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INTEGRATED STUDY MASTER'S THESIS

Safety of Implantable Cardiac Rhythm Management Devices

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Table of Contents

1. Summary

Life-saving treatments, such as pacemakers (PM), implantable cardiac defibrillators (ICDs), and cardiac resynchronization therapy (CRT) devices, are used for numerous cardiac conditions. Cardiac rhythm management devices perform different functions, including monitoring for arrhythmias, bradycardia pacing, cardiac resynchronization for heart failure, defibrillation and anti-tachycardia pacing for ventricular tachyarrhythmias. (1)

Estimating the exact rate of CIED infections is challenging due to varying definitions, differences in patient populations, and the discrepancies between retrospective and prospective study rates. CIED infections typically occur through two main mechanisms. The most common is contamination of the leads or pulse generator during the initial implantation or later adjustments. Device erosion after these procedures can lead to a pocket infection, which could cause systemic infection. The second mechanism involves infection entering through the bloodstream. (2)

Medical devices, such as cardiac implantable electronic devices, have become highly interconnected. This means now CIED's are more connected and are able to communicate with other devices or networks. This increases the risk of exploitation of cybersecurity vulnerabilities that can affect the device's function. (3)

Radiotherapy (RT) is frequently used in cancer treatment and may also be required before or after surgery as an alternative to surgical procedures. There are two types of RT: brachytherapy (internal radiation) and external beam radiation. While radiation can damage surrounding healthy tissue, it can also pose risks to cardiac implantable devices. Although ionizing radiation can harm CIED electronic circuits, and this has raised concerns about potential device malfunctions. (4)

Electromagnetic interference (EMI) could radiate from a distance or even be conducted via individuals if they are in contact with the source. Various factors could affect EMI. The programs set on these devices could influence their response to EMI. These programs include sensitivity, polarity, mode, refractory, and blanking periods. If the setting is more sensitive, the device starts to over-sense non-cardiac signals. (5)

2. Keywords

Cardiac implantable electric devices (CIEDs), Pacemakers (PM), implantable cardiac defibrillators (ICDs), cardiac resynchronization therapy (CRT), Radiotherapy, Electromagnetic interference (EMI).

3. Introduction

In recent decades, widespread clinical use has led to intensified research on cardiac rhythm management devices, such as pacemakers, implantable cardioverter defibrillators, and loop recorders. (6)

Few types of therapies are provided for cardiac management devices, such as bradycardia pacing, which prevents bradycardia in the atria (sick sinus syndrome) and /or the ventricles (atrioventricular block). Cardiac resynchronization therapy, also known as biventricular pacing, is used for patients with heart failure and reduced left ventricular function, particularly when ventricular contraction is impaired. Cardiac resynchronization therapy is pacing both the left and right ventricles of the heart simultaneously. (6) This will improve systolic function by resynchronising the heart contraction. This will not be used for every patient with heart failure, but mainly for patients with left bundle branch block, and decreased LV systolic function will benefit the most. (7) Next, we have defibrillators; here, an electric shock would be delivered to restore the normal heart rhythm, especially when there are life-threatening rapid ventricular arrhythmias (ventricular fibrillation/fast ventricular tachycardia). Also, what could help in case of a fast ventricular tachycardia is anti-tachycardia pacing (ATP), which paces faster than arrhythmia and could sometimes even break the circuit and end it. (8) These therapies are also used for monitoring and to see if there are any heart rhythm disturbances such as tachycardia, bradycardia, pauses or atrial fibrillations.

Of the types of cardiac management devices that have been used for decades already, the most common is a pacemaker. Pacemakers have a specific job to do, which is to send electrical impulses to stimulate the heart to beat. It is most commonly used in patients with symptomatic bradycardia, like in sick sinus syndrome or atrioventricular block. (8) A pacemaker could also be implanted if the patient is using medication that reduces the heart rate, for example, patients with heart failure who use beta-blockers for their cardiac function. Some patients can be dependent on the pacemaker while others are using it as a ” backup.” The heart's chamber where the pacing electrodes are placed can also differ; there are single lead, double lead, three leads, or leadless pacemakers; this, of course, depends on the patient's

underlying rhythm, and the pacemaker would be programmed accordingly. Traditional pacemakers can be inserted into the right or left side of the subclavicular area. (7)

Secondly, we have implantable cardioverter defibrillators (ICDs), primarily used for patients who are survivors of sudden cardiac arrest, as well as those with reduced left ventricular function, typically an ejection fraction of less than 35%. (9) Like pacemakers, the heart chambers where the pacing electrodes are placed can include single lead, double leads, triple leads, or subcutaneous options, which means there is no transvenous component. ICDs are usually implanted on the left side of the subclavian area, as this provides the optimal vector for defibrillation. (8)

4. History of implantable cardiac devices

The history of cardiac rhythm disorders, along with the development of anti-arrhythmic drugs and cardiac implantable devices, are both far-reaching and extensive. In the early stages, there was little understanding of the heart's anatomy, physiology or how to interpret the pulse, which is a reflection of the heart's activity. Seeing how rhythmology has developed the world widely. The world has made significant contributions over the past few centuries. The rising clinical significance of electric cardiac stimulation was acknowledged when Zoll in 1952 stated a successful resuscitation for cardiac arrest using external stimulation. (10)

The first fully implanted pacemaker was made in 1958 in Stockholm, Sweden. It was implanted by Swedish surgeon Dr. Åke Senning, and engineer Rune Elmqvist designed the device. The device incorporated a transistor circuit powered by a nickel-cadmium battery. (10) The device functioned for three hours before it stopped working. Not long after, the same year, Dr. William Chardack and electrical engineer Wilson Greatbatch started to build in Buffalo, New York, their first American implantable pacemaker, and they began their animal studies with it. After their studies, the early 1960s, this device saved 10000 people in a year. (11)

A while after the pacemaker's development, implantable cardioverter-defibrillator system was introduced in 1970 to treat ventricular flutter and fibrillation. In February 1980, Dr. Michel Mirowski and his team at Johns Hopkins Hospital in Baltimore, Maryland, successfully performed the first human implantation of the device. By early 1997, over 100000 ICD systems had been implanted worldwide. (10)

In the early 1980s, several other significant advancements were made in the USA and in the rest of the world. (10) These included dual chamber pacemakers that allow pacing in both the ventricle and atrium and rate-responsive devices that continuously and automatically adapt heart rate to the patient's changing physiological requirements. These devices gave bradycardia patients not only a steady heart rate but also the physiologic rate response necessary to resume everyday functions. As well an atrial resynchronization device has been developed to enhance AV synchrony and to improve the mechanical function of the left heart. (12)

Today, cardiologists, cardiovascular surgeons, and electrophysiologists can provide their bradycardia patients with fully integrated systems comprising multi-sensor pulse generators that provide physiologic response yet weigh as little as 25 grams. Low-threshold, steroid-eluting leads, used in conjunction with a lithium-iodine power source, can extend the practical life of the device to upwards of 10 years. (12)

5. Risk factors of CIEDs

In recent decades, the implantation of cardiac implantable electronic devices (CIED's) has increased in number and complexity. This growth is due to broader indications for use and an aging population. While these devices can significantly improve cardiovascular health, they also carry risks of complications for patients. Infection is the most common complication associated with CIED therapy, and it can lead to high mortality rates, morbidity, and substantial financial burdens on healthcare systems. (13)

There are two major mechanisms for how the infection could occur in cardiac implantable devices. The most common would be contamination of the leads and/or the pulse generator during cardiac device implantation or subsequent manipulation. Late-onset device erosion following interventions could lead to or be caused by pocket infections. In both situations, contamination, followed by bacterial colonization, could lead to pocket infection; this could extend to the intravascular portions of the leads and potentially develop into a systemic infection. Of course, the other possible route is through a bloodstream infection. Direct contamination of the lead could occur during bacteremia, which originates from an infection at a distant site, such as local septic thrombophlebitis, osteomyelitis, pneumonia, surgical site infection, contaminated vascular catheters or bacterial entry via the skin, mouth, gastrointestinal, or urinary tract. (14)

Many factors contribute to pathogenesis in CIED infections; this could be related to the host, the device, or the microorganism. Contamination could happen in many ways, for example, via the person holding the implantable device or the air in the operating room. There are also non-pathogenic microorganisms, such as coagulase-negative staphylococci (CoNS), which can attach to the CIED and create an infection site. (13) The most commonly isolated pathogens have been Gram-positive bacteria (70-90%), which, in this case, coagulase-negative staphylococci (CoNS) at 37.6% and Staphylococcus aureus at 30.8%. These bacteria are significantly more likely to adhere to non-biological materials than other microorganisms. But the most common bacteremia, which easily as well causes pocket infection, would be Staphylococcus aureus. (14)

The risk factors for cardiac implantable electric device (CIED) infections could be divided into a few factors, such as patient-related, procedure-related, or device-related. These factors could be modifiable or non-modifiable. It is essential to identify modifiable risk factors because it may let us have preventive measures to minimize the risk. On the other hand, for patients with non-modifiable risks, the best way to make sure to prevent risk factors from happening would be to lower the risks generally. One of the examples of non-modifiable patient risk factors would be renal dialysis, changing the procedure and/or even the implantable device and choosing an epicardial or subcutaneous system can help reduce the risks. (13)

In the patient-related factors, end-stage renal disease is the highest risk, so it is very important to highlight the necessity of a careful clinical evaluation in patients with end-stage renal disease. A meta-analysis was conducted to identify risk factors associated with certain conditions. The most commonly included chronic diseases were end-stage renal disease, renal insufficiency, diabetes mellitus, chronic obstructive pulmonary disease, and malignancy. Additional risk factors included corticosteroid use, a history of previous device infections, heart failure, pre-procedural fever, anticoagulant drug use, and skin disorders. Notably, age and gender were not considered risk factors in this analysis. However, the Danish device-cohort study showed that younger ages with a previous device infection had a significantly higher risk. (14)

In procedure-related factors, the factor that decreased the risk of infection is antibiotic prophylaxis, which is now the standard of care. Hematomas have been associated with about a ninefold increase in infection risk. (12) Later a BRUISE-CONTROL study, which included data from 659 patients showed threatening ratio of 7.7 for infection in those with clinically

significant hematomas. Within a one-year follow-up, up to 11% of these patients developed infections as a complication. Early reoperation due to hematoma or lead dislodgement was found to be the most significant risk factor for cardiac implantable electric device infection. This is based on data from a device registry matched with Medicare fee-for-service data. Another risk factor for infection would be temporary pacing. This could be due to breaches in sterility protocols during urgent placement, the need for lead re-manipulation, or the fact that the device is a chronic entry point into the bloodstream. The indication for temporary transvenous pacing should be thoroughly evaluated and alternative measures like backup transthoracic pacing or infusion of rate-increasing drugs should be evaluated, like backup transthoracic pacing or the infusion of drugs increases the heart rate considered. Furthermore, replacing the device generator approximately doubles the risk of infection, most likely due to the activation of pre-existing bacterial colonization or the reduced penetration of antibiotics into the encapsulated generator pocket. (14)

There are not many device-related factors for CIED infection. After many analyses and studies, the only significant risk factor turned out to be the abdominal pocket. Data from a Danish registry revealed that device complexity and the number of leads were key factors significantly linked to a higher risk of infection. The hazard ratios for infection were 1.26 for ICD systems, 1.67 for CRT-P systems, and 2.22 for CRT-D systems, compared to pacemakers. (14)

The best way to manage device-related infections is through prevention. A careful assessment should be given to determine whether device implantation's risks outweigh each patient's benefits. In high-risk cases, it might be beneficial if the implantation is delayed or antibiotics are used long-term. One-third to one-half of patients requiring device removal for infection may not need re-implantation. Again in high-risk patients, an epicardial system or leadless pacemakers does reduce the infection risks. Subcutaneous ICDs (S-ICDs) can provide sudden death protection in patients who does not need for pacing. The number of leads and abandoned leads increase the risk of infections and complications. Now, the decisions to remove or to leave the leads should be made on an individual basis; it is important to consider the risks of infection and the difficulty of future extractions. (13)

For patients with fever or signs of active infections, the procedure for CIED implantation should be delayed until the patient is fever-free for 24 hours. If possible, it is recommended to avoid temporary pacing wires because of its high risk for infection. Better glycemic control during the peri-procedural period may reduce infection rates in surgical patients. (15)

It is discovered that pocket hematomas increase the risk of infection. Bridging anticoagulation increases the risk of hematomas and is no longer recommended. For low-risk patients, anticoagulation can be held during the procedure and restarted when the bleeding risk is low. On the other hand, for patients with high risk, continuing warfarin is recommended, but low-molecule-weight heparin (LMWH) should be avoided. Antiplatelet agents should be discontinued 5–10 days before intervention, when possible. (15)

Patients can be tested for S. aureus with nasal swabs for elective procedures. Mupirocin nasal treatment and chlorhexidine skin washing may reduce colonization, though studies specific to CIED are lacking. Pre-surgical washing with antimicrobial agents is common, but evidence for its effectiveness in reducing infections is mixed, and its routine use is not strongly recommended. If chest hair removal is needed, appropriate methods should be used to avoid skin damage. (15)

Prophylactic systemic antibiotics are important for decreasing infection rates in cardiac implantable electric device procedures, with a relative risk reduction of 40–95%. (12) The antibiotics should be administered within one hour before incision to achieve effective tissue levels. The primary organism in acute CIED infections is Staphylococcus aureus, and antibiotics must at least cover this species. While routine coverage for Methicillin-Resistant S. aureus (MRSA) is unnecessary, it may be considered based on local prevalence and patient risk. Commonly used antibiotics include intravenous flucloxacillin or cefazolin, with vancomycin as an alternative for cephalosporin allergies, administered 90–120 minutes before surgery. (15)

Prescribing post-implant antibiotics, ranging from a single dose to a week of treatment, is recommended. The PADIT trial evaluated the effectiveness of additional perioperative antibiotics in nearly 20,000 patients undergoing CIED implantation. They compared a single preoperative dose of Cefazolin to a combination of Cefazolin, Vancomycin, bacitracin pocket wash, and two days of postoperative Cephalexin. The trial found a non-significant 20% reduction in hospitalization for device infections among the high-risk group. Because of low infection rates and the absence of supporting evidence, postoperative antibiotic therapy is highly recommended. (14)

6. Cybersecurity

The Internet connects our personal and professional lives through a unified platform, enabling us to manage various aspects of our daily routines using smart devices. At the same time, this technology offers increased convenience and efficiency but poses serious security risks. The increasing number of connected devices in our daily lives has raised the risks linked to inadequate cybersecurity. Hacking, which refers to unauthorized access to systems to steal information or cause disruption, continues to be a major concern in technology-focused communities. (16)

The internet, software, and computers have become essential tools in health care. Digital technology plays an ever-growing role in our daily lives. However, there is a constant need to protect the systems and data created and stored from threats such as attacks, damages, and unauthorized access. Cybersecurity risks related to cardiac implantable electronic devices are no longer theoretical concerns. The first significant event that brought up cybersecurity risks in cardiac implantable electronic devices occurred in 2016. (16) MedSec, a cybersecurity research firm, and Muddy Waters LLC, an investment firm, identified vulnerabilities in several St. Jude Medical (now Abbott) pacemakers, demonstrating a “battery drain” and a “crash” attack. Following this report, Ransford and colleagues attempted to replicate the crash attack but found no clinically significant effects. Using an experimental model with two hours of high-volume radio traffic, they observed that while the device stopped responding to radio telemetry, it continued to pace as programmed. Additionally, normal communication was restored by moving the device to a different spot in the room. (17)

The FDA issued a safety communication addressing potential vulnerabilities in certain Abbott pacemakers. Abbott subsequently released a firmware update to address these security concerns, which could be installed during a routine clinical visit in under three minutes. The risks associated with the update were minimal, with Abbott estimating a 0.003% chance of complete device failure, a 0.023% chance of lost settings, and a 0.161% chance of update failure. These cybersecurity concerns are particularly significant because CIEDs are invasive and often vital for patient survival. (17)

6.1 Controlled risks

As digital technologies become increasingly integrated into healthcare, the cybersecurity vulnerabilities of CIED’s, such as pacemakers and defibrillators, have emerged as a major

concern. Since these devices are vital for saving lives, cybersecurity measures can help identify and mitigate potential risks. (18)

One of the most significant risks is unauthorized access to CIEDs. While remote access can be used for diagnostic purposes, modifications to critical settings like pacing parameters or anti-tachycardia functions, are not permitted remotely. (19) Attackers can not remotely reprogram the device to change these settings, which makes attacks like this very unlikely. Nevertheless, attackers can still pose a threat by attempting to exploit vulnerabilities related to diagnostic data transmission or other aspects of the system. This could possibly disrupt the device's functioning or even compromise patient safety. (20)

Specific so-called threats include "crash attacks," which will cause the device to stop functioning temporarily, and "battery drain attacks," which shorten the device's lifespan. (19) These forms could potentially endanger the patient's life by disrupting life-sustaining functions and potentially endanger the patient's health. (20) Wireless communication also increases the risk, as the attackers could intercept or even manipulate the data transmitted between the device and external systems, potentially disrupting crucial functions such as pacing or defibrillation. These risks are enhanced by the possibility of firmware vulnerabilities, where cybercriminals could exploit unsecured or outdated software to cause malfunctions. (21)

Furthermore, CIED's store and transmit sensitive patient data to device direct risks, making them targets for data breaches. These attackers could steal personal health information or even track the patient's location. Denial-of-service (DoS) attacks are another concern; potentially, this could overwhelm the device's communication channels and prevent timely medical interventions. (20) Physical proximity also presents different security challenges; attackers with the right equipment could use wireless access points to reprogram the device. Moreover, vulnerabilities introduced during manufacturing or within the supply chain, like backdoors or malware, could compromise device security before it even reaches the patient. (22)

Poor authentication protocols, such as default or easily guessable passwords, increase the risk of unauthorized access. Encryption deficiencies further exacerbate these issues, leaving stored and transmitted data vulnerable to interception. In addition, inadequate monitoring and logging of device activity could allow cybersecurity to go undetected, highlighting the need for real-time monitoring to detect breaches promptly. (23)

We, as humans, also play a role in cybersecurity risks. Healthcare professionals potentially make mistakes, like neglecting critical software updates. Insider threats, whether they are intentional or accidental, pose additional challenges. Devices that fail to meet regulatory or compliance standards are also more prone to attacks, underscoring the importance of adherence to national and international cybersecurity protocols. The design and testing phases of CIED development are critical, as devices not built with cybersecurity in mind could have inherent weaknesses. Comprehensive security testing, including penetration testing, is recommended as a standard practice. (23)

Lastly, we must consider the significance of patient education. Many patients do not recognize the cybersecurity threats their devices face. (22) Not following up on security updates or suggested precautions can make CIEDs susceptible to attacks. By increasing awareness and promoting the correct usage of these devices, patients can significantly contribute to minimizing cybersecurity risks. (23)

As CIEDs rely more on wireless communication and digital technology, addressing cybersecurity risks is paramount to ensuring patient safety. A multifaceted approach involving robust security measures at the hardware, software, and human levels is necessary. From preventing unauthorized access and securing wireless communication to educating patients and adhering to regulatory standards, mitigating cybersecurity risks in CIEDs requires continuous vigilance and adaptation to emerging threats. (24)

6.2 Cybersecurity routine updates and patches

As cardiac electric devices such as pacemakers and defibrillators incorporate more digital and connectivity features, they become vulnerable to cybersecurity threats. This risk to patient health and device functionality has prompted regulatory bodies and manufacturers to prioritize cybersecurity routine updates and patches. (22)

Manufacturers like Abbott and Medtronic have implemented these recommendations by issuing regular software patches and software updates for their devices, addressing known vulnerabilities like remote code execution (RCE) and denial of service (DoS) attacks. (20) For example, Abbott recently provided patches for their pacemakers and defibrillators, which improve not only the cybersecurity but also the battery performance to enhance device safety. (21) Medtronic released their updates for its Paceart Optima cardiac device data system after

identifying vulnerabilities that could allow unauthorized access to patient data. These updates are part of ongoing efforts to safeguard devices as they interact with broader hospital networks and internet-based systems, which may be targets for malicious cyber actors. (23)

Routine cybersecurity updates are essential in preventing unauthorized data access, manipulation, and service disruptions in cardiac devices, which could directly impact patient safety. (22) With the healthcare sector increasingly interconnected, these measures are vital for maintaining operational resilience and patient trust, underscoring the critical role of cybersecurity in modern healthcare technology. (23)

6.3 Cybersecurity signal

Cybersecurity signals refer to measures or communications that help maintain the security and functionality of the device. (24) Cardiac devices, which often include wireless components for remote monitoring and adjustments, enable healthcare providers to manage and track patient health more effectively. However, these same features also present cybersecurity risks, including unauthorized access to device data or interference with device function. (25)

Encrypted communication is a source to secure data between the cardiac device and external systems such as hospital networks or remote monitoring systems. Encryption makes it extremely difficult for unauthorized users to intercept and manipulate sensitive data. Many cardiac devices are also designed to authenticate the signals they receive to ensure they come from authorized sources, such as the patient's medical provider. Authentication protocols help prevent unauthorized devices or individuals from sending commands to the cardiac device, which could potentially compromise patient safety. (25)

Cybersecurity signals often include the use of regular updates and patches. These updates address new vulnerabilities as they are discovered, helping to prevent potential exploits. For example, companies like Abbott and Medtronic regularly release device updates that fix security flaws in wireless communication and data management systems. (26)

Some advanced cardiac devices now include software capable of detecting unusual signals or activity patterns, which can signal potential cyber threats. (17) The device may alert healthcare providers to investigate further or temporarily disable non-critical functionalities to protect core operations if detected. Together, these cybersecurity signals help ensure the

safety and functionality of cardiac devices in an increasingly connected healthcare environment. (26)

6.4 FDA guidance

The FDA is responsible for ensuring the safety and effectiveness of medical devices, including addressing cybersecurity concerns, specifically for connected and implantable devices. Its guidance defines key cybersecurity terms such as vulnerabilities (potential weaknesses in devices or systems), threats (events that could exploit vulnerabilities), and exploits (actual instances where vulnerabilities are utilized, compromising device safety or function). Although, according to the FDA, vulnerabilities have been identified across devices, there have been no reported cases of exploits. (27)

The FDA is responsible for evaluating the cybersecurity of devices both before and after they hit the market. (28) This includes providing manufacturers with guidance on how to incorporate cybersecurity measures, monitor vulnerabilities, and improve transparency in their risk management processes. Although these guidelines are not legally enforceable, they outline the FDA's expectations for manufacturers and promote patient safety by incentivizing proactive cybersecurity practices. Additionally, the FDA works alongside federal agencies, academics, and ethical hackers to pinpoint potential vulnerabilities in devices. (29)

Furthermore, the FDA is working on effective ways to communicate cybersecurity risks to patients, nothing that patients prefer to control the amount of information they receive and be informed of threats promptly. A 2020 FDA discussion paper further explored best practices for relaying cybersecurity risks to patients and clinicians aiming to improve patient awareness and engagement in managing these risks. (29)

6.5 Vulnerability

The constant change in the healthcare environment and world interconnectivity exposes information technology to increased vulnerabilities. The regulatory agencies, the healthcare community as well as manufacturers are highly aware of the challenge. (18) By gaining unauthorized access to diagnostic or therapeutic medical equipment, hackers can cause different types of problems. These differ from ransomware attacks to denial of service

attacks, sensor malfunction, or degradation of device function. CIEDs could possibly be reprogrammed, or their regular function could be degraded or disabled. Remotely monitored CIEDs also require frequent communication between a home transceiver and the device using radiofrequency telemetry, adding an additional stage that could be vulnerable to a cybersecurity breach. (30)

Unreliable cybersecurity prioritization in healthcare organizations and the wide array of manufacturers supplying equipment has led to notable cybersecurity vulnerabilities. (18) Now days modern medical devices such as CIED's, rely on both hardware and software components. Many healthcare institutions often use software more than the developer supports, and the device manufacturers may not be able to provide timely updates to identify cybersecurity vulnerabilities; this will make the software vulnerable to attacks and allow an entry point for hackers to get access to the interconnected information technology environment of a health care organization. (31)

A shift in the healthcare community's culture is important to reduce vulnerabilities. Healthcare institutions have to make a commitment to timely administration of software updates and to updating or retiring software, which is no longer enforced. (30) Clinicians should take a proactive approach by consulting with information technology specialists to confirm that both new and existing systems and equipment align with recommended cybersecurity standards, which would reduce the potential risks. Healthcare professionals have to be educated about cybersecurity risks, how to minimize vulnerabilities, and as well how to include cybersecurity in conversations with patients. (32)

In the context of CIEDs, where reliance on these devices is high, clinicians need to recognize that cybersecurity vulnerabilities are typically addressed by updating device firmware. This firmware is a specialized software layer embedded within the hardware, enabling essential, low-level functions without which the device could not operate. Addressing security risks often needs these types of updates to ensure continued safe functionality. (30) When deciding whether to update a CIED's firmware, it is important that clinicians consider both the cybersecurity risks posed by vulnerabilities and the potential impact of the update itself, which, while typically low, carries some risk of affecting the device's lifespan or function. Now, when these factors are balanced, it is essential to ensure patient safety and device reliability. The best practice model involves providing patients with periodic software updates during their in-person CIED checkups. This approach addresses new vulnerabilities

as they arise, helping to manage cybersecurity risks while integrating updates into the routine care and monitoring process. (31)

The interconnected nature of healthcare settings, along with the frequent use of outdated and unsupported software, makes these facilities especially susceptible to cybersecurity threats and exploitation. Industry and regulatory agencies now prioritize security from the earliest stages of product design, aiming to reduce vulnerabilities and safeguard patient safety. (18) By growing resilience into CIEDs, they ensure that essential life-sustaining functions continue even if a security breach happens. For patients with CIEDs, this focus on security is critical, as their well-being depends on the device's reliable operation and any potential threat to functionality that could lead to heightened feelings of vulnerability and concern for their safety. Patients turn to their healthcare professionals for guidance. It is essential that professional organizations, and their partners educate healthcare professionals to reduce cybersecurity risks and to understand the present mechanisms in place to apprise threats. It is also very important to set expectations at the time of implantation that medical devices, like CIEDs, will need software updates till the battery is depleted. When certain vulnerabilities become known, the risk assessment has to balance the ease of exploitability and weigh the consequences and benefits of continuing therapy, such as remote monitoring of CIEDs. (32)

7. Radiotherapy

Improvements in monitoring and therapies have significantly improved outcomes in cardiovascular disease and cancer treatments. (33) Due to overlapping risk factors, many cancer patients also have cardiovascular disease when beginning treatment. In 2021, it was estimated that 1.9 million new cancer cases would have been diagnosed, with about half undergoing radiation therapy. Additionally, it is predicted that by 2035, over 45% of the U.S. population will have some form of cardiovascular disease. (34) Annually, nearly a million pacemakers and ICDs are implanted, highlighting the prevalence of cardiac care needs within the oncology patient population. Ionizing radiation, particularly thoracic RT, can potentially harm a cardiac implantable electronic device. In some cases, the device may even disrupt radiation treatment itself. For optimal and safe radiotherapy in patients with CIEDs, a coordinated, multidisciplinary approach is necessary to provide effective and safe RT for patients with existing CIEDs. (35)

Radiotherapy is used for many different reasons, including palliation, definitive treatment and adjuvant therapy following surgery. To see if the patient is in need of radiotherapy, the patient has to undergo computed tomography simulation in the treatment position where the target and all nontarget normal tissues are identified. The radiation dose, which is measured in Grays, the duration of treatment, which is the number of fractions, and the level of sophistication of treatment are determined by numerous clinical factors, along with the urgency of treatment, the sensitivity of the tumor to radiotherapy, and as well the goal of the therapy. Radiotherapy treatments aim to concentrate the highest possible dose on the tumor while minimizing exposure to nearby healthy tissues. Advanced imaging, motion control, and tailored delivery adjustments allow for further personalization of precision radiotherapy. (35) Superficial tumors (located less than 4 cm from the skin) are treated with electrons, whereas deeper tumors are treated with photons. These strategies enhance targeting accuracy and reduce collateral damage to surrounding tissues. Interest in proton therapy has been growing, especially due to its availability only at certain institutions and its capacity to target deeper tumors through precise energy deposition. This technique has advantages over photon-based approaches by limiting low-dose radiation exposure to surrounding areas and reducing the overall radiation dose received by normal tissues. Clinical data indicates that proton therapy shows promising effectiveness and manageable toxicity for various cancers, including those in the thoracic region, making it a valuable option in specific cases. (36)

For patients with a cardiac implantable electric device, radiotherapy planning should avoid directing radiation beams at or through the device to limit radiation exposure. Another critical factor during treatment is neuron contamination from nuclear reactions within the linear accelerator, as neutrons can be particularly harmful to CIEDs. (35)

7.1 Types of radiotherapy

For patients with cardiac implantable electronic devices, choosing a suitable type of radiotherapy is critical due to the unique risks that radiation can pose to the functionality of these devices. Each radiotherapy type needs specific considerations, which are based on the depth and location of the tumor, the patient's dependency on their CIED, and the proximity of the device to the planned treatment area. The ultimate goal is to maximize treatment effectiveness while minimizing potential harm to the device, ensuring both the efficacy of the therapy and the patient's cardiac safety. (37)

Photon therapy, commonly used in deep-seated tumors, is the standard form of radiotherapy. Nonetheless, photons produce scattered radiation, which can interfere with CIEDs, especially if the beams are directed near the device. (37) Careful planning before the radiotherapy is important to avoid direct radiation paths through the CIED, as scattered photons may cause unintended device malfunctions. Shielding techniques and precise field adjustments are often employed to limit exposure to the device area. (38)

Electron radiation therapy is effective for treating superficial tumors near the body's surface, reaching depths of around 4 cm. Electrons produce reduced scatter radiation beyond the treatment area, lowering the risk of CIEDs when the treatment is confined to the tumor surface. (35) However, if the CIED is close to the electron field, careful monitoring and potential shielding may still be required. Electron therapy presents a somewhat safer option for patients with CIEDs, especially when deeper, high-dose radiation is not needed. (36)

Proton therapy is beneficial in cases where tumor control is required for deeper tissues without compromising nearby critical structures. (37) This technique allows precise energy delivery to the tumor, sharply minimizing dose deposition outside the targeted region and sparing surrounding tissues, including any nearby CIEDs. Although proton therapy reduces low-dose exposure to non-targeted areas, including the CIED, treatment planning still considers device placement and incorporates shielding if needed, particularly when the device lies close to the tumor or within potential radiation scatter areas .(38)

Neutron radiation is not typically used directly in radiotherapy, even though it can be generated as a byproduct in high-energy photon or proton therapy when using certain linear accelerators. (35) Neutrons pose a high risk to CIEDs, as they can disrupt device function and may even cause irreparable damage. Neutron contamination is especially relevant when treating tumors close to CIEDs, and advanced treatment centers typically implement equipment and protocols to minimize or eliminate neutron exposure in such cases. Accurate planning is crucial, especially in facilities equipped with high-energy equipment. (37)

To ensure effective treatment and patient safety, RT planning for individuals with CIEDs is highly collaborative and involves input from oncologists, medical physicists, and cardiologists. Key strategies include customizing radiation fields, optimizing beam angles to avoid the device, and using shielding as necessary. Additionally, continuous monitoring of the CIED function throughout the RT process helps detect any potential device interference early, allowing for immediate adjustments. These coordinated efforts provide a safe

framework to treat cancer effectively while safeguarding the integrity and functionality of the cardiac device. (38)

7.2 Mechanism of action of radiotherapy

The effects of radiation therapy on CIEDs vary widely and are based on limited clinical data. The interaction of radiotherapy in patients with a cardiac pacemaker or implanted cardioverter-defibrillator raises certain concerns. Ionizing radiation could cause latent or permanent damage to CIEDs, which could result in loss of function in patients with asystole or ventricular fibrillation. (37)

Pacemakers expose the ventricular electric activity and are constricted if the intrinsic heart rate is sufficient. Pacemakers stimulate the heart in case of the heart rate drops below the programmed threshold rate. ICD are used in case of symptomatic ventricular tachycardia (VT) and to prevent sudden cardiac death due to ventricular fibrillation. (35) ICD functions include PM activity, anti-tachycardia pacing, and defibrillation therapy. The usage of complementary metal-oxide semiconductors (CMOS) in current CIEDs has led to the outcome of reduced energy consumption, enhanced reliability, and the development of smaller, more compact devices. Compared to the bipolar transistors used in older models, the current CMOS technology is more vulnerable to damage from ionizing radiation. Exposures like this could generate electron-hole pairs, which could cause electrical leakage or short circuits within the device. (39)

These incidents can occur anywhere within the CMOS structure and may even affect multiple locations simultaneously. The damage caused can range from temporary malfunctions to permanent failures. In CIEDs, the capacity to tolerate radiation is often constrained by factors. In CIEDs, the capacity to tolerate radiation is often constrained by factors of permanent failures. In cardiac implantable electric devices, the capacity to tolerate radiation is usually constrained by factors like the intricate design packed into a small device, limited battery life, thinner protective casings with reduced shielding, and the reliance on random access memory (RAM). RAM stores patient-related data by a small number of highly volatile energy. As a result, any damage to the RAM can potentially lead to complete loss of functionality in a cardiac implantable electronic device. (35)

The most critical malfunctions include impaired sensing, either loss or inaccurate detection, disrupted stimulation (altered frequency or amplitude), modifications to antitachyarrhythmia therapy (ATA therapy) settings in ICDs, premature battery depletion, telemetry failure, and, in the most severe cases, complete device failure. (41)

The clinical impact of CIED failures varies depending on the patient's condition. For instance, loss of pacing may be relatively benign in a patient with sick sinus syndrome, but this could result in life-threatening cardiac pump failure in someone with a grade III atrioventricular block. While the exact prevalence of pacemaker dependency remains unknown, it can arise from various causes. In patients who are pacing-dependent, PM failure may lead to ineffective or absent stimulation, potentially causing symptomatic bradycardia or asystole. These types of events may necessitate immediate intervention, such as resuscitation or temporary pacing support. Conversely, a loss of stimulation could cause rapid pacing, known as a "runway pacemaker" or "runaway ICD", which leads to severe complications such as systolic blood pressure loss, cardiogenic shock, angina pectoris, or ventricular tachycardia (VT). (35.36) Impaired sensing may result in excessive, unsynchronized ventricular stimulation during the T wave, which could trigger ventricular fibrillation (VFib), followed by cardiac arrest and potentially even death. Additionally, the failure to sense properly may prevent the activation of antitachyarrhytmia therapy in ICDs. In some cases, electromagnetic interference or artificial signals may mimic high ventricular frequencies, causing inappropriate shock delivery or other adverse events. (38) CIED can cause failure when photon radiation occurs either when the device is straight irradiated or when the energy is >6 MV. There is no established threshold dose or clear linear correlation for radiation-induced damage to cardiac implantable electric devices. However, the risk of device malfunction is believed to rise with increasing radiation dose. It is important to know that the energy delivered to a CIED during radiation therapy is cumulative, meaning that exposure over time adds up, potentially increasing the risk for damage. Energy radiation above 6-10 MV generates an increased production of secondary neutrons, which can significantly damage the RAM or CMOS components of CIEDs. At 18 MV, pacemaker defects have been observed even at relatively low radiation doses, like 15 cGy. Conversely, studies have shown that exposing 20 ICDs to 6 MV photon beams at doses up to 4 Gy caused no detectable ionizing radiation-related effects. Nevertheless, when ICDs were exposed to 18 MV radiation, whether positioned near the central beam or at a distance of 140 cm, errors happened around eight times more frequently compared to exposure at 10 MV. This

highlights the significant impact of radiation energy levels on the likelihood of device malfunction. (41)

At 18 MV, neutron production is significantly higher by approximately 14-20 times than at 10 MV. Despite this, photon scatter radiation dose rain is similar, measuring 18.8 mSv for 10 MV and 20.23 mSv for 18 MV. Studies highlight that ICDs exposed to 18 MV radiation showed failures, whereas no such issues were observed at 6 MV. When CIEDs were irradiated directly within the beam up to a cumulative dose of 150 Gy with 2 Gy per fraction, only one error was noted at 6 MV, while 14 malfunctions occurred at 18 MV. Case reports also indicate that CIED malfunctions can occur with 10- and 18 MV photon radiotherapy, even when the treated tumors are located far from the devices. Dose rate effects were evaluated systematically; a study was made where 96 pacemakers revealed that a dose rate below 0,2 Gy/min does not cause detectable issues, while rates of 1 Gy/min cause two defects and higher than 8 Gy/min over 70% of the tested devices failed. These failures primarily affected the electronics critical for sensing, potentially resulting in device resets, asystole, or inappropriate defibrillation therapy. Nevertheless, when the CIED is positioned outside the direct radiation field, the resulting dose rates are much lower, typically below 1 Gy/min, which reduces the likelihood of radiation-induced damage. (41)

Electron radiation poses less risk due to the reduced generation of secondary neutrons at equivalent energy levels. For instance, at 15 MeV, it generates just 5% of the secondary neutrons produced by photon radiation at the same nominal energy, and at 25 MeV, only 20% of the secondary neutrons produced by photon radiation at the same nominal energy. (41) Additionally, brachytherapy has a minimal impact on CIEDs, owing to the energy levels used (20-380 keV) and the sharp dose gradient involved. Notably, there have been no reported incidents of radiation-induced damage to CIEDs linked to brachytherapy. (35)

Radiological imaging techniques that utilize ionizing radiation operate at lower energy levels (kV) and involve significantly smaller radiation doses (0.01-0.4 Gy) than radiotherapy. However, direct exposure of a cardiac implantable electronic device (CIED) to radiation during imaging procedures can still lead to device malfunctions or failures. (41)

A professional study was made, where 811 patients with CIEDs who underwent radiation therapy between 2007 and 2018 across four Canadian centers (Figure 1). Only 4% from the case ended up with CIED malfunction, and the most common issues were increased lead threshold (22%) and reduced sensing (41%). High beam energy (≥10 MV) was the strongest

risk factor, while total radiation dose was not significant. Most patients received megavoltage (MV) photon therapy, with neutron-producing radiation identified as the main cause of malfunctions. Despite risks, only 39% of radiation oncology departments have CIED management policies. (42)

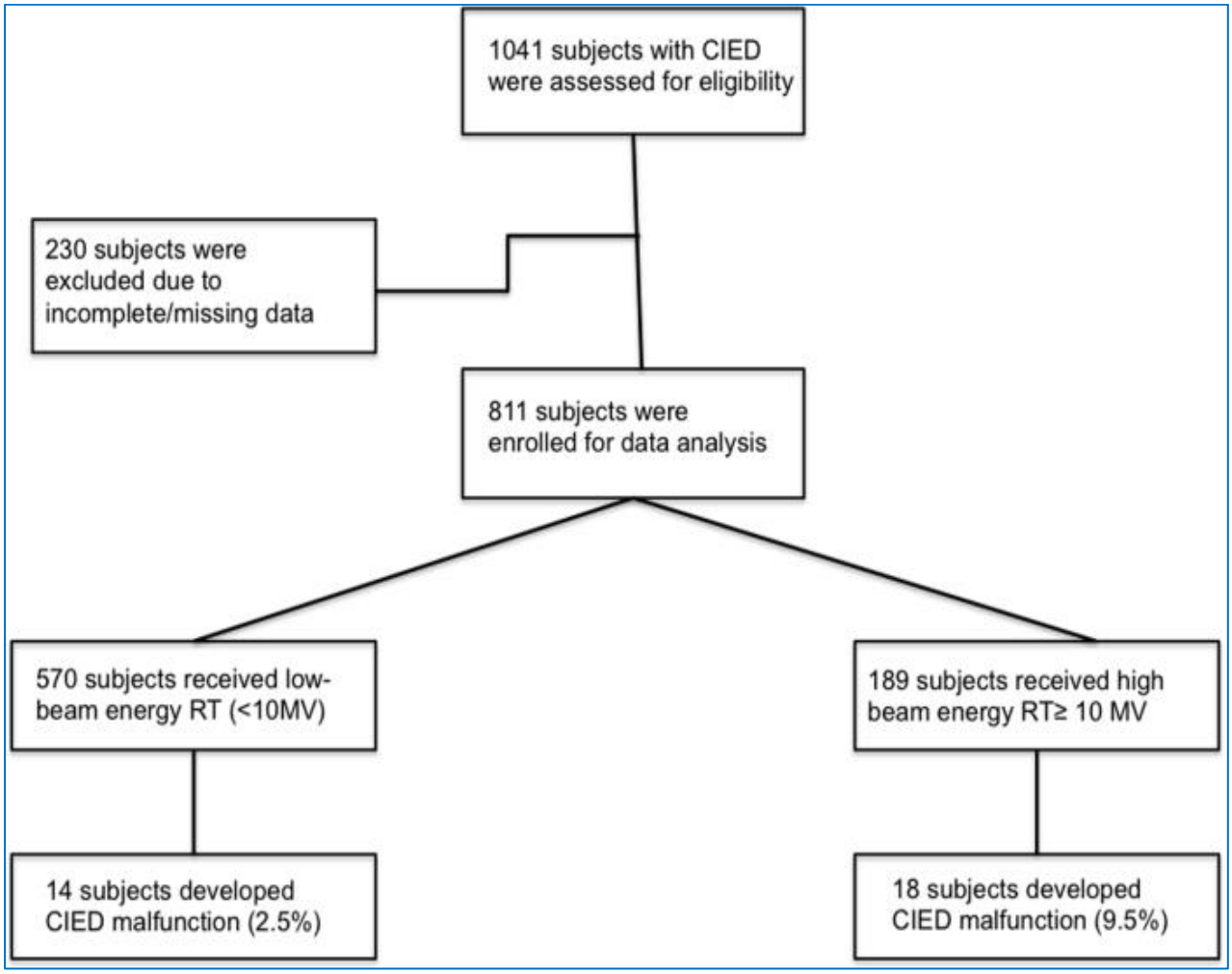

Figure 1. Assessment of Radiation-induced malfunction in cardiac implantable electronic devices. (42)

Out of 1041 patients with CIEDs who received radiotherapy, only 811 patients with available data were included in this study. The mean age for patients with CIEDs underwent radiation therapy was 78.4 +/- 9.4 years for CIEDs with normal function. Patients with CIEDs who underwent malfunction, their age was around 79.3 +/- 11.5 years. Majority of the patients who underwent this study and ended up having malfunction were male (5.2%); Women had only 2 CIED malfunctions out of 236. (42)

7.3 Impact on different cardiac rhythm devices

The effects of radiotherapy on cardiac implantable electronic devices, such as pacemakers and implantable cardioverter-defibrillators (ICDs) are influenced by the type of device, the patient dependency on the device, the absorbed radiation dose, and the planned radiotherapy energy. (35) Among CIEDs, ICDs are the most sensitive to ionizing radiation compared to pacemakers, which is due to the presence of boron in their internal circuitry; this increases their susceptibility to damage. Elevated radiotherapy (RT) dose rates can also induce oversensing and inappropriate ICD shocks, making careful planning essential. Dose rates below 0.01 Gy/min are generally considered low-risk for ICDs. (39)

Patients who rely on pacemakers—specifically those with inadequate spontaneous ventricular activity or low heart rates—are at high risk. (35) Radiotherapy can disrupt pacemaker function in these individuals, potentially resulting in severe consequences like asystole. A thorough evaluation of the patient's underlying rhythm and dependence on the device is essential, particularly for those utilizing cardiac resynchronization therapy devices. (38)

When planning a treatment, it is necessary to estimate the radiation dose absorbed by the device. The risk could increase significantly when the dose exceeds 5 Gy, which is most likely to occur when treating areas such as the thorax, neck, or proximal upper extremities. Typically, doses remain below 2 Gy when the radiation field is at least 5 cm away from the device. (36)

Radiation energy plays a significant role in determining the risk to CIEDs. Energies that are associated with neutron contamination, including photon energy above 10 MV, electron energy exceeding 20 MeV, and proton therapy, pose the highest risk of device malfunction, even at relatively low absorbed doses. (35) The generation of secondary neutrons can affect devices positioned far from the radiation field, highlighting the limitations of protective measures such as device relocation. While relocation of the device may improve radiotherapy delivery when the tumor lies in proximity to the CIED, it is not necessarily protective against neutron contamination due to its ability to penetrate substantial distances. (36)

When devices are relocated, the benefits must be weighed against possible complications, especially the risk of infection, particularly if lead revision is needed. (35) Additionally, the sparse data regarding the impact of radiotherapy on newer subcutaneous cardiac devices or leadless pacemakers underscore the importance of following manufacturer guidelines.

Planning radiotherapy should incorporate shared decision-making discussions with patients. These discussions should consider options for permanent device deactivation or removal,

guided by the patient's cardiovascular and oncologic prognoses, goals of care, and overall treatment objectives. (36)

7.4 Safety of radiotherapy in CIEDs patient

The safety of radiotherapy in patients with cardiac implantable electronic devices, such as pacemakers and implantable cardioverter-defibrillators, is a critical area of concern in medical practice. (40) While radiotherapy is an essential modality for treating various cancers, its interaction with CIEDs necessitates careful planning and multidisciplinary collaboration to mitigate risks to the devices and the patient.

Modern radiotherapy techniques often employ high-energy photon beams, which can create secondary neutron radiation, especially at energies above 10 MV. These neutrons can damage the sensitive components of CIEDs, such as complementary metal-oxide semiconductors (CMOS) and random access memory (RAM), potentially leading to malfunctions such as device resets, inappropriate shocks, or complete loss of functionality. Due to their advanced circuitry and reliance on boron, ICDs are generally more vulnerable than pacemakers. (41)

Key safety measures include estimating the radiation dose absorbed by the device and ensuring it remains below established thresholds. For instance, a dose below 2 Gy is generally considered low risk, while doses exceeding 5 Gy pose a higher likelihood of damage. Additionally, dose rates also play a significant role, as higher rates (>1 Gy/min) have been linked to increased malfunction risks. (35)

Comprehensive planning is crucial for high-risk scenarios, such as pacemaker-dependent patients or tumors located near the thorax. Strategies include avoiding direct radiation beams through the device, utilizing lower-energy photons or protons, and ensuring multidisciplinary discussions between oncologists, cardiologists, and medical physicists. (36)

In some cases, the CIED can be relocated, but this option carries its own risks, including infection and lead damage. (39) Advanced imaging techniques and real-time monitoring during treatment further enhance safety. Patients should also be closely observed during and after radiotherapy for any signs of device malfunction.

7.5 Guidelines for radiotherapy in CIED patients

After a few decades of no guidelines for managing patients with CIED undergoing radiotherapy, two updated guidelines for managing this patient shortage have been published. The two guidelines are the 2019 AAPM TG-203 and the 2017 HRS expert consensus on MRI and radiation exposure in patients with cardiac implantable electric devices. (43)

The AAPM TG-203 guideline provides a detailed framework for the safe administration of radiotherapy in patients with CIEDs, including pacemakers and implantable cardioverter-defibrillators. This comprehensive guidance ensures a balance between effective cancer treatment and the protection of these critical cardiac devices from radiation-induced damage. (43)

CIEDs are categorized by their susceptibility to radiation. Pacemaker-dependent patients are the higher risk if the device fails, as their cardiac function relies entirely on the device's ability to stimulate the heart. Radiation effects, including secondary neutron production, pose unique risks, especially at higher photon beam energies (>10 MV). (36)

It is important to minimize the dose absorbed by the CIED. The TG-203 guideline emphasizes maintaining doses below 2 Gt whenever possible, as higher doses correlate with an increased likelihood of device failure. In cases where the target area is near the CIED, treatment planning must include precise dose mapping and beam adjustments to minimize direct radiation to the device. Photon energies above 10 MV and electron energies above 20 MeV are discouraged due to neutron contamination risks, which can disrupt the functionality of the sensitive electronic components in CIEDs. (43)

During radiotherapy, close collaboration between radiation oncologists, cardiologists, and medical physicists is necessary. Continuous ECG monitoring during the initial treatment session allows for the immediate detection of any CIED interference. (36) For high-risk scenarios, monitoring throughout the RT course is recommended. Pre-treatment interrogation of the device establishes a baseline for comparison, while post-treatment interrogation identifies any changes or damage resulting from radiation exposure. (39)

Programming the device appropriately before treatment can reduce risks. As an example, deactivating rate-adaptive sensors or ICD shock functions can prevent inappropriate therapies triggered by radiation interference. (40) After treatment, devices are reprogrammed to their original settings and thoroughly tested for functionality.

The guideline underscores the importance of informing patients about the potential risks associated with radiotherapy. This includes the possibility of pacing disruption, inappropriate shock delivery, or even total device failure. Shared decision-making is encouraged, considering alternative treatment approaches or device relocation for cases where the tumor is located near the CIED. (43)

A significant aspect of TG-203 is its focus on secondary neutrons produced during high-energy radiation. These neutrons can damage the CMOS and RAM components of CIEDs, leading to permanent device malfunction. The guideline advises against using high-energy beams whenever alternatives are available. (43)

The TG-203 guideline ensures that patients with CIEDs receive safe and effective radiotherapy while minimizing the risks to their devices. It provides a structured approach to addressing the challenges posed by modern cancer treatments and sophisticated cardiac devices. By integrating multidisciplinary collaboration and advanced planning techniques, the guideline supports optimal outcomes for patients. (43)

8. Electromagnetic interference

CIEDs have become essential in managing various cardiac conditions, encompassing permanent pacemakers (PMs) and implantable cardioverter-defibrillators (ICDs). Their usage has significantly expanded in recent years, with over 300,000 devices implanted annually in the United States since 2019. (44) As these devices become more prevalent, their functionality and safety challenges, particularly electromagnetic interference (EMI), have garnered increasing attention.

EMI arises when CIEDs are exposed to electromagnetic signals from internal and external sources, like smartphones, headphones, metal detectors, and medical equipment such as deep brain stimulators, spinal cord stimulators, and electrocautery devices. Furthermore, surgical procedures involving electrical instruments can exacerbate these interactions. Such interference can have severe consequences for patients. As an example, EMI may be misinterpreted by PMs as intrinsic cardiac activity, which could result in pacing inhibition that leads to bradycardia or even cardiac arrest. (44) Similarly, ICDs may falsely detect arrhythmias, triggering inappropriate shocks that can cause discomfort, distress, or harm to the patient. (45)

Despite all the documented incidents, large-scale multi-center studies on EMI and CIEDs lacking. Current management guidelines largely rely on expert consensus and anecdotal experiences, underscoring the critical need for further research to enhance safety protocols. Addressing the risks of EMI is crucial as the complexity and number of electronic devices continue to rise in modern healthcare and everyday environments. (45)

8.1 Sources of electromagnetic interference

Electromagnetic interference (EMI) poses ongoing challenges for patients with cardiac implantable electric devices, including pacemakers and implantable cardioverter-defibrillators. These devices are susceptible to interference from various sources, including other medical implants, therapeutic devices, and external environmental signals, which could lead to inappropriate functioning. (46)

One significant source of EMI arises from left ventricular assist devices (LAVDs), which can interfere with pacemakers and ICDs due to their electrical noise. Case reports have documented situations where LVAD pump operation caused over-sensing in pacemakers or inappropriate ICD shocks. Adjustments to the device programming, such as turning off low-frequency filters or replacing subcutaneous ICDs with transvenous systems, can help mitigate these interactions. (46)

Deep brain stimulators (DBS) and spinal cord stimulators (SCS) have been shown to be less likely to cause EMI-related issues in CIEDs. Studies and case reports generally demonstrate safe coexistence, although occasional interactions have been noted. For example, a single ICD shock was reported to deactivate DBS systems in one case. Proper device placement and programming significantly reduce the likelihood of interference. (44)

In contrast, transcutaneous electrical nerve stimulation (TENS) units pose a higher risk of interference with ICDs. Case studies have revealed instances of inappropriate shocks caused by EMI during TENS therapy. These effects are more pronounced in subcutaneous ICDs due to their sensitivity to low-amplitude, high-frequency signals. Older-generation pacemakers may also be affected, particularly during synchronous pacing. (44)

It is essential to minimize risks throughout pre-use testing under ” worst-case scenario” conditions. This involves setting the stimulator and the cardiac device to their maximal operational outputs to assess potential interference. Once established, adjustments are made

to ensure therapeutic efficacy while safeguarding CIED functionality. For LVAD patients, optimizing device function and favoring right ventricular pacing over biventricular pacing can further reduce EMI risks. (46)

Overall, while interactions between CIEDs and various devices occur relatively infrequently, they can have significant clinical implications. (45) Careful device programming and individualized patient management are crucial to ensuring the safety and functionality of patients with these life-sustaining implants.

8.2 Mechanism of interaction

Electromagnetic interference could disrupt the operation of cardiac implantable electronic devices, such as pacemakers and implantable cardioverter-defibrillators, through various mechanisms. CIEDs rely on sensitive circuits to monitor heart activity and deliver therapeutic interventions. (47) When exposed to electromagnetic signals from external or internal sources, these circuits may misinterpret signals, which leads to inappropriate responses.

One primary interference mechanism is oversensing, where electromagnetic signals are detected as physiological activity. This can inhibit pacemakers, potentially causing bradycardia or asystole, or trigger inappropriate shocks in ICDs due to perceived arrhythmias. EMI could also introduce electronic noise, distorting the signals the device processes. Electromagnetic coupling may induce currents in the device leads, potentially causing tissue stimulation or malfunction. (47)

Strong EMI, such as from radiotherapy or industrial equipment, can damage the internal circuitry of CIEDs, reset or reprogramme them into a ”safe mode,” and disrupt therapeutic delivery. Familiar EMI sources include medical devices like MRI machines, electrocautery tools, industrial machinery, and consumer electronics, such as smartphones and wireless chargers. (48)

Modern CIEDs incorporate shielding, signal filters, and adaptive software to minimize interference. However, careful clinical management is necessary to evaluate potential risks and ensure device functionality, especially during medical procedures. Pre-procedure evaluations, adherence to manufacturer guidelines, and post-exposure device interrogation help mitigate EMI risks, ensuring patient safety and device reliability. (48)

EMI from swimming pools can affect CIEDs, potentially leading to inappropriate therapy (Figure 2). In a professional case study, a patient experienced malfunctioning CIED activity due to EMI while swimming. Even though no catastrophic events happend, EMI could result in inappropriate pacing inhibition, unnecessary anti-tachycardia pacing, or defibrillation, which could cause serious risks. Swimming pools are often missed as EMI source, but insufficiently grounded electrical components such as filters and lights can generate signals detected by CIEDs. Healthcare providers, like cardiologists should recognize this risk and include swimming pool safety in standard patient education after device implantation. (49)

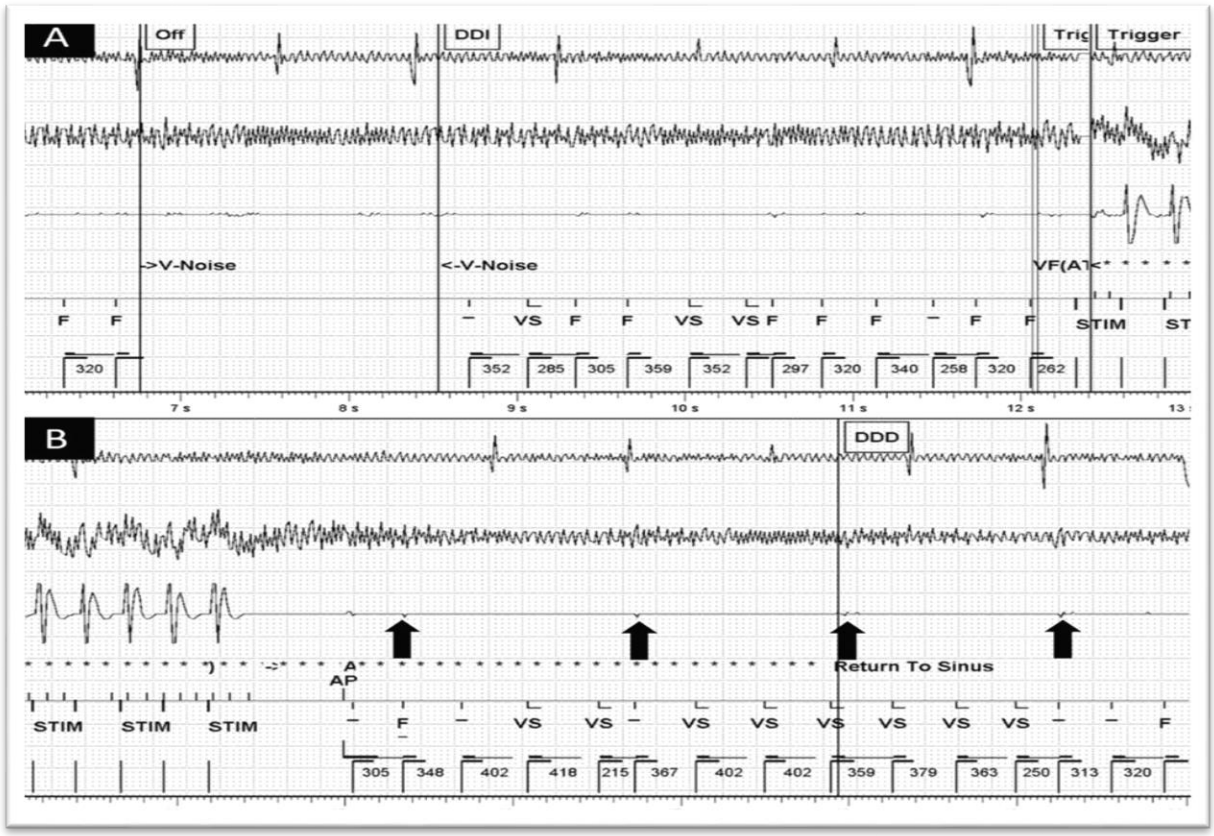

Figure 2. The image explains how swimming pools can cause electromagnetic interference on a implantable cardiac device. (49)

61-year old male, having a complex history involving nonischemic cardiomyopathy, polymorphic ventricular tachycardia, and complete heart block. He underwent cardiac resynchronization therapy with defibrillator (CRT-D). The patient started to feel lightheaded while swimming in a pool near a poolside bar with underwater lights and when he was swimming away from the bar his symptoms started to relive. An intracardiac electrogram (IEGM) from his CRT-D device revealed electromagnetic interference during these episodes.

The figure (A,B) shows an electrogram from a CRT-D device. 1st row is the atrial lead, 2nd row is the summed electrogram from the ventricular lead, the 3rd row shows the ventricular lead, and the 4th row is the marker channel, which shows how

the device interprets and responds to the signals. The CRT-D device initially detects electromagnetic interference as noise, but then misinterprets it as ventricular fibrillation (VF), this triggers a response by switching from DDD (this ensures a proper antrioventricular (AV) conduction.) to DDI mode (this will disable the atrial tracking). Then it satrts with antitachycardiac pacing (ATP), marked as STIM. Following ATP, the device starts to undersense the ventricular noise and mistakenly think it is arrhythmia.

The arrows pointing upwards, indicate intrinsic ventricular activity, this is not synchronized with the atrial events. Despite the fact that no shock was delivered, the continued oversensing of noise leads to pacing inhibition. This device was set with noise reversion off, a protective pacemaker feature switches to asynchronous mode when artifact is present. (49)

8.3 Effect on different implantable cardiac rhythm devices

Electromagnetic fields (EMFs) interact with human tissues and medical devices, producing direct and indirect effects. These effects are especially significant in environments like MRI facilities, where powerful static, gradient, and radio frequency (RF) fields are present. (48)

Direct effect on the tissue involves biological changes caused by EMFs in the body. Common issues include dizziness and sensory stimulation, as well as tissue heating. In case of dizziness and sensory stimulation, strong static magnetic fields can induce dizziness, particularly if individuals move quickly near the center of the field. This is caused by the electrical fields generated in tissues interacting with the magnetic environment. Gradient magnetic fields, which fluctuate to enable imaging, can induce electric currents that stimulate nerves and muscles, leading to tingling sensations or involuntary muscle twitching. Visual disturbances like phosphenes may also occur as electric currents stimulate the retina or optic nerve. (50) In tissue heating, RF fields used in MRI excite protons in the body, transferring energy that manifests as tissue heating. This heating depends on factors such as the RF field's strength, pulse duration, and the patient's size. (51) While typically minimal, excessive heating can cause burns if conductive loops from the skin or metallic objects are present. Safety protocols, such as monitoring the specific absorption rate (SAR), help prevent overheating and protect sensitive organs like the eyes and reproductive tissues. (50)

Indirect effects arise from EMFs interacting with external objects or implants, posing unique risks. Static magnetic fields create strong forces on Ferromagnetic objects, turning them into dangerous projectiles. Such objects may also more or align with the magnetic field direction within a patient's body, leading to potential injury. This risk necessitates strict restrictions on objects in MRI rooms, with only MRI-safe or MRI-conditional items permitted. (48) Ferromagnetic implants can shift or rotate in strong magnetic fields, while non-ferromagnetic

ones may cause image distortions or artifact formation due to interactions with gradient fields. RF fields can further heat metallic implants, harming surrounding tissues or affecting the implant's functionality. Although modern implants are often MRI-compatible, older devices may not meet safety standards, requiring detailed evaluation before imaging. (50) EMFs can disrupt implanted electronic devices like pacemakers or defibrillators, particularly from static magnetic fields. These disruptions may include distorted signals, induced currents, or overheating from conductive loops in device wires. Such risks highlight the importance of using updated databases to confirm device compatibility. (52)

Electromagnetic interference poses varying degrees of risk to cardiac rhythm devices like pacemakers and implantable cardioverter-defibrillators, depending on the source and proximity of exposure. Modern shielding in microwave ovens has eliminated concerns regarding pacemaker interference, making them safe for patients. (48) Airport metal detectors are generally safe, but patients are advised to pass through quickly, as prolonged exposure or misuse of handheld metal detectors can potentially cause inappropriate ICD shocks. Cell phones, particularly those operating at high power or placed directly over the implant, may cause over-sensing or noise reversion; however, maintaining a distance of at least 8 to 10 cm minimizes this risk, and most modern devices handle such interactions well. European phones, operating at higher power levels, require additional caution. Electronic article surveillance devices (EASDs) in retail environments can disrupt pacing, especially with prolonged exposure near detection gates, necessitating swift passage through these areas without lingering. Induction ovens have been tested and shown to pose no EMI risks for bipolar or right-sided unipolar pacemakers. Less commonly, high-voltage power lines, improperly grounded appliances, and certain leisure activities like using slot machines or swimming near poorly insulated electrical systems have led to inappropriate ICD discharges in rare cases. (51)

Industrial-grade welding equipment operating at above of 500 amperes may interfere with device function in work environments, although lower-powered hobbyist equipment poses minimal risk. Degaussing coils used in electronics repair can disrupt devices when they are within 10 cm for small coils and up to 2 meters for larger industrial coils. Spark-ignited combustion engines require a 25 cm buffer to avoid interference. (48) For industrial workers with cardiac devices, individualized assessments are essential, and device manufacturers often provide EMI testing to evaluate workplace safety. Adhering to recommended safety distances, carrying identification, and consulting healthcare providers about potential risks

are critical measures for patients to ensure their safety in environments where EMI is present. (51)

Today, many implants are designed to be MRI-compatible and classified as MR-safe, MR-conditional, or MR-unsafe, with standardized symbols indicating their safety levels. (51) Older implants, however, require detailed evaluation. Compatibility resources like the MRI Safety database or device manufacturer specifications are essential for assessing implant safety. Even if an MRI scan has been safely conducted previously, changes in the imaging protocol, magnetic field strength, or patient position can alter safety outcomes. Therefore, obtaining detailed patient histories and device specifications minimizes risks. (52)

A professional study evaluated the risks and consequences of electromagnetic interference from contemporary phones on patients with CIEDs (Figure 3). A total of 148 patients with CIEDs were tested with a phone (iPhone 6). The tests involved placing the devices directly above the implanted CIED or at the right wrist to assess EMI during standby, dialing, and connecting modes. It turned out that EMI from phones caused interference in 14% of patients, particularly with dual-chamber pacemakers. These results suggest that while the risk of EMI from the iPhone 6 CIEDs is low, close proximity of the iPhone to implanted devices could cause telemetry interferences. The findings highlight the importance of understanding potential EMI risks as phone usage increases. (53)

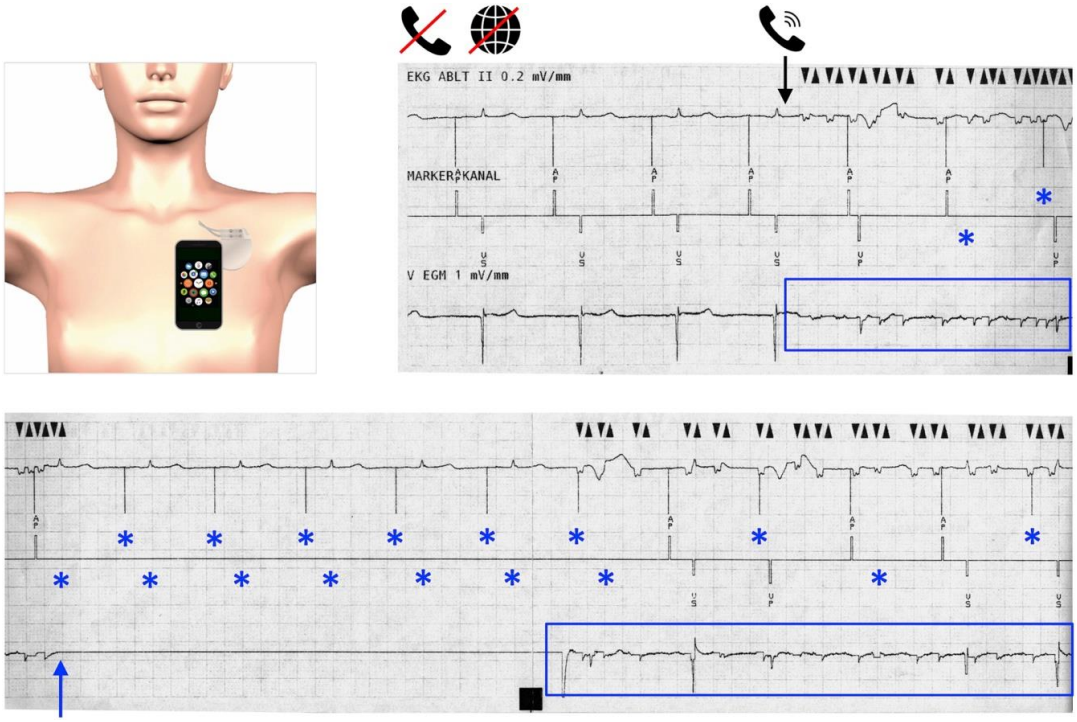

Figure 3. Electromagnetic interference from Iphone affecting Dual-chamber pacemaker Telemetry (53)

As it is illustrated in the figure above, an Iphone was placed directly on the pacemaker generator in a connection mode caused electromagnetic Interference, which resulted in loss of marker channel assignment, loss of electrogram (EGM) signal, as well as noise in the ventricular marker channel. This pacemaker that was used, it was a Medtronic Relia REDR01 model, which is programmed in DDDR mode (60-130 bpm) with mode-switching at an atrial rate of 175 bpm. Marker loss; ↑ **(blue)** = EGM loss; **blue box** = noise. AP = atrial paced event; VS = ventricular paced event (53)

8.4 Safety of electromagnetic interference

Ensuring the safety of cardiac implantable electronic devices in environments with potential electromagnetic interference is critical for device functionality and patient health. CIEDs, such as pacemakers and implantable cardioverter-defibrillators, are susceptible to EMI, which can interfere with their operations, leading to temporary malfunctions or, in rare cases, serious adverse effects. (52) The interaction between CIEDs and magnetic resonance imaging (MRI) is a notable example of EMI safety concerns.

Historically, MRI was contraindicated for CIED patients due to risks like heating of leads, magnetic field-induced device malfunctions, or inappropriate therapy delivery. However, advancements since 2011 have introduced MRI-conditional CIEDs designed to operate safely under specific MRI conditions. Today, most new devices fall into this category, provided the manufacturer's safety guidelines are strictly followed. Devices are categorized into MRI safe, which poses no risk in an MRI environment, and MRI conditional, which is secure with specific restrictions such as settings adjustments, and MRI unsafe, including older models or those with damaged components incompatible with MRI. (52)

Patients with MRI-conditional devices must undergo evaluations before imaging, including device type confirmation and functional assessment. Further risk-benefit analysis and interdisciplinary discussions are necessary if MRI-unsafe devices are identified. Beyond MRI, other EMI sources include household appliances like induction stoves, industrial equipment such as arc welders, and medical procedures like electrocautery. Recommendations for minimizing EMI risks include keeping a minimum distance from devices emitting strong electromagnetic fields, avoiding prolonged exposure to handheld or

industrial equipment near the CIED, and consulting manufacturers' guidelines for specific device behaviors under EMI exposure. (52)

Modern CIEDs feature improved shielding and circuitry, reducing EMI risks in most real-world scenarios. Diagnostic imaging, such as thoracic X-rays or a review of local CIED registries, can clarify risks when unknown device compatibility arises. (51) Close coordination between cardiologists, radiologists, and other specialists is necessary in high-risk situations to ensure patient safety.

On the day of the MRI, specific measures are taken to ensure safety. Cardiologists determine the pacemaker system's compatibility for imaging, considering that virtually all intact, functioning, permanent endocardial systems, including leadless models, can undergo imaging. Suppose the patient relies entirely on the pacemaker for rhythm control. In that case, the device is set to "asynchronous pacing mode" before imaging to secure rhythm stability, even if the electromagnetic field temporarily interferes with rhythm sensing. (50)

For implantable cardioverter defibrillators (ICDs), shock therapy is deactivated before imaging to prevent inappropriate treatments, such as ventricular arrhythmia, that may result from the device misinterpreting electromagnetic interference. After imaging, the cardiologist rechecks the pacemaker and restores its original settings. (52)

Patients with complex conditions, such as abandoned, fractured, or damaged leads, previously deactivated pacemaker systems, or temporary leads connected to external generators, require a detailed multidisciplinary evaluation and individualized risk-benefit analysis. (52) Additional considerations apply to patients with other implanted devices, foreign objects, or surgically installed epicardial leads on the heart surface.

This protocol underscores the necessity of collaboration between radiologists, cardiologists, and other healthcare professionals to minimize risks associated with electromagnetic interference during imaging for CIED patients. It provides a robust framework for safely managing MRI procedures in this vulnerable population. (52)

8.5 Mitigation strategies

Mitigating electromagnetic interference (EMI) with cardiac implantable electronic devices (CIEDs) requires advanced device technology, patient education, adherence to regulatory

guidelines, and practical safety measures in various environments. Modern CIEDs are designed with improved shielding to minimize susceptibility to EMI. These devices incorporate advanced circuits that filter disruptive signals, and many models are MRI-conditional, allowing safe use in controlled MRI settings. (52)

Educating patients plays a crucial role in mitigating risks. Patients are advised to keep mobile phones at least 15–20 cm away from their device, use the ear opposite the implantation site, and avoid placing phones in shirt pockets near the device. They should pass swiftly through airports and retail stores' security systems without leaning near or against detection gates. Prolonged exposure to high-intensity electromagnetic fields, such as those produced by transformers or power lines, should be avoided. (54)

In medical imaging, patients undergoing MRI scans must use MRI-conditional devices and follow specific manufacturer guidelines. Before the scan, device settings may be adjusted to a safe mode, such as turning off shock therapy in ICDs. (51) Post-scan checks ensure device functionality is restored to its original settings. Patients with MRI-unsafe devices or damaged leads require a comprehensive risk-benefit evaluation before imaging, involving consultations with cardiologists, radiologists, and manufacturers. (52)

High-risk industrial and household environments present unique challenges. Patients are encouraged to avoid industrial tools like arc welders and degaussing coils, which generate significant EMI. Similarly, household appliances such as induction stoves should be used cautiously, ensuring they meet safety certifications for CIED users. Workplace environments with high EMI exposure may necessitate on-site testing to establish safety protocols or reassign tasks. (54)

Surgical environments pose another risk, particularly from electrosurgical tools. Bipolar electrocautery tools are preferred, as they confine electromagnetic fields more effectively than monopolar tools. Ensuring the grounding pad is positioned away from the device and limiting tool use to short bursts are additional safeguards. (53)

Patients are advised to carry identification cards specifying their device type and settings. In cases of suspected EMI interference, prompt medical evaluation is critical. According to FDA guidelines, devices must comply with rigorous safety standards. Patients should be aware that while many electronic systems are generally safe, manufacturers’ instructions should always be followed. (55) The FDA recommends keeping potential EMI sources, like cell phones and

smart devices, at least 6 inches away and avoiding the direct placement of portable devices over the implant site. (52)

These combined measures, technological innovation, education, adherence to regulatory guidelines, and individualized risk management will reduce EMI risks and ensure the reliable performance of CIEDs in various environments.

9. Conclusion

Cardiac implantable electronic devices, including pacemakers and implantable cardioverter-defibrillators, are vital technologies that provide life-sustaining cardiac support to millions worldwide. (1) However, these sophisticated devices are inherently susceptible to electromagnetic interference (EMI), which can arise from various sources in a modern environment, ranging from household appliances to complex medical equipment. Managing the risks associated with EMI has become increasingly important as the number of patients relying on CIEDs continues to grow, along with the prevalence of advanced medical technologies and industrial processes that emit electromagnetic fields. (52)

The AAPM TG-203 guideline has established a critical framework for ensuring the safety of CIEDs during radiotherapy, one of the most technologically intensive cancer treatments. Radiotherapy presents unique challenges for CIEDs, mainly when using high-energy photon or electron beams, as these can induce secondary neutron production. Such neutrons, even at low doses, may disrupt sensitive electronic components like complementary metal-oxide semiconductors (CMOS) or random-access memory (RAM) chips, leading to permanent device malfunctions. TG-203 emphasizes minimizing the dose absorbed by the device, aiming to keep it below 2 Gy whenever possible. (43) It also discourages using photon energies above 10 MV and electron energies above 20 MeV to avoid neutron contamination. These recommendations highlight the need for meticulous treatment planning, precise dose mapping, and beam adjustments to ensure that the therapeutic goals of cancer treatment are met without compromising the integrity of CIEDs. (35)

Interdisciplinary collaboration is essential in addressing the complexities of radiotherapy in CIED patients. Radiation oncologists, cardiologists, and medical physicists must work closely to evaluate risks, develop treatment plans, and ensure continuous monitoring during therapy. (36) Pre-treatment interrogation of the device establishes a functional baseline, while

post-treatment assessments confirm that the device remains operational. For high-risk patients, such as those entirely dependent on their pacemakers, additional measures, including real-time electrocardiographic (ECG) monitoring, are recommended throughout treatment. Adjustments to device programming, such as deactivating rate-adaptive features or ICD shock therapy, are crucial to prevent inappropriate responses to radiation-induced EMI. (52)

Beyond radiotherapy, EMI remains a significant concern in other medical, industrial, and daily-life scenarios. Sources of interference are diverse, including left ventricular assist devices (LVADs), deep brain stimulators (DBS), spinal cord stimulators (SCS), and even household electronics such as mobile phones, induction stoves, and metal detectors. (44) Each source poses unique challenges, with varying mechanisms of interaction. For example, overseeing caused by EMI may lead to inappropriate pacing inhibition in pacemakers or unnecessary shocks from ICDs. Strong electromagnetic fields, such as those in MRI facilities or industrial welding equipment, can induce currents in device leads, potentially damaging tissue or resetting devices into safe mode. (45)

Modern CIEDs are designed to mitigate these risks with improved shielding, adaptive software, and filtering circuits. Many devices are now classified as MRI-conditional, enabling safe use under specific conditions, provided manufacturer guidelines are followed. However, patients with older-generation devices or damaged leads require detailed evaluations before imaging procedures, necessitating risk-benefit analyses and interdisciplinary planning. (52) For example, in MRI environments, devices must be reprogrammed to safe settings, such as asynchronous pacing modes for pacemakers or deactivating ICD shock therapy, to minimize risks of inappropriate responses during imaging.

Patient education is another cornerstone of EMI risk management. Patients must be informed about safe practices, such as maintaining a distance of 15–20 cm from mobile phones and other electronic devices, using the ear opposite to the implantation site for calls, and avoiding carrying phones in pockets near the device. They should also be advised to pass swiftly through security systems at airports or retail stores, avoiding prolonged exposure to detection gates. Awareness of risks associated with industrial tools, such as degaussing coils or arc welders, is critical for individuals in high-risk work environments. (55) For these patients, manufacturers often provide device-specific EMI testing and safety recommendations tailored to their professional needs.

Mitigating EMI requires careful equipment selection and procedural planning in surgical and therapeutic contexts. Bipolar electrosurgical tools are preferred over monopolar instruments as they more effectively confine electromagnetic fields. (48) Placement of grounding pads away from the device and short, intermittent bursts of electrocautery further reduce risks. In high-risk scenarios, such as procedures involving temporary pacing systems or fractured leads, a multidisciplinary team approach ensures patient safety through individualized planning and real-time monitoring. (52)

Regulatory standards, such as those established by the FDA, have been instrumental in guiding manufacturers to design devices with enhanced EMI resilience. These standards require rigorous testing to ensure that devices meet safety thresholds under various environmental conditions. (52) Adherence to these guidelines, combined with advancements in device technology, has significantly reduced the risks associated with EMI in modern CIEDs.

In conclusion, the safe management of CIEDs in environments with potential EMI requires a comprehensive approach that integrates advanced technology, interdisciplinary collaboration, and patient-centered care. (48) The AAPM TG-203 guideline exemplifies the structured methodologies needed to address the challenges posed by radiotherapy. At the same time, broader EMI mitigation strategies provide a framework for navigating diverse risks in medical, industrial, and everyday contexts. (43) By leveraging modern device innovations, educating patients, and adhering to regulatory guidelines, healthcare professionals can ensure that CIEDs provide reliable life-saving support while minimizing exposure to the hazards of electromagnetic interference. (52) This holistic approach underscores the importance of continuous research, technological innovation, and clinical vigilance in safeguarding the growing population of patients who rely on these essential devices.

10. References

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