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Pacemaker Reed Switch Behavior in 0.5, 1.5, and 3.0 Tesla Magnetic Resonance Imaging Units: Are Reed Switches Always Closed in Strong Magnetic Fields?

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LUECHINGER, R., ET AL.: Pacemaker Reed Switch Behavior in 0.5, 1.5, and 3.0 Tesla Magnetic Resonance Imaging Units: Are Reed Switches Always Closed in Strong Magnetic Fields? *MRI is established as an important diagnostic tool in medicine. However, the presence of a cardiac pacemaker is usually regarded as a contraindication for MRI due to safety reasons. The aim of this study was to investigate the state of a pacemaker reed switch in different orientations and positions in the main magnetic field of 0.5-, 1.5-, and 3.0-T MRI scanners. Reed switches used in current pacemakers and ICDs were tested in 0.5-, 1.5-, and 3.0-T MRI scanners. The closure of isolated reed switches was evaluated for different orientations and positions relative to the main magnetic field. The field strengths to close and open the reed switch and the orientation dependency of the closed state inside the main magnetic field were investigated. The measurements were repeated using two intact pacemakers to evaluate the potential influence of the other magnetic components, like the battery. If the reed switches were oriented parallel to the magnetic fields, they closed at 1.0 ± 0.2 mT and opened at 0.7 ± 0.2 mT. Two different reed switch behaviors were observed at different magnetic field strengths. In low magnetic fields (< 50 mT), the reed switches were closed. However, in high magnetic fields (> 200 mT), the reed switches opened in 50% of all tested orientations. No difference between the three scanners could be demonstrated. The reed switches showed the same behavior whether they were isolated or an integral part of the pacemakers. The reed switch in a pacemaker or an ICD does not necessarily remain closed in strong magnetic fields at 0.5, 1.5, or 3.0 T and the state of the reed switch may not be predictable with certainty in clinical situations. (PACE 2002; 25:1419–1423)*

MRI, magnetic resonance, pacemaker, reed switch

Introduction

Magnetic resonance imaging (MRI) is widely accepted as an important diagnostic tool and the imaging modality of choice in many disease states. However, in most institutions, patients with an implanted cardiac pacemaker are restricted from MRI due to safety reasons.[1–5] Important potential hazards include the risk of fast pacing, inhibition, or reprogramming to the electrical reset parameters of the device, damage to pacemaker components, and heating effects at the lead tip.[6,7] Nevertheless, in some clinics, patients with pacemakers underwent MRI scanning at different field strengths without apparent negative consequences.[8,9]

In previous studies investigating the interactions between MRI and pacemakers[6,8] the authors assumed that the reed switch in the device, which alters the pacemaker mode to an asynchronous mode in the presence of a magnet, is always closed within the main magnetic field of an MRI scanner. Pavlicek et al.[6] showed that the threshold for initiating the asynchronous pacing mode was as low as 17 G (1 G = 10^{-4} T). In a recently published study the investigators noted an interesting observation, that reed switch activation did not necessarily occur in a static magnetic field at 0.5 T.[9] Although the reed switch closed initially in all patients approaching the MRI scanner, they observed opening of the reed switch in some patients when they were positioned in the bore of the magnet. An explanation for this peculiar observation was left open in that report.

The aim of this study was to investigate the

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state of a pacemaker reed switch at different orientations and positions in the main magnetic field of 0.5-, 1.5-, and 3.0-T MRI scanners and to explain why a reed switch may open inside these units.

Methods

Ten reed switches used in current pacemakers and implantable cardioverter defibrillators (ICDs) (Medtronic Inc., Minneapolis, MN, USA) and one reed switch taken out of an old pacemaker (Dialog II, Siemens Elema, Solna, Sweden) were used in this study. The behavior of the reed switch as an integral part of a pacemaker was evaluated using Medtronic Kappa DR 701 and Kappa DR 730 pacemakers. All investigated reed switches had the same body dimensions of 1.4-mm diameter and 5-mm length. The evaluations were performed in an open 0.5-T MRI unit (GE Sigma SP, Milwaukee, WI, USA), in an actively shielded 1.5-T MRI unit (Philips Gyroscan ACS NT, Best, the Netherlands) and in an actively shielded 3.0-T MRI unit (Philips Intera 3T). Magnetic field strengths between 0.5 and 1.5 T are most commonly used in the currently available MRI scanners, and the 3.0 T units are expected to be widely available for clinical use in the near future.

The isolated reed switches were connected with long wires to a light emitting diode (LED) and a power supply, which were outside the high magnetic field. With a voltage of 1.65 V, a current of 5.34 mA flows through the reed switch and the LED. This current is higher than the currents in a pacemaker, but it is still lower than the recommended maximal switching power of the used reed switches. In the authors' experience, the use of an LED is an easy and fast method to display the state of the reed switch. The closure of the reed switch was evaluated for different orientations and positions relative to the main magnetic field.

By programming the pacemaker to the highest programmable pacing rate (i.e., 175 beats/min), it was visually possible to detect the initiation of the magnet mode by a sudden change of the pacing rate to 100 beats/min for 3 beats followed by a sustained magnet rate of 85 beats/min. The stimulation pulses were visualized by connecting a small circuit with an LED to the ventricular pacemaker connector (Fig. 1).

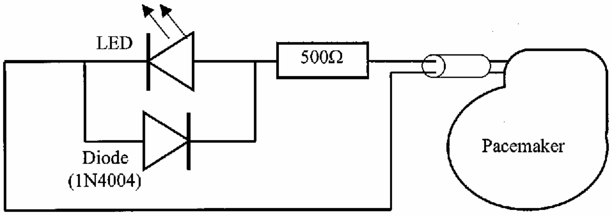

Figure 1. *The circuitry used to visualize the pacing pulses: A 500-Ohm resistance was connected in serial to the (light emitting diode) LED to limit the currents. A diode (1N4004) was inserted in parallel to the LED to allow proper pacing and to protect the LED.*

The measurements were performed using isolated reed switches and reed switches within intact pacemakers in two similar steps. First, the reed switches (or reed switch in pacemakers) were progressively moved into the MRI scanner along the central axis. The movement along the central axis was used because the orientation of the magnetic field is always parallel to the central axis, and the field strength was known from an earlier measurement.[10] At positions away from the central axis and outside the magnet bore the orientation of the magnetic field and the field strength may change. The position where the reed switches closed was noted and the magnetic field strength at this position was determined using a field strength distribution table specific to the used MRI scanners. The magnetic field strength at which the reed switch was opened was estimated by moving the reed switch out of the magnetic field. Second, the reed switches were advanced slightly into an area with a magnetic field, which was stronger than needed to close the switches. The closure of the reed switches was evaluated by rotating them in different orientations. This evaluation was repeated as the reed switches were further advanced into the MRI scanner up to the isocenter of the magnet.

Results

When the isolated reed switches were advanced along the central axis into the MRI scanner, they closed at 1.0 ± 0.2 mT. The reed switches opened at 0.7 ± 0.2 mT, as they were moved away from the scanner. The corresponding values for the reed switches in the two pacemakers were 1.1 ± 0.2 for closure and 0.7 ± 0.2 for opening. All results were in good agreement with the manufacturing specification of the reed switches.

At magnetic field strengths higher than that required for reed switch closure, the following behavior was observed:

1. Low magnetic fields (< 50 mT): In this case, the reed switch was normally closed. However, the reed switch was sensitive to the orientation relative to the magnetic fields. If the homogeneous magnetic field in MRI scanners was exactly normal to the ρz-plane shown in Figure 2, the reed switch did not close in low magnetic fields.
2. High magnetic fields (> 200 mT): The reed switches showed a different behavior in the isocenters of the 0.5-, 1.5-, and 3.0-T scanners. In

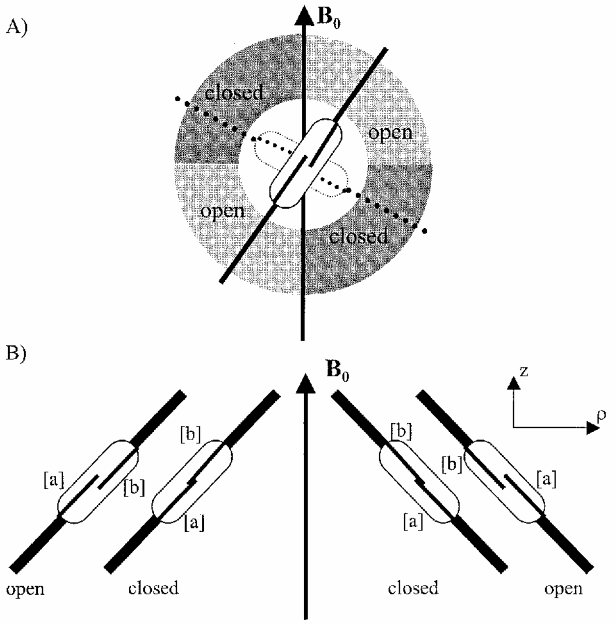

Figure 2. *Influence of reed switch orientation with respect to the main magnetic field $\mathbf{B}_0$ switch state in a magnetic field > 200 mT. (A) The light gray sectors represent open switch orientations and the dark gray sectors indicate closed reed switch orientations. (B) A rotation of 180 degrees around the long axis of a switch will invert the reed switch state.*

50% of all tested orientations, the reed switch remained open. Figure 2 shows different orientations of a reed switch with respect to the main magnetic field and the observed state. In the isocenter of all three scanners the reed showed the same paradoxical opening.

The observations were not limited to positions along the central axis of the MRI device. At other positions away from the central axis, taking into account the possible changes in the orientation and strength of the magnetic field, no changes in the described reed switch behavior could be observed.

By evaluation of the state of the reed switch mounted in the pacemakers in the high magnetic field, the orientation of the reed switch could be identified. In both pacemakers the reed switches were mounted in parallel to the connector block. When the pacemaker case was opened, the expected reed switch orientation was observed indicating that the reed switch state is not being influenced from the other metallic components of the pacemaker system. The reed switches seemed to be oriented in the same way in both pacemakers, but they showed opposite states. In other words, when the reed switch of one pacemaker was open, the reed switch of the other device was closed, provided that both devices had the same orientation. The reason for this observation was that the reed switches of the devices were rotated 180 degrees against each other along the long axis of the switch (as shown in the left two reed switches in Figure 2B).

Discussion

Since it is easily possible to initiate asynchronous pacing mode by application of a small magnet, one would expect that an MRI scanner that exerts much stronger magnetic fields would also do the same. Closure of the reed switch at magnetic field strengths used for clinical MRI at 0.5–1.5 T was generally expected in previously published reports studying interactions between pacemakers and MRI scanners.[6,8] However, the recently reported study by Sommer et al.[9] suggests the possibility that pacemakers that initially convert into asynchronous pacing mode may fall back to programmed pacing mode when positioned in the bore of the magnet for MRI. The present study confirms these findings and provides an explanation for such observations.

The following physical effects occur on a pacemaker, and thus on the reed switch, when exposed to an external magnetic field ($\mathbf{B}_0$). The magnetic field induces magnetic dipoles (+ P and—P as shown in Fig. 3) in the ferromagnetic reeds. This magnetization depends on the magnetic field in a highly nonlinear way. The magnetic dipoles of the reeds interact with each other (attraction force [$\mathbf{F}_D$]) of two different poles + P and—P'). This attracting force leads to a closed reed switch in a lower magnetic field. In addition, each of the reeds interacts with the external magnetic field $\mathbf{B}_0$. The force and torque effects of MRI scanners on pacemakers and ICDs have been investigated previously by the authors.[10] It can be expected that these effects will also act on each of the two reeds. The magnetic torque ($\mathbf{T} = \mathbf{m} \times \mathbf{B}_0$, with m = magnetic moment of the dipole) tries to rotate a ferromagnetic material parallel to the magnetic field (magnetic torque is shown in Fig. 3 with two pairs of force vectors $\pm\ \mathbf{F}_T$ and $\pm\ \mathbf{F'}_T$). Furthermore, in an inhomogeneous magnetic field a force ($\mathbf{F}_F = \mathbf{m}\nabla B_0$, with m = magnetic moment of the dipole) will act on each reed. The magnetic moment m is equal for both reeds and $\mathbf{F}_F$ will act in the same direction and does not influence the reed switch state. Furthermore, in the isocenter of the MRI device the field has to be constant ($\nabla B = \mathbf{0}$). Therefore, the two forces ($\mathbf{F}_F$) will be neglected for this evaluation. In low external fields (< 50 mT), the attracting force of the two dipoles is much stronger than the forces induced by the torque ef-

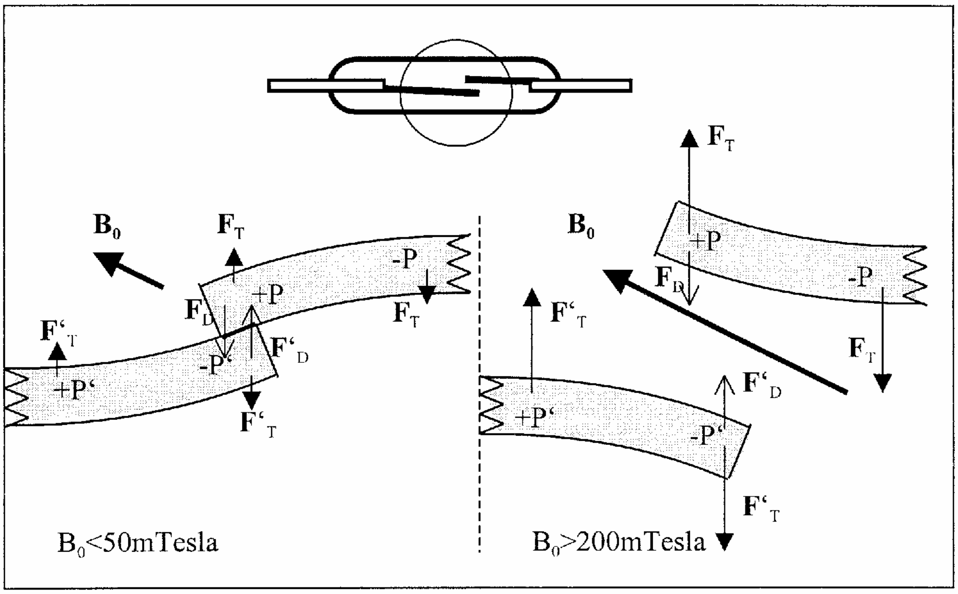

Figure 3. *Physical effects of magnetic fields on a reed switch: The magnetic field induces magnetic dipoles in both reeds (± P and ± P'). These dipoles will now interact with each other but also with the magnetic field* $\mathbf{B_0}$. The force $\mathbf{F_D}$ between the two reeds will always be attracting and bend the reeds to close the switch. The interaction of each reed with the magnetic field $\mathbf{B_0}$ causes magnetic torque (shown with two pairs of force vectors $\pm \mathbf{F_T}$ and $\pm \mathbf{F'_T}$) which tries to align the reed with the field. Depending on the orientation of the field relative to the reed switch the torque tries to open or close the reed switch. In a lower magnetic field (< 50 mT) the force $\mathbf{F_T}$ is always smaller then the attraction force $\mathbf{F_D}$ and the reed switch stays closed. In higher fields (> 200 mT) the force $\mathbf{F_T}$ will be stronger than the force $\mathbf{F_D}$ and the state of the reed switch now depends on its orientation relative to the main magnetic field $\mathbf{B_0}$.

fect and the reeds attract each other; the switch is almost always closed (Fig. 3, left). Orientations with constantly open reed switches (i.e., exactly perpendicular to the ρz-plane shown in Fig. 2B) are rare and need a very homogeneous magnetic field. If the reed switch closes, it is not possible to open the switch again in a field < 50 mT. Breathing and other movements are unlikely to allow a constant open reed switch position in practice. However, in higher magnetic fields (> 200 mT), the torque effect is stronger than the attraction force, leading to an open reed switch in the shown orientation (Fig. 3, right). Rotating the reed switch 180 degrees around its long axis will lead to a contrary reed switch state, explaining the overall reed switch closure in half of the cases (Fig. 2A).

In any kind of MRI investigation using whole-body systems (even in case of knee examination), an implanted pacemaker in a patient will be exposed to a magnetic field strength of at least 100 mT. In case of abdomen or brain imaging, the exposed field strength will be 0.5, 1.5, or 3.0 T, depending on the device. Magnetic gradients with up to 21 mT/m in current MRI units are strong enough to close the reed switch, but the generated magnetic fields have the same direction as the main magnetic field and modulate it < 1%. The magnetization of the reeds will be changed even much less due to saturation, so an influence of the gradients on the reed switch is not expected. Therefore, the results closely approximate the situation encountered in clinical practice.

It is only possible to predict the state of the reed switch if the exact orientations of the pacemaker in the MRI scanner, of the reed switch in the pacemaker, and of the reeds in the switch are known, but this is usually not possible. During the manufacturing process the reed switches are not mounted in a predefined orientation since it was assumed that the reed switch closure would be nearly independent of its orientation relative to the main magnetic field. A closed reed switch puts the device to the asynchronous mode, which is preferred during MRI investigations to avoid influences on the sensing circuits by induced voltages from the gradient and radiofrequency pulses. Since the reed switch may not be closed in specific orientations, the pacemaker should be reprogrammed to an asynchronous mode to avoid possible inhibition of pacing function. In ICD devices, reed switch closure will temporarily inhibit therapy delivery. In a strong magnetic field the reed switches will be open in half of the cases and, if an arrhythmia is detected, the ICD will start to charge the capacitor. However, this will not be possible inside a MRI scanner because the transformer core material is saturated, and due to high currents the battery may be depleted or the circuitry may be potentially destroyed. In an in vitro MR measurement, the authors observed fast depletion of a new ICD battery after 5 minutes of scanning because of inappropriate tachyarrhythmia detection and charging attempt of the capacitor. Placement of two parallel reed switches mirrored (like the left two reed switches in Fig. 2B) inside the ICD devices may reduce the probability of an open reed switch. In the authors' opinion, the unpredictable state of reed switch is not only limited to the investigated pacemakers and ICDs. The same effects are also to be expected in other devices with reed switches, like neurostimulators.

Study Limitations

Pacemakers with a hall sensor, like the Sigma series from Medtronic, or other types of magnetic field sensors were not investigated. It is possible that these sensors, which are not in common use today, may stay closed in the magnetic field of an MRI device. In addition, the study observations were only limited to the state of a pacemaker reed switch. The authors do not comment on the overall feasibility and safety of MRI in patients with implanted devices. Even if the reed switch issue is solved, this alone should not be interpreted as sufficient evidence for safe MRI investigation in pacemaker/ICD patients. With the current state of knowledge, MRI should be regarded as a contraindication unless other potential hazards, like thermal injury induced by the radiofrequency field and rapid pacing are solved.

Conclusion

The reed switch in a pacemaker or an ICD does not necessarily close in static magnetic fields at 0.5, 1.5, and 3.0 T. At low magnetic fields the attracting magnetic forces between the two reeds dominate. In contrast, in high magnetic fields the torque effects from the outer magnetic field on each reed are stronger than the attracting forces between the two reeds. It is practically impossible to predict the state of the reed switch in MRI scanners unless the exact orientations of the pacemaker in the MRI scanner, of the reed switch in the pacemaker, and of the reeds in the reed switch are known.

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