Novel Devices

Are patients with cardiac implants protected against electromagnetic interference in daily life and occupational environment?

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Utilization of cardiac implants such as pacemakers and implantable cardioverter defibrillators is now commonplace among heart disease patients. The ever-increasing technological complexity of these devices is matched by the near omnipresent exposure to electric, magnetic, and electromagnetic fields (EMFs), both in everyday life and the occupational environment. Given that electromagnetic interferences (EMIs) are associated with potential risk in device patients, physicians are increasingly confronted with managing device patients with intermittent EMI and chronic occupational exposure. The current review aims to provide a contemporary overview of cardiovascular implantable electronic devices, their function and susceptibility of non-medical EMFs and provide recommendations for physicians caring for cardiac device patients presenting with EMI.

Keywords

Implantable cardioverter defibrillators • Cardiac pacemaker • Electromagnetic fields • Electromagnetic interference • Cardiovascular implantable electronic devices

Introduction

Cardiovascular implantable electronic devices (CIEDs) such as cardiac pacemakers (PMs) and implantable cardioverter defibrillators (ICDs) are known to be susceptible to strong electromagnetic fields (EMFs). The MAUDE-database of the American Food and Drug Administration reveals for the last 4 years 1656 cases of malfunctions of medical devices induced by ‘electromagnetic interference’ (EMI). A survey in France showed that 16% of 855 physicians are confronted with EMI among their patients with cardiac implants for at least one time per year. However, a significant number of unreported cases can be estimated since devices do not record EMI in general.

In recent years, CIED implantation has increased exponentially, reaching an annual implantation rate of >263,000 in Germany, France, and the UK. In parallel to expanded CIED utilization, exposure to exogenous EMFs from sources such as high-voltage power lines, electronic article surveillance (EAS) systems or electrical appliances both in daily life and in the work environment has similarly increased. The evolution of new mobile communication standards (e.g. LTE/4G) and other developments related to electromobility makes it difficult to estimate the risk of EMI with CIED. Current available literature regarding EMI in CIED patients consists primarily of case reports and review articles and with few prospective clinical studies to examine the interaction of devices with various EMFs in a systematic way.

National and international guidelines for environmental and occupational EMFs exposure explicitly exclude CIED patients mandating a more critical look at the current literature to better understand the problem of EMI in this patient population. The current review focuses on the interaction of different electrical cardiac implants with non-medical environmental and occupational EMFs, summarizing the current literature and recommendations for CIED patients. In addition to the information summarized in excellent overview articles published in 2012 and 2013, this review will include more recent studies to highlight the current device technology most often encountered in daily practice. Electromagnetic interference of CIEDs in the medical environment has recently been summarized elsewhere.

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Cardiovascular implantable electronic devices and specific sensing algorithms

Currently, there are four main categories of different electrical cardiac implants: cardiac PMs, ICDs, cardiac contractility modulation devices (CCMs), and vagus nerve stimulators (VNS). However, CCM and VNS are not widespread in daily practice and not subject of this review.

Cardiovascular implantable electronic devices function relies on specific lead technology and sensing algorithms can vary by device type and lead location. The right atrial, right ventricular (RV), and various left ventricular leads of these devices are designed to detect the local intracardiac electrogram (iEGM).

Current lead design includes unipolar, integrated bipolar, and true bipolar leads (Figure 1). Unipolar leads register the iEGM from the distal pole of the lead to the device can. In contrast, integrated bipolar high-voltage leads use the distal pole and the shock coil while true bipolar leads record the iEGM at the distal tip-pole and a ring usually placed 10–15 mm proximal of the distal pole (Figure 1).

In addition to differences in lead technology, device sensing algorithms also differ depending on the desired function. Programming of sensing algorithms is of critical importance for the effect of EMFs on the different CIED.

Pacemaker

Most PMs are programmed with static sensitivity settings, i.e. signals underneath a defined range are not sensed. While the limit value may be fixed or dynamically adjusted to the maximum intrinsic EGM amplitude, typically there is no decay of the sensitivity curve within one cardiac cycle (Figure 2). In case of pacing either a fixed value or a multiple of the programmed maximum sensitivity is set.

Implantable cardioverter defibrillator

Appropriately, sensing various heart rhythms is one of the challenges of ICD therapy. Differentiation between sinus rhythm, atrial fibrillation, ventricular tachycardia (VT), or ventricular fibrillation (VF) needs special preconditions due to changes in iEGM morphology, frequency, and signal amplitude. For example, during VF iEGM signals are substantially smaller, more irregular and have shorter cycle length than VT or sinus rhythm.

Implantable cardioverter defibrillators sense primarily from the RV channel via integrated or true bipolar leads. Defibrillator sensing algorithms adjust the sensitivity throughout a single cardiac cycle via a programmed decremental decay of the sensitivity that is dependent upon the R-wave amplitude and cycle length (Figure 3).

The goal of a variable sensitivity algorithm is to detect small irregular signals like ventricular fibrillation while avoiding inappropriate double counting of T-waves or fractionated QRS-complexes in sinus rhythm.

The subcutaneous ICD is a novel therapy that can provide tachyarhythmia therapy but not antibradycardia pacing via an entirely subcutaneous system. Hence, iEGMs are not recorded and sensing is dependent upon a far-field electrogram signal in one of three vectors (distal to proximal sensing electrode, distal sensing electrode to can, proximal sensing electrode to can). The sensing algorithm is similar to transvenous sensing algorithms in that there is an adaptive sensing threshold based upon the R wave amplitude with decay over time. Given the susceptibility of far-field signals to oversensing, additional algorithms based upon heart rate, morphology, and QRS width are applied to prevent inappropriate therapies. Nevertheless, the large distance between sensing electrodes results in the lead functioning as a large ‘antenna’ with potential negative effects regarding EMI.

**Figure 1** Left: implantable cardioverter defibrillator and pacemaker with ventricular leads. (A) Unipolar sensing vector between lead tip and can, (B) true bipolar vector between tip and ring, and (C) integrated bipolar vector between tip and coil. Right: Electromagnetic interference in a unipolar pacemaker at the ventricular lead. The intracardiac electrogram shows a strong noise with device oversensing as seen in the marker channel and switch to an asynchronous pacing mode (VOO).
Electromagnetic fields in daily life and occupational environment

Electromagnetic fields arise as a result of natural processes such as lightning, and the earth's magnetic field or, they are artificially created in association with technical processes or devices. Electromagnetic fields are classified according to their wavelength and frequency (Figure 4). For example, low-frequency EMFs (e.g. emitted from power lines or electrical household devices) have a lower frequency and a longer wavelength while radiofrequency EMFs
(e.g. mobile phones or microwave ovens) have a shorter wavelength and high frequency. The fields of the various frequency ranges differ significantly in their effects on humans and electronic implants.

Static fields occur with permanent magnets or batteries, and between objects with different electrical charges. In medicine, strong static magnetic fields are used in magnetic resonance imaging (MRI). Static fields typically do not change their polarity at all or only very slowly; thus, the frequency is 0 Hz. Static electric fields do not enter the body; thus, pose no risk for electronic implants. Static magnetic fields, in contrast, penetrate the body and implanted devices, potentially activating a reed switch or hall sensor that may trigger the so-called magnet mode.

Low-frequency fields are in the frequency range of 0.1–30 kHz. The upper limit is not strictly standardized. Low-frequency fields are generated by technical appliances such as power lines, wiring, and household appliances. A low-frequency electric field is created between charge carriers, when an electrical voltage is present due to electrical potential difference, whereas low-frequency magnetic fields result from moving charges (current). The electric field strength and magnetic flux density are measured in volts per meter and Tesla, respectively. Under power lines 1.9–7 kV/m\(^2\) and 7.5–71 mT occur, depending on the voltage level and load. Electrical household devices emit fields of different intensities depending on the type, e.g., hand mixer 3.182 mT, washing machine 338 mT (all measured at the surface), and distance, e.g., hair dryers up to 2000 mT (at 3 cm distance) and 7 mT (at 30 cm distance).

The radiofrequency range generally covers frequencies between 30 kHz and 300 GHz. The lower limit is not strictly standardized. The range between 30 kHz to 10 MHz is allocated to the intermediate frequencies. Typical radiofrequency field-emitting devices are mobile phones, microwave ovens, or other wireless transmitters (e.g. bluetooth and WLAN). Radiofrequency fields are measured as volts per meter or ampere per meter. The magnitude in tissues is measured by the specific absorption rate (SAR) as watts per kilogram. Specific absorption rate values of mobile phones are relatively high due to the close proximity to the head (up to 2.55 W/kg); while in comparison, mobile phone base stations result in lower SAR values (0.03 W/kg).

The effects of EMFs on cardiac implants include the following: local increases in the current density, heating of the implant, disturbances of the electronic circuit, and disturbances of the sensing capabilities. Low-frequency fields induce electric currents within the human body and the leads of the CIED. Depending on the strength and frequency, this may result in a critical local increase in the current density, especially at the tip of the lead.

Likewise, radiofrequency fields can heat up the metal-made implant system and harm the surrounding tissue. The CIED electric circuit is fully enclosed in a metallic can, shielding the circuit against electric fields, and radiofrequency fields. However, low-frequency magnetic fields of up to 10 kHz can enter the can and induce a voltage directly in the electric circuit of the implant, leading to malfunction or even damage of the electronic components. Furthermore, EMFs may disturb the sensing capabilities of cardiac implants by inducing noise signals that interfere with the iEGM. The induced electric current by low-frequency fields superimposes intrinsic bio-signals that might result in missensing by the device. Additionally, magnetic fields induce a voltage in the lead because of the loop created by the device, lead, and tissue. These low-frequency noise signals cannot entirely be filtered out because of an overlap with the iEGM frequency range (0 Hz to \(\approx 1\) kHz). However, narrow band-stop filters, so-called notch filter, can be implemented for single frequencies like 50/60 Hz preventing interference from power frequency field sources. With exposure to radiofrequency fields, the lead acts as an antenna in which EMFs induce a voltage and, thus, disturb the sensing capabilities of the device. To mitigate radiofrequency interference, feedthrough filter capacitors are integrated in the device header (lead connector) acting as low-pass filter, thus, strongly attenuate high-frequencies noise signals, e.g., from mobile phones. The interference of the sensing capability depends on the device setting, lead configuration and position, as well as physical body characteristics.
Effects of electromagnetic fields on implanted devices and functional consequences

Since low-frequency EMFs (e.g., power frequency 50/60 Hz) represent the most prevalent EMFs in daily life, the following section will focus principally on these EMFs. For physicians caring for cardiac device patients, oversensing of noise signals due to EMF exposure may be seen in daily practice. A retrospective single centre study showed that the risk for receiving inappropriate ICD shocks due to EMI is <1% per year and patient. The functional consequences of EMF exposure depend predominantly on the strength of the EMF and the duration of interference.

To date, the lack of interference threshold testing is a major limitation of various in vivo studies examining the effect of EMFs on CIED. Moreover, worst-case conditions, such as maximum sensitivity settings of the device or body position perpendicular to the magnetic field, are often not addressed in these studies. Our group has recently introduced an experimental setup allowing interference threshold testing under worst-case conditions in 50 Hz EMF.

Pacemaker

In DDD-PM, EMF-induced inappropriate oversensing in the atrial channel causes a change in pacing mode to either VVI(+R) or DDI(+R) mode, resulting in atioventricular dysynchrony (Figure 5). If the interference is brief, the event may be unnoticed and clinically silent. However, extended atioventricular dysynchrony in patients with a high ventricular pacing percentage may develop PM syndrome with symptoms of palpitations, dizziness, and reduced physical capacity. If atrial oversensing occurs and mode switch is disabled, inappropriate ventricular pacing may be triggered up to the upper tracking rate (Table 1). Electromagnetic field-induced interference in the ventricular channel may lead to pacing inhibition with subsequent severe bradyarrhythmias, near-syncope, syncope, or asystole in PM-dependent patients. Thus, a longer duration of EMF interference may pose a substantial risk. With exposure to strong EMFs, such as those occurring in proximity to high-voltage transformers, oversensing in the ventricular channel may be recognized as exogenous noise and result in an appropriate mode switch to a completely asynchronous mode of pacing (VOO/DOO) with deactivation of sensing and the risk of potential harmful stimulation during the vulnerable phase. Recent in vivo studies have demonstrated that a unipolar sensing configuration in PM patients results in higher susceptibility to EMF interference (at power frequency 50/60 Hz), while bipolar sensing seems to be rather safe. With exposure to very high energy EMFs, devices may change permanently to a ‘power-on reset’ mode resulting in reprogramming of the device to manufacturer specific safety settings. This can only be fixed by manual reprogramming of the device.

With respect to the most prevalent EMF, low-frequency EMFs, bipolar sensing seems to be safe during EMF exposure in daily life with disturbances only occurring at stronger field strengths such as those observed in the occupational environment. See Supplementary material online, Table S1, summarizes in vivo studies reporting on EMI with low-frequency EMF in PMs published since the year 2000.

Implantable cardioverter defibrillator

Electromagnetic interference in ICDs can differ from PMs. Electromagnetic interference-induced atrial oversensing in a dual chamber defibrillator will yield a similar mode switch to PM (Figure 5). In contrast, sustained EMI exposure may result in oversensing of the RV channel with subsequent inappropriate shock delivery. Not only are inappropriate shocks painful and result in psychological distress...
but they can be potentially proarrhythmic and are associated with adverse overall survival. If the EMF is strong enough, the asynchronous noise mode will be activated. In a noise reversion mode, the subsequent loss of sensing of the intrinsic signal neither allows for detection of underlying intrinsic rhythm faster than pacing frequency with risk of T-wave stimuli nor a perception of ventricular arrhythmias. Thus, anti-tachycardia therapy would be withheld with potential lethal consequences. In contrast to PMs, activation of the reed switch of ICDs due to static magnetic fields suspends tachycardia therapy without affecting the pacing mode. Only a few studies have systematically investigated EMI with 50/60 Hz EMFs in defibrillator patients (see Supplementary material online, Table S2). Clinically significant interference only occurred with exposure to strong EMFs above the ICNIRP limit for public exposure, i.e. in the occupational environment. To the best of our knowledge, there are no studies investigating EMI of specific household appliances operating at 50/60 Hz. However, some household devices can emit very strong fields in a very close proximity (see above), thus EMI cannot generally be excluded.

The different theoretical types of interference of EMFs with implanted cardiac devices are summarized in Table 1.

### Other sources of electromagnetic interference in cardiovascular implantable electronic device patients

The disturbance of cardiac implants by EMFs is in many parts not systematically investigated. The EMF-Portal (www.emf-portal.org), a scientific literature database on the effects of EMFs, currently revealed ~360 publications on EMI with cardiac implants with major differences in their study design (e.g. in vitro tests, provocation studies, and case studies), the investigated frequency range, or the type of device. Thus, it is difficult to compare these studies and to draw general conclusions for the safety of patients in specific EMFs. Typically, studied devices of everyday life comprise, e.g. mobile phones, article surveillance devices, radiofrequency identification systems (RFIDs), or digital music players.

In vitro data on EMI with PM and ICDs with RFID readers suggested that the low-frequency RFID technique (e.g. 134 kHz) may be of potential risk for device patients. This technique is usually implemented in EAS or access control to restricted areas like ski slopes. Emitted EMFs differ between commercially available systems. In vivo studies of RFID EMF in cardiac device patients are scarce. See Supplementary material online, Table S3, summarizes the in vivo studies on RFID, EAS systems, and metal detectors evoking device disturbances published since 2000.

While EMI by household articles are often related to technical defects or improper grounding, dosimetric data suggest that induction ovens emit EMFs in the intermediate frequency range which may be of potential risk for device patients. However, in vivo studies of PM and ICD patients did not demonstrate interference at distances >25 cm, suggesting little risk for device patients with the use of induction ovens.

Mobile phones are ubiquitously present in everyday life. Mobile phones are more likely to cause interference in the atrial channel due to the small intrinsic atrial signal and a corresponding poor signal-to-noise ratio. As with other forms of EMF, unipolar sensing seems to be unfavourable. An in vivo study of PM patients showed that clinically significant interference only occurred when cellular phones were directly held over the PM. However, these data are from the mid-1990s and subsequent, novel device developments have rendered electrical cardiac devices less susceptible to interference by these EMFs. Moreover, these previous studies have shown that a few safety measures such as a minimum compliance distance of ~20–30 cm are sufficient to ensure safe operation of mobile phones by patients with active CIEDs.

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**Table 1** Theoretical constellation of interference of different device types and their clinical consequences

<table>
<thead>
<tr>
<th>Device</th>
<th>Interference type</th>
<th>Clinical consequence</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pacemaker</td>
<td>Atrial oversensing</td>
<td>• Inappropriate mode switch (DDI/VVI) with AV dyssynchrony</td>
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<tr>
<td></td>
<td></td>
<td>• Increased ventricular pacing in the event of atrial oversensing</td>
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<tr>
<td></td>
<td>Ventricular oversensing</td>
<td>Pacing inhibition</td>
</tr>
<tr>
<td></td>
<td>Switch to noise mode (strong EMFs)</td>
<td>Completely asynchronous pacing with risk of pacing in the vulnerable phase and subsequent induction of arrhythmia</td>
</tr>
<tr>
<td></td>
<td>Reed switch activation</td>
<td>Asynchronous pacing (mode sometimes programmable)</td>
</tr>
<tr>
<td>Transvenous ICD</td>
<td>Atrial oversensing</td>
<td>Inappropriate mode switch (DDI/VVI) with AV dyssynchrony</td>
</tr>
<tr>
<td></td>
<td>Ventricular oversensing</td>
<td>• Inappropriate tachycardia detection → ATP/Shock</td>
</tr>
<tr>
<td></td>
<td>Switch to noise mode (strong EMFs)</td>
<td>• Pacing inhibition</td>
</tr>
<tr>
<td></td>
<td>Reed switch activation</td>
<td>Asynchronous pacing with risk of pacing in the vulnerable phase. No tachycardia detection.</td>
</tr>
<tr>
<td>Subcutaneous ICD</td>
<td>Oversensing</td>
<td>• Inappropriate tachycardia detection → Shock</td>
</tr>
<tr>
<td></td>
<td>Noise detection</td>
<td>• T-wave oversense → doublecount → Inappropriate high-voltage shock</td>
</tr>
<tr>
<td></td>
<td>Reed switch activation</td>
<td>• Withhold of anti-tachycardia therapy</td>
</tr>
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In addition, Mattei and coworkers investigated in an in vitro study the potential influence of Wi-Fi EMF on cardiac implants. They concluded that Wi-Fi devices do not pose risks of EMI to PMs. Ostiguy and coworker did not find any disturbance from smart meters or routers. The growth of electromobility in recent years makes it difficult to estimate the risk of EMI for CIED patients due to differentially configured EMFs. Wireless charging stations may be of particular interest because of higher field strength. However, no case reports or in vivo studies have been published to date. Thus, unrestricted use of this technology among cardiac device patients cannot be recommended at present.

Use of diagnostic and therapeutic technics in medicine emitting strong EMF is limited in CIED patients due to potential interference with the device. Generally, it is important to differentiate between EMF emitting devices for the purpose of clinical use (e.g. MRI) and devices with galvanic coupling, where the body is part of the current cycle (e.g. monopolar electrocautery, transcutaneous electrical nerve stimulation). Galvanic coupling at the thorax often causes substantial interference with the device leading to inappropriate oversensing with, e.g. subsequent pacing inhibition in PM or inappropriate anti-tachycardia therapy in ICDs. A switch to a noise mode causes asynchronous pacing (VOO/DOO) in PM and loss of tachycardia detection and therapy in ICDs. Device defect is a rarely observed phenomenon. Regarding MRI, the very intense static magnetic field may activate the reed switch with change to an asynchronous magnet mode in PM or deactivation of anti-tachycardia therapies in ICDs. During the scan alternating magnetic fields were applied leading to heating of the lead tip due to induced current with subsequent thermal tissue damage. This can lead to elevation of the pacing threshold or exit block and sensing failure. However, differentiated scan protocols and device programming allow MRI scans. Detailed review of this topic can be found elsewhere.

How to care of device patients exposed to electromagnetic field

Current guidelines provide important information on the management of patients with CIEDs, e.g. in the context of surgery and certain diagnostic procedures such as MRI. However, structured recommendations for patients with CIEDs exposed to EMFs in daily life are currently lacking. In patients presenting with recent exposure to EMI, the technical integrity of the device should carefully be evaluated. In addition, an in-depth analysis of the situation of interference and a history of earlier device disturbances should be obtained.

In general, true bipolar leads should be implanted in all patients if possible because of a better signal-to-noise ratio and a smaller ‘functional antenna’ to sense EMFs. In the case of pre-existing unipolar leads, physicians and patients should be aware of a higher likelihood of interaction with EMFs. Sensitivity settings should carefully be evaluated and programmed. The lowest possible sensitivity should be chosen, which ensures an appropriate sensing of intrinsic signals. Implantable cardioverter defibrillator testing with VF induction may be necessary to evaluate appropriate sensing of fibrillation waves with sensitivity settings lower than the manufacturer’s recommendations. This is especially helpful if exposure to EMFs is unavoidable. Since noise signals superimpose intrinsic iEGM signals, T-wave oversensing (TWOS) may occur more often, thus potentially leading to inappropriate anti-tachycardia therapy. Inclusion of the far-field-EGM in the arrhythmia discrimination algorithm may be useful. In PM-dependent patients, TWOS may lead to a decrease in heart rate. In the case of foreseeable strong EMF exposure like in the occupational environment, field measurements at the workplace can be performed to estimate EMI risk. Due to short-term interference with inappropriate oversensing in ICDs, modification of the arrhythmia detection settings may be useful. Prolonged detection intervals and elevation of the VT/VF zones as mentioned in several studies may prevent inappropriate shocks without impairing the outcome of the patients. As algorithms like automatic capture measurement or adaptive sensitivity control may lead to inappropriate automatic reprogramming (especially sensitivity) of the device, these features should be switched off. An assessment of local occurring EMFs in the workplace should be performed. Patients who present with noise reversion mode due to strong EMFs should be advised to maintain a greater distance (usually >30 cm) to the source of EMFs. Furthermore, telemonitoring of devices may be of great help to early detect EMI or EMF-related device failure.

Gaps of knowledge

While experimental in vivo data exist for PMs and ICDs in 50/60 Hz EMFs, additional studies are needed to investigate EMI thresholds of all CIEDs in vivo and under worst-case conditions. In particular, different field configurations should be rigorously studied given the increased implementation of technology with EMF emission in daily life, including mobile phones, RFID and electric vehicles.

Conclusion and clinical implications

For the vast majority of PM and ICD patients, the presence of true bipolar leads and rationally adjusted sensitivity settings virtually eliminate the risk of clinical relevant EMI in daily life with rare events predominantly affecting the atrial channel. VVI programming is the preferred mode of pacing among CIED patients with foreseeable exposure to very strong EMFs. With respect to occupational EMF exposure, data suggest that low-frequency EMFs are relatively safe for ICD patients especially with respect to the ventricular channel. Remote monitoring of devices may help with early detection of EMI and device failure. Implantation/exchange of a CIED or major modification of the device sensitivity settings warrants appropriate risk assessment.

Supplementary material

Supplementary material is available at European Heart Journal online.

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