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Dental Implant Artifacts in MRI: Compatibility and Considerations

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Abstract

This review investigated dental implant artifacts in magnetic resonance imaging (MRI) and their safety in clinical practice. Dental prostheses, including implants, crowns, and orthodontic appliances, cause artifacts due to their high magnetic susceptibility, particularly in materials like iron, stainless steel, and cobalt-chromium. Titanium implants are considered safe under MRI environments according to the American Society for Testing and Material (ASTM) standards, with no reported thermal injury or dislodgement during examinations. Despite limited artifacts from titanium's paramagnetic nature, minute ferromagnetic components can still affect visualization. Thus, reducing artifacts in oral and maxillofacial MRI scans is crucial.

Two main categories of artifact reduction techniques are identified: improved porous titanium or alternative materials like zirconia and adjusting MR parameters with advanced sequences. Recommendations include increasing the readout bandwidth, reducing slice thickness, using spin-echo sequences instead of gradient-echo, and employing short tau inversion recovery or DIXON techniques for fat suppression. Additional methods like VAT, VAT-SEMAC combination, and MAVRIC show promise, although applicability may be restricted in specific MRI scanners.

Continuous advancements in dental implant materials and MRI sequences are needed to improve imaging quality and reduce artifacts. Collaboration among dental practitioners, radiologists, and MRI technologists is essential for refining techniques and ensuring patient safety. Although overall dental implant artifacts pose challenges, safety in MRI is well-established. Ongoing developments hold significant potential to enhance MRI imaging quality in patients with dental devices.

Keywords: artifact reduction techniques, dental implant artifact, MRI compatibility, MRI safety, titanium implants

Introduction

Dental implants have become a popular and widely used treatment option for patients with missing teeth. While there are less invasive alternatives that involve preserving natural teeth, dental implants offer a viable solution if these options are not feasible or fail to provide satisfactory results.[1] The prevalence of dental implants has seen a significant rise in recent years, with studies indicating an increase from 0.7% in 1999-2000 to 5.7% in 2015-2016 among adults missing any teeth in the United States. This growth is especially prominent in the 55 to 64 age group, with projections suggesting continued expansion but limited overall access by 2026.[2]

Magnetic Resonance Imaging (MRI) is a non-invasive imaging technique widely used for evaluating various medical and dental conditions without involving ionizing radiation.[3,4] In dentistry, MRI finds major applications in examining soft tissue lesions, salivary gland pathologies, and internal derangements of the temporomandibular joint (TMJ), benefiting from its exceptional soft tissue contrast resolution. Researchers have noted MRI's superiority in detecting tumor staging, odontogenic cysts, and perineural spread compared to computed tomography (CT).[4,5] Moreover, MRI has emerged as a valuable tool for dental implant planning and postoperative evaluation due to its ability to define implant positions and assess relations with the inferior alveolar nerve.[3,6-9] In certain cases, MRI can even be a viable alternative to CBCT for fully guided implant placement,[10] making it potentially useful throughout the workflow of implant surgery.[11]

Despite its benefits, MRI is contraindicated in patients with ferromagnetic medical devices or dental materials in their bodies, as these can interact detrimentally with the MRI's magnetic field. Such interactions may result in undesirable effects like artifact production, radiofrequency (RF)-induced heating, and magnetically induced displacement of objects. Among dental materials, metallic dental devices like orthodontic brackets, metal crowns, and dental implants have been found to cause artifacts in oral and maxillofacial MRI, potentially complicating diagnostic interpretations.[6,8,9,12] This review aims to elucidate the specific artifacts that can emerge in oral and maxillofacial MRI due to dental materials, with a particular focus on dental implants. Furthermore, the review will offer insights into MRI safety considerations for patients with implant-retained restorations undergoing MRI examinations.

MRI Physics and Artifact Formation

MRI physics

MRI is a diagnostic imaging technique that relies on the behavior of hydrogen atoms (H^+) in a strong magnetic field (B_0). Each H^+ spins randomly at a specific speed known as the 'Larmor frequency', which depends on the strength of the local static magnetic field B_0. This relationship is represented by the following equation[13]:

$$\omega = \gamma B_0,$$

where ω is the Larmor frequency in MHz, γ is the gyromagnetic ratio in MHz/Tesla, and B_0 is the strength of the static magnetic field in Tesla. Common human imging procedures use 1.5T or 3T magnetic field strengths. For instance, at 1.5T, the Larmor frequency of a hydrogen proton is approximately 63.8 MHz.

When patients or objects with hydrogen nuclei are placed in a strong magnetic field, the hydrogen nuclei align and undergo precession around the magnetic field in the similar manner that gyroscopes or tops precess around a gravitational field. Resonance is initiated by applying short-burst RF pulses with a frequency and speed similar to that of the H^+ spins. These RF pulses are emitted from the RF coils built into the MRI unit. The H^+ align themselves, spin synchronously (in-phase) and simultaneously flip according to the angle of the RF pulses (e.g., 90° or 180°). Different degrees of resonance can be achieved, emphasizing or de-emphasizing certain tissue types. After the RF pulses are switched off, the H^+ relax back to their original stage with T1 (longitudinal) and T2 (transverse) relaxation times. Simultaneously, the energy released from the atoms is detected by the receiver coil, inducing an electrical voltage that is processed to create MR images.[4,12,13] The diagram showing basic MR physics is illustrated in Figure 1.

Magnetic susceptibility

Magnetic susceptibility is the dimensionless ratio of the magnetization (M) in a material to the intensity of the magnetic field (H). It is measured in amperes per meter ($A \cdot m^{-1}$) and expressed in parts per million (ppm or 10^{-6}) as Chi (χ). The relationship of these parameters is defined by the following equation[14]:

$$\chi = \frac{M}{H}$$

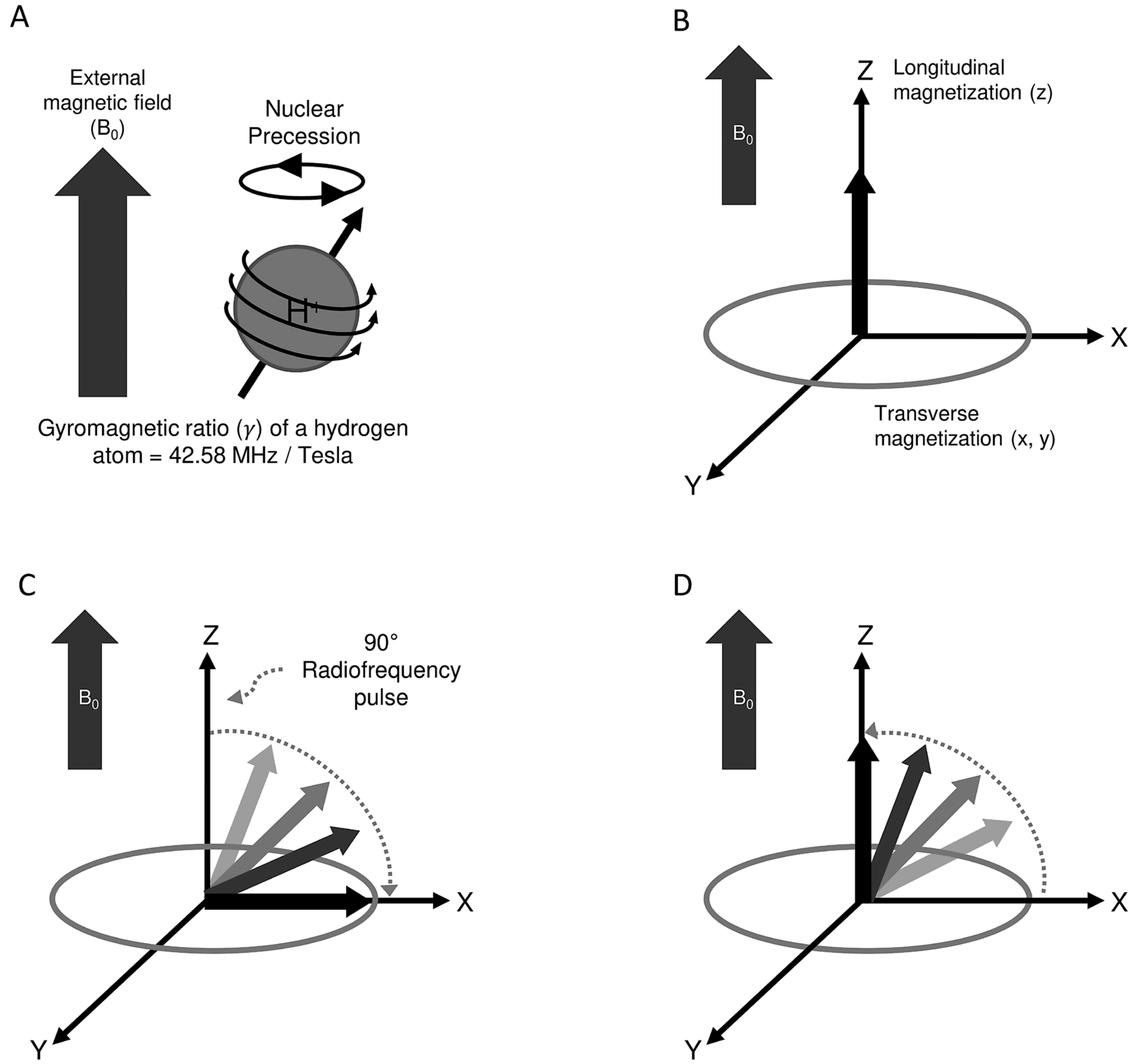

Figure 1: Diagram of basic MRI physics: A, Hydrogen atom or proton (H^+) precesses when placed in the external magnetic field (B_0) with its gyromagnetic ratio (γ) of 42.58 MHz/Tesla; B, when protons are positioned in the B_0, they align in longitudinal magnetization (z); C, when a 90° radiofrequency (RF) pulse is applied, protons move to transverse plane (x, y); D, when the RF pulse is switched off, protons relax back to their original state.

In other words, magnetic susceptibility determines the material's ability to be magnetized by an external magnetic field. Materials can be characterized into three types based on their magnetic susceptibility,[15-17] as illustrated in Figure 2 and described in Table 1[18-20]:

1. Diamagnetism ($\chi < 0$ ppm): These materials have negative magnetic susceptibility and are repelled by magnets. They are less likely to cause MRI artifacts. Examples include wood, zinc, copper, silver, gold, and most biological tissues.

2. Paramagnetism ($0<\chi< 300$ ppm): These materials have positive magnetic susceptibility and weakly attract to a magnet. They are far less likely to cause MRI artifacts. Examples include lithium, tantalum, titanium, and dental amalgam.

3. Ferromagnetism ($\chi>300$ ppm): These materials have high magnetic susceptibility values and are strongly attracted to a magnet. They have a high potential to cause MRI artifacts when positioned in the patient's body due to the significant difference in magnetic susceptibility between these materials and human tissues. Examples include ferrite (iron), magnetite, and stainless steel.

Even materials with trace amounts of ferromagnetic ingredients can cause artifacts and disturbances in MRI. Dental restorations such as gold and titanium are less likely to induce artifacts, but they can generate artifacts and distortions due to traces of other ferromagnetic metal components, especially iron.[21] Understanding the magnetic susceptibility of dental implant materials is crucial in managing potential artifacts and ensuring patient safety during MRI procedures.

Dental implant materials and artifact formation

To replace missing teeth, oral implants are recommended as the treatment of choice.[22] These dental implants are typically made from various materials, each having its own advantages and disadvantages. One common material used for dental implants is titanium and its alloys because of its biocompatibility, corrosion resistance, high strength for resisting occlusal force and suitable modulus for transmitting force to bone.[23] The American Society for Testing and Materials (ASTM) classified titanium implants into six grades. Four of these grades (grades I to IV) are commercially pure titanium (CpTi), known as unalloyed titanium. The mechanical property of CpTi was improved by oxygen, nitrogen, carbon, and iron. It can result in increasing the concentration of these trace elements from grade I to IV, respectively.[23,24] Grade IV CpTi is the most used type of titanium for dental implants because it has the highest oxygen content (0.4%) and excellent mechanical strength.[25] The other two grades (Grades V and VI) are titanium alloys. Grade V titanium (Ti-6Al-4) is an alloy composed of 90% titanium, 6% aluminum (Al), and 4% vanadium (V). The alloying elements enhance the material's strength and stability. Grade VI, also known as Ti-6Al-4V ELI (Extra Low Interstitial), has a similar composition to Grade V but with lower levels of interstitial elements like oxygen and iron. This results in improved ductility and toughness. Titanium alloys have become prominent in biomedical applications due to their cost-effectiveness and desirable properties. These alloys are categorized based on their stabilizing elements: alpha (α), beta (β), or a combination (α-β). The most common dental alloy, Ti-6Al-4V, offers high strength and corrosion resistance. However, concerns about the potential toxicity of aluminum and vanadium have led to the development of alternative alloys using non-toxic elements like niobium, tantalum, zirconium, and palladium. The surface composition of titanium implants, typically TiO_2, plays a crucial role in bone interaction and corrosion resistance. Recent advancements include a binary titanium-zirconium alloy

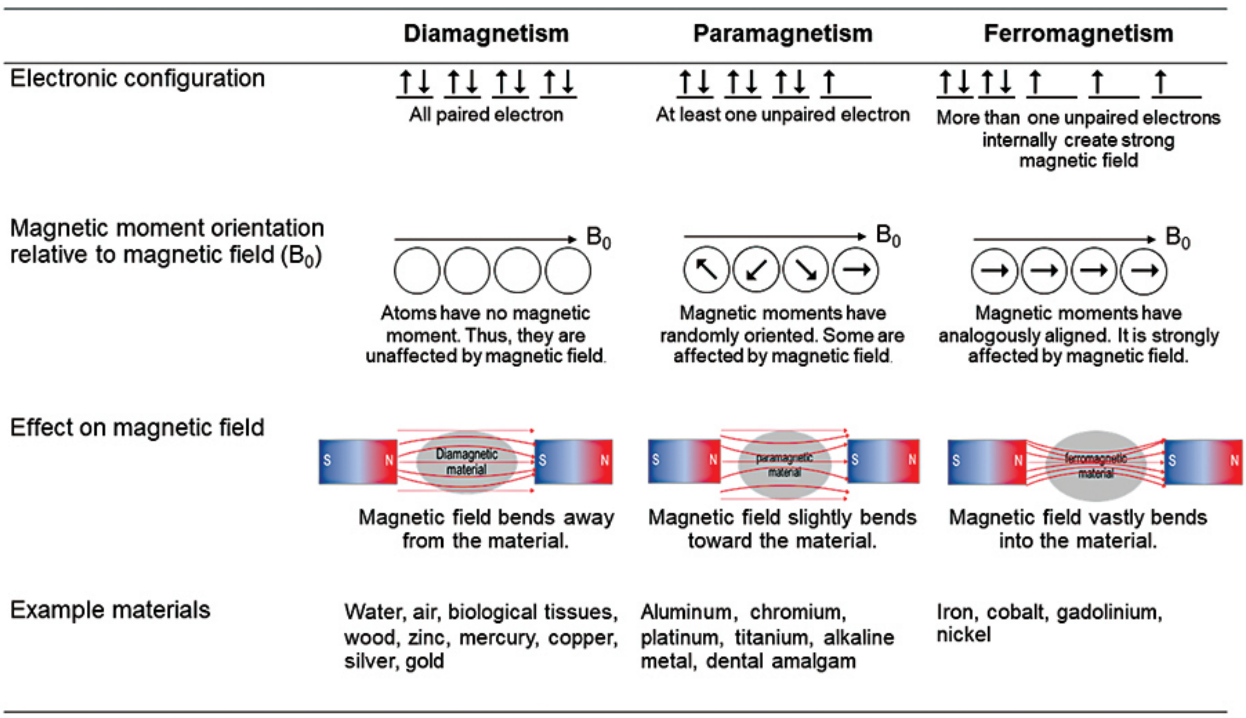

Figure 2: Illustration of each type of magnetism showing schematic diagrams of electronic configuration, magnetic moment orientations relative to magnetic field, schematic diagrams of effect on magnetic field, and examples of materials in response to such magnetism.

Table 1: Magnetic susceptibility (χ) of biological compounds and various prosthetic materials that could be found in human body.[17-19]

Materials	χ (ppm)
Gold	−34.0
Human bone	−11.0 to −8.86
Human tissue	−11.0 to −7.0
Copper	−9.63
Water (37°C)	−9.05
Air	0.264
Aluminum	20.7
Zirconium	109
Titanium	182
Gadolinium-based contrast agent (0.1 mol / l)	249
Platinum	279
Chromium-cobalt	900
Stainless steel	9000
Iron	200×10^9

(Roxolid®, Straumann Manufacturing Inc., Mansfield, TX, USA) that demonstrates improved strength and bone integration compared to traditional titanium alloys. These developments reflect ongoing efforts to enhance the biocompatibility and performance of dental implant materials.[26]

Recent research indicates that titanium implants produce more severe artifacts than zirconia implants, making zirconia a preferable option in scenarios where MRI compatibility is crucial. For instance, a study highlighted that titanium and titanium-zirconium alloys generated extensive artifacts compared to zirconium implants, which had minor distortion artifacts.[9] The metal-related MRI artifacts are described in the following section.

Types of MRI artifacts associated with metallic dental materials

The presence of metallic dental materials in the MRI field of view can lead to several types of artifacts that can affect image quality, as displayed in Figure 3. These artifacts depend on the shape and form of the implant material and can be classified as follows[27]:

1. Signal void due to dephasing: rapid changes in magnetic field variations near metal objects cause magnetization within a single image to precess at different rates. This results in dephasing or loss of coherence, leading to signal void and the appearance of black areas in the MR image.

2. Failure of fat suppression: fat suppression techniques are commonly used in MR examinations to suppress signals from adipose tissue. However, the high signal from fat can still be recognized in the presence of metallic materials, reducing the effectiveness of fat suppression in the vicinity of dental materials.

3. Displacement artifacts: these artifacts result from geometric distortion, signal void, and signal pile-up during the process of slice selection and readout directions. The varying frequency induced by metallic materials can cause the MRI machine to select incorrect positions, leading to errors such as slice shifting, curving, and disunion of multiple regions known as pile-up effects.

During MRI, the magnetic field causes protons in the body's tissues to precess, generating signals used to create images. However, the magnetic susceptibility of titanium dental implants significantly differs from that of surrounding biological tissues, leading to increased frequency offsets and magnetic field inhomogeneity. Ferromagnetic metals present in dental materials can create their own magnetic fields, inducing a precession of proton frequencies in neighboring body tissues. This disruption of normal precession results in susceptibility artifacts, causing signal void and image distortion in the area surrounding the implant.[27,28] While minor artifacts caused by dental implants have been reported in limited areas around the implants in T1-weighted and T2-weighted images,[29] MRI artifacts can be more significant when titanium blade dental implants were placed near the orbital area after surgical treatment for oncological diagnosis.[30] The susceptibility of metallic dental implants compared to neighboring tissue results in signal void and distortion, which can impair image quality in the area of interest for clinicians.[17,31] Furthermore, there is a reported case involving the surgical failure of an MRI deep brain stimulation patient caused by a neodymium magnetic dental implant-supported overdenture. The distortions in areas closer to the dental magnets measured as large as 11-22 mm, resulting in postoperative lead location errors of 5.4 mm on the right side and 2.7 mm on the left side from the intended targets, respectively.[32] This could be implied that the greater the differences in magnetic susceptibility between the metallic dental materials and surrounding tissues, the stronger susceptibility artifacts are presented.[16,33]

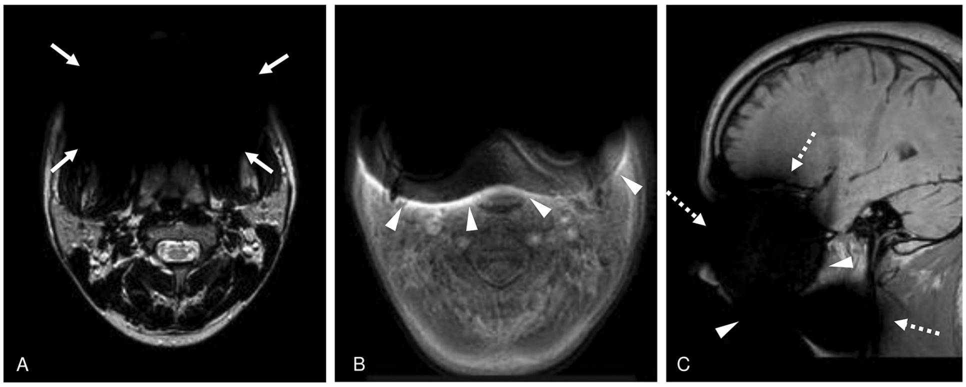

Figure 3: Various types of artifacts caused by metallic dental materials presenting in 1.5 T-MR images: A, an axial T2-weighted image (WI) presents a black area at anterior region of the jaw due to loss of MR signal (solid arrows); B, an axial T1-WI with fat suppression presents loss of fat saturation around the metal-related artifacts (arrowheads); C, a sagittal T1-WI presents displacement artifacts including a large black area of signal loss, geometric distortion (dashed arrows), and enhanced rim of signal pile-up artifact (arrowheads).

Safety concerns of dental implants in the MRI environment

With the increasing prevalence of dental implants in various age groups, a growing number of patients are required to undergo MRI examinations. However, the presence of metallic implants and other medical devices can introduce risks due to the creation of artifacts and MRI-related heating, raising concerns about patient safety in MRI applications.[34,35]

To address these safety concerns, the U.S. Food and Drug Administration (FDA), in collaboration with the MR Task Group of the ASTM International Committee F04 on medical and surgical materials and devices, has developed standardized tests and labeling terms for medical devices and dental implants used in MRI environment (ASTM F2503).[36,37]

These new MR labeling terms and associated icons help differentiate the safety status of different items in or near MR environments.[34] The associated symbols, definitions, and examples of dental materials are described in Figure 4.

The impact of static magnetic fields on dental materials has been extensively studied to verify their safety in the MR environment in terms of thermal changes, dislocation of prostheses, and artifact formation, among other factors. Concerning heating effects, RF exposure dose is commonly measured and expressed as Specific Absorption Rate (SAR), representing the absorbed electric power of RF per unit mass of body weight (W/kg).[38] Standards set by organizations apart from the ASTM (ASTM F2182-02a)[39] like the International Electrotechnical Commission (IEC) and the Japanese Industrial Standards (JIS) help regulate SAR values. Although some metallic objects involved in MR procedures have been observed to cause minor temperature changes,[30] it has been shown that magnetic dental attachments with castable alloys under 3T MRI produce temperature elevations of only 1.42°C, which is below the heat-pain threshold of oral mucosa, ensuring patient safety.[40]

Regarding prosthesis dislocation, metallic dental materials are considered safe if the deflection angle is less than 45° according to the ASTM standard (ASTM F2052).[41] Dental luting cement's retention forces further contribute to preventing prosthesis dislodgement under the MRI environment.[40] A study on different metallic dental materials at different MRI field strengths has shown minimal deflection angles, ensuring the stability of dental prostheses.[42] Metallic dental implants, including coping and implants, do not exhibit apparent translational attraction or heating, meeting the ASTM standards for magnetically induced displacement and RF heating at 3T MRI.[42,43]

Artifact formation is another aspect of concern, with all metallic objects causing artifacts in MRI images. Orthodontic brackets, nickel-chromium materials, and titanium dental implants are among the most susceptible to magnetic fields.[44] While dental crowns cause minimal artifacts, orthodontic appliances, such as orthodontic devices and steel alloy arch wires, can lead to significant image distortions and obstruction of critical anatomical details[17,45,46], as displayed in Figure 5. Consequently, it is crucial to avoid the presence of stainless-steel orthodontic appliances in the oral cavity during MRI procedures to ensure image quality.[47]

Despite causing artifacts, titanium-based implants have been shown to cause minimal visualization disturbance and do not significantly affect examination and diagnosis[17,48,49], as shown in Figure 6. Although the possible influences of static magnetic fields and interactions of dental materials or devices have been investigated, no reports of injuries caused by dental materials during MRI procedures have been documented to date.

Symbol	Definition	Example materials
MR safe	This term applies to items composed of nonmagnetic, nonmetallic, and nonconducting materials, which pose no hazard in all MR environments.	Dental materials like dental amalgam, gutta percha points, and most dental implants fall under the category of MR safe items.
MR conditional	Items classified as MR conditional have been shown to pose no known risks in specified MR environments under specific conditions of use. Any conditions of concern affecting safety must be described.	Dental castable alloys, stainless steel keepers, and certain dental implants are examples of materials falling under the MR conditional category.
MR unsafe	This term is used for materials known to pose hazards in all MR environments.	Dentistry-related devices like ferromagnetic scissors and palladium-clad magnets fall under the MR unsafe category due to their magnetic properties.

Figure 4: MR labeling terms and icons used for implants and medical devices (reprinted with permission from ASTM F2503-20 Standard Practice for Marking Medical Devices and Other Items for Safety in the Magnetic Resonance Environment, copyright ASTM International, 100 Barr Harbor Drive, West Conshohocken, PA 19428. A copy of the complete standard can be obtained from ASTM, www.astm.org.).

Figure 5: Artifacts due to stainless steel orthodontic appliances. A, CBCT panoramic reformatted image shows fixed orthodontic appliances in both maxillary and mandibular arches; B, Axial T2-weighted image spin-echo of the same patient illustrates severe artifacts at the oral cavity extending to ramus of the mandible, masseter muscles, and left pterygoid muscle causing signal loss (black area) and image distortion; C, Sagittal 3D proton density-weighted image illustrates a dark area of signal loss in both oral cavity, orbital area, as well as frontal lobe and oropharyngeal area.

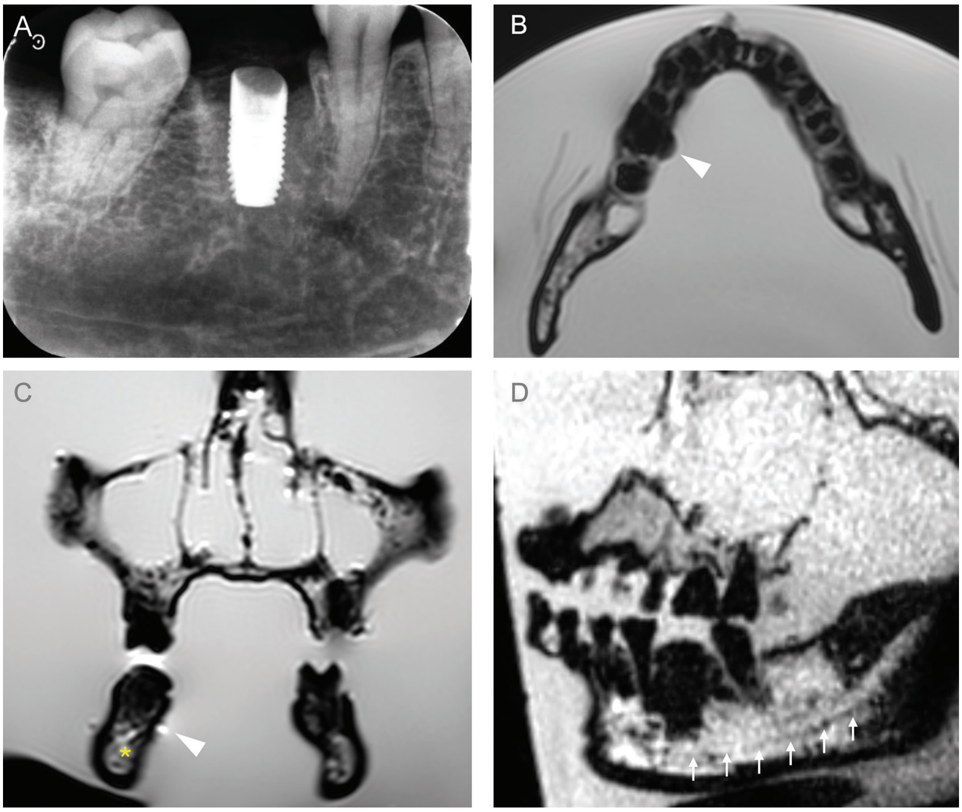

Figure 6: Artifacts caused by dental implants placed in a dry skull. A, a titanium dental implant was placed at the mandibular right first molar area of a dry skull as shown in a periapical radiograph; B, axial T1-weighet image (WI) shows artifacts limited within the mandibular alveolar process; C, coronal T2-WI illustrates a dark area of artifact (arrowhead) extending above the inferior alveolar canal (asterisk); D, sagittal ultrashort echo-time demonstrates the dark artifact above the inferior alveolar canal (arrows).

Safety Considerations for Patients with Titanium Implants

Concerns about patient preparation prior to MRI examination

In 2019, the International Society for Magnetic Resonance in Medicine (ISMRM) released an update and expert consensus addressing the primary safety, screening, and scanning concerns related to MRI examinations. This comprehensive report also includes adverse event reports for each device category, offering practical recommendations to the MRI community.[50] Notably, titanium, being a paramagnetic material, remains unaffected by the magnetic field of MRI, resulting in a very low risk of complications for patients with titanium implants, affirming the safe use of MRI in patients with implants.[51] However, caution is advised when dealing with strong ferromagnetic metals incorporated into dental implants, such as overdenture magnets, stainless steel brackets, and wires. It is recommended to remove these components before undergoing an MRI examination to mitigate potential risks. To ensure patient safety, thorough screening should be conducted, evaluating the possible hazards of unwanted incidents or artifacts that may occur during MRI procedures. For further information, all resources and recommendations are available online on http://www.mrisafety.com/ (Shellock R&D Services, Inc., CA, USA).

Metal artifact reduction strategies

Metal artifact reduction sequence (MARS) has been developed to improve image quality by minimizing the size and intensity of susceptibility artifacts from magnetic field distortion. It is based on view angle tilting (VAT) and increasing gradient strength. MARS is compatible with any spin-echo sequence without adding extra image acquisition time.[30]

Conventional MARS can be achieved by selecting suitable prostheses, such as standard titanium implants at 1.5T instead of 3T MRI. Additionally, adjustment of basic MR sequence parameters, such as voxel size, three-dimensional (3D) spatial encoding, a high-resolution matrix, and using multishot spin-echo (SE) or fast/turbo SE (FSE/TSE) sequences instead of gradient-echo (GRE) sequences, can further refine the MR image[52,53], as displayed in Figure 7. GRE sequences induce artifact volume due to signal intensity loss from intravoxel dephasing in the magnetic field inhomogeneity area.[53] Consequently, using TSE sequences is preferable to generate fewer artifacts than GRE with its high spatial resolution, high readout bandwidth[54], as well as its compatibility with diffusion-weighted imaging (DWI). This ultimately leads to better image quality, especially when compared to single-shot echo-planar imaging-based DWI (EPI-DWI).[55]

Standard methods of fat suppression technique, such as short tau inversion recovery (STIR), have been utilized to clarify image areas by eliminating fat signal and chemical shift misregistration. However, STIR may suffer from relatively low signal-to-noise ratio (SNR) and result in impaired anatomical details. Improved SNR and fat suppression can be achieved by using the DIXON technique, but it is susceptible to artifacts near implants.[27]

To overcome the limitations of conventional methods, advanced sequences have been commercially available, such as Orthopedics-Metal Artifact Reduction (O-MAR) from Philips (Best, Netherlands), and WARP from Siemens (Erlangen, Germany). These sequences are operated by combining conventional MARS with VAT. Additionally, multiacquisition variable-resonance image combination (MAVRIC) and MAVRIC-SL from General Electric (GE, Milwaukee, WI, USA) have been developed.[27,53,56,57] Below are some examples of these novel techniques:

1. VAT is used to correct in-plane distortion via slice-selection gradients concurrently with conventional readout gradients, in combination with the slice encoding for metal artifact correlation (SEMAC) technique. However, VAT-induced blurring in the image is a consequence of the shearing effect within an image slice. The reduction of through-plane distortion is a main limitation of VAT.[53,56] Consequently, SEMAC has been developed based on a 2D TSE sequence to reduce through-plane distortion using additional phase encoding in the slice selection. Signals excited in the wrong slice positions are corrected. SEMAC demonstrates superiority in metallic artifact reduction compared to VAT, standard MR sequences, and high bandwidth protocols.[53,56] The combination of VAT and SEMAC has been shown to reduce artifacts related to titanium implants by up to 43% *in vitro* and up to 80% *in vivo* study in 3T MRI. The standard TSE sequence with VAT and SEMAC has also been effective in reducing artifacts from titanium orthodontic appliances in 1.5T MRI.[58,59] When combined with WARP, both VAT and SEMAC showed a reduction of 69.1% in dental implant artifacts relative to inferior alveolar nerve (IAN) in comparison to GRE sequences in both volunteers and patients with postoperative IAN impairment.[54] Furthermore, SEMAC can be used with ultrashort echo time (UTE) sequences to reduce susceptibility artifacts resulting from osseous-fixation titanium plates in 3T MRI.[60]

2. MAVRIC, a nonselective 3D acquisition technique, prevents slice-direction displacement using phase encoding and decreases susceptibility artifacts by combining multiple image datasets of wide range frequency offsets near the metallic implant into a single image. MAVRIC can further minimize distortion compared to conventional TSE techniques and has the advantage of reducing scan time. However, image blurring is a limitation of MAVRIC.[53,56] The use of MAVRIC and MAVRIC-fast sequences combined with hybrid positron emission tomography (PET)/MRI resulted in artifact reduction from dental implants in comparison to conventional GRE sequences (LAVA-Flex) and T1-WI FSE.[52] This modified PET/MRI technique is presented as an excellent method for oropharyngeal cancer examination.

In the context of dental implants, SEMAC and MAVRIC techniques in MRI can significantly reduce metal-related artifacts, but with increased scan times. These techniques require additional phase-encoding steps, leading to scan times 2-3 times longer than conventional MRI sequences.[61-63] The prolonged scan duration can impact patient comfort and compliance. Extended time in the MRI machine may increase the risk of involuntary movements, such as swallowing or shifting positions, potentially introducing new artifacts. It can also exacerbate claustrophobia and anxiety in some patients particularly those with pre-existing conditions or previous negative experiences with MRI, further complicating the imaging process. From a clinical perspective, the increased scan times can reduce throughput and efficiency, potentially leading to longer wait times for patients and impacting clinic workflow and efficiency for healthcare providers.[63]

To mitigate the increased scan time, strategies such as optimizing sequence parameters or using parallel imaging techniques may be employed.[61,62] Healthcare providers should carefully consider these factors when selecting the most appropriate imaging strategy for patients with dental implants, balancing the need for artifact reduction with practical clinical considerations.

Apart from postprocessing scan sequences, modifying the titanium implant structure is another artifact reduction method. The material composition of dental implants and implant-supported single crowns significantly influences artifact volumes on MRI. Crowns containing high amounts of cobalt, chromium, or tungsten were associated with large artifact volumes.[64] A study modified Ti-6Al-4V specimens to have a porous structure, which decreased the density of the implants and resulted in a reduction of susceptibility artifacts compared to solid materials in the 3T MRI system. Decreasing the mass of octahedral and diamond lattice structures by half reduced the artifact volume by approximately 50%.[65] Furthermore, the fewest MR artifacts were observed in zirconia implants combined with monolithic zirconia crowns compared to titanium implants combined with different single crown materials on 3T MRI.[21] Zirconia implants have been shown to produce fewer artifacts than titanium-based implants, especially in T1-WI.[9,66-68] From these previous reports, it is suggested that manufacturing dental implants with titanium can be replaced with alternative non-metallic substances for MRI artifact reduction. Techniques suggested to reduce metal-induced artifacts are shown in Table 2.[69]

Conclusions and Recommendations

Our review of dental implant artifacts in MRI and their safety has revealed significant insights into the potential challenges and solutions in clinical practice. Dental devices, including dental implants, dental crowns, and orthodontic appliances, can cause artifacts in MRI due to their high magnetic susceptibility, particularly in materials like iron, stainless steel, and cobalt-chromium. These artifacts can vary in size, ranging from localized distortions around the materials to larger artifacts obscuring neighboring structures.

Clear communication between dentists, radiologists, and MRI technicians is essential for optimal patient care and imaging outcomes. Dentists should be concerned with the following before their patients undergo MRI:

1. Providing a detailed dental history, including the types and materials of implants, crowns, and other dental works.

2. Advising patients to remove removable dentures or orthodontic devices before the MRI procedure.

3. Informing radiologists about the presence and location of any fixed dental prostheses that might affect imaging.

While dental implants introduce minute but detectable artifacts into MRI imaging, their removal prior to MRI examinations is impractical. Therefore, optimizing image acquisition and processing techniques to minimize artifact size becomes paramount. Titanium dental implants are generally considered safe in the MRI environment due to their paramagnetic nature, conforming to ASTM

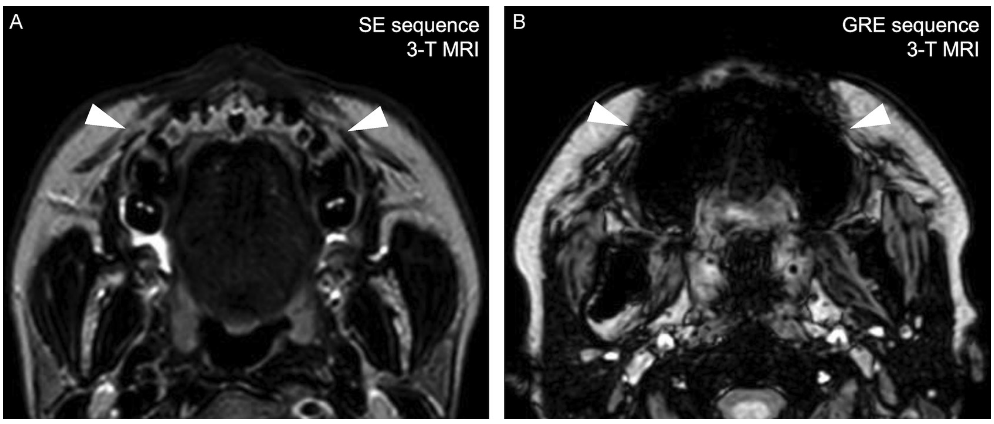

Figure 7: Artifacts according to different MR sequence acquisition: A, Spin-echo (SE); B, Gradient-echo (GRE). The areas of signal void present less in SE than in GRE (arrowheads).

Table 2. Suggested techniques to reduce metal-induced artifacts.[54]

Options	Consequences	Limitations
Preprocessing scan		
Use Zirconium (Zr) rather than Titanium (Ti) implant	Lessen metal-related artifacts	N/A
Use 1.5T rather than 3T	Metal artifact reduction	Machine availability and specification
Postprocessing scan		
Increase the read-out bandwidth	In-plane distortion reduction	Signal-to-noise (SNR) decrease
Reduce the slice thickness	Trough-slice distortion reduction	
Use fast spin echo (TSE or FSE) instead of gradient echo (GRE) sequence	Signal loss reduction	Anatomical evaluation degradation such as vessels, nerves, salivary gland
Use fat suppression technique such as short tau inversion recovery (STIR) or Dixon technique	Homogeneous fat suppression	SNR decrease
Use a metal artifact reduction sequences or combination of such sequences such as VAT-SEMAC, OMAR, WARP, MAVRIC or MAVRIC-SL	In-plane distortion reduction and trough-slice distortion reduction	Not available in all MR scanners, acquisition time increase

standards. However, even titanium can produce limited artifacts, and trivial ferromagnetic components can cause undesirable metal-related artifacts affecting visualization. Two primary categories of artifact reduction techniques have been identified:

1. Utilizing improved porous structures of titanium or alternative materials like zirconia.

2. Adjusting basic MR parameters and employing advanced sequences, such as increasing readout bandwidth, reducing slice thickness, choosing SE or FSE over GE, and employing STIR or DIXON for fat suppression.

Advanced methods like VAT, VAT-SEMAC combination, and MAVRIC have shown promise in reducing artifacts, although their applicability may be limited in certain MR scanners.

Continuous efforts should be made to develop suitable dental implant materials and optimize MRI sequences to overcome susceptibility artifacts and enhance imaging quality. The collaboration between dental practitioners, radiologists, and MRI technologists is mandatory in refining techniques and ensuring patient safety during MRI examinations involving dental devices.

In conclusion, while dental implant artifacts can present challenges, their safety under MRI is well-established. Advancements in reducing artifacts offer promising solutions for improving the overall quality and reliability of MRI imaging in patients with dental devices. Effective communication among healthcare professionals is key to navigating these challenges and providing the best possible care for patients.

Acknowledgments

We would like to clarify that we utilized generative artificial intelligence technology for language correction purposes in the preparation of this manuscript.

Confliets of Interest

The authors declare no conflict of interest in the study.

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