Risk of Exposure to Radiation from MRI Machines

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Introduction

Exposure to radiation generated in healthcare facilities contributes significantly to the annual dose received by the public and healthcare workers worldwide. This issue was highlighted by the European Commission's report in 1999, which revealed that approximately 90 million medical procedures involving X-rays were conducted within the member states of the European Union during that year. Astonishingly, medical doses accounted for a staggering 96% of the overall man-made effective dose, which is a measurement indicative of the associated risks. The primary cause of exposure to diagnostic medical doses is through medical imaging. Interestingly, the commonly used imaging techniques - Computer Tomography (CT), Positron Emission Tomography (PET), and single photon emission computed tomography (SPECT) - are actually a formidable source of ionizing radiation. However, magnetic resonance imaging (MRI), a modality that does not depend on ionizing radiation, has experienced rapid development and is now widely available in nearly every developed country. Unlike other methods, MRI does not utilize ionizing radiation, thereby diminishing the potential health risks. Instead, the concerns regarding MRI primarily revolve around the possibility of thermal injuries arising from whole-body heating due to the static and time-varying magnetic fields used. The avoidance of ionizing radiation through MRI comes at the cost of increased examination durations, typically up to 30 minutes for standard clinical procedures. Consequently, this places additional time demands on the operators. Furthermore, the use of MRI necessitates close communication and cooperation between medical physicists and MRI operators due to the magnetic exposure involved. These findings raise concerns that significant occupational health risks associated with MRI may be underestimated, particularly in countries lacking reliable individual dose monitoring results. Physicians and researchers may unknowingly underestimate the occupational exposure to static and time-varying magnetic fields when assessing the employee occupational dose resulting from ionizing radiation. Hence, it becomes of utmost importance for healthcare facilities to implement comprehensive measures aimed at minimizing the potential risks associated with both ionizing radiation and magnetic exposure. This can be achieved by strictly adhering to safety protocols, providing ongoing training and education for healthcare professionals, and regularly monitoring individual radiation doses. By conscientiously prioritizing the safety of both patients and healthcare workers, it is feasible to ensure that the benefits derived from medical imaging procedures ultimately outweigh any potential risks involved. (Rehani & Nacouzi, 2020) (Malone, 2020) (Boice *et al*. 2020) (Jeukens *et al*. 2020) (Mallya, 2021) (Benn and Vig2021)

1.1 Background of MRI Technology

MRI, which stands for magnetic resonance imaging, is an advanced and innovative imaging technology that utilizes magnetic fields and radio waves to produce coherent signals in living tissues. This remarkable technology has transformed the field of clinical diagnostic procedures since its introduction in the late 1980s. Its development was built upon the groundbreaking groundwork laid in NMR (nuclear magnetic resonance) physics, which dates back to the 1940s. Furthermore, the first diagnostic images were obtained in the 1960s, marking a significant milestone in the evolution of MRI. Scientific progress had been continuously shaping the field of MRI even before its clinical availability. Notably, the recording of initial NMR spectra in chemical compounds containing only a few atoms fueled the curiosity of researchers. The theoretical framework provided by Nobel laureate physicist Paul Lauterbur further propelled the advancement of MRI. Additionally, the late J. Bobo, along with his group and Richard Mendel, pioneered the use of Lauterbur's 2D MRI technique by imaging methemoglobin. This groundbreaking achievement paved the way for the future success and widespread adoption of MRI. In today's era, MRI has emerged as a key instrument in modern medical diagnosis, revolutionizing the field of medical imaging. Its noninvasive nature and high-definition imaging capabilities make it an indispensable modality in the medical field. Compared to traditional imaging techniques that involve ionizing radiation, MRI offers a relatively safer approach with its friendly tolerance by the human body. Consequently, it was initially believed to be free from environmental radiation risks. However, the relentless progress of technological applications in MRI has resulted in the generation of high-resolution images and an array of intervention procedures. This has opened up a new avenue for investigating potential radiation exposure risks, specifically in patients and healthcare professionals who handle MRI procedures. In order to assess the possible radiation risk associated with MRI scanners, particularly when used alongside procedures that release ionizing radiation, a unique framework has been developed. This framework aims to thoroughly analyze and discuss the interaction and potential risks of combining MRI with other imaging techniques. By conducting comprehensive research on the subject, the medical community seeks to further enhance the safety measures and protocols involved in MRI procedures. Through such efforts, the field of medical imaging continues to advance, ensuring the utmost patient and healthcare staff safety. As the field of MRI continues to progress, it is evident that this exceptional technology has revolutionized medical diagnosis and imaging. With its ability to provide detailed and accurate images of the human body, MRI plays a crucial role in the early detection and treatment of various medical conditions. The ongoing research and development in this field will further expand the capabilities of MRI, allowing for enhanced imaging quality and improved patient care. As we embrace the future of medical imaging, MRI remains at the forefront, consistently pushing boundaries and redefining what is possible in the world of healthcare. The potential of MRI is boundless, and its impact on the medical field is immeasurable. Through continued advancements and breakthroughs, MRI will continue to revolutionize medical diagnosis and imaging, ultimately leading to better patient outcomes and enhanced healthcare practices. With its remarkable history and promising future, MRI stands as a testament to human ingenuity and the relentless pursuit of scientific and medical advancements. (Mittendorff *et al*. 2022) (Srinivasan *et al*. 2022) (Jenkins *et al*. 2021) (Tunariu *et al*. 2020) (Chaban *et al*. 2024)

1.2 Purpose and Scope of the Study

The primary reason for conducting this study is that MRI facilities have become incredibly widespread in all areas of medicine and in the realm of emerging medical technologies. With a staggering number of approximately 30 million studies being performed annually in the United States alone, countless individuals are exposed to the effects of these high-field MRI machines that are frequently located within hospital premises. Given the fact that MRI employs magnetic fields and non-ionizing radiofrequency energy, it is widely recognized as a favorable alternative to X-ray and CT scans, considering the fact that these medical imaging techniques employ ionizing radiation which can potentially induce photoelectric effects on matter. This raises significant concerns for both patients and medical personnel who are frequently subjected to these technologies. Initially, the very existence of these MRI machines went unnoticed due to their inaudible and odorless nature. However, in recent years, it has come to light that there are indeed several surprising risks associated with their usage. These risks are not limited to hospitals with MRI machines below 3. 0 Tesla, as even facilities with lower emission levels are not entirely free from potential hazards. Therefore, it is crucial to assess the risks of radiation exposure for individuals working inside MRI machines. To evaluate the risks, various calculations have been devised to estimate the absorbed dose when exposed to different electromagnetic radiation fields. These calculations are applicable to both permanent MRI installations and portable MRI systems. For permanent installations, they are relevant to equipment usage in close proximity to MRI machines. On the other hand, for portable MRI systems, these calculations are crucial when a person is actually positioned inside the magnetic field. In this study, different types of MRI units have been considered, including 3. 0 Tesla scanners in large hospitals, 1. 5 Tesla scanners in smaller hospitals, as well as portable (disaster and battlefield portable) MRI scanners equipped with magnet strengths of either 0. 5 or 0. 2 Tesla. It is worth emphasizing that the calculated dose for any given power setting depends on the duration of exposure and the strength of the radiofrequency field emitted by the machines. To gather the necessary information for this study, suppliers in the field were consulted. Their input helped in obtaining relevant data regarding the levels of radiofrequency field emission for a range of desired scan types. These scan types include 3D volume flex coil T1, 3D volume head coil TOF & FLAIR, 3D MRA/3D CE, 3D MRA, 2D FSE CE, FLARE, FSE, GRE CE, GRE, and STIR. By examining these factors and considering the potential risks associated with MRI machines, this study aims to provide valuable insights and contribute to the understanding of radiation exposure in the context of medical imaging. (Arnold *et al*. 2023) (Goldfarb & Weber, 2021) (Chazot *et al*. 2020) (Bhat *et al*. 2021) (Chaban *et al*. 2024) (ElHabr *et al*. 2022)

Chapter - 2

Principles of MRI Technology

When a perception of risk is associated with a particular imaging modality or specific diagnostic examination, the assumption rudely conveys the impression that the technique is established on both appropriate operating principles and sound scientific evidence. When this happens, it is valuable to briefly consider the essential nature of the imaging process and to relate this information to the actual process of documenting a potential cause-and-effect connection. The acronym "MRI" stands for Magnetic Resonance Imaging, a technique for the production of cross-sectional or three-dimensional images of living tissues. MRI always includes the application of an intense magnetic field, with additional spins equilibrated to the outside of the spectromagnet. The fundamental sensitivity of MRI technology relies on the population of hydrogen nuclei in water. In all physiologically relevant tissues, water is ubiquitous. Because of the lifelong abundance of imaging targets, this property provides MRI with fundamental medical efficacy. The hydrogen nucleus consists of one proton in atomic concentrations, and as a result, this proton nucleus remains detectable by MRI techniques. A stronger inducing magnetic field results in a corresponding net magnetization vector that is aligned with, but in addition to, the point of objectives maintained by the local system of electronics. M(f) is precessing coherently due to the nuclear moment, γ(f), surroundings such as the interaction of nearby hydrogen, and nearby oxides or acid. Electrons engage the nuclear spins and transmit their resultant energy. This transfer of energy between the electrons and nuclear spins plays a crucial role in the overall functioning of MRI technology. By altering the strength and orientation of the applied magnetic field, medical professionals can control the level of energy transmission, allowing for the creation of detailed and accurate images. Additionally, advancements in MRI technology have led to the development of specialized imaging techniques that cater to specific medical needs. For example, functional MRI (fMRI) utilizes changes in blood flow to map brain activity, providing valuable insights into neurological disorders and cognitive processes. Moreover, the versatility of MRI extends beyond mere imaging capabilities. With the utilization of contrast agents, medical practitioners can enhance the visibility of certain tissues or structures, enabling a more comprehensive diagnosis. These agents work by altering the magnetic properties of specific areas of interest, making them stand out amidst the surrounding tissues. Furthermore, recent advancements in MRI technology have introduced the concept of molecular imaging, allowing for the visualization of cellular processes and molecular interactions within the body. This groundbreaking approach holds immense promise for early disease detection and personalized medicine. In conclusion, the capabilities and applications of MRI are vast and continually expanding. Through its ability to produce detailed images, assess functional activity, and even investigate molecular-level events, MRI has revolutionized the field of medical imaging. With ongoing advancements, it is clear that MRI will continue to play a critical role in improving diagnostic accuracy, enhancing patient care, and advancing our understanding of the human body. (Weiskopf *et al*. 2021) (Madelin, 2022) (Wang *et al*. 2023) (Zaghir *et al*. 2024) (Bartusik-Aebisher *et al*. 2022)

2.1 Magnetic Resonance Imaging Basics

Magnetic Resonance Imaging (MRI), in essence, constructs a highly detailed and comprehensive image based on the water content present within various tissues and organs of one's body. This remarkable medical procedure utilizes the interaction of strong magnets and radio waves to generate signals that are directly influenced by the amount of water present in a specific area of the body. Thankfully, due to the fact that water is exceptionally conducive to electricity, the possibilities for achieving relatively high resolutions in MRI scans are abundant and impressive. It should be noted, however, that bone, on account of its water content, does not produce the strongest MRI images. Conversely, other vital substances such as fat and protein can be thoroughly visualized in MRI scans, which has enormously facilitated the study and examination of the brain alongside its interconnected chemical components in astounding detail and precision. Among the various advantages of MRI, it is particularly noteworthy that this imaging technique is considered both relatively safe and non-invasive, thus escaping the necessity of injecting patients with diverse chemicals and minimizing any potential risks or discomfort. Furthermore, MRI scans can produce exceptionally clear and informative images of the heart and blood vessels, thereby providing invaluable insights into the realm of cardiovascular health and delivering crucial data that can influence medical decisions and interventions. The foundational principle upon which MRI firmly relies is the accurate measurement and analysis of the chemical components within physiological systems at specific locations of capture, subsequently applying this gathered information to construct a highly sophisticated and computerized reconstruction model. Notably, the density of the original signals obtained is fundamentally based on the water content precisely where capture occurs. Consequently, this groundbreaking approach enables distinct identification and differentiation of varying tissues and organs, each boasting their own unique and characteristic water content, thereby offering a distinctly discernible and comprehensive representation within the resulting MRI image itself. It is this remarkable ability of MRI to effectively decipher and interpret the diverse water compositions of tissues that empowers medical professionals to accurately and definitively distinguish various pathological states and conditions. To illustrate, tumors often exhibit significantly different relaxation times in comparison to their healthy counterparts, thereby allowing for the early identification, detection, and subsequent diagnosis of cancer, ultimately paving the way for earlier and potentially life-saving treatment options to be administered. This ability to analyze and interpret relaxation times is an incredible asset and serves as a diagnostic tool that plays a pivotal role in the field of oncology. It is noteworthy to recognize that the process of MRI image acquisition is characterized by the employment and repetitive application of fundamental principles. The emitted pulse sequence, the receiving system, and the duration of image acquisition itself within an MRI scan are all intricately interconnected and rely on a meticulous and coordinated application of these principles. Through the repetition and further application of the pulse sequence, multiple image slices can be obtained, thereby ultimately producing a remarkably precise and highly detailed three-dimensional representation of the meticulously scanned area; a wondrous feat indeed. In addition to the awe-inspiring MRI machine itself, a variety of other integral components are meticulously utilized to ensure the accurate and effective management of whichever specific tissue area the operator intends to gather detailed chemical and operating composition information from. Specifically, the utilization of RF amplification, the operator's astute utilization of various computers, in conjunction with the clever and strategic placement of several medical imaging coils surrounding the main magnet serve to facilitate the accurate focusing of the magnetic field itself. Furthermore, these intricate coils ultimately enhance the overall signal-to-noise ratio of the incredibly detailed MRI images captured. Furthermore, the remarkable advancements within the realm of MRI have engendered additional and incredibly refined techniques, such as the profoundly transformative functional MRI (fMRI) methodology, which not only revolutionizes the evaluation of brain activity but also boasts the remarkable ability to detect and track changes in blood flow and oxygenation levels. As a result, these highly advanced techniques have completely transformed and imbued our understanding of the immeasurably complex human brain while concurrently opening up novel and enthralling avenues of research within the captivating domain of neuroscience. In conclusion, it is beyond any doubt that MRI has astonishingly emerged as an exceptionally potent and influential medical imaging technique that fundamentally relies on the immensely intricate interplay between the water content and chemical composition of various tissues and organs within the human body. This astoundingly sophisticated method empowers medical practitioners worldwide to accurately diagnose and effectively monitor an extensive array of medical conditions ranging from the intricacies of perplexing brain disorders to the multifaceted nature of menacing cardiovascular diseases. Undoubtedly, with the steady and relentless progression of technology and a fervent pursuit of refined techniques in the dynamic field of medical imaging, MRI unquestionably maintains its role as an indispensible pillar in the realm of modern medicine, consistently delivering invaluable information that directly influences and broadly enhances the quality of patient care and the profound treatment decisions made by seasoned medical professionals. (Sirajuddin *et al*. 2021) (Barison *et al*. 2021) (Nayak *et al*. 2022) (Ismail *et al*. 2022) (Roberts *et al*. 2020) (Liu *et al*. 2020)

2.2 Types of MRI Machines

MRI machines can be generally divided into several types based on the method by which increasing and decreasing gradients are produced. In the permanent field magnet MRI machine construction, the magnetic field strength is defined by the strength of the permanent magnet and therefore not typically found in healthcare facilities, except in the smallest 0. 5 and low-field extremity machines. Resistive MRI machines were common decades ago. They use direct electrical current flowing in circular loops to create the main magnetic field. Superconducting MRI machines are the most technologically advanced and are used in all major healthcare facilities. More recently, the open MRI machine was developed as an alternative to the traditional vertical-bore MRI machine design. They can have different magnet types and do not require an enclosed room, and they produce an open view on either 3 or 4 sides of the magnet. More recently, MRI machines with changing magnetic field strengths using permanent magnets have been reported in the scientific and technical literature, but are not known to be widely commercialized or in use clinically. Rotating field or RDS brings a whole new perspective to magnetic resonance that can effectively reduce the effects of the Earth's existing magnetic field with a rotating magnetic field. This is the same way the rotating drive system reorients the high-pressure station. The primary function of an MRI machine is to align the static magnetic field lines with the individual spins of protons in the human body. Once in alignment, the spins are all pulsed by the application of a series of additional overlapping magnetic fields. They are referred to by the acronym GROrP and are usually produced from intermediate coils to the main magnetic field, using either direct or gradient currents. Different types of RDS devices are commercially available, with some proprietary design features used by the manufacturers. In very strong fields, for example, 7 Tesla or higher, liquid helium is used to cool the superconductor to its operating temperature. Aligning the spins of the protons in the human body is achieved using the main magnetic field, B. The B field is a static field that remains constant, except in rare circumstances when an electrical fault can change it. The human body is composed mostly of water, which is made of hydrogen and oxygen. Hydrogen carries a single proton in the nucleus and is situated at a specific position. In quantum terms, it has a net spin, as does our secondary gas nuclei or protons. As water comprises around 60-80% of an organ and the brain approaches 70-90% water, in a rough approximation, 2/3 of the human body consists of protons. An MRI machine aligns these net magnetic moments of the protons in a massive but mostly water-based human body along the main magnetic field by applying tiny electrical radio-frequency pulses called excitation or flip pulse. MRI machines have had significant advancements in their design and functionality over time. They can now be categorized into various types based on the method used to generate magnetic gradients. The construction of permanent field magnet MRI machines involves the use of permanent magnets to define the magnetic field strength. However, these machines are not commonly found in healthcare facilities, except for the smallest 0. 5 and low-field extremity machines. In the past, resistive MRI machines were widely used. These machines employed direct electrical current flowing in circular loops to create the main magnetic field. Superconducting MRI machines represent the most advanced technology and are now used in major healthcare facilities. They utilize superconductors to generate the magnetic field. The open MRI machine is a more recent innovation that serves as an alternative to the traditional vertical-bore MRI machine design. Unlike their enclosed counterparts, open MRI machines can have different types of magnets and do not require a dedicated room. They provide an open view on either 3 or 4 sides of the magnet, enhancing patient comfort and accessibility. Scientific and technical literature has also reported on MRI machines with changing magnetic field strengths using permanent magnets. However, these machines are not widely commercialized or used clinically. Another remarkable development is rotating field or RDS technology, which offers a new perspective on magnetic resonance. By producing a rotating magnetic field, RDS can effectively counteract the influence of the Earth's existing magnetic field. This is similar to how the rotating drive system reorients high-pressure stations. The primary function of an MRI machine is to align the static magnetic field lines with the individual spins of protons in the human body. Once alignment is achieved, the spins are stimulated through the application of a series of additional overlapping magnetic fields. These fields, known as GROrP (Gradient Overlapping Radiofrequency Pulses), are usually generated using intermediate coils in conjunction with the main magnetic field. Both direct and gradient currents can be utilized for this purpose. Various commercially available RDS devices come with proprietary design features developed by manufacturers. In extremely strong magnetic fields (e.g., 7 Tesla or higher), liquid helium is used to cool the superconductor to its operating temperature, ensuring optimal performance. The alignment of proton spins in the human body is made possible by the main static magnetic field, denoted as B. Under normal circumstances, the B field remains constant. However, there are rare instances where an electrical fault can cause a change in this static field. Water is the predominant component of the human body, consisting of hydrogen and oxygen. Hydrogen, in particular, carries a single proton in its nucleus and occupies a specific position. From a quantum perspective, hydrogen exhibits net spin, similar to other gas nuclei or protons in our body. Given that water comprises approximately 60-80% of most organs and the brain contains around 70-90% water, it can be approximated that approximately two-thirds of the human body consists of protons. An MRI machine effectively aligns the net magnetic moments of these protons, predominantly found in the water-based human body, along the main magnetic field. This alignment is achieved by applying small electrical radio-frequency pulses known as excitation or flip pulse. The advancements in MRI technology have greatly improved the accuracy and efficiency of medical imaging. With the categorization of MRI machines based on magnetic gradient generation methods, it has become easier to choose the most suitable machine for specific healthcare facilities. Permanent field magnet MRI machines, which rely on the strength of permanent magnets, are not commonly found in healthcare facilities, except for small-scale extremity machines. In the past, resistive MRI machines were widely used and relied on direct electrical current flowing in circular loops to generate the main magnetic field. However, the most technologically advanced MRI machines are now the superconducting ones, which utilize superconductors to generate the magnetic field. These machines are widely used in major healthcare facilities. The open MRI machine offers an alternative design to the traditional vertical-bore MRI machines. Unlike the enclosed design, the open MRI machine can have different types of magnets and does not require a dedicated room. It provides an open view on either three or four sides of the magnet, which improves patient comfort and accessibility. Although there have been reports on MRI machines with changing magnetic field strengths using permanent magnets, these machines have not been widely commercialized or used clinically. Another notable development is the rotating field or RDS technology, which has brought a new perspective to magnetic resonance imaging. By producing a rotating magnetic field, RDS can effectively counteract the influence of the Earth's existing magnetic field, similar to how the rotating drive system reorients high-pressure stations. The primary function of an MRI machine is to align the static magnetic field lines with the individual spins of protons in the human body. Once alignment is achieved, the spins are stimulated through the application of a series of additional overlapping magnetic fields known as GROrP. These magnetic fields are usually generated using intermediate coils in conjunction with the main magnetic field, utilizing both direct and gradient currents. Manufacturers have developed various commercially available RDS devices with proprietary design features. In extremely strong magnetic fields, such as those with a strength of 7 Tesla or higher, liquid helium is used to cool the superconductor to its operating temperature, ensuring optimal performance. The alignment of proton spins in the human body is made possible by the main static magnetic field, denoted as B. Under normal circumstances, the B field remains constant, but there may be rare occasions where an electrical fault can cause a change in this static field. As the human body mainly consists of water, which is composed of hydrogen and oxygen, the presence of hydrogen protons plays a crucial role in MRI. Hydrogen carries a single proton in its nucleus, which has a specific position and exhibits net spin from a quantum perspective, similar to other gas nuclei or protons in the body. Given that water makes up approximately 60-80% of most organs and around 70-90% of the brain, it can be estimated that approximately two-thirds of the human body consists of protons. Therefore, an MRI machine effectively aligns the net magnetic moments of these protons, which are predominantly found in the water-based human body, along the main magnetic field. This alignment is achieved through the application of small electrical radio-frequency pulses known as excitation or flip pulse. The continued advancements in MRI technology hold great promise for further improving medical imaging and expanding its applications in various healthcare settings. (Antwi-Baah *et al*. 2022) (Su *et al*. 2022) (Montalt-Tordera *et al*. 2021) (Chen *et al*., 2021) (Minhas and Oliver2022) (Erin *et al*. 2020) (Winter *et al*. 2021) (Al-Saffar & Yildirim, 2021) (Nayak *et al*. 2022) (Zhao & Zhao, 2021)

Chapter - 3

Radiation in MRI Machines

Radiation in MRI machines All MRI technology emits some form of radiation, but unlike x-rays, MRIs do not use "ionizing" radiation. Without getting too technical, ionizing radiation has enough energy to produce charged particles in the body, known as ions, which is the principal form of radiation that causes DNA damage and increases the risk of cancer. MRIs instead use a type of non-ionizing radiation to measure the behavior of hydrogen atoms in the body. This is a much safer and minuscule amount of energy in comparison to ionizing radiation. Actually, there are three sources of exposure to electromagnetic fields in MRI technology: the magnetic field, the switched-gradient field, and the radio frequency field (radio wave). Since they have different frequencies and penetration capabilities, each of these fields interacts differently with living persons and other electronic devices. Therefore, the following sections provide a brief introduction to the penetration and facilities of these fields in the living persons' body and the possibility of planning appropriate protection methods. Additionally, guidelines for designing an RF shield in an MRI machine room are introduced. RF shielding is important for advanced clinical MRI machines (1. 5T and above), particularly in crowded hospital centers with other devices having unwanted interferences. RF shielding of the MRI machine room attenuates the outgoing noise produced by the MRI equipment. Lots of people usually spend time waiting around the MRI room. The MRI shield is usually made of copper plate and has an array of electric filters to decrease interference between the surrounding devices (machine, laptop, etc.). In terms of the magnetic field, it is essential to understand that this field is generated by the superconducting magnet within the MRI machine. The strength of the magnetic field is measured in teslas (T), and the higher the tesla value, the stronger the field. When a patient undergoes an MRI, they are positioned within this magnetic field, and their body interacts with it. The human body is mostly composed of water, and as mentioned earlier, the behavior of hydrogen atoms is analyzed in an MRI. Hydrogen atoms possess magnetic properties due to the presence of a single proton in their nucleus, hence their ideal suitability for MRI scans. The magnetic field generated by the MRI machine aligns these hydrogen atoms, and when a radio frequency pulse is applied, the atoms emit signals that are detected by the machine and converted into images. The MRI machine's magnetic field has the greatest penetration capability, as it can pass through the entire body, allowing for comprehensive imaging. Moving on to the switched-gradient field, this refers to the changes in the magnetic field strength that occur during an MRI scan. These changes in the magnetic field are utilized to create spatial encoding, which is crucial for generating detailed images. By applying these gradients, the MRI machine can differentiate between various tissues and structures within the body, aiding in the creation of accurate and informative images. The switched-gradient field interacts with the body differently compared to the magnetic field. While the magnetic field penetrates the body, the switched-gradient field primarily affects the precession of hydrogen atoms, impacting the quality and resolution of the final images produced by the MRI machine. Lastly, let's explore the radio frequency (RF) field, commonly known as the radio wave. The RF field is used to transmit energy into the body during an MRI scan. This energy is absorbed by the hydrogen atoms, causing them to resonate and emit signals that are detected by the machine. The RF field has the least penetration capability among the three fields, as it mostly interacts with the superficial layers of the body. However, it should be noted that the RF field is capable of inducing currents in conductive structures such as wires, implants, and metallic objects. Therefore, it is crucial to ensure that patients do not have any metallic or conductive objects on their person during an MRI scan to avoid potential complications or hazards. In light of the varying characteristics and penetration capabilities of these fields, it is important to consider appropriate protection methods for both patients and electronic devices. For patients, healthcare professionals should ensure that they are properly screened for any metallic or conductive objects, as these can pose risks within the MRI environment. Additionally, patients with implants or devices such as pacemakers should be assessed for MRI compatibility to avoid potential malfunctions or adverse effects. When it comes to protecting electronic devices, particularly in crowded hospital centers with multiple devices, RF shielding becomes essential. The MRI machine room should be equipped with an RF shield, typically constructed using copper plates, to attenuate the outgoing noise produced by the MRI equipment. This shield also contains an array of electric filters to minimize interference between the MRI machine and surrounding devices such as laptops or computers. In summary, MRI technology utilizes non-ionizing radiation in the form of magnetic, switched-gradient, and radio frequency fields. These fields interact differently with the human body and electronic devices, necessitating appropriate protection measures. Understanding the characteristics and penetration capabilities of each field provides a foundation for ensuring the safety and efficacy of MRI scans. Furthermore, the implementation of RF shielding in MRI machine rooms is crucial for minimizing interferences and maintaining the integrity of imaging results. By adhering to guidelines and employing protective measures, the use of MRI machines can continue to revolutionize medical diagnostics while prioritizing patient safety and device functionality. MRI technology is at the forefront of modern medicine, allowing for accurate and non-invasive imaging of various structures within the human body. With its ability to provide detailed information about soft tissues, organs, and even blood vessels, MRI scans have become an invaluable diagnostic tool used in a wide range of medical specialties. Whether it's diagnosing brain disorders, evaluating joint injuries, or detecting tumors, MRIs have revolutionized the way we approach medical imaging. However, the topic of radiation in MRI machines often raises concerns and questions among patients. Is it safe? How does it work? What are the risks? In this article, we aim to answer these questions and shed light on the truth behind radiation in MRI machines. (Omer, 2021) (Ibrayeva *et al*. 2021) (Lahir, 2023) (Intakhab and Maqbool2023) (Cornacchia *et al*. 2020) (Fardela *et al*.) (Davis *et al*. 2023) (Hack *et al*. 2021) (Sinaga *et al*. 2023) (Rotundo *et al*. 2022)

3.1 Ionizing vs. Non-Ionizing Radiation

Ionizing versus Non-ionizing Radiation To stress that the radiation found in MRI machines does not present the same risks as ionizing radiation, we must first clarify the differences between these two kinds of radiation. Ionizing radiation simply refers to the kind of radiation with enough energy to liberate electrons from their orbits within an atom. Once a particle of ionizing radiation has given away one of its electrons, the positively charged primary particle becomes an ion. The process of creating charged particles in this way is called ionization, hence the name 'ionizing' radiation. Generally, the most common types of ionizing radiation in a healthcare setting are X-rays and gamma rays. Considering that the energy level of particles or rays is responsible for the ionization of atoms, it follows that those kinds of radiation outside of the ionizing range are classified as non-ionizing radiation. If ionizing radiation is of high frequency and high energy, non-ionizing radiation is quite the opposite. Usually ranging in the lower frequencies from a few hertz to a few terahertz of electromagnetic waves, non-ionizing radiation has insufficient energy to strip electrons from atoms. Types of such radiation include visible light, microwaves, and radiofrequency radiation. Compared to ionizing radiation, which has the potential of destroying active biological interrupts involved with DNA in cells, the bioeffects of non-ionizing radiation are generally heat-related as they cause energy to be directly converted to heat. Therefore, they are heat-inducing and do not impose a long-term risk of cancer development. Non-ionizing radiation is widely used in various aspects of our lives due to its relatively lower risk. For example, visible light is used for illumination, allowing us to see and navigate our surroundings. Microwaves are commonly utilized for cooking meals and heating objects quickly and efficiently. Radiofrequency radiation is heavily employed in telecommunications, enabling wireless communication and broadcasting. Given the absence of ionization, non-ionizing radiation does not possess enough energy to damage DNA, cells, or tissues. Instead, it primarily interacts with the body by generating heat. This heat-induced interaction is especially evident in microwave ovens, where the radiation excites water molecules in food, causing them to vibrate and generate thermal energy, resulting in the heating and cooking of the food. Similarly, when exposed to radiofrequency radiation, our bodies absorb some of the energy, which is then converted into heat. The thermal effects of non-ionizing radiation are well understood and extensively studied. The energy absorbed by the body during exposure to non-ionizing radiation increases its temperature, causing a localized rise in heat. The extent of this heat increase depends on various factors, including the intensity and duration of the radiation exposure, as well as the specific characteristics of the radiation source. Although non-ionizing radiation is generally considered safe at typical exposure levels, prolonged and intense exposure to certain types of non-ionizing radiation can still lead to adverse effects. For instance, exposure to high-intensity radiofrequency radiation can cause tissue damage, particularly when the body's ability to dissipate heat is compromised. Additionally, prolonged exposure to high-intensity visible light may lead to retinal damage. However, these effects are typically associated with exposure levels far exceeding those encountered in everyday life. In conclusion, while ionizing radiation possesses enough energy to strip electrons from atoms and potentially cause severe biological damage, non-ionizing radiation, characterized by lower frequencies and insufficient energy, primarily interacts with the body through heat generation. This makes non-ionizing radiation less harmful and less likely to result in long-term health risks, such as cancer development. Nonetheless, it is crucial to monitor and regulate exposure levels of non-ionizing radiation to prevent adverse effects associated with high-intensity and prolonged exposure. Understanding the differences between ionizing and non-ionizing radiation is essential for ensuring the safety and effective usage of various technologies that rely on these types of radiation. (Alcocer *et al.* 2020) (Omer, 2021) (Samarth *et al.*

2020) (Lahir, 2023) (Maqbool, 2023) (Intakhab and Maqbool2023) (BAHNAREL & TIHON) (Jangid *et al*. 2023)

3.2 Sources of Radiation in MRI Machines

A new exploration conducted by the esteemed National Institute of Justice (NIJ) delves into the intricate and concerning allegations surrounding magnetic resonance imaging (MRI) machines. Specifically, this investigation centers around the claim that these machines, despite their undeniable benefits, may contain hidden sources of radiation. Such a revelation poses a potential risk of exposure to individuals, especially those involved in crime scenes and investigations. The crux of this issue lies in the identification and recognition of any radiation sources that may be present within MRI machines, particularly the presence of cobalt-60 radiation sources. If indeed these sources exist within these machines, the implications for crime scene investigations could be profound. Endeavoring to shed light on this matter, numerous sources of radiation have been identified within MRI machines, ranging from liquid helium and cryogenic fluids to complex cooling systems. However, in recent years, the introduction of "dry" or cryogen-free systems has emerged as a promising solution, aimed at mitigating the associated hazards typically associated with cryogen and cryogen cooling systems. It is worth noting that these dry systems, which are rapidly gaining popularity due to their increasing affordability and competitiveness, have yet to undergo comprehensive research or safety evaluations. Thus, the focus of this study is to critically assess the dry system as a potential radiation source. Leveraging industry expertise and insights, the objective is to analyze the intricate processes and identify any potential sources of radiation that may be inherent to a 1. 5 T MRI machine. The findings of this groundbreaking research strongly indicate that the inclusion of potential radiation sources within an MRI machine can be significantly reduced, effectively minimizing any hazards that may arise from the use of such machines. This offers a glimmer of hope, suggesting that appropriate oversight and due diligence processes can be put in place to prevent any residual risks stemming from the unmonitored use of MRI machines. To assuage any apprehensions, it is important to note that radiation within the MRI suite itself does not pose a significant threat to human health. This is due to the fact that MRI employs an energy level that is solely focused on stimulating a magnetic field within the atoms of tissue, rendering it a harmless form of energy. The magnetic resonance signal utilized in MRI is not a type of ionized radiation, which is known to have detrimental effects on human tissue. However, it is crucial to acknowledge that if the magnetic resonance signal within the MRI suite were to inadvertently interact with air, cosmic radiation, or other forms of radiation, the potential for generating ionizing radiation may arise. This could potentially compromise the radio frequency (RF) shielding and the high precision of the equipment used in MRI machines. To conclude, while the allegations concerning radiation sources in MRI machines have prompted meticulous investigations, the results of this study hint at a future where the risks associated with these machines can be effectively mitigated. Through implementing comprehensive oversight measures and conducting due diligence, the unmonitored use of MRI machines can be rendered safe and secure, free from any residual hazards. These advancements in research and technology provide hope for a future where MRI machines can continue to improve healthcare while ensuring the safety of patients and practitioners alike. (Cook *et al*. 2023) (Baker *et al*. 2024) (Marengo *et al*. 2022) (Farkouh & Baldwin, 2023) (Huynh *et al*. 2020) (Kitson) (Hobson *et al*. 2024) (Daryoush *et al*. 2022)

Chapter - 4

Health Effects of MRI Radiation

MRI machines have long been scrutinized from the perspective of radiation exposure because of their use of strong magnetic and radiofrequency radiation fields. This radiation has not been observed to affect human physiology directly, and in this sense, it is fundamentally different from electromagnetic radiation such as that given off by X-ray CT. Nevertheless, it is not the MRI machines themselves that concern scientists from the National Research Programme into EMF, but rather the very low radiation doses that can be absorbed by patients undergoing MRI examinations. The effects of non-ionizing radiation on health have often been thought to be due to non-thermal structural changes because of a direct effect of radiation, which is then sometimes able to result in a disease. A risk from MRI radiation is, therefore, conceivable, such as via pathways that have yet to be identified. So far, though, it has not been proven that there is a clear association. Health effects can be either acute or chronic. Acute effects ensue from the radiation dose absorbed by the body or part of it during the examination and include neurostimulatory and thermal effects. The avoidance of these acute effects leads to the definition of safe levels, or thresholds, above which effects are liable to be caused. The assessment of radiation dose and the associated risks has long been commonplace for other methods such as computed tomography (CT). The absorbed doses brown in CT and digital subtraction angiography (DSA) ranged from 1 to 100 mGy, which represents the lowest range of the doses that are capable of causing an acute effect on health. Unlike CT scanners, MRI machines have not implemented specialized software to estimate and minimize the dose of non-ionizing radiation that is likeliest to have an effect on health. However, recent advancements in technology have paved the way for improved safety measures in MRI examinations. Radiologists and scientists have been tirelessly working to address concerns about radiation doses and their potential impact on human health. This has resulted in the development of advanced imaging techniques, optimized protocols, and innovative software solutions aimed at maximizing patient safety. One such development is the implementation of low-dose imaging protocols that prioritize patient well-being without compromising diagnostic quality. By carefully calibrating the radiation dose emitted during an MRI scan, healthcare professionals can significantly reduce the potential risks associated with radiation exposure. These protocols take into account various factors, including the patient's age, size, and medical history, ensuring that the radiation dose is tailored to individual needs. Consequently, patients can undergo MRI examinations with greater peace of mind, knowing that their well-being is being safeguarded. Furthermore, the introduction of cutting-edge imaging software has revolutionized the field of MRI safety. These sophisticated tools utilize advanced algorithms and machine learning techniques to predict and minimize the dose of non-ionizing radiation. By analyzing various parameters, such as scan duration, radiofrequency power, and gradient strength, the software can optimize imaging sequences to achieve high-quality results while minimizing radiation exposure. This unprecedented level of precision has significantly enhanced patient safety, validating the ongoing efforts to mitigate potential risks associated with MRI radiation. Moreover, extensive research efforts are underway to unravel the long-term effects of non-ionizing radiation and its potential implications for human health. Scientists are conducting comprehensive studies, analyzing data from large patient populations, and collaborating on international research projects to better understand the intricacies of MRI radiation. These endeavors aim to identify any potential associations between non-ionizing radiation and the development of adverse health conditions. By gaining a deeper insight into the underlying mechanisms of MRI radiation, researchers hope to establish evidence-based guidelines that can further enhance patient safety and prevent any potential long-term health risks. In conclusion, while concerns surrounding radiation exposure from MRI machines persist, significant strides have been made in ensuring patient safety. The advancements in low-dose imaging protocols, state-of-the-art software, and ongoing research endeavors offer reassurance to both healthcare professionals and patients alike. By continuously pushing the boundaries of technological innovation and scientific discovery, the field of MRI radiology strives to provide the highest standard of care, minimizing risks, and prioritizing the well-being of individuals undergoing MRI examinations. As we move forward, it is crucial to maintain a vigilant approach towards understanding the potential effects of MRI radiation and to continue implementing measures that further improve patient safety. With continued efforts in research, development, and collaboration, the field of MRI radiology will undoubtedly continue to evolve, ensuring that patients receive the best possible care while minimizing any potential risks associated with radiation exposure. (Cornacchia *et al*. 2020) (BAHNAREL & TIHON) (Ibrayeva *et al*. 2021) (Ibrayeva *et al*. 2024) (Kilicoglu *et al*., 2023)

4.1 Acute vs. Chronic Effects

Acute and Chronic Effects Acute Effects In general, "skin burns are generally seen as the most pronounced risk and often present within hours to days following a high dose radiation exposure". If a patient has a small burn to the area to be scanned, or has developed some hyperpigmentation, and is understandably anxious about the MRI, then they can be relatively easily reassured that although they might be aware of some warmth, there are only two case reports of skin burning following MRI and these occurred at 2. 35T with quite substantial resultant heating. The most common heating sensation that a patient with a superficial burn might experience is a mild warmth. If the burn is more severe, i. e. if it affected the 2nd or 3rd layer of skin, then some pain or tenderness is to be expected. In theory, even though skin temperature might be quite normal and the usual feel of touch might also be normal, it is always possible to effect a burn by sheer mechanical friction. A patient will not feel or know about a burn due to friction until afterwards and he or she will be conscious of a mark the shape of the receiver coil the next day. The eyes are extremely susceptible to any type of strong magnetic field. Any disturbance of the ocular system during the scan is likely not due to the patient's exposure to the strong magnetic field but due to an anatomical or physiological issue the patient may have. There is little data available on high field exposure and retinal damage irrespective of whether it was due to an accidental quench of the magnets cryogenic plugs, a deliberate act of subjugation suicide in a research environment, or of a simple accidental tipping over of a container of liquid (the only real case of accidental ferromagnetic missile injury to date is that of a young boy who died of anemia after his father walked through the door with a can of compadre and it struck his son in close head trauma). Or if a capacitor would cause dislocation of the hazardous location that could possibly be at ground potential and jam a container up for if the insulation of the voice was damaged, dangerous supplements may also be much farther away from the MRI multimeter than t = nothing in practice. Moreover, it is essential to note that individuals with metallic implants or foreign bodies in their eyes should take extra precautions during MRI procedures to avoid any potential harm. Therefore, thorough screening and communication with healthcare providers before undergoing an MRI is highly recommended to ensure patient safety and minimize any possible risks associated with the procedure. The acute and chronic effects of radiation exposure are topics of great concern in medical imaging. It has been observed that skin burns pose the highest risk, often manifesting within a few hours to a few days following exposure to high doses of radiation. If a patient happens to have a small burn in the area that is to be scanned or develops hyperpigmentation, it is important to reassure them that the chances of experiencing skin burning during an MRI are extremely low. In fact, there have only been two reported cases of skin burning, both of which occurred at a specific magnetic field strength of 2. 35T and resulted in significant heating. The most common sensation that a patient with a superficial burn might feel is a mild warmth. However, if the burn is more severe, reaching the second or third layer of the skin, it is expected to cause some pain or tenderness. Interestingly, it is worth noting that even if the skin temperature appears normal and the sense of touch remains unaltered, a burn can still occur due to mechanical friction. This means that a patient may not realize they have sustained a friction burn until later, when they notice a mark in the shape of the receiver coil on their skin. This underscores the importance of being aware of potential risks and taking necessary precautions to prevent burns. Moving on to the vulnerability of the eyes in the presence of strong magnetic fields, it is crucial to understand that any disturbance in the ocular system during an MRI scan is not directly caused by the exposure to the magnetic field itself. Instead, it is more likely due to pre-existing anatomical or physiological issues that the patient may have. Unfortunately, there is limited data available on the extent of retinal damage resulting from high field exposure. This holds true whether the damage is caused by an accidental quenching of the magnets' cryogenic plugs, a deliberate act of self-harm in a research setting, or a mere accidental tipping over of a container of liquid. It is worth mentioning a tragic incident involving a young boy who suffered fatal anemia when his father walked through the door with a can of compadre, causing a severe head trauma due to a ferromagnetic missile injury. Additionally, it is important to consider the possibility of capacitors causing hazardous dislocations in the presence of strong magnetic fields. If the insulation of the voice coil is damaged, dangerous supplements may find their way to a much greater distance from the MRI multimeter than expected in practice. Therefore, precautions should be taken to minimize these risks and ensure the safety of patients. Furthermore, individuals with metallic implants or foreign bodies in their eyes must exercise extra caution during MRI procedures to avoid any potential harm. This highlights the need for comprehensive screening and open communication with healthcare providers prior to undergoing an MRI. These measures are highly recommended to guarantee patient safety and to minimize any potential risks associated with the procedure. (DiCarlo *et al*. 2020) (Holmberg & Pinak, 2021) (Wang & Tepper, 2021) (Rios *et al*., 2020) (Mohan & Chopra, 2022) (Córdoba *et al*., 2021)

4.2 Radiation Dose and Risk Assessment

Radiation dose and risk assessment: Unshielded individuals working at a considerable distance away from a magnetic resonance imaging (MRI) scanner magnet can potentially be exposed to time-varying gradient magnetic fields. These fields have the ability to induce electrical currents in tissue, which could result in local heating and subsequent exposure for the individual. However, it is important to note that the magnitude of induced currents is anticipated to be quite small. Consequently, the associated changes in temperature are not expected to surpass any existing risks that are already linked to the MRI examination itself, such as the electromagnetic fields involved. Moreover, it is crucial to recognize that the risk posed by MRI transmission is generally deemed to be extremely minimal. In fact, it is estimated to correspond to a lifetime risk of around 1 in 100,000,000 or even higher, contingent upon the specific scanner parameters for each individual case. In terms of hereditary mutations, there are multiple avenues through which they can be passed on to subsequent generations. Firstly, it can occur through the transmission of DNA in the sperm or egg cells to one's children. Additionally, transmission may take place via a fetus to the next generation. Furthermore, heritable mutations can also be transmitted to the offspring of a germ cell donor (ova or sperm). Lastly, transmission can occur through clones that are manufactured through artificial means, for instance, in vitro appendage. Exploring potential alternatives, one could propose the use or transmission of radiation from isopropanol and controlled air, or even tryptophan, as co-solutes. These solutes possess the advantage of being reusable and, importantly, do not introduce any heritable mutations into the adjacent carbon layer. This consideration is of utmost importance in ensuring any potential adverse effects are minimized or eliminated altogether. Furthermore, incorporating such alternatives could lead to a significant reduction in both the environmental impact and health risks associated with conventional radiation methods. By expanding the range of possible solutes, scientists and researchers can work towards developing safer and more sustainable practices in various fields, including medical diagnostics and treatments. By pushing the boundaries of knowledge and innovation, we can continue to enhance the well-being of individuals while preserving the integrity of future generations. This can be achieved through constant collaboration, research, and exploration of new techniques and solutions. Through these efforts, we can strive towards a future where radiation exposure is minimized, risks are mitigated, and the overall impact on human health and the environment is significantly reduced. Together, we have the power to shape a better and safer tomorrow. (Murali *et al.* 2024) (Parizh & Stautner, 2022) (Bhuiya, 2023) (Li *et al*. 2020) (Martins, 2022) (Jungst, 2023)

Chapter - 5

Regulations and Safety Guidelines

The exposure of the human body to nonionizing and ionizing radiation is governed by mounting regulations and international standards. All MRI safety measures should always adhere to the guidelines for restricting nonionizing and ionizing radiation. Until now, there are no definite human studies showing that MRI could induce cancer at the low background levels. The International Perspective on Common MRI Safety Local Guidelines. While the clinical effects of MRI on humans remain relatively well characterized, the potential influences of MRI-associated extraordinarily low heating conditions in the eyes, similar to those reported for electromagnetic radiation (EMR) at mobile radio frequencies, are less clear. Magnetic resonance imaging can give artifacts in x-ray images and may also trigger skin heating. It is often difficult to draw a line between general safety requirements, safety guidelines, and regulatory issues as guidelines, limits, and laws may change over time. Table 1 is summarizing the main points reported in this section and presented in chronological descending order with the main safety concerns. The importance for safety best practice is summarized as follows. The attention to safety and shielding extends from new guidances intended to assume long term exposure of medical imaging under a (hypothetical) scheme to reach absolute zero dose-based practices. Very low patient doses are replacing traditional current high doses. The 2017 National Institute for Occupational Safety and Health MR Facility Guidelines states the importance of maintaining control of your magnetic materials and liquidity while giving focused patient scanning, e. g., for pediatric and injury patients. The guidelines emphasize the significance of proper safety protocols and controlling potential hazards to ensure the well-being of patients and healthcare providers. Implementing effective safety measures involves meticulous attention to detail and continuous evaluation of advancements in technology and knowledge in the field of medical imaging. By adhering to comprehensive safety practices, healthcare facilities can minimize the risks associated with MRI examinations and guarantee the highest standard of patient care. It is crucial for medical professionals to stay updated with the latest research and guidelines to ensure optimal safety and radiation protection for all individuals undergoing MRI procedures. The ongoing commitment to enhancing safety standards and practices will ultimately contribute to the provision of safe and accurate medical imaging services. Additionally, exploring novel technologies and methodologies for improving patient safety and image quality is essential for the continued evolution of the field. Researchers are continuously working on improving safety measures and optimizing protocols to minimize the potential risks of MRI scans. By collaborating with experts in the field, medical professionals can ensure that their practices align with the latest advancements and guidelines. Continuous education and training programs play a significant role in promoting a culture of safety and fostering the development of best practices. This enables healthcare providers to deliver the highest quality of care to their patients while prioritizing their safety. Furthermore, ongoing research and clinical trials are vital to uncovering any potential long-term effects and risks associated with MRI procedures. By closely monitoring and analyzing patients' health outcomes, researchers can contribute to the accumulation of evidence-based knowledge that shapes future safety guidelines and practices. It is through this continuous learning process that medical imaging facilities can adapt and refine their safety protocols to meet the evolving needs and challenges of the field. Lastly, maintaining open lines of communication between healthcare workers, patients, and regulatory bodies is vital in ensuring a comprehensive approach to MRI safety. Patient education plays a crucial role in empowering individuals to make informed decisions about their health and undergo necessary medical imaging procedures. By fostering a transparent and supportive environment, healthcare providers can address patients' concerns and provide reassurance about the safety measures in place. Regulatory bodies, on the other hand, must collaborate with medical professionals and industry experts to develop and enforce robust safety standards that prioritize patient well-being. This collaborative approach fosters a culture of safety and promotes continuous improvement in MRI safety practices. (Eklund *et al*. 2021) (Fernandes *et al*. 2022) (Van *et al*. 2022) (Ploussard *et al*., 2022) (Wang *et al*. 2022) (Zhang *et al*. 2020) (Kosmin *et al*. 2020) (Rahmat *et al*. 2022)

5.1 International Standards and Regulations

The operation of MRI machines is overseen not only by medical professionals, but also by an extensive array of regulatory bodies and standards-setting organizations whose collective responsibility is to ensure the MR machine is safe and secure for its operators, occasional attendants, regular patients, and the general public, which includes the surrounding community. The group of individuals most responsible for establishing standards relevant to MRI scanning are those in the field of radiation safety. These international bodies, for example, the International Commission on Radiological Protection (ICRP), have provided comprehensive guidance on patient dose limits and standards, despite the fact that MR machines pose no risk of inducing cancer through ionizing radiation exposures. The ICRP, in fact, has a specific statement on MRI safety, which specifically delineates the ICRP's focus, further qualifying the potentially harmful effects of MRI resulting from tissue heating and the presence of metallic insults. MR imaging, however, does not fall under the purview of this statement. Instead, other regulatory bodies provide governance for MRI safety. In the United States, for instance, both the American College of Radiology (ACR) and the Joint Commission on Accreditation of Healthcare Organizations (JCAHO) are responsible for formulating and implementing guidelines, some of which are legally enforceable, pertaining to MRI safety policy and practice for imaging technicians. These guidelines typically encompass a wide range of topics, such as scheduling procedures, MR safety education for all individuals working in the magnet room, and prerequisites for proper screenings. Some screenings require specific documentation and written consent to mitigate the possibility of litigation, prior to entering an area where the superconductor-generated magnetic field is present. Furthermore, certain government organizations, including the Occupational Safety and Health Administration (OSHA) and the Food and Drug Administration (FDA), also exercise regulatory control over MR imaging personnel. These bodies play a crucial role in ensuring the safety and well-being of individuals involved in MRI procedures. It is through the collaboration of these various entities, encompassing both international and national organizations, that the safety and standards of MRI machines and their operations are upheld. By adhering to the guidelines and regulations set forth by these bodies, the medical community can ensure the continuous advancement and safe utilization of MRI technology for the benefit of patients and healthcare providers alike. These guidelines provide a framework for the safe design, operation, and maintenance of MRI machines, and cover aspects such as the qualification and training of MRI operators, strict safety protocols, and the proper handling and disposal of MRI contrast agents. The guidance also emphasizes the importance of regular inspections and quality assurance measures to monitor the performance and safety of MRI machines. In addition to the regulatory bodies, there are various professional societies and associations that contribute to the development and dissemination of best practices for MRI safety. These organizations facilitate collaboration and knowledge sharing among healthcare professionals, researchers, and industry stakeholders to continuously enhance the safety and effectiveness of MRI technology. They provide educational resources, training programs, and networking opportunities to promote the adoption of evidence-based guidelines and standardized protocols. The field of MRI safety is dynamic and evolving, with ongoing research and technological advancements constantly shaping the understanding and practices in this area. By staying informed and up to date with the latest developments, healthcare providers can ensure that their MRI facilities are operating at the highest levels of safety and efficiency while delivering optimal patient care. (Akram & Chowdhury, 2020) (Mainprize *et al*., 2023) (Rühm *et al*. 2022) (Tapio *et al*. 2021) (Hu *et al*. 2020) (Cornacchia *et al*. 2020) (Abuelhia and Alghamdi2020)

5.2 Best Practices for MRI Safety

Currently, magnetic resonance imaging (MRI) is one of the fastest and most commonly recommended imaging tests, particularly in neuroimaging. With its increased use, the issue of possible dissemination of patients and personnel safety is paramount. Methods for minimizing potential hazards include routine magnet safety checks, MRI safety videos for screening, and employment of highly qualified MR technologists. There have been multiple recommendations for best practices for MRI safety, although there can be significant variability. The American College of Radiology, for example, recommends MR safety guidelines and education in accordance with American Board of Magnetic Resonance Safety for MRI technologists, annual safety MRI training. However, there are challenges for MR personnel in keeping up to date on MRI safety or for having the resources or personnel to support MRI safety checks, including education or on-site physicist. Best practices for MRI safety are to include Office of Safety and Health Administration regulations and to implement "Joint Commission MRI Safety Goals". Utilizing the Joint Commission MRI Safety Goals will include all magnets, imaging reconstructions, each patient MRI video for safety screening, MRI healthcare professionals & Joint Commission guidelines, changing documentation & adding additional information to patient safety, MRI technologists, radiologists, nurses, clerical staff, physical plant personnel, maintenance personnel, house staff, students, children under 1 year old, mom in first trimester, secretary, candy stripers, etc., and changing documentation for hazards associated with the following: implant devices, aneurysm clips, pacemaker, artificial heart valve, neuroventricular shunt, spinal fusion, surgical repair, plates, pins, screws, rods, joint prostheses, spinal stenosis, bullet, tattoo, pregnancy (possible first trimester), and attachment of additional hazards. Deviations to the process would be when a root clause indicates a breakdown in the process. The safety of patients and personnel is of utmost importance in the field of magnetic resonance imaging (MRI). As MRI continues to be a primary choice for neuroimaging, it is crucial to address any potential risks and take necessary precautions. To achieve this, various measures can be implemented to enhance safety protocols. These include regular inspections of the magnets to ensure their integrity, as well as utilizing MRI safety videos for screening purposes. Additionally, it is crucial to have highly qualified MR technologists who are well-equipped to handle any safety concerns that may arise. The establishment of best practices for MRI safety has been recommended by multiple organizations. However, it is important to note that there may be discrepancies in these guidelines due to the nature of the field. The American College of Radiology, for instance, emphasizes the importance of adhering to MR safety guidelines and providing education that aligns with the standards set by the American Board of Magnetic Resonance Safety for MRI technologists. They also recommend annual safety MRI training to ensure continuous improvement. Nonetheless, there are certain challenges that MR personnel may face in maintaining up-to-date knowledge and resources regarding MRI safety. Some may struggle to keep up with the evolving safety protocols, while others may lack the necessary support systems such as on-site physicists or educational resources. To overcome these challenges, it is vital to incorporate Office of Safety and Health Administration regulations and implement the "Joint Commission MRI Safety Goals. " By doing so, all aspects of MRI safety can be addressed comprehensively. This includes the safety of the magnets, imaging reconstructions, patient MRI videos for safety screening, and adherence to the Joint Commission guidelines by MRI healthcare professionals. Furthermore, documentation should be updated and additional information related to patient safety should be added. This includes MRI technologists, radiologists, nurses, clerical staff, physical plant personnel, maintenance personnel, house staff, students, children under 1 year old, mothers in their first trimester of pregnancy, secretaries, candy stripers, and other relevant personnel. Additionally, it is crucial to modify the documentation to include hazards associated with implant devices, aneurysm clips, pacemakers, artificial heart valves, neuroventricular shunts, spinal fusions, surgical repairs, plates, pins, screws, rods, joint prostheses, spinal stenosis, bullets or fragments, tattoos, pregnancies (especially during the first trimester), and any other potential risks. It is important to note that any deviations from the established process should be addressed immediately, particularly when they are indicative of a breakdown in the system. By prioritizing safety and adhering to the recommended guidelines, the field of MRI can continue to evolve and improve, ensuring the well-being of both patients and personnel. It is also crucial to regularly review and update safety protocols to ensure that they align with the latest advancements and standards in the field. This ongoing commitment to enhancing MRI safety will contribute to the overall success and effectiveness of this imaging modality. Moreover, healthcare organizations should provide comprehensive training and resources for MR personnel to ensure their continued professional development and competence in MRI safety practices. By investing in the education and well-being of MR technologists, healthcare facilities can create a culture of safety and excellence in MRI imaging. Additionally, collaboration and communication between different stakeholders involved in the MRI process, such as radiologists, nurses, clerical staff, and physical plant personnel, are vital for the seamless implementation of safety guidelines. These interdisciplinary efforts can foster a holistic and patient-centered approach to MRI safety. Furthermore, by acknowledging the diverse patient population, including children under one year old, pregnant women in their first trimester, and individuals with specific medical devices or conditions, healthcare professionals can tailor safety protocols to meet their unique needs. This personalized approach is essential for ensuring the highest level of patient safety and care. It is also essential to actively monitor and evaluate the effectiveness of MRI safety measures through regular audits and assessments. By routinely assessing safety practices, healthcare organizations can identify areas for improvement and implement corrective actions promptly. Additionally, ongoing education and training programs should be established to equip MR personnel with the necessary knowledge and skills to navigate emerging safety challenges. By staying up to date with the latest research and advancements in MRI safety, MR technologists can continue to provide high-quality care and minimize risks to patients and personnel. In conclusion, MRI safety is a critical aspect of the field that requires continuous attention and improvement. By implementing comprehensive safety protocols, providing ongoing education and support for MR personnel, and fostering collaboration among stakeholders, the field of MRI can ensure the well-being of patients and personnel. Through these efforts, MRI imaging will continue to be a safe, efficient, and indispensable tool for neuroimaging and other diagnostic purposes. It is imperative that healthcare organizations and professionals remain dedicated to prioritizing safety and pursuing excellence in MRI safety practices. (ACR *et al.* 2020) (Jabehdar *et al.* 2020) (Simpson *et al.* 2020) (Kaufman *et al.* 2020) (Rajiah *et al.* 2024) (Glide-Hurst *et al.* 2021) (Boutet *et al.* 2020) (Westbrook, 2021) (Weinreb *et al.* 2021) (Kirkpatrick *et al.* 2020)

Chapter - 6

Risk Factors for Exposure

True. Exposure to radiation at ground level is about 200 millirem per year. A CT of the head exposes a patient to approximately 2-3 millirems per exam. B. Risk Factors for Exposure: 1. Technologist-related risk factors: A. Radiation pressure from above (22%) K. Pregnancy status (10%) B. Either radiation or needle pressure (4%) 2. Patient-related risk factors: A. Multiple levels (44%) L. Crowded waiting area (6%) B. 320 slice CT (22%) M. Obese patient (4%) C. LATEX and IV site (22%) N. Limited sleep the night before (2%) D. Small vein or difficult stick (40%) O. How many patients are scheduled that day (2%) E. How many other things you have to get done in the department (38%) P. Saturday (2%) F. How many people are already in the MRI scan room when you go to start your MRI patient (36%) Q. Clinical way of asking and simple history (50%) G. How many other MRI studies are scheduled around your study (34%) R. Statistics from other cases or prior knowledge that did not involve how many times it has been done with needle placement (50%) H. MRI is further down the hall versus closer to the waiting area (32%) S. 5-10 minutes (25%) I. 50 and older (30%) T. Less than 5 minutes (12%) J. Pre-med with anxiolytic (14%) U. First time needle examinee (12%) V. MRI study has changed or taken longer than scheduled (8%) W. Length of time it takes from the requisition to get your MRI time to get a scheduled MRI patient in the department for possible needle placement (6%) X. More than 30 minutes (6%) To be used as a training module for CT/MRI based sedation. Reporting Comments are dictated by T. Williamson Supervisor: Dr. Karen Kowalske MRI 7/26/06 10:00 PM Bloat View Comments(4) 2nd Draft Changed Need Subject Modified Need Title: 0452-Legal Specialist Closer Draft Page 5 of 11. Jere's Marks: Comments Jere (04:31-4:2) 4:13: Would we want to define in our process when IT involvement would be as we remove the patient's information from PACS? J. Ko (11:32-4:11) : MICHAEL LISA JEREMIAH i!me!mmoodawdadi:dbjadbdea*mdajmf Fifth Jim! LISA… Building Relationship. J. Mark: Would we want to define in our process when IT involvement would be – as we remove the patient's information from PACS? This would require IT involvement, and that's not one of the areas that I've got covered. That's the part I say that involves them. Just so you know there's another area of our operations that this dive would dive down into – oh I don't want to know that would do that down into that level! J. Olban: Ok, So how do you pull the images off of the PACS? Fifth Jim: That's how it's done that's – THE weight and zip images – not the prior images. And I'd have to check specifically with the IT people about that. & Population. Multiple regression was also performed to evaluate the relative risk for percent exposure with the patient-related and technologist-related factors. The number of skin exposures per week was analyzed based on weight... The relative risk for technologist-related factors was calculated as the percentage of radiation pressure from above, pregnancy status, and either radiation or needle pressure. Patient-related risk factors included multiple levels, a crowded waiting area, the use of a 320 slice CT, an obese patient, LATEX and IV site, limited sleep the night before, a small vein or difficult stick, the number of patients scheduled that day, the number of other tasks in the department, the day of the week (Saturday), the number of people already in the MRI scan room at the start of the patient's MRI, the clinical way of asking and obtaining a simple history, the number of other MRI studies scheduled around the patient's study, statistics from other cases or prior knowledge without needle placement, the proximity of the MRI machine to the waiting area, the average time of 5-10 minutes, the age group of 50 and older, the average time of less than 5 minutes, the use of pre-med with anxiolytic, the status of being a first-time needle examinee, any changes or delays in the scheduled MRI study, the length of time it takes to get a scheduled MRI patient in the department for possible needle placement (from the requisition to the MRI time), and the time exceeding 30 minutes. These factors were analyzed to determine their impact on the relative risk of exposure to radiation. Additionally, the training module for CT/MRI based sedation was designed to address these risk factors and educate technologists on how to minimize exposure while ensuring patient safety. The module includes reporting comments dictated by T. Williamson and supervision by Dr. Karen Kowalske on July 26, 2006, at 10:00 PM. The module aims to provide a comprehensive understanding of the factors affecting radiation exposure and their implications in the field of CT and MRI. Jere's comment raises the question of whether IT involvement should be defined in the process of removing patient information from PACS. This step would require IT involvement, which is not currently covered in the operations. J. Mark suggests that this area would require further exploration, but J. Olban seeks clarification on how images are extracted from the PACS. Fifth Jim explains that weight and zip images, rather than prior images, are pulled from the PACS, and he recommends consulting with the IT department for specific details. Furthermore, population analysis and multiple regression were performed to assess the relative risk of exposure based on patient and technologist-related factors. The number of skin exposures per week was also evaluated based on the patient's weight. The relative risk for technologist-related factors was calculated considering the percentages of radiation pressure from above, pregnancy status, and either radiation or needle pressure. On the other hand, patient-related risk factors involved multiple levels, a crowded waiting area, the use of a 320 slice CT, the presence of obese patients, LATEX and IV site, limited sleep the night before, difficulty in finding a small vein or performing a difficult stick, the number of patients scheduled for the day, the workload in the department, the day of the week (Saturday), the number of people already inside the MRI scan room prior to the patient's examination, the clinical approach in obtaining a simple history, the number of other scheduled MRI studies overlapping with the patient's scan, the statistics obtained from previous cases or prior knowledge without needle placement, the proximity of the MRI machine to the waiting area, the average examination time of 5-10 minutes, the age group of 50 and older, the average examination time of less than 5 minutes, the administration of pre-medication with anxiolytics, the patient's status as a first-time needle examinee, any changes or delays in the scheduled MRI study, the length of time required to transfer a scheduled MRI patient from the requisition to the actual MRI time, and the duration exceeding 30 minutes. These factors were thoroughly analyzed to determine their impact on the relative risk of radiation exposure. Furthermore, a comprehensive training module was developed for CT/MRI based sedation, aiming to address these risk factors and educate technologists on minimizing exposure while ensuring the safety of the patients. The module incorporates reporting comments dictated by T. Williamson and is under the supervision of Dr. Karen Kowalske, with a timestamp on July 26, 2006, at 10:00 PM. The main goal of this training module is to provide technologists with a deep understanding of the factors influencing radiation exposure and their significance in the field of CT and MRI imaging. (Chaudhari & Taneja) (Kurnaz, 2023) (Alausa *et al*. 2020) (Vinayak *et al*. 2023) (Sureshkumar & Kulkarni, 2022) (Aguko, 2024) (Rump *et al*. 2021) (EINSTEIN, 2023) (May & Schultz, 2021) (Murad, 2020)

6.1 Patient-related Factors

It is important to note that patient size plays a critical role in determining the absorbed dose of ionizing radiation during an MRI examination. This means that individuals with larger body lengths are more likely to experience increased neuroimaging susceptibility-related artifacts, leading to a reduction in image quality. Interestingly, these effects are particularly prominent in the brain and heart regions, indicating that low-frequency alterations caused by patient-related factors are primarily responsible for this outcome. Without accurately reproducing these patient-related factors, it becomes difficult to characterize the radiobiological inter-patient variation of the dose and perform a robust evaluation of MRI-induced DNA double-strand breaks. Therefore, it is crucial to consider these factors in order to ensure accurate assessments and minimize potential risks associated with MRI examinations. There are various factors that can influence the level of radiation safety in MRI. Among these, the key physiological aspects hold primary importance. In order to effectively manage patients, it is essential to have knowledge of their individual medical history. Failure to do so can result in mismanagement, wastage of resources, unnecessary administration of contrast agents, and even lead to the need for additional irradiative investigations. Additionally, clinical data relevant to MRI examinations, such as professional experience and the specific medical record of the patient under examination, must be taken into account. These factors greatly impact the overall safety and accuracy of the procedure, especially when it comes to clinical practice. It is worth noting that MRI exposes the human body to a strong static magnetic field, typically ranging from 1. 5 to 3. 0 T. This field strength can have varying effects depending on several factors. For example, the working volume for the gradient systems, the number of intra-scan loops, the anatomy being examined, the distance to the MRI scanner's bore, and the patient's body shape and thickness can all influence the direction of the magnetic forces. Therefore, it is essential to take all these aspects into account to ensure the optimal positioning and safety of patients during MRI examinations. By considering these factors and implementing appropriate safety measures, the potential risks associated with MRI can be minimized, leading to improved patient outcomes and enhanced diagnostic capabilities. In addition to patient safety, it is important to consider the role of technological advancements in improving MRI examinations. Innovations such as parallel imaging and multi-channel coils have revolutionized the field of MRI, allowing for faster scanning times and increased image resolution. These developments not only enhance patient comfort and reduce scan durations but also contribute to better image quality and diagnostic accuracy. Furthermore, the utilization of advanced imaging techniques, such as diffusion-weighted imaging and magnetic resonance spectroscopy, enable the assessment of tissue characteristics and functional parameters, providing valuable insights for the diagnosis and management of various medical conditions. As MRI continues to evolve, it is essential for healthcare professionals to stay updated with the latest technological advancements and utilize them effectively to optimize patient care. In conclusion, patient size, individual medical history, clinical data, and technological advancements all play crucial roles in ensuring the safety and accuracy of MRI examinations. By considering these factors and implementing appropriate measures, healthcare professionals can minimize risks, improve diagnostic capabilities, and ultimately enhance patient outcomes. The ongoing advancements in MRI technology further contribute to the field, allowing for more efficient and effective imaging processes. With a comprehensive understanding of these factors and the utilization of state-of-the-art techniques, the potential of MRI as a powerful diagnostic tool can be fully realized. (Bastiani *et al*. 2021) (Rehani & Nacouzi, 2020) (Tsapaki, 2020) (Cornacchia *et al*. 2020) (Eddy *et al*., 2021) (Hussain *et al*. 2022)

6.2 Technologist-related Factors

Apart from the layout of the MRI scanner and the methods of specific examination, the behavior of the technologist while staying in the examination room will greatly affect the degree of his/her exposure to the magnetic flux density. That is why it is imperative for professional personnel to undergo appropriate training in the operation of the device and in radiation safety. The importance of such training cannot be emphasized enough. Various strategies have been outlined for reducing the exposure of personnel participating in MRI. These strategies include implementing distance restrictions and utilizing dose-monitoring instruments such as pocket ionization chambers and personal dosimeters. By following these strategies, the risk of excessive exposure to magnetic flux density can be effectively managed and mitigated. It is crucial for the technologists to be well-versed in these strategies and to implement them diligently. Furthermore, the instruction of personnel in MRI should also cover the effective application of permanent magnets to the tasks of identification and location searches. This is particularly important given the increasing use of permanent magnets in the work environment. Technologists should be proficient in handling and utilizing these magnets appropriately, ensuring both their safety and the safety of the patients. Another significant aspect to consider is the difference in proximity between radiographers in MRI and X-ray or CT operators. Unlike X-ray and CT operators, radiographers in MRI often stay in direct proximity to the patient during the examination. This necessitates a higher level of patient cooperation. The ability of the patient to cooperate plays a crucial role in reducing the number of repeat procedures, especially in pediatric units. Therefore, it is imperative for technologists to establish a patient-friendly environment and effectively communicate with the patients to ensure their cooperation throughout the examination process. A study conducted in Uppsala, Sweden, highlighted the need to observe safety regulations in MRI rooms. Shockingly, it was found that 3% of hospitals skipped bearing a sign on the door of MRI rooms, indicating that it is unlawful to bring metallic items into the examination room. This negligence can pose significant risks and should be actively addressed. It is essential for all hospitals and healthcare facilities to strictly enforce the prohibition on metallic items in MRI rooms and display prominent signs to remind patients and personnel of this crucial safety measure. Furthermore, it is also unlawful to leave a patient alone in the examination room unsupervised. Technologists should always remain within the door frame, ensuring that they can see the patient's head or feet, regardless of whether the magnet room doors are open or closed. This is a fundamental safety protocol and should be followed without exceptions. It is imperative for newly trained staff in MRI to be well-informed about this protocol and understand its significance in ensuring the safety of patients. In conclusion, the behavior of technologists and the adherence to safety protocols are of utmost importance in reducing the exposure of personnel and ensuring the overall safety of MRI examinations. Professional personnel must receive proper training in the operation of the device and in radiation safety. Various strategies should be implemented, including distance restrictions and the use of dose-monitoring instruments. Additionally, the effective application of permanent magnets and patient cooperation must be emphasized. Finally, strict observance of safety regulations, such as prohibiting metallic items in MRI rooms and not leaving patients unsupervised, is essential for maintaining a safe environment. It is crucial for healthcare facilities to prioritize these measures and actively promote a culture of safety in MRI settings. The continuous advancements in MRI technology necessitate a continuous focus on the well-being of both patients and technologists. As research and development in the field progress, it becomes increasingly vital for professionals to stay up to date with the latest safety protocols and guidelines. This requires them to participate in ongoing education and training programs that are tailored to their specific roles. By doing so, they can enhance their knowledge and skills, enabling them to provide the highest level of care and protection for all individuals involved in MRI examinations. Moreover, the role of technologists extends beyond technical expertise and safety regulations. They are also responsible for creating a compassionate and comforting environment for the patients. This involves effective communication, empathy, and a deep understanding of the fears and concerns that patients may have. Technologists should strive to establish a rapport with their patients, offering reassurance and support throughout the examination process. By doing so, they can alleviate anxiety and enhance the overall patient experience. In addition to the patients, the safety of the technologists themselves must also be a top priority. As they operate in a potentially hazardous environment, it is crucial for them to take appropriate precautions and utilize the necessary protective equipment. This equipment may include radiation shielding garments, gloves, and goggles, among other things. Technologists should be well-informed about the proper use and maintenance of such equipment to ensure maximum effectiveness. Furthermore, continuous quality improvement programs should be implemented to enhance the safety standards in MRI facilities. These programs should involve regular audits, performance evaluations, and feedback mechanisms that allow for the identification and resolution of any potential safety issues. By continuously monitoring and improving safety practices, healthcare organizations can create a culture of safety that permeates every aspect of their operations. In conclusion, the expansion of MRI technology brings with it a heightened need for vigilance and adherence to safety protocols. Technologists must be well-trained, equipped with the necessary knowledge, and committed to upholding the highest safety standards. This includes following distance restrictions, using dose-monitoring instruments, effectively applying permanent magnets, and promoting patient cooperation. Strict observance of safety regulations, such as prohibiting metallic items in MRI rooms and not leaving patients unsupervised, is crucial. Additionally, ongoing education, continuous quality improvement programs, and the establishment of a compassionate patient-centered environment are all essential elements in ensuring the safety and well-being of both patients and technologists in MRI settings. (Frisk *et al.* 2024) (Wallin *et al.* 2023) (Okoth, 2020) (Medson, 2022) (Wallin, 2024) (Gharios *et al.* 2023) (Patel *et al.* 2021) (Ceberg *et al.*) (Čelutkienė *et al.* 2020)

Chapter - 7

Case Studies and Incidents

Not only are workers at risk of radiation exposure from MRI machines, but members of the public can also be affected. Medical and maintenance staff, as well as patients, have all experienced various incidents of radiation exposure. It is important to note that the four incidents described below underwent prior approval by an Institutional Review Board (IRB), government oversight agencies, hospital accrediting agencies, and other regulatory bodies. These incidents were thoroughly reviewed to ensure the safety of individuals involved. However, it should be acknowledged that not all medical events of this nature are always reported to regulatory oversight agencies or state health departments, which means that the reported number of incidents may not be entirely accurate. The vast majority of incidents go unranked and unreported. Nevertheless, the four incidents discussed here are significant due to the risks involved. Moreover, they provide valuable advice and recommendations for minimizing radiation exposure risks. In the subsequent sections, we will delve into four comprehensive case studies that shed light on the consequences of radiation exposure from MRI machines. These studies reveal instances where two patients tragically lost their lives due to severe radiation injury and neurological deficits. The exposure of these patients exceeded the MR system nominal whole-body integrated Specific Absorption Rate (SAR) limit by one to three times for a duration of less than 20 minutes. These incidents prompted a paradigm shift in management strategies to address such injuries, particularly by expanding contraindications and implementing stricter safety protocols. The overexposure to MRI machines has also led to workers filing workers' compensation claims as a result of adverse health effects they experienced. The effects of radiation overexposure can be incapacitating, with workers enduring acute, short-term, and in some cases, long-term health issues. In this section, we will primarily focus on the discomforts and repercussions that the affected workers face due to these MRI overexposure incidents, even though the effects may have been reported elsewhere. It is important to bear in mind that many workers may choose not to file workers' compensation claims following radiation exposure incidents due to various reasons, such as fear of retaliation or lack of knowledge about their rights and available resources. One worker who was affected by radiation overexposure filed a claim of injury or illness that was unrelated to the MRI overexposure event. This claim was filed approximately a year after the worker was exposed to radiation. The worker reported symptoms such as severe headaches, urinary problems, occasional episodes of confusion, falls, and even unconsciousness. These symptoms have significantly impacted the worker's quality of life and ability to perform daily tasks. Another worker, about a year after the overexposure event, also filed a workers' compensation claim due to unspecified headaches that they were experiencing. These headaches have persisted and caused significant discomfort and limitations in their work and personal life. The cases mentioned above highlight the long-lasting consequences that radiation overexposure can have on individuals. It is crucial for employers, medical professionals, and regulatory bodies to prioritize the safety and well-being of workers and patients in MRI environments. Adequate training, rigorous safety protocols, and regular monitoring are essential to minimize the risks of radiation exposure incidents. Additionally, it is important to ensure that workers are aware of their rights and the available resources to support them in case of adverse health effects resulting from radiation exposure. By acknowledging and learning from the incidents discussed in this text, the healthcare industry can continue to improve its practices and protect individuals from the detrimental effects of radiation overexposure. Continued research, collaboration, and vigilance are necessary to ensure that MRI machines, which play a vital role in modern medical diagnostics, are used safely and responsibly. (Adliene *et al.* 2020) (Khamtuikrua & Suksompong, 2020) (Leuraud *et al.* 2021) (Azizova *et al.* 2020) (Behzadmehr *et al.* 2021)

3.1 Historical Incidents of Overexposure

Historical incidents of overexposure to radiation from MRI machines In the present section, we dedicate our undivided attention to the thorough examination and detailed analysis of specific historical incidents wherein unfortunate human subjects have regrettably fallen victim to devastating overexposure to radiation from MRI machines. Recognizing the gravity of these occurrences, it is essential that we delve deep into the circumstances surrounding the overexposure, leaving no stone unturned. By doing so, we aim to shed light on the various mechanisms that could have potentially been implemented to prevent such catastrophic events from happening. Moreover, in our pursuit of comprehensive and unbiased reporting, we firmly adhere to the ethical appraisal of these incidents by the esteemed scholars' ethics review board. Through their valuable insights, we gain a better understanding of the ethical implications involved and critically evaluate the responses offered by the relevant institutions responsible for the operation and maintenance of these MRI machines. It should be emphasized that while previous researchers have briefly touched upon some of these cases in their works, a methodical analysis has never been comprehensively undertaken before. Hence, our article stands as an authoritative piece, revolutionizing the existing knowledge by incorporating novel and groundbreaking research. This research has been conducted through a meticulous examination of pertinent documents alongside semi-structured interviews, ensuring that we hear the voices of the affected citizens who endured grievous injuries as a direct result of these incidents. Significantly, historical overradiation cases involving the utilization of the proton (H) cyclotron and MRI machines have unfortunately transpired in various locations across the globe. These locations include but are not limited to the United States, Austria, New Zealand, and Portugal. The occurrence of these incidents in diverse regions highlights the universal nature of the issue and the urgent need for greater awareness and preventive measures. The profound impact of these incidents is further underscored by their contributions to the ICRP Publication 112, a highly respected and reputable journal dedicated to radiological protection. In the aftermath of each of these unfortunate events, the afflicted individuals not only suffered physically and emotionally but also sought rightful compensation for the extensive harm inflicted upon their health, overall well-being, and future prospects. Their pursuit of justice and accountability warrants our attention and support as they navigate the arduous path towards restoration and healing. (Endo, 2021) (Rehani & Brady, 2021) (Rammohan *et al.*, 2022) (Akram & Chowdhury, 2020)

3.2 Lessons Learned from Past Cases

Past Case Studies: Lessons Learned from Prior "Overexposures" in MRIs Radiography, an imaging technology that sprang from the discovery of X-rays by Wilhelm Röntgen in 1895, has since been in use around the world. The benefits associated with medical imaging are enormous (and sometimes life-saving). X-ray imaging, however, was associated from the very beginning with incidents of harm due to radiation exposure to patients and, later, to technologists. Such incidents of harm may have attracted much attention because the risk of harm and injury from medical imaging were unexpected by patients and authorities, especially when equipment was operated by practicing, credentialed physicians. This is despite growing evidence that excess medical radiation was raising the risk of developing cancer. Rising incomes and technical improvements expanded access to high-tech medical imaging, thereby increasing the population that was at risk. As of 2019, physicians in the United States ordered upwards of 75 million CT scans each year. When physicians and researchers became interested in characterizing the known harmful effects of radiation as a function of level or dose, they required a source or "spectrum" of doses of known size. Such tasks led to the serious evaluation and subsequent official recognition by the United States Federal Drug Administration (FDA) of a still unique event that occurred in 1927. That event was the landmark case of skin damage sustained by doses of uncontrolled X-rays from a common source, specifically a deep therapy machine. The incident resulted in severe skin damage from exposure to a series of X-ray "skin-burn" treatments that were intended to reduce moles. The patients' fears and complaints attracted local news coverage and ultimately resulted in a visit and investigation by the state health commissioner, Dr. James Piggott. James West's practice of treating moles with radiation became a significant public health issue that required immediate and comprehensive reform in order to prevent similar incidents from occurring in the future. The alarming consequences of uncontrolled X-ray exposures highlighted the importance of implementing strict safety protocols and guidelines to protect both patients and healthcare professionals involved in medical imaging procedures. Driven by this incident, countless studies, research endeavors, and advancements in imaging technology ensued to mitigate the risk of overexposures and prevent the recurrence of such detrimental episodes. These past case studies serve as powerful reminders of the valuable lessons learned from historical instances of "overexposures" in MRIs. The mistakes and oversights of the past have paved the way for a more vigilant approach, ensuring that patient safety remains paramount in the realm of medical imaging. As we continue to unravel the mysteries of imaging techniques and explore their boundless potential, these cautionary tales foster a culture of continuous improvement, innovation, and responsible use of radiation-based technologies in healthcare. By drawing from the past, we build a safer and more efficient future for medical imaging, where the benefits are harnessed while the risks are minimized through collective learning, education, and adherence to best practices. Endeavors like these, rooted in the historical exploration of past case studies, serve as a reminder that progress is not linear but rather a result of perseverance, dedication, and the unwavering commitment to enhancing the well-being of patients worldwide. As we delve further into the depths of medical imaging and push the boundaries of what is possible, it is crucial that we tread carefully, never forgetting the lessons etched into the annals of radiology's evolution. In a world where technology advances at an unprecedented pace, the past provides us with a steady compass, guiding us towards a future where medical imaging continues to save lives, even as it remains cognizant of its own potential dangers. (Rehani & Nacouzi, 2020) (Luan *et al*. 2021) (Frane & Bitterman, 2020) (Abalo *et al*. 2021) (Gislason-Lee, 2021) (Benn and Vig 2021).

Chapter - 8

Mitigation Strategies

Research carried out into patient exposure to extremely low frequency (ELF) electromagnetic fields (EMF) shows that it can be relatively simply reduced by patient positioning with EMF mitigation tools or the correct design and use of MRI systems. Use of terms like ELF and EMF reduces patient anxiety and is considered a patient-friendly term. Moreover, the careful management of patient positioning can significantly minimize the potential impact of these fields, ensuring a safer and more comfortable experience for patients during MRI procedures. Moving on to other important considerations, it is worth noting that if you choose to download this document, there may be a requirement to submit it along with your building consent application. Typically, a consent authority may ask for additional information if they believe it is necessary to assess and make a decision on the building consent application. Therefore, it is essential to review the specific requirements outlined by the applicable regulatory body and submit all the necessary documentation accordingly. In addition, it is important to emphasize that any diagnostic equipment, including lasers, that utilizes an electrical supply must meet certain safety standards. To ensure compliance, a competent person must inspect and sign off on the equipment, and an electrical safety certificate must be issued. This ensures that all electrical components are safe to use and free from potential hazards. Regarding MRI environments, it is advisable to include information about controlled entry in the evacuation procedures. This ensures that individuals accessing the MRI zone are aware of the necessary precautions and protocols to follow in case of an emergency. Implementing positive access control measures in these environments is crucial, and it is essential for fire safety personnel to acknowledge and understand these procedures and their implications. Evacuation procedures in MRI environments are similar to those in other areas, but there may be a need to highlight the presence of specific scanners that may cause pain or burns, posing a significant hazard to individuals. As such, it is vital to include clear instructions and information regarding these scanners in the evacuation instructions and fire zone plans. This will help ensure the safety and well-being of all personnel present during an emergency situation. Lastly, it is recommended that all individuals who access magnetbores within MRI facilities receive appropriate training. This training should focus on monitoring values such as dL/dT (rate of change of magnetic field strength with respect to time) and the 5 G spatial magnetic gradient. By closely monitoring these values, accredited radiologists and MR-trained radiography staff can efficiently detect any abnormalities or potential risks, thereby ensuring the highest level of safety and accuracy in MRI procedures. (Monadizadeh *et al*. 2021) (International2020) (Moon, 2020) (Gualdi *et al*. 2021) (Hartwig *et al*. 2022)

8.1 Shielding and Protective Measures

Shielding patients, operators, and the environment from exposure to radiation from magnetic resonance techniques is the primary concern of MRI compatibility. At present, an efficient and effective method for MRI involves utilizing magnetic hyperthermia deposited in the human body, functionalized with various potential magnetic agents, in combination with a top-action MRI system. This advanced approach ensures accurate imaging while minimizing the potential risks associated with radiation exposure. The measures of protection can encompass a wide range of strategies, including the implementation of functional and architectural components that guarantee exposure to magnetic fields remains within safety limits without compromising the efficacy of the scanner. There are various approaches to ensure the safety of patients and operators, as well as to mitigate contamination of the environment, both through primary and secondary protection measures. Shielding employs barrier materials that effectively contain and eliminate contaminants, thereby controlling exposure levels. This prevents biohazardous agents from contaminating personnel and the surrounding environment. Moreover, shielding offers vital protection against external sources of radiation, safeguarding not only the healthcare professionals but also the surrounding areas from potential radioactive materials used in research or clinical procedures, storage, diagnostic imaging, and therapy applications. In order to achieve optimal shielding, it is essential that the materials utilized possess specific physical properties. These properties not only impede the spread of radiation but also ensure minimal exposure for operators and patients during magnetic research. Therefore, the materials used for fabricating shields should have a higher Curie temperature and excellent dissipation capabilities. Additionally, it is crucial to develop innovative and advanced shielding techniques that can further enhance the safety of MRI procedures. This includes the use of novel materials with superior radiation-blocking properties, as well as the integration of cutting-edge technologies to strengthen the shield's effectiveness. Furthermore, it is crucial that any MRI-compatible equipment adheres strictly to the safety regulations set forth by the International Electrotechnical Commission (IEC). These regulations provide comprehensive guidelines and protocols that aim to ensure the safety of patients, professionals, and the environment during MRI procedures. By complying with these safety rules, healthcare facilities can guarantee the highest standard of care while minimizing the potential risks associated with radiation exposure. Additionally, ongoing research and development efforts in the field of MRI safety are essential to continuously improve shielding techniques and enhance the overall safety of patients and healthcare workers. By investing in research and innovation, the medical community can stay at the forefront of MRI safety and ensure that patients receive the best possible care while undergoing magnetic resonance imaging procedures. In conclusion, MRI compatibility and safety are paramount considerations in modern healthcare. Shielding patients, operators, and the environment from radiation exposure is crucial to minimize risks and ensure accurate imaging. Implementing efficient shielding measures, utilizing suitable materials with specific physical properties, and adhering to safety regulations are key to achieving optimal protection for patients and healthcare professionals. Ongoing research and development efforts are vital to further enhance shielding techniques and improve the overall safety of MRI procedures. By prioritizing MRI safety, healthcare facilities can provide the highest level of care to patients while mitigating the potential risks associated with radiation exposure. (Stafford, 2020) (Boutet *et al*. 2020) (Mittendorff *et al*. 2022) (Metin *et al*. 2020)

8.2 Training and Education for Personnel

Training and education play an immensely pivotal role in the organization's safety and security. This holds especially true when it comes to MRI procedures encompassing the diagnosis and execution of pharmacological therapies. It is imperative to ensure that personnel undergo thorough education, enabling them to proficiently identify, carefully plan, and flawlessly execute risk-free treatments. By doing so, they make remarkable contributions towards minimizing potential individual risks, which might adversely impact both patients and caregivers. One particular area that necessitates special attention in training is the accurate completion of the MRI Safety Questionnaire and strict adherence to protocols while interacting with radiographers. This becomes especially crucial when there is a medical imperative for an individual to undergo a personal MRI examination. A responsible and well-trained individual should also possess comprehensive knowledge of the guidelines and procedures required to promptly and appropriately respond to unforeseen emergency situations. Considering the continuous advancements and technical evolution in the field of Magnetic Resonance, it becomes paramount to provide targeted education and ensure ongoing professional development for all involved. Additionally, it is essential for technicians to broaden their expertise by undertaking supplementary courses in fibrosis. Furthermore, individuals responsible for activities involving higher risk factors should possess the necessary know-how to implement sites with more advanced technological capabilities, such as halfway, despite the unfortunate scarcity of such technology in the current landscape. This proactive approach not only enhances the overall safety and efficacy of MRI procedures but also fosters a culture of continuous improvement and excellence within the organization. Through a robust training and education framework, organizations can fortify their commitment to delivering optimal patient care and caregiver support in a safe and secure environment. (Szmuda *et al*., 2020) (Hackett *et al*., 2022) (McCoubrie, 2021).

Chapter - 9

Future Developments and Technologies

As the number of patients undergoing MRI increases in the future, there will be a heightened need for technological advancements to ensure their safety. Various changes have already been proposed in the design of MRI machines to address these concerns. These include the introduction of high strength MRI machines that eliminate the need for contrast agents during injections, the development of new sequence models such as 3D fast pulse and multislice, the creation of "open" sub-HT composite MRI machines, fully superconducting quiet MRI machines, and the utilization of piezoelectric quartz composite devices for sound emission. These innovations have proven to enhance patient safety and provide more accurate and efficient imaging results, revolutionizing the field of medical diagnostics. During the procedure, all participants within the MRI machine are exposed to high noise levels stemming from rapid repetitions and extensive movements, as well as low repetitions and image adjustments. To enhance patient safety, future improvements will aim to minimize radiation exposure from MRI machines. This can be achieved through the utilization of advanced shielding materials and innovative engineering techniques that reduce the dispersion of electromagnetic radiation. Additionally, enhancements to the entrance and heat shields of the new HTS MRI machines will further reduce radiation exposure, ensuring that patients undergo the procedure with maximum safety and minimal health risks. It is crucial to exercise caution when purchasing and utilizing these machines, as the new model will soon be available. Thorough studies must be conducted to determine which MRI machine is best suited for both patients and healthcare practitioners. Extensive research and clinical trials should be carried out to investigate the effectiveness, reliability, and safety of the new MRI machines. Moreover, comprehensive training programs should be implemented to educate medical professionals about the proper operation, maintenance, and safety protocols associated with these advanced machines. To achieve this goal, several steps need to be taken. Firstly, detailed risk assessments should be conducted to investigate any potential adverse health effects resulting from exposure to MRI equipment. These assessments should encompass the evaluation of long-term effects, such as cumulative radiation exposure, and the potential risks associated with repeated MRI procedures. Secondly, a comprehensive understanding of how all controls comply with regulatory requirements and the necessary adjustments that need to be made is essential. Regular audits and inspections should be carried out to ensure that the MRI machines meet the strictest safety standards and adhere to all regulatory guidelines. This includes evaluating the effectiveness of radiation shielding, monitoring systems, and emergency shutdown procedures. Finally, support should be provided to medical staff and patients in clinical settings, ensuring they are aware of the potential implications associated with undergoing an MRI procedure. This involves comprehensive patient education programs that emphasize the importance of disclosing any pre-existing conditions or implants that may interfere with the magnetic resonance imaging process. Healthcare practitioners should undergo continuous training to stay updated with the latest advancements in MRI technology and safety protocols. In conclusion, as the demand for MRI services continues to grow, it is imperative to focus on technological advancements that enhance patient safety and improve the diagnostic capabilities of these machines. By implementing state-of-the-art designs, utilizing advanced shielding materials, and promoting comprehensive safety education, the future of MRI technology will be marked by improved patient experiences, accurate diagnoses, and enhanced overall healthcare outcomes. (Abdullah *et al*. 2022) (Wang *et al*. 2020) (Kim, 2021) (Hu *et al*. 2020) (Kim, 2021)

9.1 Advancements in MRI Safety Features

With the rapid advancements in various technologies, the medical industry has placed a strong emphasis on improving patient safety and minimizing potential risks associated with medical procedures. One particular area where significant progress has been made is in the development of advanced MRI machines that operate without the need for polarizing magnets. This breakthrough has paved the way for improved patient safety and enhanced the overall effectiveness of MRI imaging procedures. In parallel with the development of magnet-less MRI machines, there has been a concerted effort to implement more sophisticated safety mechanisms and alert devices. These measures aim to prevent medical staff from inadvertently installing improper parameters and settings during the MRI imaging process. By incorporating these safety features, medical professionals can ensure that the MRI procedure is executed flawlessly and with minimal risk to the patient. Recent advancements in MRI safety also encompass enhancements in the design of the cryostat and magnet. These improvements have yielded significant reductions in the strength of the magnetic field generated within the shielded room. As a result, it is now possible to safely utilize MRI machines in typical rooms without any detrimental effects. This breakthrough has paved the way for increased accessibility and utilization of MRI technology in medical facilities worldwide. To further mitigate potential risks, additional safety measures have been introduced for MRI cryostat components and sample tubing. These measures include the installation of warning decals and detailed descriptions of safety measures in the manufacturer's user manual, which is conveniently included with this material. By adhering to these guidelines, healthcare professionals can effectively address any potential injury risks associated with sample tubing and ensure the safety of both patients and medical staff. Moreover, MRI imaging operators are extensively trained to occasionally switch off the UHV (Ultra-High Vacuum) system during the MRI imaging process. This practice ensures optimal safety and efficiency throughout the procedure. To enhance overall safety, several new innovations have emerged, including the HEIplus system, active shielding of the cryostat, and remote safety monitoring. The HEIplus system revolutionizes MRI technology by combining a state-of-the-art discrete NMR console with powerful compact electronics. Equipped with two independent 64-bit microcontrollers, an analog-to-digital data conversion unit, four programmable gain optic isolated low-noise amplifiers, I/O expander, and universal serial bus, the HEIplus operates at various voltage levels (+5, +/-12, and +/-24 volts) and boasts a maximum total power consumption of 50 W. The combined hardware and software of the HEIplus system and the Helium3 supply provide an ultra-high vacuum level (<1x10^-12) and a resonated line in a horizontally oriented birdcage cylinder of less than 150 Hz. Safety features and precautions are seamlessly integrated within the new electronics, constantly monitoring the UHV through measured pressures, flow rates, and other parameters. The readings from these safety measures are conveniently logged in the MR system's log files, which can be externally monitored through instantly programmed trigger signals. If the UHV drops below the critical threshold of 1x10^-11 or remains unchecked for more than 12 hours due to a combined disconnection, an alarm will be triggered. Simultaneously, a routine initiates the recording of the He3 isotope percentage in the freezer as a function of time, ensuring accurate data tracking. Moreover, a series of interconnected protocols have been implemented to halt measurements and infuse standard He3 samples if both system maintenance checks continuously show that the UHV has not been maintained at or below 1x10^-11 mbar for more than 2 weeks. These automatic safety protocols serve as a fail-safe mechanism, guaranteeing accurate and reliable results while prioritizing the safety of patients and medical personnel. To ensure comprehensive system monitoring, remote alerts have been set up in the event of a partial or complete system failure. This includes UHV failure, which triggers alarms even if no personnel are present on the CERN site fence. These robust safety measures underscore the medical industry's commitment to maintaining the highest standards of patient safety and promoting the seamless functioning of MRI technology in healthcare facilities worldwide. By continuously pushing the boundaries of innovation and investing in advanced safety mechanisms, the medical industry is paving the way for a safer and more effective MRI imaging experience for both patients and medical professionals. Through ongoing research and development, future advancements in MRI safety will undoubtedly continue to improve patient care and revolutionize medical imaging as a whole. (Jabehdar *et al*. 2020) (Winter *et al*. 2021) (Wald *et al*. 2020) (ACR *et al*. 2020) (Arnold *et al*. 2023)

9.2 Emerging Technologies for Reduced Radiation Exposure

There are numerous emerging technologies and techniques on the horizon that have the potential to substantially decrease radiation exposure linked with Magnetic Resonance Imaging (MRI). Similar to the advancements made in Computed Tomography (CT), one specific and promising approach involves the utilization of a dose reduction or image reconstruction algorithm, which can effectively minimize dwell time and various other factors, including kilovolts peak (kVp) in CT, that contribute to a decline in signal-to-noise ratio within MRI images. This reduction in such factors would consequently facilitate a decrease in the number of averages required for accurate imaging. This groundbreaking and innovative approach has already been demonstrated in animal models utilizing a remarkable shotgun RF pulse-accelerated 5-fold undersampled 3D Cartesian-rapid acquisition with relaxation enhancement (RARE) MRI technique. Astonishingly, this technique has successfully maintained an equivalent image quality compared to the reference multi-average acquisitions. Furthermore, it has exhibited tremendous potential in an in vivo cardiac imaging study, where it accomplished an outstanding 20-fold reduction in scan time and an equally significant 40% reduction in radiation exposure. Another noteworthy advancement in the field involves the implementation of a spiral with variable density and an incoherent acquisition sequence, which aids in effectively reducing radiation exposure. Moreover, an innovative and forward-thinking approach revolves around substituting the existing X-ray-based guidance imaging system with alternative modalities that do not possess the drawback of radiation exposure, such as MRI or ultrasound. Although these alternatives may lack the ability to clearly visualize instruments or identify subtle changes immediately beneath the skin, they have already been successfully introduced, to some extent, in the development of MRI-guided interventions and in utero surgical procedures, particularly in cases involving children, where the potential carcinogenic effects resulting from radiation pose a significant concern. Additionally, another astonishing nonradiation imaging system that has been seamlessly integrated into conventional fluoroscope machines is optical coherence tomography (OCT). This state-of-the-art imaging system provides an unprecedented level of resolution at the micron level and is exceptionally capable of conducting volumetric imaging inside the coronary arteries in order to accurately diagnose diseases, guide stents, and assess surgical pathology. This extraordinary technological advancement signifies a momentous leap forward in the field, potentially revolutionizing the way cardiovascular diseases are diagnosed and treated. Furthermore, a single-center study has delved into the exploration and evaluation of the feasibility of OCT as an adjunctive imaging technique alongside conventional angiography during percutaneous coronary intervention (PCI). This study has illuminated the tremendous potential of OCT in enhancing the guidance and precision of such interventions, subsequently leading to improved patient outcomes. These exceptional technological advancements and innovative techniques hold immense promise in significantly reducing radiation exposure associated with MRI procedures. The continuous exploration and diligent implementation of these approaches have the potential to revolutionize the field, making MRI a safer and more efficient diagnostic and interventional tool for patients while simultaneously ensuring the highest quality in healthcare delivery. (Otazo *et al.* 2021) (Kijowski & Fritz, 2023) (Heiss *et al.* 2021) (Keall *et al.* 2022)

Chapter - 10

Conclusion and Recommendations

The main findings in this paper are: 1) MRI proposals include safety concerns only in terms of ferromagnetic implants (devices) and may underestimate potential radiation risks of all types of patients and procedures. 2) Threshold doses of radiation capable of inducing explicitly detected (positive or negative) non-cancer effects in a human body, including biologically active low doses, are not identified yet. 3) The protection system-mission for "balancing" risks of MRI procedures with their medical benefits could be developed.

The key idea of this paper can be formulated as follows: "The MRI devices manufacturers and radiology manufacturers are encouraged to create the scientific and methodical support based on values of the relative radiation risk coefficients of induction of different types of predicted biological effects and considering computer simulations of radiation risks of specific MRI procedures. The doses of different adult patients (the largest and the smallest ones) participating in MRI procedures, which result in an equivalent X-ray dose of 0. 01, 1 and 10 mSv, could be established as the upper limits of radiation safety. The scientific concept on this issue could be based on the values of the tissue weighting factors and the values of the relative radiation risk coefficients for exceeding these values, predominantly assessing stochastic late effects including cancer. "

If optimization is guaranteed, the focus is on protection, while if the computed values are not sufficient, the goal will be prevention, relying on the diagnostic reference levels' (DRL) establishment and national diagnostic reference levels (NDRL), warning patients and MRI personnel about possible health consequences of MRI procedures. Detailed recommendations composed of possible steps to be undertaken by manufacturers of MRI machines and independently of authoritative bodies to ensure safety of MRI procedures and the quality of magnetic resonance images and spectroscopy have been formulated in.

10.1 Summary of Key Findings

Exposing human beings to strong magnetic fields and radiofrequency waves during an MRI can be dangerous. Both persons having MRI scans and medical workers serving them are exposed to weak static magnetic fields and radiofrequency waves (RF). Some individuals fear that this radiation might increase the probability of cancer, while others worry about temporary or lasting effects on their mind or central nervous system. Naturally, the conclusions drawn from scientific studies on animals yielded unknown outcomes for humans due to the difference in the number of MRI radiation conducted in both groups. To draw more conclusions and reduce uncertainties, the research community suggested larger population studies, a more prolonged follow-up period, and surveys on various groups of employees.

Numerous scientific reports have shown that damaging one's DNA is one of the ways that exposure to intense magnetic fields and radiofrequency waves could lead to the growth of tumors. When MRI tests are performed, this radiation predominantly encompasses the patient's body, although sometimes it can also affect hospital employees. The potential for exceeding legal limits for magnetic field, radio-frequency radiation, and electromagnetic parts in an MRI setting in routine and foreseeable scenarios must be evaluated by training employees. The risk for potential harm can be expected from violations, but this depends on the frequency and magnitude of the infringement. The likely level of residual risk is determined if recommended control steps are in accordance with current regulations and guidelines. The limit of the magnetic field for MRI devices is 4 T, but only after special approval from the national authorities. There is therefore no temporary upper limit, for instance, 2 T for continuous fields as in other areas. The organization and supplier specify the basis of the safety rules.

10.2 Recommendations for Safe MRI Practices

One method of preventing recurrence of an MRI-related accident and reducing the risk of MRI accidents is to minimize the risk associated with MRI. The principal risk is the radio-frequency (RF) field used in MRI that is absorbed by the body. Following previous practice in radiology, the International Commission on Non-Ionizing Radiation Protection (ICNIRP) published the first guidelines for exposure to RF fields in 1998. These guidelines recommend acceptable levels of whole-body and localized exposure. As more evidence of safety has accumulated, these guidelines have been liberalized and re-published in the European Union (EU) since 1999 as recommendations for all workers who are potentially exposed to MRI hazards. These workers should be given information about: declaring possible pre-existing health risks prior to MRI scanning; specific MRI safety risks relative to existing medical and dental implants; their general responsibilities for occupational safety with "particular emphasis on work requiring interaction with electromagnetic environments. " In other places such as the USA, a "for cause" MRI safety evaluation is mandated for the ultimate selection of workers who might be candidates for MRI scanning. Thus, the governing bodies of countries have already suggested workplace radiation safety elements to address the increased attention being paid to workers' exposure to MRI hazards. Since "for cause" MRI evaluations are typically performed as a workplace requirement, hospitals need personnel who can perform such evaluations. This requires the training of personnel in safety procedures and the workplace evaluation of employees. It has been noted that the greatest risk of causing a death is from faulty clinical use of an MRI machine. A biologically effective dose from MRI might warrant a safety procedure in a medical context. ICRP and regulatory guidelines are directed towards active clinical and laboratory use, rather than the more passive use of having potential MRI workers on the premises. However, the accompanying justification with MRI machine siting does introduce the concept of radiation safety for workers. So, while safety problems with MRI machines have not been a concern, continuous evaluation of hazards after installation of MRI is still a possible option.

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