



Published in final edited form as:

*Circulation*. 2013 December 24; 128(25): 2799–2809. doi:10.1161/CIRCULATIONAHA.113.005697.

## Effects of External Electrical and Magnetic Fields on Pacemakers and Defibrillators: From Engineering Principles to Clinical Practice

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### Keywords

pacemaker; implantable cardioverter-defibrillator; magnetic resonance imaging; surgery; electromagnetic interference

### Introduction

According to a recent worldwide survey, current rates of de novo pacemaker and implantable cardioverter defibrillator (ICD) implantation are higher than previous years at >700,000 and >200,000 per year, respectively.<sup>1</sup> Parallel to the growth in cardiovascular implantable electronic devices (CIEDs) use, technological advances have led to new sources of electromagnetic radiation. Modern CIEDs utilize shielding, filters, and bipolar leads to mitigate electromagnetic interference (EMI). Nevertheless, EMI sporadically results in harmful consequences. Physicians attending to patients with CIEDs must be aware of typical EMI sources and strategies to prevent malfunction of CIEDs.

### Electromagnetic Interference: Engineering Principles Terminology and Definitions

Electromagnetic field is the term used to describe combined electric and magnetic fields. Electric fields exist whenever electric charges are present, i.e., whenever electricity or electrical equipment is in use. A magnetic field is produced when electrical current flows in a conductor with magnetic field lines perpendicular to the current flow. Electromagnetic interference can occur as a result of conducted or radiated electromagnetic energy. Medical equipment such as transcutaneous electronic nerve stimulators (TENS) or poorly grounded electrical equipment may result in directly conducted electromagnetic energy in the form of galvanic currents. Electromagnetic radiation is the term used to describe electromagnetic energy radiating away from its source. Electromagnetic radiation can be described as ionizing versus nonionizing radiation. Ionizing radiation consists of very short wavelengths, such as X-rays, which have enough power to move electrons off their nuclear orbits. In contrast, non-ionizing radiation consists of longer wavelengths with less power and is incapable of moving electrons off their orbit around the nucleus.

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**Conflict of Interest Disclosures:** Dr. Nazarian is on the MRI advisory panel (unpaid) for Medtronic; and is a scientific advisor to Biosense-Webster Inc.

Electromagnetic fields are characterized by wavelength, frequency, and field strength. Radiofrequency energy, defined by a frequency range between 0 Hz to 450 MHz, is emitted by sources including MRI, electrosurgery, and radio/television broadcasting. Cellular telephones, microwave ovens, and radar transmitters typically emit microwave energy, defined by a frequency range between 450 MHz to 12 GHz. The electric field strength and magnetic field intensity components of electromagnetic fields are measured in volts per meter, and amperes per meter, respectively. The magnitude of energy deposition in tissues is measured by the specific absorption rate (SAR) measured as watts per kilogram (W/kg). Electromagnetic field energy decreases as an inverse squared function of distance from the source. Thus, doubling the distance from the source results in a four-fold exposure reduction. For example in the setting of magnetic resonance imaging (MRI) or static magnetic fields created by linear accelerators or betatrons, the intensity of static magnetic fields decreases as a function of distance from the source and creates a spatial gradient magnetic field. The intensity of the static magnetic field is typically reported in units of tesla (T), where 1T is the equivalent of 10,000 gauss (G), and 796 amperes per meter (A/m). In general, it is accepted that local field strengths of greater than 10 G are sufficient to induce EMI. In contrast to static and spatial gradient magnetic fields, gradient coils in MRI scanners, produce time-varying gradient magnetic fields for spatial encoding of the MRI signal.<sup>2</sup> Acoustic radiation involves pressure waves, which is emitted from medical equipment such as lithotripsy equipment.

## Summary of Potential Transient and Permanent Effects of Electromagnetic Fields

Disturbances in CIEDs circuitry or behavior due to electromagnetic radiation emitted from an external source are known as EMI. Electromagnetic radiation properties and CIEDs distance from the EMI source, as well as CIEDs design, materials, shielding, programming, sensitivity, and filtering properties modulate the extent of EMI.

Spatial gradients in static magnetic fields result in translational and rotational forces on ferromagnetic objects.<sup>3</sup> If the translational force exceeds counterforces from sutures, scarring, and tissue ingrowth, permanent and dangerous effects may occur from dislodgement and movement of CIEDs. A transient effect of spatial gradients in static magnetic fields is the magnetohydrodynamic effect, which occurs due to the conductive effect of blood that results in a voltage difference across the vessel in a direction perpendicular to the blood flow. This effect is dependent upon the velocity of blood flow, magnetic field strength, vessel diameter, and angle of flow with respect to the magnetic field. Peaked T waves may be sensed as a result of the magnetohydrodynamic effect and may lead to transient over-sensing by CIEDs.<sup>4</sup> A case of transient pacemaker inhibition has been attributed to the magnetohydrodynamic effect.<sup>5</sup> Exposure of older CIEDs with reed switches to static magnetic fields may transiently cause asynchronous pacing, and inhibit tachycardia therapies. Modern CIEDs have largely replaced the reed switch with integrated solid-state detection, Hall sensors, telemetry coils, or giant magnetoresistor (GMR) circuits.

Time varying gradient magnetic fields may be associated with transient and permanent effects upon CIEDs. The main concern in this setting is the potential for current induction within conductive wires in the field that may result in transient inhibition of pacemaker output, and direct stimulation of the myocardium, in addition to permanent effects due to heating of the conductor and tissue burns.

Radiofrequency fields can be associated with tissue heating and burns. Conductive implants and leads, particularly when placed in a loop configuration, can greatly increase the risk of burns as a result of inductive heating of the lead conductor from radiofrequency fields.<sup>4</sup>

Additionally transient EMI effects can be observed when radiofrequency energy is used for thermal ablation of the myocardium or other tissues. When performing radiofrequency ablation current flows from the conducting electrode toward a dispersive or ground electrode. Proper placement of the dispersive electrode may result in current a path that minimizes EMI with CIEDs; however, appropriate precautions are warranted if the path includes the thorax.

Ionizing radiation can have cumulative and permanent effects on CIEDs. The complementary metal oxide semiconductor (CMOS) circuitry in CIEDs uses silicon and silicon dioxide as insulators between circuitry components.<sup>6</sup> Exposure of the semiconductor to ionizing radiation results in build up of charge in the silicon dioxide insulation and leakage current within the circuits, thus risking unpredictable function including programming changes, loss of diagnostics, power-on-reset, and circuitry failure.

Acoustic radiation may transiently activate the rate response features of some CIEDs and permanently damage others if in close proximity.<sup>7</sup>

## Electromagnetic compatibility

Electromagnetic compatibility (EMC) describes efforts to minimize the possibility of EMI. These efforts include shielding, which includes protecting the CIEDs generator and/or lead circuitry with electromagnetic field barriers composed of conductive or magnetic materials. CIEDs generators are typically shielded by hermetically sealed titanium or stainless steel cases. Nano-magnetic insulation has recently been utilized in lead design to improve shielding from radiofrequency and time varying gradient magnetic fields. Additionally, body tissues add to the shielding of leads because leads placed in a conductive medium are poor antennas. The extent of CIEDs shielding vary depending upon the manufacturer and can impact product weight, handling, and dimensions. In the case of the generator, the shielding must be adequate to reject electric fields above 2 MHz. The use of bipolar sensing, and low pass filters reduces conducted and radiated interference. Additionally, feedthrough capacitor filters are utilized to prevent EMI from a wide range of frequencies including mobile phone frequencies.<sup>8</sup> The term feedthrough describes a conductor used to carry a signal through the pacemaker casing. The conductor is capable of holding a guaranteed minimum value of charge and is therefore called a feedthrough capacitor. The conductor is meant to participate in unipolar (to generator) sensing/pacing functions but may also act as an antenna that carries EMI. Feedthrough capacitor filters decouple and shield against conduction of radiofrequency carrier signals from mobile phones into the pacemaker circuitry. Additionally, incorporation of bandpass filters allows rejection of frequencies outside the range of interest. However, electromagnetic radiation with frequencies between 0–60 Hz overlaps the cardiac signal range. Therefore, rejection of this frequency range by band pass filters would affect proper pacemaker function.<sup>7</sup> To address EMI that bypasses filtering schemes, the noise reversion feature, typically programmed for asynchronous pacing, activates when signals are detected in the noise-sampling period of the atrial and ventricular refractory periods. Table 1 summarizes design features to enable electromagnetic compatibility.

## CIEDs Response to EMI

In addition to the EMI characteristics, programming of CIEDs is a significant determinant of device response to EMI. During inhibited pacing modes (AAI, VVI, or DDI), EMI results in pacing inhibition and bradycardia or asystole. Whereas while in tracking mode (DDD), preferential sensing of EMI in the atrial channel (which often occurs due to higher programmed sensitivity) could result in a) increased rate ventricular pacing, or b) atrial arrhythmia detection and CIEDs “mode-switch” to inhibited pacing (AAI, VVI, or DDI).

Detection of EMI may result in pacing at the sensor-triggered upper rate limit if rate response is activated. In ICD recipients, sensing of EMI in the tachyarrhythmia frequency range could result in inappropriate therapies. Activation of the magnet response by EMI may lead to asynchronous pacing in pacemakers and transient or permanent disabling of tachycardia therapies in certain ICD systems. Importantly, although rare, CIEDs may revert to a back-up programming mode known as “power-on-reset” when exposed to high energy EMI. Power-on-reset events are generally resolved by reprogramming the CIEDs to patient specific settings. However, it is important to realize that during power-on-reset, pacing is typically set to an inhibited mode (VVI) and tachycardia therapies are enabled.

## Everyday Sources of EMI

Routinely used equipment seldom cause EMI with CIEDs. Table 2 summarizes potential sources of EMI, documented effects and recommended precautions. Several common sources are also discussed below.

### Digital Music Players, Headphones, and Neodymium Magnets

Digital music players may result in isolated telemetry EMI without direct impact upon CIEDs function.<sup>9, 10</sup> Portable headphones contain strong magnets that may interfere with CIEDs function at close range. Similar neodymium magnets are used in the jewelry and clothing industry and can lead to magnetic field effects.<sup>12, 13</sup>

### Security Systems and Equipment

Walk-through metal detector security systems use either continuous (5–10 kHz) or pulsed (200–400 Hz) wave modes. In contrast, handheld detectors operate in higher frequency continuous-wave mode (80–130 KHz) with lower magnetic-field strength and lower likelihood for EMI.<sup>14</sup> The risk of EMI appears to be very low in the setting of walk-through<sup>15</sup> and handheld metal detectors.<sup>80</sup> Nevertheless, CIED recipients should alert security personnel regarding the implanted device as recommended by the Transportation Security Administration. Electronic article surveillance devices utilizing magnetic, acoustomagnetic, radiofrequency, and/or microwave transmissions are used to prevent theft in stores and libraries. Instances of EMI with tracking and pacing inhibition due to ventricular oversensing, asynchronous pacing, current induction with myocardial capture/extrasystoles, and inappropriate shocks have been reported with close exposure to magnetic, radiofrequency, and acoustomagnetic surveillance systems.<sup>16–19, 81</sup> CIEDs recipients should not linger near surveillance devices thus avoiding adequate EMI duration for activation of tachyarrhythmia therapies by the CIED. Tasers are weapons that deliver short pulses of current with a peak voltage of 1000–1500 V. Instances of inappropriate sensing resulting in pacing inhibition, noise reversion, and tachycardia detection, in addition to ventricular capture secondary to direct delivery of the Taser pulse to the myocardium have been reported.<sup>28–30</sup>

### Cellular Phones

Instances of EMI with CIEDs resulting in over-sensing, tracking, pacing inhibition, and asynchronous pacing were readily observed with early cellular phones placed directly on the device.<sup>22</sup> Studies of modern cellular phones and CIEDs with routine use of dedicated feedthrough filters have noted minimal or no EMI.<sup>23, 26</sup> In the setting of ICDs, only transient telemetry loss,<sup>24</sup> without clinically significant EMI has been reported.<sup>20, 21, 25</sup> Current recommendations indicate holding cellular phones to the ear contralateral to the CIEDs, avoiding close contact between the CIEDs and the phone, and avoiding the use of cellular phones during programming of CIEDs.

## Other routine or workplace sources

Rare reports of malfunction of CIEDs due to EMI from other sources including slot machines,<sup>82</sup> washing machines,<sup>33</sup> power drills,<sup>83</sup> and alternative medicine devices<sup>84</sup> exist in the literature. In general, recipients should be advised to avoid close contact of electrical equipment with CIEDs' generator.

Potential industrial sources of EMI include welding equipment, electric motors, and degaussing coils.<sup>35</sup> High electromagnetic radiation levels exist in aircraft cockpits, but based upon in vitro studies appear unlikely to cause significant EMI with CIEDs.<sup>36</sup> Similarly, high-voltage power lines are unlikely to result in EMI with routine exposure and bipolar sensing configuration.<sup>38, 39</sup> If a CIEDs recipient is employed in an area with industrial equipment, assessment of the threshold source distance for EMI and follow up device interrogations should be arranged. Additionally, the employer should be notified regarding CIEDs and the importance of environmental testing. This type of assessment can be performed by a trained EMI testing consultant at the employer's request. The CIEDs' manufacturer can provide a list of consultants.

## Medical Sources

The medical environment has abundant sources of EMI with the potential to cause malfunction in CIEDs. Cardioversion procedures may cause transient or permanent changes in CIEDs function including lead sensing and capture parameters.<sup>48, 85</sup> This may be secondary to shunting the energy through the lead to the electrode tip causing electrical injury and impedance changes at the electrode-myocardial interface.<sup>86, 87</sup> Power-on-reset and pacing mode changes have also been observed.<sup>46, 88</sup> Radiofrequency ablation generates signal frequencies between 500–1000 kHz in a unipolar configuration. Asynchronous pacing, pacing inhibition, loss of capture, power-on-reset and rarely, runaway pacing have been reported in the setting of radiofrequency ablation and older CIEDs.<sup>52, 53, 55</sup> Due to the abundance of EMI sources in the medical environment and for brevity, most have been summarized in Table 2. However, MRI, radiotherapy and electrosurgery are discussed in detail below.

## Magnetic Resonance Imaging

There are three distinct sources of EMI in the setting of MRI: the static magnetic field, radiofrequency fields, and time varying gradient magnetic fields. The static magnetic field can exert force and torque on CIEDs, and may change the reed switch state in older devices, causing unpredictable pacing behaviors. The radiofrequency and gradient magnetic fields may induce electrical currents in leads within the field if the current loop is completed through the body. Current induction may lead to myocardial capture and induction of fatal ventricular arrhythmias. Additionally, the generator and leads can act as an antenna that amplifies local radiofrequency energy deposition, resulting in heating at the device-tissue interface. Finally, EMI may result in inhibition of pacing, asynchronous pacing (Figure 1), power-on-reset events, inappropriate tracking, inappropriate ICD therapies, and runaway pacing with induction of potentially life-threatening ventricular arrhythmias.

Due to the benefits of MRI, our group and others have developed protocols to safely perform imaging in CIEDs recipients. At our institution, we have performed MRI at 1.5-Tesla on over 1000 patients with CIEDs using a protocol that incorporates device selection and programming, and patient monitoring. We exclude patients with a) recently implanted leads (<6 weeks), b) abandoned leads, c) non-transvenous epicardial leads, and d) dependence upon the pacing function of an ICD. Additionally, we require the presence of a provider experienced in advanced cardiac life support and programming of CIEDs. Prior to

MRI, baseline interrogation is performed and system parameters are recorded. If the patient has a hemodynamically stable underlying rhythm, an inhibited pacing mode is utilized (AAI, VVI, or DDI). If the patient is dependent upon pacing, the pacemaker is set to an asynchronous mode. All other pacing functions and tachyarrhythmia therapies are disabled. Upon completion of the MRI examination the device is re-interrogated. Battery status and lead parameters are rechecked and programming is restored to baseline settings. The protocol is summarized in Table 3. We have published our experience of utilizing this protocol for performing 555 MRI examinations on pacemaker and ICD recipients. Immediately after MRI, clinically insignificant decreases in right ventricular sensing and lead impedances were noted. Long-term differences included increased right ventricular capture threshold, decreased right ventricular sensing and impedance, and decreased battery voltage. These changes did not warrant CIEDs system revision or reprogramming. In our study, sub-clinical changes in sensing and battery voltage were associated with thoracic imaging. Given the extent of image susceptibility artifacts that affect the anterior and apical left ventricle,<sup>89</sup> the potentially elevated risks versus benefits of thoracic MRI must be carefully weighed in patients with left-sided ICD systems. Artifact reduction methodologies are currently under development and will improve the performance of MRI in patients with left-sided ICD systems. Additionally, we observed acute power-on-reset events in 3 patients.<sup>40</sup> Power-on-reset is important to recognize because inhibition of pacing and/or delivery of tachycardia therapies may occur if EMI is sensed before the CIEDs are reprogrammed. The use of MRI at 3-Tesla for neurologic, musculoskeletal, abdominal, and cardiovascular applications is increasing owing to increased signal-to-noise ratio, spatial resolution, and imaging speed. However, there is only limited experience in MRI safety of CIEDs at 3-Tesla.<sup>90, 91</sup>

It is important to note that MRI in the setting of standard CIEDs is performed off-label and generally considered to be a contraindication. The Center for Medicare and Medicaid Services will cover MRI for beneficiaries with implanted CIEDs a) through Coverage with Evidence Development (CED)/Coverage with Study Participation (CSP) in approved clinical studies of MRI, or b) in the setting of “MRI-conditional” pacemakers (discussed below) used according to the FDA-approved labeling for use in the MRI environment.<sup>92</sup> The American Heart Association (AHA), the American College of Radiology (ACR) and the European Society of Cardiology (ESC) recommendations emphasize the necessity a) to perform MRI at experienced centers utilizing a strict protocol for patient monitoring and device programming, and b) to individualize the decision making process based upon the risk-benefit ratio of MRI and the utility of modalities alternative to MRI.<sup>93–95</sup>

In recent years device manufacturers have made substantial efforts to develop MRI-conditional CIEDs. This terminology implies the lack of known hazards when MRI is performed using pre-defined device programming, patient monitoring, and imaging protocols. MRI-conditional CIEDs contain less ferromagnetic materials and incorporate lead design changes to mitigate heating. A Hall sensor is used instead of the reed switch to reduce unpredictable behavior within the MRI scanner. Other modifications include the availability of an easily programmable MRI mode, which requires a mandatory system integrity check before enabling increased pacing output and selection of asynchronous or inhibited modes (AAI, VVI, or DDI). The United States Food and Drug Administration (FDA) approved the Revo MRI SureScan Pacing System (Medtronic, Inc., Minneapolis, MN) in early 2011. To assess implantation safety, 100 patients with pacing indications were randomized to receiving the MRI-conditional versus a conventional system. No excess complications were observed; however, there was a trend towards lower successful cephalic vein access.<sup>41</sup> Next, MRI safety was assessed utilizing a randomized prospective multicenter study. Up to 12 weeks following implantation, 211 patients with the MRI-conditional system underwent MRI (1.5 Tesla, SAR = 2 W/kg, and gradient slew rate < 200 T/m/s). The

iso-center position was limited to regions above the superior surface of C1 and below the inferior surface of T12 vertebra. No MRI related events or overt complications such as failure to capture, lead dislodgement, or pericardial effusion were noted, and recorded measurements were similar between the study groups.<sup>42</sup> Importantly, the system requires the use of manufacturer specific leads, and the approved MRI field strength is limited to 1.5-Tesla. Other manufacturers have also developed MRI-conditional CIEDs, which have been approved in Europe. These include pacemaker systems including the Evia and Estella (Biotronik, Berlin, Germany), the Accent MRI (St Jude Medical, St. Paul, MN), as well as the Lumax 740 ICD system (Biotronik, Berlin, Germany).

## Radiotherapy and ionizing radiation

Instances of EMI have been reported in the setting of computed tomography, inducing single beat inhibition, but are otherwise infrequent with routine diagnostic radiation.<sup>96</sup> In contrast, therapeutic radiation is associated with various sources of EMI including couch drive motors, shutters, x-ray tube rotors, cooling pumps, x-ray transformers, power supplies, magnetrons, klystrons, waveguide assemblies, beam pulse forming circuits, as well as ionizing radiation sources, including continuous beam gamma-ray, beta particle radioisotopes, pulsed x-ray and electron beams from linear accelerators and betatrons, and cyclotron produced proton or neutron beams.<sup>97-99</sup> Exposure to therapeutic radiation has been associated with pacing inhibition, inappropriate tracking, noise-reversion, inappropriate shocks, CIEDs failure, and runaway pacing with induction of potentially life-threatening ventricular arrhythmias.<sup>73, 74, 100</sup> The cumulative effect of ionizing radiation on the oxide layers of CMOS circuits utilized in CIEDs<sup>75</sup> vary depending on the type (photon vs. proton based therapy), dose measured as energy absorbed per mass with units of joule per kilogram or gray (Gy), direction of radiation, and device type and location.<sup>101, 102</sup> A dose range as wide as 0.5 to 120 Gy could be associated with ICD failure.<sup>71, 72</sup> CIEDs manufacturer recommendations regarding maximal tolerable radiation dose varies from no safe dose (Boston Scientific), to 1–5 Gy (Medtronic), to 20–30 Gy (St. Jude Medical). In addition, shielding should be maximized at the machine head during radiotherapy using multi-leaf collimators, or even placing a lead apron over CIEDs to minimize the amount of radiation scatter.<sup>6</sup> The HRS and ASA recommend interrogation within 24 hours of each treatment when using a direct beam to the chest or high-energy photon radiation for pacemaker dependent patients.<sup>43</sup> Remote follow-up can be used in many CIEDs for this purpose. Programming CIEDs to a higher pacing rate than baseline allows rapid recognition of power-on-reset or device malfunction when onsite interrogation is unavailable. It is also recommended that radiation therapy specialists perform energy field calculations and discuss the case with an electrophysiologist prior to the procedure.

## Electrosurgery

Electrosurgery current in the frequency range of 100–5000 kHz is typically delivered in a unipolar configuration between the cauterizing instrument and ground electrode. The infrequently utilized bipolar cautery system, delivers the current between 2 electrodes at the tip of the instrument, thus reducing the likelihood for EMI with CIEDs.<sup>103</sup> There are many reports of EMI with CIEDs from unipolar cautery (Figure 2). Most instances of EMI occur when electrosurgery is performed within 8 cm of the device.<sup>60</sup> Electrosurgery below the umbilicus with a grounding pad on the thigh is unlikely to result in EMI with thoracic CIEDs. A protocol for management of patients undergoing electrosurgery has been summarized in Table 4. The Heart Rhythm Society (HRS)/American Society of Anesthesiologists (ASA) Expert Consensus Statement recommends either no intervention or magnet application for subumbilical procedures. In contrast, for procedures above the umbilicus, the document indicates a) programming or magnet application to activate

asynchronous pacing for pacemaker dependent patients, and b) to deactivate tachyarrhythmia therapies for ICD recipients, and programming of the ICD to an asynchronous mode for pacemaker dependent patients.<sup>43</sup> Additional measures that may minimize EMI include the use of short bursts of bipolar electrosurgery and positioning the ground electrode to direct the current path away from CIEDs. Importantly, failure to resume initial programming or to reactivate tachyarrhythmia functions post surgery must be avoided through careful planning.

## Summary

The overall risk of clinically significant adverse events related to EMI in recipients of CIEDs is very low. Therefore, no special precautions are needed when using household appliances. Environmental and industrial sources of EMI are relatively safe when the exposure time is limited and distance with the CIEDs is maximized. The risk of EMI induced events, are highest within the hospital environment. Physician awareness of the possible interactions and methods to minimize them is warranted.

## Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

## Acknowledgments

**Funding Sources:** Dr. Nazarian is principal investigator for research funding to Johns Hopkins University from Biosense-Webster Incorporated and the National Heart, Lung, and Blood Institute of the National Institutes of Health grants K23HL089333 and R01HL116280. The content is solely the responsibility of the authors and does not necessarily represent the official views of the National Institutes of Health.

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**Table 1**

Electromagnetic Compatibility Features and Corresponding EMI Types

	Ionizing Radiation	Electric Fields	Static and Spatial Gradient Magnetic Field	Time Varying Gradient Magnetic Field	Radiofrequency	Microwave
Shielding the Generator and Leads	✖	✖		✖	✖	
Bipolar Sensing		✖		✖	✖	
Feedthrough Capacitor Filters					✖	✖
Lowpass filters		✖			✖	
Bandpass Filters		✖			✖	
Noise Reversion		✖		✖	✖	
Use of Hall Sensor (instead of Reed Switch)			✖			
Increasing Lead Conductor Resistance				✖	✖	
Reduction of Ferromagnetic Components			✖	✖		

Table 2

Sources of EMI and their potential effects

Type of field	Environment	Source	Potential effects										Warranted Precautions			
			Damage to CIEDs Circuitry	Pacemaker inhibition	Noise Tracking	Asynchronous pacing	Noise reversion	Communication failure	Current induction	Arrhythmia Detection/ICD shocks	Inhibition of Tachyarrhythmia Detection	Sensing Pacing Threshold Changes		Power-on-reset	Rate Adaptive Sensor Activation	
Electromagnetic	Daily life	Digital music players <sup>9,10</sup>					T								Avoid close proximity (<30 cm) with generator.	
		Stereo Speaker and headphones <sup>11</sup> (magnetic field strength 10 gauss)				T	T								Avoid close proximity with generator.	
		Neodymium-iron-boron magnets incorporated into toys, jewelry, and clothes <sup>12,13</sup>				T									Avoid close proximity with generator.	
		Metal detectors <sup>14, 15</sup>				T				T					Alert security personnel regarding the implanted device.	
		Electronic Article Surveillance Devices <sup>16-19</sup>		T	T	T				T					Patients should not linger near surveillance devices to minimize the duration of EMI that might be detected by the CIEDs.	
		Cellular Phones <sup>20-26</sup>		T	T	T				T					Avoid close proximity with generator.	
		Hand held home phones <sup>27</sup>		T		T									Avoid close proximity with generator.	
		Tasers <sup>28-30</sup>		T						T						
		Household leakage current from improper grounding <sup>31-34</sup>		T							T					Avoid contact with improperly grounded equipment.
		Automotive engine <sup>11</sup>		T						T						Avoid close proximity of ignition system, engine, and alternator with generator.
		Arc welding equipment, electric motors, and degaussing coils <sup>35</sup>		T		T				T						Advise employer regarding implanted medical device and consider environmental testing by a trained EMI consultant (list of consultants can be provided by the CIEDs manufacturer). Maintain a minimal distance of 2 ft (61 cm) from the welding arc and cables or large motors. Do not exceed tested currents with the welding equipment. wear insulated gloves while operating electrical equipment, and verify that electrical equipment is properly grounded.
		Aircraft cockpits <sup>36</sup>		T		T										
		RF ID equipment <sup>37</sup>		T												
		High voltage power coils <sup>38,39</sup>		T			T									Assessment of the threshold safe distance for EMI and follow up device interrogations should be arranged.
Medical		MRI <sup>40</sup>	T	T	T	T								MRI should be performed at experienced centers utilizing a strict protocol for patient monitoring and CIEDs programming (refer to Table 3).		
		Electrosurgery <sup>41, 42</sup>	T	T		T								No intervention or magnet application is needed for sub-atrial procedures. For procedures above the umbilicus, programming or magnet application should be performed to activate asynchronous pacing for pacemaker dependent		

Type of field	Environment	Source	Potential effects										Warranted Precautions			
			Damage to CIEDs Circuitry	Pacemaker Inhibition	Noise Tracking	Asynchronous pacing	Noise reversion	Communication failure	Current Induction	Arrhythmia Detection/ICD shocks	Inhibition of Tachyarrhythmia Detection	Sensing and Pacing Threshold Changes		Power-on-reset	Rate Adaptive Sensor Activation	
																patients as well as deactivation of tachyarrhythmia therapies for ICD recipients. The ground electrode to direct the current path away from the CIEDs.
		LVAD <sup>43-45</sup>								T						CIEDs should be programmed to a bipolar sensing configuration and should be excluded from the current path by use of an antero-posterior patches/paddles position, placed >6 inches away from the generator. <sup>48</sup> Immediate access to a CIEDs programmer is recommended.
		Cardioversion <sup>46-48</sup>	T													
		Dental equipment <sup>49-51</sup>		T												
		Radiofrequency catheter ablation <sup>52-55</sup>	T	T	T	T	T	T								Deactivate tachyarrhythmia therapies and activate asynchronous pacing for pacemaker dependent patients.
		Spinal cord <sup>56, 57</sup> and deep brain stimulators <sup>58, 59</sup>	T	T												Program bipolar sensing configuration. Test for interactions intraoperatively and when modifying programming.
		Gastroscopy, endoscopy, and colonoscopy <sup>60</sup>														No anticipated effects in the absence of electrostimulation.
		Capsule endoscopy <sup>61-64</sup>														Tachyarrhythmia therapies should be turned off prior to procedure
		Transcutaneous electrical nerve stimulation <sup>65-67</sup>		T												Magnet application or programming to an asynchronous mode (VDDDDO) is recommended in pacemaker dependent patients. ICD therapies should be disabled during the treatment.
		Telemetry monitors <sup>68</sup>														Consider deactivation of minute ventilation sensors.
		Electroconvulsive therapy <sup>69, 70</sup>		T												Availability of a magnet or CIEDs programming equipment is advised.
		Radiotherapy <sup>71-75</sup>	T	T	T	T	T	T								CIEDs should be interrogated within 24 hours of each treatment when using a direct beam to the chest or high-energy photon radiation for pacemaker dependent patients. <sup>43</sup> Programming the CIEDs to a higher pacing rate than baseline allows rapid recognition of power-on-reset or device malfunction when onsite interrogation is unavailable.
Ionizing Radiation		Lithotripsy <sup>76-79</sup>		T												Patients should be continuously monitored. Also, synchronization of the hydraulic shocks to the R wave should be performed. Dual chamber pacemakers should be reprogrammed to VVI mode. ICD tachyarrhythmia therapies should be deactivated during treatment. CIEDs should be interrogated post procedure.

**Table 3**

Safety Protocol for MRI in the setting of CIEDs

	<ul style="list-style-type: none"> <li>• Consider alternate imaging modalities.</li> <li>• Discuss the benefits and risks of MRI in the setting of CIEDs including risks of EMI, device failure, and arrhythmia and obtain informed consent.</li> <li>• Exclude patient with the following characteristics</li> </ul>	<ul style="list-style-type: none"> <li>• CIEDs implanted prior to 2000</li> <li>• Recently implanted leads (&lt;6 weeks)</li> <li>• Abandoned leads</li> <li>• Non-transvenous epicardial leads</li> <li>• Dependence upon the pacing function of an ICD</li> </ul>
<b>Pre-Procedure</b>	<ul style="list-style-type: none"> <li>• Perform baseline interrogation and programming</li> </ul>	<ul style="list-style-type: none"> <li>• For hemodynamically stable underlying rhythm – inhibited pacing mode (AAI/VVI/DDI)</li> <li>• For pacemaker dependent patients – asynchronous mode (VOO/DOO)</li> <li>• All other pacing functions (magnet, rate, PVC, noise, ventricular sense, and conducted atrial fibrillation response), and tachyarrhythmia therapies should be disabled</li> </ul>
<b>Intra-procedure</b>	<ul style="list-style-type: none"> <li>• A provider experienced in CIEDs programming and advanced cardiac life support should be present to monitor symptoms, blood pressure, ECG, and pulse oximetry.</li> <li>• Resuscitation equipment should be immediately available.</li> </ul>	
<b>Post-procedure</b>	<ul style="list-style-type: none"> <li>• Re-interrogate CIEDs with recording of battery status and lead parameters, and reprogramming of the system to baseline settings.</li> <li>• Schedule follow-up interrogation in 3–6 months.</li> </ul>	

Table 4

Management of patients undergoing electrosurgery

<p><b>General considerations:</b></p> <ul style="list-style-type: none"> <li>• The perioperative management of CIEDs must be individualized to the patient, the type of CIEDs and the procedure being performed.</li> <li>• All patients with pacemakers and ICDs undergoing elective surgery should have had a device check as part of routine care within the past 12 and 6 months, respectively.</li> <li>• Maximize the distance between the electrosurgery current path and the CIED. Consider the use of bipolar cautery.</li> <li>• Use the minimum power settings required for adequate electrosurgery. Using short bursts may also be required if inhibitions are observed.</li> <li>• Emergency equipment should be easily accessible to the procedure area. External defibrillation equipment is required in the procedure room.</li> <li>• All patients with pacemakers or ICDs require blood pressure monitoring for all surgical and sedation procedures.</li> <li>• Use an ECG monitor with a pacing mode set to recognize pacing stimuli.</li> <li>• Keep a magnet immediately available for all patients with CIEDs who are undergoing a procedure that may involve EMI.</li> <li>• If central venous access is required, guide wires should be advanced carefully particularly if the CIEDs lead has been recently placed, and should not contact the sensing electrodes of an ICD lead (which may include the distal coil). Delivery of a shock as a result of inappropriate detection of noise or to treat a real arrhythmia when the guide wire has created a short circuit by touching the high voltage anode and cathode may result in catastrophic pulse generator failure.</li> <li>• After the surgery, reprogram CIEDs to pre-surgical settings.</li> </ul>	<p><b>Specific considerations:</b></p> <ul style="list-style-type: none"> <li>• If the current path is distant and appropriate monitoring is available, programming to an asynchronous mode (VOO/DOO) in pacemaker dependent patients is not a universal requirement.</li> <li>• If the current path is distant, turning off ICD arrhythmia detection is not a universal requirement for all procedures. ICD arrhythmia detection can be turned off by placement of a magnet over the pulse generator, provided the pulse generator is accessible. However, placing a magnet over an ICD generator will not render pacemaker function asynchronous. All patients with ICDs deactivated should be on a cardiac monitor, and defibrillation patches should be placed.</li> <li>• Turning off ICD arrhythmia detection (by programming or magnet application) is recommended for all procedures above the umbilicus that utilize monopolar electrosurgery or radiofrequency ablation.</li> <li>• For procedures below the umbilicus pacemaker programming is typically unnecessary.</li> <li>• Because of interactions with monitoring, ventilation, and other impedance monitoring operative devices, deactivation of minute ventilation sensors should be considered.</li> </ul>
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