of medical physics alone. It finds application in a myriad of domains such as nuclear energy, environmental research, and R&D activities. However, this chapter focuses specifically on elucidating the extensive benefits and potential of employing Monte Carlo simulations in the medical field. Within this context, harnessing the Phase Space file as a parallelized facet of a Monte Carlo program proves to be an intriguing avenue worth exploring, highlighting its adaptability and efficacy. Moreover, in addition to its evident role in input files for alternative simulations or collimation purposes, the Phase Space file harbors immense potential as a consequential asset for optimization endeavors within the realm of Monte Carlo simulations. Although the nature of random number-based simulations presents inherent challenges that require sequential generation, parallelizing Monte Carlo simulations can yield remarkable time efficiency gains. This efficiency is exemplified by the widely acclaimed XiO code, a radiotherapy planner that thrives on the utilization of a Phase Space file. The all-encompassing configuration of treatment plans encompasses bespoke source and calculation data settings tailored to the specific treatment under consideration. These settings involve determining the emission characteristics of particles and their associated properties. The integration of supplementary phase space file utilization into the planning process for the designated particle ushers in significant enhancements. Most notably, this approach boasts advantages such as expedited and precise data acquisition, obviating the need for random numbers. As a result, both the generation of random numbers and code consolidation can operate unobstructed, further enhancing the efficiency and accuracy of the simulations. (Faddegon *et al.* 2020) (Kurz *et al.* 2020) (Paganetti *et al.* 2021) (Glide-Hurst *et al.* 2021)

5.2 Finite Element Analysis

The finite element method (FEM) or analysis (FEA) represents an approach to predicting the inherent behavior of a component or assembly during manufacturing, assembly, and end-use. The technique is a powerful analysis tool that is utilized in many physics-related problems. For the presented work, the problems can be considered of a multi-physics nature, meaning that the mechanical response of tissue is not independent of the electromagnetic nature. FEM can be used to model the mechanical deformation effects on the constituent dielectric properties during hydraulic loading by solving the related set of electrohydraulic coupling equations. Furthermore, Fourier's Law and Fick's First Law can be used to relate the temperature/heat changes to the electromagnetic tissue response. By considering these equations, a comprehensive understanding of the interplay between mechanical and electromagnetic phenomena can be achieved using the FEM. In practice, the model can be implemented in a three-dimensional manner using COMSOL Multiphysics. This software facilitates the analysis and visualization of complex physical phenomena, enabling engineers and researchers to gain valuable insights. Moreover, in order to accurately simulate the behavior of organs under hydraulic loading, it is necessary to develop a linear phased-array antenna design that has dynamic beam steering capability. This design enables the organ components to be forced into a three-dimensional exposure configuration, which is crucial for capturing the realistic behavior of the system. The presented FEM model is a time-harmonic open boundary scattering model. In the context of hydration flow, the flow rate remains steady state. To accurately predict the maximum temperature and temperature profile of irregular body geometry simulations, it is essential to employ infinite element models that provide open boundary excitations. These excitations are necessary to capture the true behavior of the system. The infinite element models can be analyzed using the transmission/reflection scattering equations, which allow for the calculation of the component triple integral form of the absorbed electromagnetic field. These detailed calculations provide valuable insights into the behavior of the system and can be used to inform the design of a cooling system for the microwave liner.

Additionally, the results from the FEM model can inform the development of an internal load compensation algorithm for use in bench testing, enabling engineers to accurately assess the performance of the system. Furthermore, the utilization of the FEM model allows researchers to overcome traditional conceptual design flaws and simulate advanced techniques. It provides a platform to explore different scenarios and trade-offs related to endoscopic microwave ablation and hyperthermia. By examining the various parameters and their effects, researchers can gain a deeper understanding of these techniques and optimize their application in clinical settings. In conclusion, the FEM model presented here offers a comprehensive approach to studying the behavior of components and assemblies in various physics-related problems. By considering the multi-physics nature and employing advanced mathematical techniques, the model enables the accurate prediction of mechanical and electromagnetic phenomena. Its implementation in COMSOL Multiphysics, alongside the utilization of infinite element models and scattering equations, allows for detailed analyses and insights. Ultimately, the model serves as a valuable tool for engineers and researchers alike, enabling them to design and optimize systems for various applications such as microwave ablation and hyperthermia. (Elkhodbia *et al*. 2023) (Ye *et al*. 2020) (Yakovlev & Konovalov, 2023) (Liu *et al*. 2021)

5.3 Machine Learning in Medical Imaging

In the context of medical physics, machine learning techniques usually refer to algorithms allowing computers to learn to do a certain task without being programmed to do so. The learning comes from the analysis of large quantities of data, metrics are defined, and the system is pushed to optimize the matching with these metrics. Due to its capabilities, robustness, and convenience, machine learning techniques have been increasingly used in medical imaging. This section reviews some representative applications related to medical image formation and pattern recognition.

In medical imaging applications, the data is in the form of images representing anatomical or clinical information of patients, most likely in 3D, acquired by various imaging equipment. Among the machine learning techniques, deep learning-based methods have demonstrated great success in various tasks on medical images. Deep learning uses a Deep Neural Network, which takes the image as input, processes in a hierarchical fashion through many layers, and accomplishes the task, such as detection of some clinical sign in the image. Most successful techniques are variants of Convolutional Neural Networks (CNNs), which are built and trained to perform specialized tasks such as image recognition and classification. The large success of deep learning over conventional machine learning is usually attributed to its reusable and compositional feature representation. Convolutional and deconvolutional operators are the key components in CNNs. The convolutional operation captures the spatial correlations of patterns. The deconvolution layers upsample and combine the patterns. The training of deep learning models involves the minimization of a loss function. Special optimization algorithms are used for efficient training, such as the backpropagation technique. (Liu *et al*. 2021) (Puttagunta & Ravi, 2021) (Liu *et al*., 2021)

Chapter - 6

Quality Assurance and Safety in Medical Physics

Quality assurance (QA) and safety in medical physics are subfields that overlap with several technologies and procedures of medical physics, but also involve interactions and collaborations with several other fields. For example, to ensure safe, effective, and consistent patient care (including diagnosis, treatment, and monitoring) that is provided by radiological equipment, regulations and best strategies should be established by radiation protection innovations, engineering principles (such as formal design), and national quality assurance interventions.

Interactions between medical physics and engineering also include professional communication and potential participation in laboratory and clinical engineering activities. Cross-organizational communication and active participation can ensure that equipment and protocols are designed to be patient-focused, developed with a short timeline, and practical to implement. Other elements of safety include effective radiological equipment sterilization, registration, and maintenance; information technology requirements; and backup safety systems of medical devices. Overall, a nationwide QA program aimed at evaluating the national medical physics infrastructure is crucial as well to maintaining the safety features of radiological equipment mainly in developing countries, where many of these topics are not yet formalized. (Fiorino *et al*. 2020) (Buchanan *et al*. 2020)

6.1 Regulatory Compliance

At its core, compliance is the process of creating and documenting an internal operating structure to meet the mandates of external regulated requirements. The overall responsibility starts at the top of the organizational chart; thus, the Radiation Safety Officer (RSO) literally shoulders the burden for assuring individuals and the institution comply with the conditions and standards set forth in the radioactive materials or use licenses. Above all, it’s the RSO’s job to make sure proper training and documentation are in place, to assure devices and materials are properly secured, and to report all uses of radiation-producing devices to the appropriate governmental agency in a timely fashion. In short, the RSO is expected to carry the burden of what might be considered Quality Assurance (QA) for radiation at the institution, on par or higher with that carried out by medical physicists for radiation therapy or diagnostic radiology. Since the institution is primarily responsible for meeting all the regulatory requirements pertinent to the radiation use under its license or registration, many of the RSO's requirements cross over to the healthcare practitioner engaged in the field. The RSO generally has broad oversight of radiation protection at a facility, with the task of ensuring ALARA and hands-on assistance with necessary exposure monitoring and recording. (Morgan & Konerth, 2022) (Morgan, 2020)

6.2 Dosimetry and Calibration

Calibration of magnitudes implies a comparison of a dosimetric system to a standard, internationally accepted dosimetric system. Calibration of unsealed sources is performed at NPP Bone Tissue Irradiator DOSVYAZ' (JV 'Radon'). Calibration of the dosimetric system for radionuclide research is also a very important stage of preparation for a series of experiments. A wide range of dosimetric systems is used - ionometric, semiconductor, scintillation, track and activation, thermoluminescent dosimeters, and the bubble-type dosimeter. The shortest-range detector which provides the reliable dose-distribution recording of high dose fields of neutrons is the range dosimeter-a fission chamber. It makes the use of thermoluminescent dosimeters obligatory for dosimetry at low doses, especially in a mixed gamma-neutron field. Maximum measurement errors do not exceed 20-30%.

Calibration of magnitudes of the dose of ionizing radiation is one of the elements of the quality assurance of radiation protection during medical research. The first step of calibration is to measure the values of exposure or ambient dose equivalent by using an ionometric system. The second step of calibration is to measure internal ionization-current calibration checks of an ionometric system. Unidos-1, a democratic unit with a temperature crystal, the diameter, and the height of which are 62 mm, not exceeding 0.5% for high doses as well beta/p=100 mSv, for low doses (50 mSv, the uncertainty for beta radiation is equal to 0.5% approximately. It is assumed that recommendations described above and N50M-89 will be used further. (Van Rossum, 2022) (Lim *et al*. 2023)

6.3 Patient Safety Protocols

The discharge of patients from a highly specialized radiotherapy department following their successful treatment may potentially give rise to significant dangers to members of the public due to the levels of radioactivity that still remain in the patients' bodies. This is particularly applicable to patients who have undergone PET imaging using the 18F-FDG radiopharmaceutical, which is known for its high energy and gamma emitting character. It is crucial to understand that the physical half-life of the 18F isotope is relatively short, lasting only 109.74 minutes. During this time, approximately 17.7% of the isotope converts into 511-keV positrons, which ultimately annihilate in a process resulting in the emission of two photons of the same energy. These photons act as incident photons for the PET camera, enabling the generation of detailed images. The utilization of 18F as a biomarker has revolutionized medical practice, as it allows for a more extensive evaluation of the patient after the administration of the radiopharmaceutical. This extended consideration period significantly contributes to the accurate assessment of the patient's response to the treatment. However, it is essential to recognize that potential hazards associated with exposure to persons and close contacts after the administration of 18F-FDG are fundamentally comparable to those experienced with other radio-labeled metabolites. Nevertheless, due to the extraordinary characteristics of the 18F emissions, including their high energy, high frequency, and wide photo peak of 511-keV, individuals entrusted with the detection and quantification of even small quantities of 18F in patients following inoculation with 18F-FDG must adhere to special procedures and precautions. The prevailing guidance dictates that both the half-life of the radionuclide and the particular manner in which it is used must be taken into careful consideration. Consequently, in order to effectively manage the potential risks associated with the 511-keV radiation that arises from the administration of 150 MBq of 18F according to a predefined protocol, it is imperative to utilize an attenuation coefficient and a submersion calorimeter. By conscientiously implementing these specialized techniques and instruments, the health and safety of both patients and medical personnel can be upheld to the highest possible standard, ensuring optimal outcomes for all parties involved. (Hassan, 2022) (Mincke *et al*. 2021) (Mincke, 2020)

Chapter - 7

Emerging Technologies in Medical Physics

Today’s medical physicists have unparalleled opportunities. The federal government and industry appear willing to invest research and development (R&D) funds in new clinical projects, subatomic physics, and space exploration, as well as in support of new and expanding medical facilities. Educational and salary prospects have never been better. As the field has evolved, we have seen the line between medical physics and its parent disciplines (medicine, physics, and engineering) blur. Subspecialties have proliferated, providing not only advanced career opportunities but also increasing dynamism within the field and an expanding array of scientific, experimental, and clinical questions that can be pursued. The excitement and challenges of such basic-level developments as the discovery of the recently hypothesized Higgs boson or the applied-level questions of molding the power of synchrotrons into new and better medical tools can only invigorate our field and its role in our parent disciplines as well. The dynamism of medical physics is sure to continue. The transition from an academic union dominated by established centers to a more distributed network of hospitals and universities as the primary locus of faculty positions has just about run its course. Continued reliance on hospitals, however, could expose the profession to economic declines that could weaken the field. This concern reflects another continuing trend in medical physics: the slow but relentless differentiation of the roles and opportunities for both the clinical physicists and their associates. Accurate definitions of the current and future roles of medical physicists are crucial if regulatory and other oversight bodies are to make informed policy decisions about levels of training, expertise, and supervision. In the face of this growing external scrutiny, objective evidence of educational and credentialing standards must be collected, using strategies to inform these bodies as well as those interested in joining the field. Meanwhile, we face the continuing challenge of preparing students for careers and the expanding possibilities of a rapidly evolving field. Recession combined with uncertainty in energy research trends have yielded only modest short-term declines in student interest. The specter of weak demand in both academic and clinical employment markets looms. The lessons of history suggest that these cyclical downturns will be temporary. More than two-thirds of faculty positions turn over every 15 years, even without market pressures on such institutions as private institutions, research centers, and universities. Most experts forecast some level of unmet demand for faculty over that time period. We must prepare ourselves to be competitive within this changing landscape. (Sampat & Shadlen, 2021) (Collins & Stoffels, 2020) (Bloom *et al*. 2021)

7.1 Artificial Intelligence in Radiology

Radiologists face enormous challenges in managing and interpreting the colossal volume of data produced every single day, in addition to grappling with the escalating complexity of radiological studies and therapies. The integration of Artificial Intelligence (AI) in medical imaging appears to hold the key solution for streamlining their work, augmenting the quality of services rendered, and enabling a broader utilization of the potential bestowed upon imaging as an early diagnostic tool. Currently, scientific research on this very topic is exceptionally active and vibrant. Numerous tools and dedicated algorithms have been meticulously developed, demonstrating characteristics of considerable usefulness in managing emergency situations, providing unwavering support to radiologists, and substantially diminishing errors. These invaluable tools are not only employed with immense patient satisfaction, but in certain scenarios, they have also achieved therapeutic success independently, without the need for human intervention. Notwithstanding these resounding accomplishments, it is imperative to acknowledge the latent risk associated with the utilization of AI tools by individuals who lack the necessary qualifications, as they may fail to discern the appropriate solution to a radiological predicament, consequently posing serious potential harm to the patient. Hence, it is vital for MedicAI, which draws one step closer to achieving a Turing test for radiological technologies, to be solely entrusted to proficient professionals who possess unequivocal guidelines regarding the correct utilization of these cutting-edge technologies. The primary objective of this chapter is to furnish medical readers with invaluable insight that will enable them to approach these technologies with absolute transparency, much akin to the Machine Learning model of AI that serves as our source of inspiration. As the field of AI continues to evolve and expand, it is crucial for radiologists to stay updated and well-versed in the latest advancements and developments in order to provide the highest level of care to their patients. By embracing AI technology and incorporating it effectively into their practice, radiologists can greatly improve efficiency, accuracy, and patient outcomes. This chapter aims to equip radiologists with the knowledge and understanding needed to navigate the complexities of AI in medical imaging, ensuring that they can leverage its potential fully and responsibly. Moreover, it will explore the ethical considerations and potential risks associated with AI in radiology, helping radiologists make informed decisions about its implementation and use. Furthermore, this chapter will delve into the various applications of AI in radiology, highlighting its role in early detection, diagnosis, treatment planning, and patient monitoring. It will discuss the capabilities and limitations of AI algorithms, addressing concerns about reliability, bias, and interpretability. Additionally, the chapter will explore the integration of AI with other advanced imaging technologies and modalities, such as magnetic resonance imaging (MRI), computed tomography (CT), and positron emission tomography (PET), to enhance the accuracy and precision of diagnosis. It will also touch upon the potential future developments and advancements in AI technology, such as deep learning algorithms and neural networks, and their implications for radiology practice. In conclusion, the integration of AI in medical imaging holds immense potential for revolutionizing the field of radiology. It offers unprecedented opportunities to enhance diagnostic capabilities, improve patient care, and optimize workflow efficiency. However, it is crucial for radiologists to approach AI technologies with caution, ensuring that they have the necessary expertise and guidelines to utilize them effectively and responsibly. This chapter aims to provide radiologists with valuable insights and knowledge to navigate the evolving landscape of AI in radiology, empowering them to make informed decisions and leverage its benefits to the fullest extent. By embracing AI as a tool for collaboration and augmentation rather than replacement, radiologists can continue to deliver exceptional care and contribute to advancing the field of medicine. (Najjar, 2023) (Barragán-Montero *et al*. 2021) (Panayides *et al*. 2020) (Wang *et al*. 2021)

7.2 Augmented Reality in Surgery

Augmented reality (AR) refers to the enhancement and enrichment of the physical world by incorporating additional pertinent information. This innovative and groundbreaking technology allows users to gain valuable insights and data while perceiving and interacting with the real environment surrounding them. By seamlessly merging the virtual with the real, AR offers limitless possibilities and potential applications across various industries. In the field of medicine, surgeons can harness the power of AR to revolutionize the way they approach surgeries and procedures. Imagine a scenario where a surgeon is about to perform a complex surgery. Utilizing AR technology, the surgeon can first examine a detailed and accurate scanned model of the particular body part that requires attention. This advance preparation and analysis enable the surgeon to have a clear understanding of the anatomical structures and identify any potential complications or challenges that may arise during the procedure. With this knowledge in hand, the surgeon can strategically plan and strategize the surgery, ensuring the best possible outcome for the patient. During the actual surgical procedure, AR continues to play a crucial role in assisting the surgeon. By projecting medical images, such as CT scans or MRI images, onto the patient's body in real-time, AR provides visual cues and essential information that guide the surgeon's actions. Surgical cutting lines, vital organ positions, and other relevant data are seamlessly integrated into the surgeon's field of view, enhancing precision and minimizing risks. This transformative capability and augmented visualization set AR apart from virtual reality (VR) and underline its immense potential in the medical field. Virtual reality, although distinct from AR, has also made significant contributions to the medical industry. VR involves creating computer-generated three-dimensional (3-D) environments that users can fully immerse themselves in. By donning head-mounted displays or utilizing screens, individuals can navigate through these virtual realms and interact with the digital environment. In the medical realm, VR has been used to simulate surgeries and provide training opportunities for medical professionals. It allows surgeons to practice complex procedures in a risk-free virtual environment, thereby enhancing their skills and confidence before operating on real patients. When it comes to complex surgeries, the integration of AR technology becomes not only beneficial but imperative. Tumor surgeries, for instance, frequently require meticulous resection procedures and the precise positioning of medical devices. Prior to the actual operation, AR technology can effectively display the exact location and orientation of critical anatomical structures, thus aiding the surgeon in detailed planning and strategizing. This crucial information enables surgeons to precisely navigate through the surgical site and achieve optimal outcomes. The benefits of AR extend beyond the operating room. Postoperative evaluation and radiation therapy can be greatly enhanced through the implementation of AR technology. By accurately visualizing and analyzing the changes made during the surgical procedure, surgeons can monitor and track the progress of the patient's recovery. This real-time visualization and analysis enable medical professionals to make informed decisions and adjustments to the treatment plan, resulting in improved patient care and outcomes. While the concept of AR in medicine is still being developed, certain prototype devices, such as the impressive VOXEL-MAN AR, have showcased similar functionalities that can be utilized within the medical field. These devices serve as a glimpse into the future of AR in healthcare and demonstrate its immense potential to revolutionize the way medical professionals work and collaborate. However, it is important to acknowledge and address the challenges that come with implementing AR technology in medicine. Handling and processing the vast amount of data involved in AR applications can prove to be a daunting task. The retrieval of computer-generated patient information, as well as the subsequent computation and display of high-quality images, necessitates advanced algorithms and technologies. Moreover, ensuring the timely delivery of accurate information without introducing potential delays or errors is of paramount importance. Therefore, optimizing and streamlining the AR experience for medical professionals is critical to ensuring real-time access to reliable and precise data. In conclusion, augmented reality has the power to revolutionize the medical field by seamlessly merging the virtual and real worlds. The transformative capabilities of AR enable surgeons to enhance their preoperative planning, improve precision during surgeries, and facilitate postoperative evaluation and treatment. While there are challenges to overcome, such as data handling and processing, the potential benefits of AR in medicine are undeniable. As technology continues to advance, it is crucial to invest in refining and optimizing the AR experience for medical professionals, ensuring that they have real-time access to reliable and precise data that can ultimately improve patient outcomes. Augmented reality has the potential to reshape the future of medicine and bring significant advancements to the healthcare industry. (Vles *et al.* 2020) (Goh *et al.* 2021) (De *et al.* 2024) (Wendler *et al.* 2021) (Verhey *et al.* 2020)

7.3 Nanotechnology Applications

Much of nanotechnology's early development was associated with molecular manufacturing, which was greatly promoted by the groundbreaking and visionary 1986 book "Engines of Creation" authored by K. Eric Drexler. This influential publication laid the foundation for the advancements in this emerging field of science and technology. Additionally, it led to the establishment of two highly influential organizations, namely the Foresight Institute and the Institute of Molecular Manufacturing. These organizations further propelled the progress in nanotechnology, fostering research and development in various domains. Drexler's seminal work continued to pave the way for progress with his 1992 publication titled "Nanosystems." In this work, he delved into crucial subjects such as the physical and chemical principles governing nanoscale systems. He also explored the intricate mechanisms behind the design, manufacture, and integration of devices at an astonishing atomic or nonmolecular scale. Nanosystems provided a comprehensive framework and theoretical understanding of nanotechnology, guiding researchers and scientists across the globe. However, while molecular manufacturing has shown immense promise, it still remains more theoretical in nature when compared to the practicality and real-world application of 3D printing. 3D printing gained its first glimpse of feasibility in the year 1986 through the pioneering efforts of 3D Systems, a renowned company. The advent of 3D printing revolutionized manufacturing processes, allowing for the creation of complex structures and prototypes with unprecedented precision and efficiency. This technology has found widespread application in numerous industries, including aerospace, automotive, healthcare, and consumer goods. Another remarkable scientific breakthrough in the early days of nanotechnology was the invention of the scanning tunneling microscope in 1981 by Gerd Binnig and Heinrich Rohrer. This revolutionary microscope allowed scientists to observe matter at an unprecedented level, enabling remarkable advancements in nanolithography and nanomanipulation on an atomic scale. Researchers gained the ability to manipulate individual atoms and molecules, opening new possibilities for the development of novel materials and nanoscale devices. The subsequent continuous development of numerous miniature machines has undeniably revolutionized various industries across the globe, capturing the imagination of scientists, researchers, and innovators alike. These machines, operating at the nanoscale, exhibit unique properties and capabilities that were previously unimaginable. They have found application in fields such as electronics, medicine, energy, and environmental science, playing a crucial role in driving technological progress. Today, nanotechnology has already left an indelible impact on the lives of countless individuals, many of whom may not even be aware of the direct influence it has on their daily experiences. From the astonishing performance of superlight composite tennis rackets to the remarkable healing properties of medical dressings, every aspect of these innovations harnesses the extraordinary power of nanotechnology. The utilization of nanomaterials and nanoscale devices has brought about groundbreaking advancements in diverse areas, including electronics, medicine, energy, and environmental science. Moreover, nanotechnology has paved the way for the creation of innovative materials and devices with enhanced functionality and performance. The development of nanocomposites, for instance, has led to the fabrication of materials with superior mechanical, thermal, and electrical properties. These materials find application in a wide range of industries, from aerospace to automotive, from construction to electronics, and from healthcare to renewable energy. The very term "nanotechnology" encompasses the creation, manipulation, and utilization of materials, devices, and systems at atomic, molecular and supramolecular scales. It signifies a profound paradigm shift that has revolutionized various scientific fields. Researchers and scientists continue to explore the vast potential of nanotechnology, seeking to unravel its mysteries and leverage its capabilities for the betterment of society. In the realm of dentistry, the application of nanotechnology has truly been transformative, rendering far-reaching effects on dental materials and oral healthcare practices. By employing nanotechnology, substantial advancements have been made in the development of dental materials, exponentially enhancing their properties and expanding their applications. Nanomaterials, such as nanocomposites and nanoceramics, exhibit superior mechanical strength, wear resistance, and aesthetic properties compared to traditional materials. These advancements have revolutionized restorative and cosmetic dentistry, enabling more efficient and aesthetically pleasing dental treatments. Furthermore, nanotechnology has paved the way for the creation of biocompatible mechanisms that ensure optimal outcomes after dental materials are placed within the intricate oral cavity. Dental products incorporating nanotechnology have proven to offer exceptional antimicrobial benefits, inhibiting the growth of bacteria and reducing the risk of infections. Additionally, nanomaterials used in dental applications exhibit outstanding tooth remineralization capabilities, repairing damaged enamel and improving overall oral health. Nevertheless, in order to ensure the safe and effective utilization of nanotechnology in dental products, it is paramount to establish stricter regulations and conduct comprehensive scientific studies. The potential environmental and health implications of nanomaterials must be thoroughly evaluated, taking into account their life cycle, disposal, and interaction with biological systems. By addressing these concerns, the dental community can harness the full potential of nanotechnology while ensuring patient safety and well-being. This article aims to provide an in-depth review and discussion of the remarkable advancements in dental materials enabled by nanotechnology and their subsequent clinical application. The primary focus will be on three distinct categories of dental materials, namely impression materials, resin-based composites, and ceramics. Each of these categories plays a pivotal role within the field of dentistry. Throughout the review, the impact of nanotechnology on the development of these dental materials will be explored from various perspectives, encompassing coagulation rate, mechanical properties, durability, and biocompatibility. In order to facilitate a comprehensive analysis, the review is divided into several sections. Section 9.1 will serve as an introduction, presenting dentistry as a captivating application of nanotechnology. Subsequently, Section 9.2 will delve into the fascinating development of impression materials. Building upon this foundation, the following sections will focus on resin-based composites and ceramics, respectively, as these two materials hold immense significance in the realm of dentistry. Each section will shed light on the substantial impact nanotechnology has had on the advancement of these materials. Finally, the discussions will culminate in Section 9.5, where the challenges and future perspectives of nanotechnology in dentistry will be carefully examined and addressed. The rapid progress in nanotechnology presents both opportunities and challenges for the dental field. While nanotechnology has the potential to revolutionize oral healthcare, it also raises ethical, social, and economic considerations. By critically evaluating these factors, the dental community can effectively navigate the path towards a sustainable and responsible integration of nanotechnology in dental practices. Through this comprehensive review, our objective is to emphasize and shed light on the monumental contributions of nanotechnology in the continuous improvement of dental materials and the relentless advancement of oral healthcare practices. By exploring the various facets and dimensions of this rapidly evolving field, we hope to lay the foundation for further innovation and scientific exploration, ultimately leading to enhanced oral health outcomes for individuals worldwide. The transformative power of nanotechnology in dentistry holds immense promise, heralding a new era of precision, effectiveness, and patient-centered care. (Agarwal *et al.*, 2021) (Nazir *et al.* 2024) (Sahu *et al.* 2023) (Fatima *et al.*) (Ejidike *et al.* 2024) (Zhao, 2023) (Trope & Souls, 2020) (Mukherjee *et al.* 2022) (Reith & Brajković, 2021) (Woinska, 2022)

Chapter - 8

Future Trends and Innovations

With the continuous advancements in accelerator design, researchers have made significant strides in introducing state-of-the-art behavioral techniques within the realm of radiotherapy. These cutting-edge techniques, including respiratory gating and tumor tracking, when combined with intensity-modulated multi-leaf collimation, hold immense potential in substantially augmenting the efficacy of digital image-guided modalities. It is important to highlight that the majority of radiotherapy equipment manufacturers now offer readily accessible commercial solutions for the implementation of these techniques. The primary focus of these advanced techniques centers around the development of novel clinical methodologies for treatment delivery. Numerous techniques have emerged, leveraging the observed phenomenon that subjecting tissue to ultrasound prior to radiation exposure can significantly intensify the response of tumor tissue to ionizing radiation. This groundbreaking discovery has laid the foundation for pioneering treatment approaches in the field of radiotherapy. Notably, academics specializing in the field of radiotherapy physics have played a pivotal role in propelling the boundaries of the discipline, chiefly through their instrumental contributions to the development of the selsyn technique. The selsyn technique holds extraordinary relevance, particularly when it comes to the accurate localization of selsyn sources across extensive distances, with the ultimate aim of attaining a specific level of dose localization. The selsyn distribution boasts remarkable linear characteristics and a substantial dose gradient, rendering it exceptionally well-suited for active forms of treatment that require multiple sessions. With the utilization of this technique, it becomes feasible to administer up to eight consecutive treatments, continuously exposing the patient to a diverse array of ultrasonic sources. These sources are carefully calibrated to emit precise levels of ultrasound energy, targeting specific areas of concern within the tumor mass. By doing so, clinicians can effectively enhance the overall response rate and tumor control probability. Moreover, the integration of the selsyn technique with other advanced radiotherapy modalities further propels the field into uncharted territories of precision medicine. In addition to its therapeutic applications, the selsyn technique has also found utility in diagnostic imaging procedures. The ability to accurately localize selsyn sources allows for the creation of highly detailed maps of anatomical structures and pathological abnormalities. This, in turn, enables clinicians to make more informed decisions regarding the optimal treatment approach for each individual patient. Through the seamless integration of diagnostic and therapeutic capabilities, the selsyn technique offers a comprehensive solution that maximizes treatment outcomes while minimizing the risk of radiation-induced complications. With each passing day, new breakthroughs and refinements continue to transform the landscape of radiotherapy. As researchers delve deeper into the intricate mechanisms underlying tumor response to radiation, novel therapeutic approaches are being devised to specifically exploit these biological phenomena. The future holds immense promise, with the potential for personalized treatment strategies tailored to the unique characteristics of each patient's tumor. Through the convergence of cutting-edge technology and innovative scientific inquiry, the field of radiotherapy is poised to revolutionize cancer care, offering renewed hope and improved outcomes for patients worldwide. In recent years, the utilization of advanced radiation techniques in the field of radiotherapy has witnessed unprecedented growth. These remarkable advancements have revolutionized the landscape of cancer treatment, greatly enhancing the precision and effectiveness of therapeutic interventions. Oncologists and researchers alike are constantly pushing the boundaries of innovation, exploring new avenues to improve patient outcomes and refine treatment protocols. One such avenue is the integration of novel behavioral techniques into radiotherapy practice. Respiratory gating and tumor tracking, for instance, have emerged as game-changing approaches that allow clinicians to account for organ motion and ensure accurate delivery of radiation doses. These techniques, when combined with intensity-modulated multi-leaf collimation, enable precise targeting of tumor tissues while minimizing harm to surrounding healthy cells. The transformative potential of these advanced techniques cannot be overstated, and their availability from commercial solutions offered by radiotherapy equipment manufacturers further facilitates their widespread adoption. A striking development in the field of radiotherapy is the discovery that ultrasound exposure prior to radiation can significantly enhance the response of tumor tissues to ionizing radiation. This breakthrough finding has paved the way for revolutionary treatment approaches, capitalizing on the synergistic effects of ultrasound and radiotherapy. Esteemed physicists specializing in radiotherapy have played a key role in the development of the selsyn technique, an instrumental advancement for accurate localization of radiation sources across varying distances. The selsyn technique, renowned for its exceptional dose localization capabilities, enables the administration of multiple treatment sessions with high precision and efficacy. Through the iterative application of the selsyn technique, patients can receive up to eight consecutive treatments, each utilizing ultrasonic sources meticulously calibrated to emit targeted levels of energy. This tailored approach significantly enhances the response rate and control probability of tumors, presenting an unprecedented opportunity for improved patient outcomes. When combined with other state-of-the-art radiotherapy modalities, the integration of the selsyn technique opens up new frontiers in precision medicine, offering uncharted possibilities for personalized treatment approaches. Importantly, the selsyn technique is not limited to therapeutic applications alone; it has also proven invaluable in diagnostic imaging. Accurate localization of selsyn sources enables the creation of highly detailed maps, providing clinicians with crucial insights for optimal treatment planning and decision-making. The remarkable advancements in radiotherapy continue to reshape the trajectory of cancer care. With each passing day, researchers uncover intricate mechanisms underlying tumor responses to radiation, enabling the development of targeted therapeutic approaches that leverage these biological phenomena. The future holds immense promise, with the potential for tailored treatment strategies that take into account the unique characteristics of each patient's tumor. As cutting-edge technology and scientific inquiry converge, the field of radiotherapy is on the cusp of transformative breakthroughs, offering renewed hope and improved outcomes to patients worldwide. (Cook 2021) (Pettinato *et al.* 2022) (Kivi *et al.* 2024) (Sasiain *et al.* 2024) (Zhu *et al.* 2024) (Pan & Zhang, 2023) (Sánchez San Blas & Sales Mendes…) (Cordill 2024)

8.1 Personalized Medicine

Classification of medical data to determine diseases clearly defines a new and complex challenge when considering the large dimensionality and vast range of medical diagnostic procedures in modern times. Moreover, this challenge necessitates the exploration and development of innovative mathematical models and methodologies that can significantly enhance the accuracy of medical diagnoses. Unlike traditional clinical approaches, the results obtained through classification methods are objective in nature, capable of being validated and interpreted as outcomes derived from data and the specific laws governing various diseases. The pivotal role played by classification in medical diagnostics cannot be understated. While classification may have broader implications, this paper will primarily focus on the utilization of support vector machines (SVM) to classify medical diagnostic results. Medical diagnostics revolves around the identification of diseases, a task accomplished by seeking out distinctive patterns within the medical data that set different diseases apart. Pattern recognition and classification methods guide the identification of these patterns through the use of two or more predefined classes, establishing a foundation for supervised learning. Computer-based pattern recognition methods have been extensively employed to enhance medical diagnostics, leading to the development of numerous techniques aimed at delivering clinically acceptable solutions. Presently, artificial neural networks, self-organizing maps, and SVM stand out as the most widely adopted pattern recognition methods. These methods have demonstrated remarkable performance in the realm of medical diagnostics, exhibiting exceptional classification accuracy and a proven track record of success. The utilization of artificial neural networks and SVM has consistently provided clinically significant outcomes, enabling healthcare professionals to make informed decisions based on accurate diagnoses. By leveraging the power of machine learning algorithms like SVM, medical professionals can achieve more precise and reliable diagnostic results. SVM, specifically, offers several advantages that make it well-suited for medical data classification. It can effectively handle high-dimensional data, account for complex relationships among variables, and provide robust generalization capabilities. These attributes contribute to its ability to accurately discern between different diseases based on specific patterns identified within the medical data. Furthermore, the use of SVM in medical diagnostics ensures that the classification process remains transparent and interpretable. The decisions made by SVM models can be explained and understood, providing valuable insights into the diagnostic reasoning behind the assigned disease labels. This interpretability is crucial for building trust in the classification system and facilitating collaboration among healthcare professionals. In conclusion, support vector machines (SVM) are instrumental in the classification of medical diagnostic results, offering exceptional accuracy and interpretability. As medical data continues to grow in complexity and volume, the utilization of advanced pattern recognition methods becomes indispensable. SVM, along with other machine learning techniques, paves the way for improved medical diagnoses and ultimately enhances patient care. With ongoing research and innovation, the field of medical diagnostics can expect continuous advancements in classification methodologies, leading to better healthcare outcomes for individuals worldwide. These advancements will undoubtedly shape the future of medical diagnostics and contribute to the overall betterment of healthcare practices, ultimately benefiting patients and healthcare professionals alike. The integration of artificial intelligence, deep learning, and big data analytics in medical diagnostics holds great promise, opening up new horizons for precision medicine and personalized healthcare. Cutting-edge technologies such as deep neural networks, convolutional neural networks, and recurrent neural networks offer incredible potential for breakthroughs in disease detection, prognosis, and treatment. As these technologies continue to evolve, the field of medical diagnostics will witness a paradigm shift, ushering in a new era of healthcare excellence. Through collaboration between medical professionals, data scientists, and technology experts, the possibilities are limitless. Together, we can revolutionize medical diagnostics and transform the healthcare landscape for the betterment of humanity. (Vichianin *et al.* 2021) (Sharma *et al.* 2021) (David 2020) (Maktabi *et al.* 2020)

8.2 Image-Guided Interventions

Introduction

Interventional Radiology (IR) involves a broad range of minimally invasive, therapeutic, and diagnostic procedures performed under imaging guidance. The images used to guide that performance include various modalities representing different European guidelines. Currently, the dominant imaging technique utilized in IR is digital subtraction angiography (DSA). However, it is being frequently complemented and in some cases replaced by new rapidly developing radiation-free X-ray techniques, in particular, MRI.

CT guidance for different procedures is getting an increasing role, preserving at the same time the X-ray benefits of fast, highly detailed, and spatially accurate performance. A very important trend is the fusion of information from different imaging modalities, thus increasing the potential of percutaneous or surgical or hybrid combinations of two, solving complex medical problems. And finally, we should consider the problems related to new higher doses in radiation protection of patients according to common concepts of RPO (Radiological Protection of Patient in Europe). (Campos and Schenning 2020) (Shaban *et al.* 2022)

8.3 Biomedical Engineering Collaborations

Medical physics is a truly interdisciplinary field, and many advances have occurred because of strong links between medical physicists and other professionals such as medical doctors, engineering scientists, computer scientists, biologists, chemists, and researchers from diverse backgrounds. These collaborations have led to groundbreaking discoveries and innovations in the field of medicine, pushing the boundaries of what is possible in patient care, diagnostics, treatment, and overall healthcare. The convergence of diverse expertise, perspectives, and cutting-edge technologies has sparked a revolution in healthcare, enabling more accurate diagnoses, precise treatments, and enhanced quality of life for patients around the world. These remarkable advancements have transformed the way we approach healthcare, with medical physicists and their counterparts at the forefront of this transformative journey. The strong societal interest in medical advances has fostered a rich history of funding and collaboration between the physical and biological sciences. Governments, organizations, and institutions alike have recognized the invaluable contributions of medical physicists and their counterparts, pouring significant resources into research, development, and technological advancements. This unyielding support has propelled the field forward, enabling medical physicists to explore new frontiers and address complex challenges in healthcare. As a result, the impact of their work resonates across various domains, from academia to clinical settings, and from small communities to global populations. These tireless efforts have reshaped the landscape of modern medicine, inspiring hope and fostering a sense of tremendous potential for the future. One such entity making a significant impact on the field is the National Institute of Biomedical Engineering and Bioengineering (NIBIB), operating under the umbrella of the esteemed National Institutes of Health. NIBIB serves as a beacon of innovation and excellence, championing research efforts that strive to revolutionize patient care, improve overall well-being, and address pressing healthcare challenges. With unwavering commitment and a forward-thinking approach, NIBIB provides direct support for cutting-edge research aimed at transforming medical practice and advancing our understanding of the human body. By fostering collaboration between medical physicists, biomedical engineers, and other professionals, NIBIB facilitates the translation of groundbreaking discoveries into tangible solutions that have a profound impact on individuals and communities worldwide. At the heart of these transformative efforts lies the profound field of biomedical engineering (BME). Biomedical engineers serve as the catalysts for innovation, leveraging the principles, methodologies, and problem-solving techniques of engineering to advance biology, medicine, and healthcare as a whole. They immerse themselves in both the medical and engineering domains, collaborating closely with a diverse array of medical professionals, researchers, and experts from various disciplines. Together, they tirelessly strive to develop and enhance tools, information systems, and materials that have the power to revolutionize patient care, rehabilitation, diagnostics, and disease prevention. The role of biomedical engineers encompasses a wide range of responsibilities and applications. They play a pivotal role in the development of state-of-the-art medical devices, working hand in hand with physicians, surgeons, and other healthcare practitioners to improve existing technologies or create groundbreaking solutions from scratch. By leveraging their expertise in engineering, these professionals meticulously design, iterate, and refine tools that enable accurate diagnoses, effective treatments, and precise interventions, empowering medical practitioners to deliver the best possible care and outcomes for patients. Through their collaborative efforts, they are reshaping the way healthcare is delivered, making it more personalized, efficient, and effective. Moreover, biomedical engineers make significant contributions in the realm of information systems and digital health. In an era defined by data-driven decision-making and technological advancements, these experts harness their computational skills, data analysis techniques, and innovation mindset to develop sophisticated software, algorithms, and data platforms that streamline medical processes, improve workflow efficiency, and facilitate seamless healthcare delivery. From electronic health records (EHRs) to medical imaging and analytical tools, these information systems and digital solutions are designed with the utmost precision, security, and effectiveness, enabling healthcare providers to access, analyze, and utilize critical patient data in real-time. This integration of advanced technology into healthcare systems leads to improved clinical outcomes, enhanced patient safety, and personalized care tailored to individual needs. Additionally, biomedical engineers focus on the development of advanced materials and biomaterials that revolutionize the way we approach healthcare and medical interventions. These materials range from biocompatible implants and prosthetics to drug delivery systems, nano-scale structures, and tissue engineering constructs. By combining their engineering prowess with a deep understanding of biology, these professionals pave the way for groundbreaking therapeutic interventions, regenerative medicine approaches, and precision medicine solutions. These innovative materials enable more efficient drug delivery, promote tissue regeneration, and enhance the overall effectiveness of medical interventions. Through their contributions, biomedical engineers are unlocking new possibilities in healthcare, giving patients a renewed chance at a healthier and happier life, minimizing complications, and maximizing the potential for complete recovery. In conclusion, medical physics thrives on collaboration, innovation, and the integration of knowledge from multiple scientific disciplines, bridging the gap between medicine and engineering. The unwavering dedication, passion, and collaboration of medical physicists, alongside their colleagues in various fields such as biomedical engineering, have opened up a world of possibilities in patient care, treatment, and health outcomes. With each passing day, these pioneering professionals push boundaries, challenge conventions, and reshape the future of healthcare. Through their relentless efforts, medical physicists and biomedical engineers continue to forge a remarkable path towards a brighter, healthier, and more promising tomorrow for individuals, communities, and society as a whole. Their contribution to the advancement of medical science, technology, and patient care is truly transformative, and their impact will be felt for generations to come. (Kane & Gelman, 2020) (Avanzo *et al*. 2021) (Smye & Frangi, 2021) (Chougule 2022) (Barabino *et al*. 2020) (Stewart *et al*. 2020) (Day-Duro *et al*. 2020) (Crews *et al*. 2020)

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