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Review / Derleme

The reliability of magnetic resonance imaging in patients undergoing cardiologic and cardiovascular surgical interventions

Kardiyolojik ve kardiyovasküler cerrahi girişim yapılan hastalarda manyetik rezonans görüntülemenin güvenirliği

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ABSTRACT

Magnetic resonance imaging is an invaluable diagnostic tool which is increasingly more frequently used in clinical practice. However, the utility of this imaging technique may be limited in patients with metallic implants placed during previous cardiologic or cardiovascular surgical interventions due to increased complication rates. Despite increased rates of compatibility between such devices and magnetic resonance imaging thanks to technological advances, the risk of interaction with untoward consequences is still high in many cases. Herein, we describe a practical source of information and guidance on the reliability of magnetic resonance imaging in this patient population in the clinical practice in the light of evidence-based data.

Keywords: Cardiac intervention; cardiovascular surgery; magnetic resonance imaging.

ÖZ

Manyetik rezonans görüntüleme klinik uygulamada giderek daha sık kullanılan değerli bir tanı aracıdır. Ancak, bu görüntüleme tekniğinin kullanımı, komplikasyon oranını artırdığı için, daha önceki kardiyolojik veya kardiyovasküler cerrahi girişimler sırasında metalik implant takılan hastalarda sınırlı olabilir. Teknolojik gelişmeler sayesinde bu tür cihazlar ve manyetik rezonans görüntüleme arasındaki geçimlilik oranı artmakla birlikte, beklenmedik sonuçlar ile birlikte etkileşim riski halen birçok olguda yüksektir. Bu yazıda, kanıta dayalı veriler eşliğinde, bu hasta popülasyonunda klinik uygulamada manyetik rezonans görüntülemenin güvenirliğine ilişkin pratik bir bilgi kaynağı ve rehber sunuldu.

Anahtar sözcükler: Kardiyak girişim; kardiyovasküler cerrahi; manyetik rezonans görüntüleme.

Magnetic resonance imaging (MRI) is one of the most useful diagnostic imaging techniques for clinicians.[1] Thanks to various properties of the device such as the absence of ionizing radiation, no need for potential nephrotoxic contrast enhancement agents, high soft tissue sensitivity, and three-dimensional imaging capabilities, MRI is currently more frequently used for the diagnosis and treatment of a wide variety of medical conditions, particularly for those involving the brain, spinal cord, and musculoskeletal system.[1,2] Furthermore, cardiac MRI has been used not only for diagnostic tests, but also for cardiologic interventions even for complex entities.[3]

Each year, millions of people are estimated to be implanted with cardiac devices worldwide. In addition, there is a growing number of patients having a prior cardiac surgery or a cardiovascular device implant and undergoing MRI examination.[1] It is a well-known fact that certain cardiac devices, particularly implantable cardioverter defibrillators (ICD) and cardiac pacemakers, may result in potentially hazardous interactions when used in combination with MRI.[4] In study conducted in 2004, it was reported that approximately 200,000 patients are unable to undergo an MRI examination due to the presence of such devices.[5] On the other hand, it has been also estimated that nearly 75% of these individuals will

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have one or another indication for an MRI examination in the rest of their lives.[6,7] Due to increasing number of individuals affected, several guidelines have been developed.[8] Also, many case reports, clinical researches, and systematic reviews focused on this issue. Despite the availability of a consensus on the level of potential magnetic-interactions for a number of different devices, controversial reports have been published for complex and major electronic devices such as ICD and pacemakers. In the update version of American College of Cardiology Foundation/ American Heart Association (ACCF/AHA) 2007 Clinical Competence Statement on Vascular Imaging With Computed Tomography and Magnetic Resonance guidelines in 2007,[8] no potential risks are cited for non-ferromagnetic items such as mechanical cardiac valve prostheses, clips, and sternal wires, while an absolute contraindication is assigned for ICD and pacemakers, despite reports suggesting safely use up to 1.5 Tesla.[9-11]

Such controversy in the literature data may lead to painstaking decision processes in the daily clinical practice for physicians in different specialties of medicine including cardiologists, cardiovascular surgeons, and radiologists. Considering this obscurity and increasing number of patients undergoing cardiovascular interventions, in this review, we describe a practical source of information and guidance on the reliability of magnetic resonance imaging in this patient population in the clinical practice in the light of evidence-based data.

THE TECHNIQUE OF MAGNETIC RESONANCE IMAGING

Magnetic resonance imaging is based on the absorption and emission of nuclear electromagnetic energy following a wave of radiofrequency (RF) directed at the atomic nucleus. This method utilizes magnetic fields and RF waves. The risks associated with medical use arise from these different types of energy and are usually categorized in three main groups. The first is the static magnetic field, which is expressed with Tesla (T) units denoting the magnetic power of the device. A 3T magnetic field is equal to 60 thousand times the magnetic field on the surface of the earth. The term ferromagnetic refers to the materials which react to the magnetic pull force of a magnetic field and has been derived on the basis of the high magnetic quality of the iron element. The most prominent effect of the static magnetic field is its ability to cause movements involving displacement, rotation, or direction in materials with ferromagnetic or weak ferromagnetic properties. Secondly, short-term spatial variations in the magnetic field force of the device caused by the gradient coils are referred to as the gradient magnetic field. Despite being weak, they may be associated with the production of electrical currents due to their repetitive nature. Although they are not powerful enough to impact the myocytes, they may lead to arrhythmias after being amplified by coils, wires or similar devices around the heart.[9] Thirdly and lastly, there are certain risks associated with the RF energy, the primary effect of which is heating. This effect which can be sensed even in normal tissues may be accumulated particularly by intravascular battery leads, leading to serious consequences due to the antenna effect occurring at their tips.[10] The dosimetric equivalent of the RF which can be absorbed by a specific tissue is expressed as the Specific Absorption Rate (SAR) in watts/kg. This unit directly correlates with the square of the magnetic field force. Thus, a more powerful MRI device may be expected a more marked effect of this kind.

Furthermore, it should also be kept in mind that the metallic materials embedded in the body may lead to artifacts due to their own magnetic fields. These artifacts usually tend to occur 10 to 15 cm distant from the metallic material[2,12] and, therefore, can be ignored except for imaging studies involving the thorax.

To eliminate or prevent the potential effects of aforementioned forces, a careful assessment of patients undergoing MRI before and during the procedure is essential. This is mostly accomplished by site-specific patient questionnaires in each center.

Various equipment and devices utilized in cardiovascular surgery and cardiology exist such as:

STERNAL WIRES, STERNAL CLOSURE EQUIPMENT, AND HEMOCLIPS

Although iron is used for steel production, steel has weak ferromagnetic properties leading to its frequent medical use.[13] Several subtypes of steel exist depending on the proportion of other elements within its structure. Several types such as 316L and 304V are usually used in stents or closure devices, displaying weak ferromagnetic properties at 1.5 T with an increased effect at 3 T.[13-16] Sternal wires are usually produced from stainless steel. There are no published reports on their MRI-associated side effects and they are usually considered safe at 3 T and below.[8,16,17]

Titanium and nitinol are non-ferromagnetic and magnetically inert materials. Screws, adjustable clips, and nitinol clips used for the sternal closure other than the steel wires do not represent a contraindication to MRI, since they are produced from titanium and nitinol.[15,16]

Almost all hemoclips (i.e. vascular clips) are made from titanium. Therefore, they are not a contraindication to MRI thanks to non-ferromagnetic properties of titanium.[18]

TEMPORARY EPICARDIAL PACE WIRES

For the treatment of postoperative bradyarrhythmias in patients undergoing cardiac surgery, steel wires which are sutured to epicardium and covered by isolating material are utilized.[19] In general, they are removed before the patient is discharged. However, in some cases, removal of the wires may be challenging due to a number of causes such as the tangling of the wire in its course, entrapment between bony structures or sternum, or inability to remove from the epicardial suture area. In such situations, slight tension is placed on the wire, cut, and left in the subcutaneous area. Due to the reported potential hazards of these remaining wire segments, it has been proposed that care must be practiced during an MRI exam.[19] On the other hand, in another study involving 51 patients with temporary epicardial wires, no problems were reported.[17] In our unit, our policy is to limit the use of temporary epicardial pace wires, as they are likely to be associated with increased complication rates and further complications.[20] In cases where an MRI should be performed, we believe that an electrocardiography monitorization is essential for the safety of the procedure, even in the absence of any cardiac complaints or in the presence of a long time-interval between current MRI examination and the previous surgery.

PERMANENT TRANSVENOUS PACE LEADS

Following removal or revision of pacemakers or ICDs, the remaining leads in the intravascular space may be associated with potential risks such as producing heat or electrical currents due to the RF energy and magnetism.[21] Broken leads during the procedure are thought to pose a particular risk due to an antenna effect.[21] Except for a recent study on this issue, no detailed literature data exist.[21] In the aforementioned study, a total of 19 patients in whom pacemakers were removed with left leads were assessed. Although none of the equipment was MRI-compatible, no adverse events were reported. In another *ex-vivo* study, the temperature of the transvenous pacemaker catheter raised up to 63.1 °C.[22]

PERIPHERAL VASCULAR STENTS AND AORTIC STENT GRAFTS

Most of the modern peripheral stents do not possess ferromagnetic properties and are suitable for an MRI examination right after stent implantation.[8] In the case of weak ferromagnetic stents, the decision must be individualized. Unless absolutely required, a six-week waiting period is recommended for examinations to be performed at ≤3 T to allow tight attachment of the stent to the vessel wall, limiting its mobility.[8]

A similar approach is recommended for aortic stent grafts. Modern stent grafts are usually MRI-safe and can be implanted with MRI assistance. In an *in-vitro* study, six different brands of grafts frequently utilized [Relay (Bolton Medical, Sunrise, FL, USA), Zenith (Cook, Bloomington, IN, USA), TAG (W.L. Gore & Associates, Flagstaff, AZ, USA), Evita (Jotec, Hechingen, Germany), and Talent (Medtronic Vascular, Santa Rosa, CA, USA)] were assessed.[23] While nitinol-based grafts were extremely rarely associated with MRI artifacts during the procedure and in further MRI images, the devices produced from stainless steel (Relay, Zenith, Talent) resulted in interpretation difficulties due to the presence of artifacts around the graft.[23] In another study examining the Zenith endografts produced from 304 stainless steel, MRI and CT images were evaluated in a group of patients with previous graft placement.[24] The authors concluded that MRI did not result in significant anatomic adverse effects and that potential diagnostic benefits of MRI should not be discarded in every patient with Zenith grafts.[24]

In an *in-vitro* study involving a number of different aortic stent-grafts, only three (AneuRx, Excluder, and Vanguard) of the eight popular brands (AneuRx, Endofit, PowerLink, Excluder, LifePath, Talent, Vanguard, Zenith) proved to be effectively compatible with MRI, while others were associated significant artifacts.[25]

CARDIAC VALVE PROSTHESES AND ANNULOPLASTY RINGS

These devices are produced from metals (aluminum, titanium, vanadium, tungsten), polymers (polytetrafluoroethylene, polyethylene terephthalate) or pyrolytic carbon components.[12,13] These valves do not tend to produce significant heat or mobility, when exposed to magnetic and radiofrequency forces, thanks to their production material.[13] Also, the production of electrical currents is unlikely. The minimum heating at ≤3 T can be effectively absorbed by the high blood flow rate and their mobility under a magnetic force is negligible compared to the beating heart and blood pressure-related mobility.[12,26] Thus, most of the products available can be considered safe.[27-32]

In studies examining metallic valves, no adverse effects were reported during and after an MRI.[17,33,34] Also, there are no reports suggesting permanent closure or opening of the valve leaflets between 1.5 to 3 T.[18]

The movement of mobile mechanical prostheses such as cardiac valves results in the production of a magnetic field in the opposite direction consistent with the Lenz law.[35] Although several authors suggest that this theoretical effect can be neglected, an editorial letter reported some concerns for selected patients.[36] In this case report, a 75-year-old patient previously implanted with a St. Jude aortic mechanical valve was described with moderate-to-severe paravalvular leak following an MRI examination which was unable to be explained otherwise than by an MRI-device interaction. However, our literature search did not reveal any comprehensive studies specifically examining this combination.

Artifacts in the surrounding tissues in patients with mechanical cardiac valves undergoing MRI are a known phenomenon, and the old-style Björk-Shiley valve prostheses were reported to lead to the formation of distant artifacts.[37] In three patients with this type of prostheses, black dot formation was observed during a cerebral MRI. Possible explanations put forth include the leakage of micro-particles from the prosthesis into the cerebral circulations or a magnetic effect.

Similarly, there are no large patient series on the annuloplasty rings. Except for the Carpentier-Edwards Physio Annuloplasty Ring (Edwards Lifesciences, Irvine, CA), these rings are usually considered safe below a 4.7 MRI.[28] This specific brand may result in a deflection angle which is three times larger than other brands under 4.7 T due to the Elgiloy content of the material.[28] Currently, most manufacturers produce MRI-safe rings.

Sorin Carbomedics, ATS, Saint Jude Medical and Edwards Life sciences are the common prosthetic heart valve and annuloplasty ring trademarks in the Turkish market. Manufacturer data claim that all prostheses, which are commercially available, are MRI-conditional in 3 Tesla or less magnetic field.[27-35] For previous versions before year 2000, further information can be supplied from the manufacturers' websites.

CORONARY STENTS

Coronary stenting is one of the most frequent cardiac interventions, resulting in an interest for MRI interactions. Initial in vitro studies reported possible migration of stents under 3 T.[38,39] Subsequent studies concluded that most of the stents available were safe.[38,40] Previously, a six to eight week time interval was recommended between stenting and MRI examination, while even MRI right after the stent implantation is now considered safe.[8,38,41] Similar reports exist regarding the primary stents implanted during an acute myocardial infarction.[41,42] In the light of these data, it can be concluded that MRI examination in patients with bare or coated stents can be safe at any time after myocardial infarction, even immediately following an myocardial infarction.[18]

TEMPORARY PACEMAKERS AND HEMODYNAMIC MONITORIZATION CATHETERS

Temporary transvenous pacemakers and hemodynamic monitorization catheters of the pulmonary artery or thermodilution catheters usually do not possess ferromagnetic materials.[13,17,43] However, they may lead to thermal injury, if they are heated.[44,45] Burns at the entry point of the Swan-Ganz catheter during an MRI possibly due to RF energy emitted by the MRI device were reported.[46] Despite the lack of studies examining the safety of temporary pacemakers, recent guidelines issued by the European Society of Cardiology recommend avoiding the implantation of temporary pacemakers as much as possible to minimize the risk of complications.[8] However, no recommendations are available with respect to the MRI safety. Potential interactions during an MRI examination include the followings: displacement of the leads, as they do not have a fixed position; exposure to higher intensity currents than permanent pacemakers due to longer leads leading to a possibility of more heat production; and a higher sensitivity of their generators to the electromagnetic fields due to their less sophisticated technology. Temporary pacemaker leads and catheters with conductive wires are labelled as non-MRI safe.[47] Magnetic resonance imaging should not be performed in patients with hemodynamic monitorization catheters of the pulmonary artery as well as in patients with thermodilution catheters or conductive catheters. However, MRI can be performed in patients with pulmonary artery catheters which are produced from electrically-isolated or non-ferromagnetic materials.[48]

PERMANENT PACEMAKERS AND IMPLANTABLE CARDIOVERTER DEFIBRILLATORS

In such devices consisting of highly-complex electrical systems, there is at least one lead within the myocardium, despite the presence of a number of ferromagnetic metals with different characteristics. Thus, they are potentially associated with a number of adverse effects such as the displacement of the leads, change in the software of the program, asynchronous stimulation, activation of tachyarrhythmia treatments, inhibition of pacing, increased heat production on the lead due to the electrical currents, and cardiac stimulation.[30,49-56] These may lead to changes in the stimulation or defibrillation thresholds, device dysfunction, discharging of the device batteries, arrhythmia, or even death. Previously, deaths were reported.[57-60] The closer the device is to the area of MRI examination, the higher risk of such untoward effects is present. However, 0.5 and 1.5 Tesla MRI can be safely performed in such cases, provided that appropriate precautions are implemented and adequate expertise is available.[61]

Table 1 shows the large MRI-safety studies involving patients with cardiac devices.[62] In the study by Sommer et al.,[63] it was shown that non-thoracic MRI examination was able to be performed in non-pacemaker dependent patients with an acceptable to risk to benefit ratio, provided that appropriate safety precautions were taken. Mollerus et al.[64] found only a weak correlation between SAR and potential changes in device parameters. In a study by Gimbel[65] with 3 T MRI, no effects such as clinically significant device parameter changes, arrhythmia, or re-programming of the software were observed. In these studies with small-sample size, it was often suggested that the presence of cardiac devices should not refrain physicians from performing an MRI. In the largest study up to date, Nazarian et al.[66] concluded that MRI might represent an appropriate imaging modality in patients with cardiac devices, unless other alternatives existed and if specific equipment for close monitoring and appropriate specialties were available for urgent interventions. Despite all these evidence, all ICDs and most of the permanent pacemakers represent a contraindication for MRI according to FDA and manufacturers.[61]

The 2013 guidelines issued by the European Cardiology Society recommend the followings for programming cardiac devices during an MRI:[61]

a) Experienced personnel who are able to monitor the changes in device programs and parameters during MRI

b) Exclusion of patients who received an implantation within the past six weeks before MRI or patients who have unremoved or epicardial leads

c) To set the asynchronous pacing mode in pacemaker dependent patients in order to avoid inappropriate pacing inhibition

d) Conversely, in non-pacemaker dependent patients to turn of the pacing mode in order to prevent inappropriate pacing

Table 1. Major studies comparing the safety of magnetic resonance imaging in patients with implantable cardioverter defibrillator and pacemakers

Study	Number of patients	Cardiac devices	Magnetic field strength (Tesla)	SAR (watts/kg)	Imaging sites	Adverse events
Sommer et al.[63]	82	PPM	1.5	1.5	Extrathoracic	Increased capture threshold, seven electrical resets, four increased troponin values
Mollerus et al.[64]	103	PPM/ICD	1.5	No specific limit	Extrathoracic, thoracic	One PPM electrical reset, one ICD arrhythmia log erased, decrease in sensing amplitudes and pacing lead impedances
Gimbel et al.[65]	14	PPM/ICD	3.0	2.0	Extrathoracic	One artifactually recorded prolonged asystole event
Nazarian et al.[66]	438	PPM/ICD	1.5	2.0	Extrathoracic, thoracic	Decreased atrial and ventricular lead impedances and RV sensing, decreased battery voltage, increased RV capture threshold, 3 power-on reset events

SAR: Systemic absorption rate; PPM: Permanent pacemaker; ICD: Implantable cardioverter defibrillator; RV: Right ventricle; Adapted from Kodali et al.[63]

Table 2. Common metallic materials and their magnetic resonance imaging compatibility

	MRI*-safe	MRI-not safe	Controversial
Steel sternal wires	•		
Nitinol/titanium sternal closure equipments	•		
Titanium vascular clips	•		
Temporary epicardial pacing wires (cut)			•
Permanent transvenous pacing leads (cut)			•
Peripheral vascular stents	•		
Peripheral vascular stent grafts	•		
Mechanical heart valves (carbon)†	•		
Annuloplasty rings	•		
Coronary stents	•		
Temporary pacemakers‡		•	
Hemodynamic monitorization catheters‡		•	
Permanent pacemakers‡		•	
Internal cardioverter defibrillators‡		•	
Intraortic balloon pumps		•	
Ventricular assist devices		•	

MRI: Magnetic resonance imaging; * 3 Tesla or lower; † Bileaflet pyrolytic carbon valves. Please search for previous types; ‡ Except MRI compatible types.

e) Deactivation of other pacing functions (magnet, rate, ventricular sense, sense, noise)

f) Deactivation of tachyarrhythmia monitorization and treatment

g) Prompt re-programming of the device following the imaging study.

There are also some recommendations for the programming of MRI-compatible cardiac devices, if required.[61] Essentially the recommendations are similar. The programming is performed in accordance with c, d, e, and f items. According to the guidelines, MRI should be avoided in the presence of an alternative imaging modality and should only be performed if potential benefits outweigh the potential risks. Also a consultation should be requested from an electrophysiology specialist prior to the procedure. Due to the lack of data for MRI devices with a magnetic force greater than 1.5 Tesla even for MRI-conditional devices, further studies are warranted.

For MRI recommendations, the level of evidence for traditional cardiac devices is class 2b and the level of evidence for MRI-conditional pacemaker systems is class 2b.[61]

OTHER DEVICES AND EQUIPMENT

There are no reports on the use of MRI in patients with intra-aortic balloon pump and ventricular support devices, which can be considered to represent a similar equipment category. Due to the presence of structural electrical conduits and mobile metallic components, these devices should not be considered safe, unless they are labeled with “MRI-safe” notification.

Furthermore, sporadic reports exist suggesting that certain anastomosis equipment used infrequently for cardiovascular surgical procedures may be MRI-safe.[67] Similarly, clips used for the closure of left atrial appendix were reported to be safe.[68] Table 2 shows various metallic materials presented in the text with their MRI compatibility.

In conclusion, an increasing number of cardiovascular interventions and surgery allows millions of individuals to regain their health. Patients with metallic materials should be closely monitored during each magnetic resonance imaging examination during their lifespan. A concerted effort between radiologists, cardiologists, and cardiovascular surgeons is essential for the patient’s safety during the diagnostic procedures. Also, relevant guidelines should be closely followed to remain updated in terms of capturing recent information and of implementing institutional policies.

Although most of the aforementioned studies report safe use with magnetic resonance imaging for a number of different equipment or devices, magnetic resonance imaging indications in patients with such equipment should be based on solid assessments and all patients should be certainly monitored closely during the procedure, if an magnetic resonance imaging is deemed necessary. Furthermore, patients should be closely followed after the imaging study for possible adverse consequences.

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