Diagnosis of patients with metallic implants in MR systems-possibilities and limitations

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Abstract

Magnetic resonance imaging (MRI) is a widely used medical imaging technique crucial in diagnosing many conditions. However, metallic implants in the patient's body can present challenges due to differences in magnetic susceptibility between the metal and surrounding tissues. This can lead to imaging artefacts, torsional forces, current induction and heating, which reduces the diagnostic quality of the images and can affect patient safety. This paper discusses techniques to minimize artefacts, such as adjusting scanning parameters, using particular pulse sequences (e.g. VAT, FSE) and using implants with low magnetic susceptibility. Procedures for qualifying patients with implants for MRI are also presented, and the impact of specific implant types (cardiovascular, orthopedic) on imaging quality and safety is discussed. The need to develop standardized procedures for assessing the risk of thermal and mechanical effects generated by MRI is pointed out, which is essential in further improving MRI diagnosis in patients with metallic implants.

Keywords: MRI, implants, diagnostics

Introduction

Magnetic resonance imaging (MRI) is a widely used medical imaging technique in radiology and diagnostic imaging to visualize anatomical structures and physiological processes. Over the past 30 years, MRI has become a key diagnostic tool for various clinical conditions, including ischemia, cancer, osteoarthritis and joint lesions.

However, performing MRI in patients with various metal implants placed in the body is challenging due to differences in magnetic susceptibility between the metal parts of the implant and adjacent tissues. Placing such an implant (located in the body) in a strong MRI magnetic field can result in the following interactions: torsional force exertion, voltage induction, heating and imaging artefacts. The resulting artefacts can impair diagnostic accuracy and assessment of surrounding anatomical structures. The research in this area aims to introduce techniques to reduce artefacts in magnetic resonance imaging by improving hardware components, such as multi-channel coils or parallel imaging techniques. At the same time, implants with low magnetic susceptibility are introduced, and magnetic fields with low magnetic induction values are used. The second approach uses metal artefact reduction techniques, e.g. VAT- View Angle Tilting or Slice-Encoding For Metal Artifact Correction (SEMAC). Iterative reconstruction algorithms or deep learning methods estimate and correct artefact-related errors in the resulting images [1-3].

This paper presents the possibilities and limitations of using MRI as a functional imaging study in patients with exemplary metal implants.

Implant versus MRI possibility

The term 'implant' comes from Latin and means 'implantation'. Medically, an implant is referred to as a foreign body placed in the body to restore the aesthetics or function of an organ. The

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definition includes any biomaterial device in the body [4]. The most common implants are used in orthopedics, dentistry, cosmetic surgery, and body modifications.

Implants are made from biomaterials such as composites, metals, bioceramics and plastics [5]. Implants made of non-ferromagnetic materials (e.g. titanium, titanium alloys, zirconium) are safe for magnetic resonance imaging (MRI). In contrast, those with ferromagnetic properties (steel, cobalt, nickel) can cause various effects such as [6]:

- Imaging artefacts that prevent correct interpretation of the results. An example of the natural occurrence of such imaging artefacts is the air-tissue interface area, e.g. near the mouth or nose. However, much larger imaging artefacts arise near metals due to the significant difference in magnetic susceptibility. The artefact resulting from the presence of a ferromagnetic object in the tissue, such as a permanent magnet (e.g. with cochlear implants), is so significant that it affects the entire image [7].
- Displacement of the implant can lead to injury (a result of the Lenz force and the torque exerted by the static magnetic field).
- Energy absorption increases temperature, with the risk of burns, due to currents induced in the implant by interaction with time-varying electromagnetic fields in the radiofrequency (RF) range and emerging field gradients. Although the small size of implants (metal parts) makes it unlikely that there will be a significant increase in temperature of such a component, this depends on the electrical properties and, for example, with an elongated implant shape, the risk of RF-induced heating of the surrounding tissues is significantly higher [8].

Absolute contraindications to MRI include cochlear implants, neurostimulators, ferromagnetic prostheses, defibrillators, infusion pumps and metallic foreign bodies in the body [9,10]. Relative contraindications include stents, orthopedic implants, IUDs, tattoos, and cosmetics containing metals that may cause irritation or burns [11].

Magnetic resonance image artefacts caused by metallic implants and techniques to reduce them.

Magnetic resonance imaging (MRI) artefacts caused by metal implants can seriously affect diagnostic quality. As a result of differences in magnetic susceptibility between the metal and surrounding tissues, magnetic field disturbances occur, resulting in changes in the Larmor frequency of hydrogen nuclei in adjacent tissues. The consequences include insufficient excitation, low signal or misregistration of spins, which leads to image distortions such as signal-free (black) areas or other distortions [12-15].

These artefacts can be reduced by modifying the test parameters, such as:

- Lowering the magnetic field induction (e.g. 1.5T instead of 3T) [15],
- Increasing the receiver bandwidth, which reduces spatial coding errors [15],
- Reducing the section thickness and increasing the image matrix, which reduces spin defocusing [15],
- Reducing echo time (TE) minimizes defocus differences [15].

It is also helpful to adjust the patient's position or the frequency encoding gradient so that the long dimension of the implant is in line with the direction of the constant magnetic field (B0), which can reduce the resulting artefacts [15,16].

In addition, different pulse sequences are used to reduce artefacts, such as:

- FSE/TSE (Fast/Turbo Spin Echo).
  In contrast to conventional spin echo, these sequences use 180° focusing pulses, allowing multiple lines of k-space to be acquired in a single repetition time. Nevertheless, FSE images may exhibit blurring due to long TE and TR times. Gradient echo sequences do not use focal pulses, making them more artefact-prone. However, they offer shorter acquisition times with FSE, which does not help with spatial misregistration, especially for implant imaging [12,16].
- Fat suppression (STIR, Dixon)
  Fat suppression errors often occur in the vicinity of implants. Based on a short T1 relaxation time, STIR is robust to metal-induced frequency changes but reduces the signal-to-noise ratio and can affect contrast imaging [12,17]. Based on the difference in the precession of water and fat, Dixon allows for more uniform fat suppression, yielding images without or with quantification of fat [12,19].
- VAT (View Angle Tilting)
  The view angle tilting technique minimizes metal artefacts by applying additional gradients during reading, compensating for metal-induced displacement. However, it is limited by lower resolution and potential image blurring [12,15,19].

These methods improve the quality of MRI images near metal implants, but each has limitations.

A limitation of the method is the spatial resolution that can be achieved. A high-bandwidth readout is desirable when using a tilted viewing angle to avoid image blurring and minimize residual artefacts due to voxel tilt.

Finally, modern implant materials such as titanium, carbon fibre-reinforced polymers or biodegradable magnesium alloys can generate more minor artefacts than traditional metals such as stainless steel or cobalt-chromium [19,20].

The process of qualifying a patient with metallic implants for MRI

The process of qualifying a patient with a metal implant in the body for MRI is shown in Figure 1. The procedure requires that

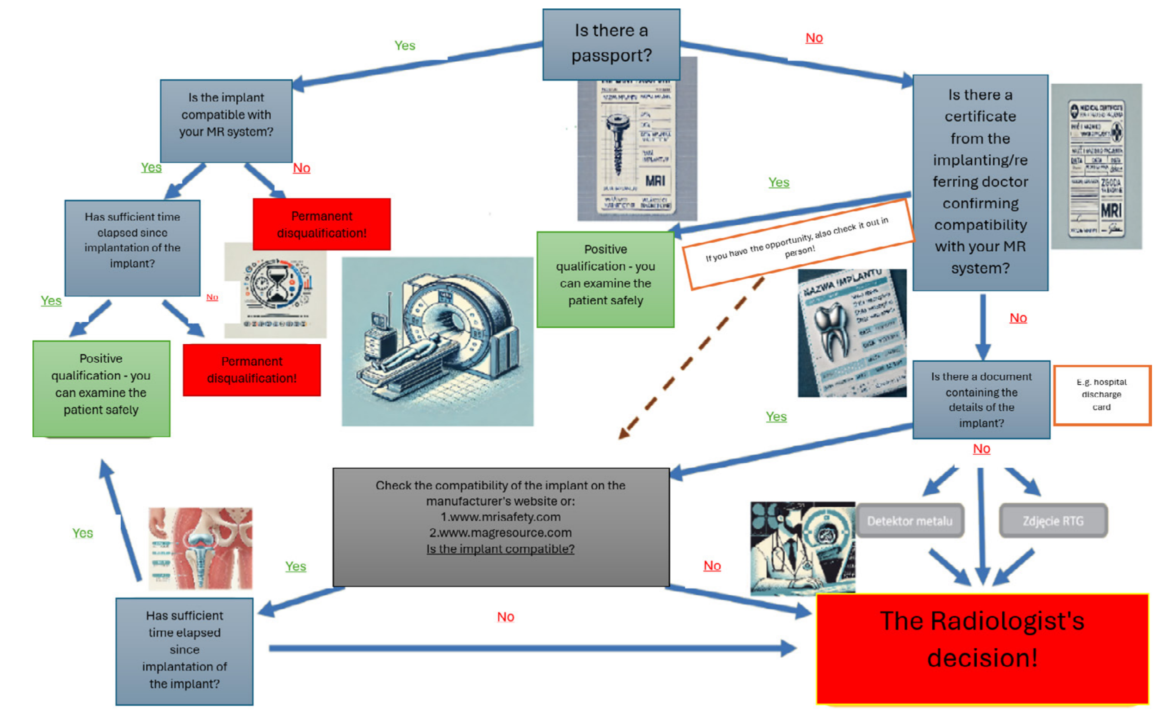

Fig.1 *The process of qualifying a patient with metal implants for MRI*

the implant's material and compatibility with the MR device be established, in addition to its origin, type and time since implantation [21].

The simplest and quickest method of qualifying an implant for an MRI scan is to determine its compatibility by checking the passport issued by the manufacturer. This document contains the patient's identification data, the name of the implant and the date of the implantation procedure performed, as well as its properties in a strong magnetic field environment. The timing of the implant made of metal is crucial because even if the material qualification is positive, the MRI procedure may involve risks, as mentioned above.

If the patient does not have a manufacturer's certificate or passport, a certificate (from the implanting physician or referring physician) stating that there are no contraindications to the MRI scan can be used for MRI qualification. In this case, the technical parameters of the tests performed, i.e. the value and speed of the spatial gradient rise, PEM intensity, etc., are essential information. The implant in question should also be rechecked using publicly available online platforms that address the safety issue in MRI, e.g., www.magresource.com, www.mrisafety.com, etc.

Examples of implants and diagnostic management

Patients with cardiovascular implants

Metallic cardiovascular implants placed in a magnetic field may twist or shift. Still, the forces acting on them are less than those generated by heart contraction, blood flow or gravitational troops [22]. During MRI, changes in magnetic field gradients and radiofrequency emissions can induce electrical currents, causing the implants to heat up. Studies have shown only a slight increase in the temperature of valve prostheses, atrial occluders and other cardiac implants, as confirmed even in high fields with induction up to 7.0 T. The temperature increase in pacemakers or cardioverter-defibrillators was a maximum of 7°C in vitro studies, which was not clinically relevant [23]. However, electromagnetic field disturbances can lead to device resets, interfere with cardiac pacing or prevent cardioverter-defibrillators from functioning adequately. Older device models may have more problems functioning in the MRI field. Newer implantable devices have better technology, which reduces the risk of interference.

MRI fields can induce signals that are interpreted by the cardioverter-defibrillator as ventricular fibrillation, which can cause it to attempt to mischarge and deliver a shock. However, the shock is unlikely to occur because the MRI magnetic field will saturate the high-voltage transformer, and the capacitor is doubtful to charge adequately for the voltage desired for the shock. New implantable cardiac devices have replaced the reed switch with an integrated solid-state detector, Hall sensor, telemetry coil or magnetoresistor circuit, so the latter problem is now less common.

In the case of ferromagnetic implants, it is recommended to defer the MRI examination beyond six weeks after implantation or after confirmation of secure fixation. Haemodynamic support devices, such as intra-aortic balloons, are not examined in an MR setting, making them potentially unsafe. MRI can be performed at a field of ≤1.5 T, and the duration of one sequence should not exceed 15 minutes [22].

MRI examination in patients with orthopaedic implants

Numerous studies have assessed the potential for displacement, heating and artefacts associated with current metal orthopaedic implants. Studies have shown that implant displacement in 1.5T, 3.0T and 7.0T scanners is negligible [24, 25]. According to the American Society for Testing and Materials International, when the implant is deflected by less than 45°, the magnetically induced deflecting force is less than the force of gravity (its weight) and therefore, any risk resulting from the application of magnetic force is assumed to be no greater than any risk resulting from the patient's regular daily activity in the Earth's gravitational field. It is also worth noting that the experiments ignore the magnetically induced torque that causes objects to rotate to match the magnetic field.

Experimental studies show that the temperature rise of implants during MRI sequencing is less than 1°C. In the Zou study, the material heating associated with MRI was assessed on an implant in a pig thigh (the lack of blood circulation prevented efficient heat transport and thermoregulation). The results showed that the most significant temperature changes were 0.6°C for titanium alloy implants and 0.9°C for stainless steel implants. It has been shown that an increase in temperature will not cause thermal injury in humans with an MR system of 1.5 T or less. However, for example, Muranaka et al., in a stainless-steel shoulder implant and cobalt-chromium and titanium hip implants, demonstrated a temperature increase of 5.3-14.7°C. These experiments were conducted under laboratory conditions using a tissue-equivalent gel-filled polypropylene model. In these studies, implants deeper (6 cm) in the model showed a minor temperature increase (<5.0°C), and the edges of the implants showed the most significant temperature increase.

According to Mosher, MRI with magnetic induction up to 7.0 T can be safely used in patients with orthopedic implants, with an extremely low risk of associated complications. The clinical relevance of orthopedic implant migration during MRI remains questionable, and the results of in vivo studies confirm that orthopedic implants are unlikely to be affected by translational forces during MRI imaging, as they are permanently attached to the bone, providing sufficient counterforce [28].

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The above findings indicate the safety of MR imaging in this patient group. Nevertheless, it is necessary to carefully review the manufacturer's information regarding its compatibility with MRI before examining a patient with an orthopaedic implant.

Conclusion

Patients with ferromagnetic implants present a challenge when performing an MRI scan. Qualification for such an examination requires careful analysis and a final decision by the radiologist. Implants can cause artefacts, displacement or heating, making diagnosis difficult and a risk factor in both imaging quality and patient safety. Minimizing artefacts is possible by optimizing scanning parameters and using specialized sequences, which are available and used in modern diagnostic MRI. However, developing methods to assess the occurrence of various effects related to the forces generated during the scan and thermal effects requires introducing appropriate standardized test procedures that can be applied in diagnostic practice.

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