INTRODUCTION

Over the last decade, the use of dental and medical implants to replace or repair damaged tissue or bone has rapidly increased due to the aging world population\(^1,2\). Metals continue to be a mainstay of these devices as they provide a good balance of strength and rigidity\(^3\). However, while metals have many favorable mechanical properties, their presence within the body can produce artifacts in magnetic resonance imaging (MRI), which can affect MRI diagnoses\(^4,5\). These artifacts occur because of the large susceptibility mismatch between metal and living tissue, which causes magnetic field distortions and signal losses, thereby generating an artifact in the image\(^6\).

In recent years, the field strengths used for MRI have increased rapidly, with 3 T now commonly being applied to examine various diseases instead of the more typical 1.5 T. Higher field strengths are advantageous because they provide a greater intrinsic signal-to-noise ratio (SNR). Moreover, it is expected that even higher field strengths will be used, as the SNR is predicted to grow at least linearly with the field strength\(^7-9\). For example, ultra-high-field (7 T or above) MRI scanners allow higher spatial resolution imaging in human applications, which is expected to contribute to the early detection of microstructural changes, clarification of mechanisms, and accurate identification of treatment results in numerous diseases such as epilepsy\(^10\), multiple sclerosis\(^11\), and Alzheimer’s\(^12\). However, as the volume of the abovementioned artifact increases with increasing magnetic field strength of MRI\(^7\), it is critical to understand how the magnetic susceptibility, volume, and mass of implanted metal devices influence artifact formation, particularly as ultra-high-field MRI becomes more common in the future.

Decreasing the magnetic susceptibility of metallic devices is an effective method to suppress artifacts\(^6\). Among various metals and alloys, Zr-14Nb alloy has attracted attention for medical applications because of its low magnetic susceptibility, good mechanical properties, and biocompatibility\(^3,13,14\). Imai et al. reported that there is a significant linear correlation between artifact volume and the magnetic susceptibility of an implanted metal\(^6\). From this, we predict that the artifact volume of Zr-14Nb alloy will be reduced compared to that of Ti and Co-Cr-Mo alloys, by an amount dependent on the differences of magnetic susceptibility between Zr-14Nb alloy and those alloys. However, the effect of material volume on artifacts is still unclear, and the relationships among artifact volume, material volume, and magnetic susceptibility have not been reported quantitatively.

Clarification of these relationships will allow us to predict the artifact volume and devise an MRI safety guideline for patients. Therefore, in this study, the influence of magnetic susceptibility and volume on the MRI artifacts produced was analyzed with a low-magnetic-susceptibility Zr-14Nb alloy and two common dental alloys.
MATERIALS AND METHODS

Preparation of the specimens
To evaluate how the magnetic susceptibility of the implant alloy affects the volume of the artifacts generated in MRI, we selected two kinds of commercial dental alloys (Ti-6Al-7Nb and Co-29Cr-6Mo) and a new low-magnetic-susceptibility alloy (Zr-14Nb). Ingots of Zr-14Nb alloy were prepared by arc-melting a pure Zr button (99.8 mass%) and a Nb shot (99.9 mass%) in an argon atmosphere on a water-cooled copper hearth in an arc-melting furnace. Each alloy ingot was flipped and remelted at least 10 times to homogenize the composition. The chemical compositions of the Zr-14Nb alloys were examined by X-ray fluorescence analysis (XGT-1000WR, Horiba, Kyoto, Japan), and have been presented in a previous study (Zr: 86.07±0.08; Nb: 13.59±0.04; Fe: 0.04±0.02; Sn: 0.30±0.05 mass%)\(^{14}\).

Ingots of the three alloys were remelted and cast with a centrifugal casting machine (MSE-50TMD-Z, Yoshida Cast, Saitama, Japan) using cylindrical copper dies (diameter: 3 or 16 mm; length 70 mm). The 3-mm-diameter cast rods were cut with a low-speed diamond cutter to produce cylindrical specimens (diameter: 3 mm; length: 25 mm) for measuring the magnetic susceptibility. The 16-mm-diameter cast rods were subjected to milling to form spherical specimens (diameter: 7.9, 9.5, 11.1, and 12.7 mm) for measuring the artifact volume.

Magnetic susceptibility
To evaluate the magnetic susceptibility of each alloy, the apparent density was first measured based on Archimedes law (i.e., hydrostatic weighing, Table 1). The magnetic susceptibility of each metal was then measured using a magnetic balance (MSB-MKI, Sherwood Scientific, Cambridge, UK) with cylindrical specimens (diameter: 3 mm; length: 25 mm). Each sample was tested five times and the average value was obtained.

Quantification of image artifacts
A cuboidal plastic phantom (168×130×163 mm) was prepared and half-filled with a Ni-doped agarose solution, consisting of 10 mM Ni(NO\(_3\))\(_2\) and 2% agarose, formulated to simulate the T1 and T2 characteristics of gray matter\(^{15}\). The phantom was kept in a chamber at 90°C and 80% humidity for 3 h, then slowly cooled to room temperature in air to allow the gel to form without bubbles. Subsequently, each spherical specimen was carefully placed on top of the solid agar gel using a positioning guide to achieve the same placement for each MRI test (Fig. 1a). Following the addition of the specimen, a second layer of Ni-doped agarose solution was poured to fill the phantom.

Magnetic resonance (MR) images were obtained using a 3.0 T MR scanner (MAGNETOM Spectra 3T, Siemens, Tokyo, Japan) with standard head coils. T1-weighted sequences for fast spin echo (FSE) and gradient echo (GRE) were used with a frequency matrix of 512 voxels, phase matrix of 512 voxels, field of view (FOV) of

Table 1  Apparent density of alloys examined in this study

| Alloy         | Zr-14Nb         | Ti-6Al-7Nb       | Co-Cr-Mo        |
|---------------|-----------------|-----------------|-----------------|
| Density (g/cm\(^3\)) | 6.7878 (±0.0047) | 4.5252 (±0.036) | 8.3729 (±0.022) |

Fig. 1  Specimen prepared for MRI, its MRI image at 3.0 T, and a rendering from the image.
(a) Phantom used in the study. (b) Standard slice of MR image for construction of 3-D rendering, showing four ROIs used to determine the background signal. (c) Artifact rendering indicating regions where the signal intensity is less than 70% and more than 130% of the background.
150×150 mm, and 1-mm multislice acquisitions without an inter-slice gap, resulting in a total of 96 slices; the frequency and slice direction were parallel to B₀ (head to foot, HF). For FSE sequences, the sequence-specific parameters were bandwidth (BW): 210 Hz; echo train length: 10; repetition time (TR): 400 ms; echo time (TE), 16 ms; and number of excitations (NEX): 1; whereas for GRE sequences, the parameters were BW: 210 Hz; echo train length: 10; TR: 20 ms; TE: 7.8 ms; and NEX: 2, with a flip angle of 60°.

The images were transferred to a PC and analyzed using image-analyzing software (Osirix, Newton Graphics, Hokkaido, Japan). To determine the range of artifacts caused by the metals in the MR images, the average signal intensity of the background was determined according to a reported method⁶. Tangential lines along the phase and frequency encoding directions were drawn around the provisional fringes of the artifact, which were determined visually. Then, four circular regions of interest (ROIs), 10 mm in diameter and tangential to both lines, were positioned where the lines intersected (Fig. 1b). The background signal intensity was obtained by averaging the signal intensities within the four circles.

According to ASTM F2119, an artifact is defined as an area showing a signal intensity that differs from the average signal intensity by more than 30%¹⁶. The same threshold was used in this study, and artifact areas from all the slices were calculated and added to obtain the artifact volume of each specimen. An example of the rendering is shown in Fig. 1c. Areas with signal intensities less than 70% or more than 130% of the average signal intensity of the background are shown in gray, and are regarded as artifact areas. The artifact volume (Vₐ) was determined by subtracting the original volume of the metal from the total artifact volume.

**RESULTS**

The mass magnetic susceptibility (χₘ) and volume magnetic susceptibility (χᵥ) of the three alloys are listed in Table 2. The Zr-14Nb alloy showed lower magnetic susceptibility compared to the other alloys. Specifically, its mass magnetic susceptibility was about 50% of that of Ti-6Al-7Nb and 17% of that of Co-Cr-Mo alloy; its volume magnetic susceptibility was about 77% of that of Ti-6Al-7Nb alloy and 14% of that of Co-Cr-Mo alloy.

Figure 2 shows the MRI images (upper) and artifact areas (lower) of the center of the slice for each alloy of diameter 9.5 mm. Zr-14Nb alloys generated the smallest artifacts, whereas Co-Cr-Mo alloys produced the largest artifacts under both FSE and GRE conditions.

Figure 3 shows the MRI images and artifact areas of the center of the slices of Ti-6Al-7Nb specimens with four different diameters. The artifact volume increased with increasing specimen diameter under both FSE and GRE conditions.

The quantitative relationships of the absolute value of the artifact volume with specimen mass and volume are shown in Figs. 4 and 5, respectively. The artifact volume increases linearly in relation to the mass and volume of the sample. The proportionality factor increases in the

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**Table 2** Mass magnetic susceptibilities (χₘ) and volume magnetic susceptibilities (χᵥ) of the alloys examined in this study

| Alloy      | Zr-14Nb | Ti-6Al-7Nb | Co-Cr-Mo |
|------------|---------|------------|----------|
| χₘ/10⁻⁴ m³kg⁻¹ | 1.56    | 3.05       | 9.22     |
| χᵥ/10⁻⁶     | 106     | 137        | 774      |

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Fig. 2 Typical configuration of the artifact from the 3 different metals under the 2 imaging conditions (FSE and GRE). Standard slices of MR images (upper) and artifact renderings (lower) are shown.
Fig. 3 Typical configuration of the artifact from the Ti-6Al-7Nb with four different diameters under (a)–(d) FSE and (e)–(h) GRE imaging conditions. (a) and (e): diameter 7.9 mm, (b) and (f): diameter 9.5 mm, (c) and (g): diameter 11.1 mm, (d) and (h): diameter 12.7 mm.

Fig. 4 Quantitative relationship between absolute value of the artifact volume and mass. Regression lines for Zr-14Nb (TSE), Zr-14Nb (GRE), Ti-6Al-7Nb (TSE), Ti-6Al-7Nb (GRE), Co-Cr-Mo (TSE), and Co-Cr-Mo (GRE) are $Y=2.425X+0.159$ ($R^2=0.999$), $Y=2.178X+3.116$ ($R^2=0.999$), $Y=5.197X-0.284$ ($R^2=0.999$), $Y=4.671X+2.536$ ($R^2=0.999$), $Y=14.279X+1.940$ ($R^2=0.999$), and $Y=11.929X+3.489$ ($R^2=0.999$), respectively.

Fig. 5 Quantitative relationship between absolute value of the artifact volume and specimen volume. Regression lines for Zr-14Nb (TSE), Zr-14Nb (GRE), Ti-6Al-7Nb (TSE), Ti-6Al-7Nb (GRE), Co-Cr-Mo (TSE), and Co-Cr-Mo (GRE) are $Y=0.016X+0.152$ ($R^2=0.999$), $Y=0.015X+3.109$ ($R^2=0.999$), $Y=0.021X-0.08$ ($R^2=0.999$), $Y=0.021X+2.452$ ($R^2=0.999$), $Y=0.119X+2.228$ ($R^2=0.999$), and $Y=0.099X+3.729$ ($R^2=0.999$), respectively.

Fig. 6 Quantitative relationship between the absolute value of $\chi_v$ and the artifact volume. Regression lines for $\Phi 7.9$ mm (TSE), $\Phi 7.9$ mm (GRE), $\Phi 9.5$ mm (TSE), $\Phi 9.5$ mm (GRE), $\Phi 11.1$ mm (TSE), $\Phi 11.1$ mm (GRE), $\Phi 12.7$ mm (TSE), and $\Phi 12.7$ mm (GRE) are $Y=0.529X-0.080$ ($R^2=1$), $Y=0.420X+3.224$ ($R^2=0.999$), $Y=0.908X-0.120$ ($R^2=1$), $Y=0.726X+3.877$ ($R^2=1$), $Y=1.426X+0.369$ ($R^2=0.999$), $Y=1.148X+4.732$ ($R^2=0.999$), $Y=2.077X+1.760$ ($R^2=0.999$), and $Y=1.702X+5.450$ ($R^2=0.999$), respectively.

**DISCUSSION**

Magnetic susceptibility is an important factor that affects MRI artifacts. In this study, the magnetic susceptibilities determined for the alloys descended in the order Co-Cr-Mo>Ti-6Al-7Nb>Zr-14Nb. There were significant linear correlations between the artifact volume and volume magnetic susceptibility (Fig. 6), which agrees well with previously reported results.

Additionally, this study investigated the influence of the metal sample volume on the artifact volume using spherical specimens with four different diameters. The artifact volume increased linearly in relation to
the mass and volume of the metal samples. The mass magnetic susceptibility of Zr-14Nb alloy was ~50% of that of Ti-6Al-7Nb. However, the density of Zr-14Nb alloy is greater, resulting in the artifact range of Zr-14Nb alloy being ~77% of that of Ti-6Al-7Nb for the same sample volumes. These results indicate that the artifact volume is influenced not only by the mass magnetic susceptibility of the metal sample but also its density. Thus, when comparing alloys with the same mass magnetic susceptibility, lower density materials have an advantage in terms of reducing artifact range.

In addition, the proportionality factor increased as the diameter of the specimen increased (Fig. 6). Thus, the influence of the magnetic susceptibility on the artifact range increases with volume of the metal material. It is therefore important to use metals with low magnetic susceptibility in dental restorations with large-volume devices, such as full arch prostheses and orthodontic braces, in order to suppress susceptibility to artifacts in MRI.

In this study, we evaluated the low-magnetic-susceptibility Zr-14Nb alloy and succeeded in reducing the artifact volume compared to other alloys examined. However, the artifact is still present; hence, it is essential to predict the artifact volume in advance to explain the influence of metal devices on MR images for patients. By examining the artifact volumes for the three kinds of metals with various diameters, the artifact volume $V$ can be estimated by Eqs. (1) and (2) for the TSE and GRE conditions, respectively.

\[
\text{(TSE)} \quad V_a = \frac{a}{m} \times \chi \times m \times \frac{a}{m} \times \chi \times V
\]

\[
\text{(GRE)} \quad V_a = b \times m \times m \times b \times \chi \times V
\]

where $m$, $V$, $\chi$, $m$, and $\chi$ are the mass (kg), volume ($m^3$), mass magnetic susceptibility ($10^{-8} m^4kg^{-1}$), and volume magnetic susceptibility ($10^{-7}$) of the metal device, respectively. $a$ and $b$ depend on the imaging conditions. In this study, they were calculated as $a=1.6 \times 10^5$; $b=1.4 \times 10^8$.

These equations will aid in the prediction of artifact volume if the magnetic susceptibility and mass of the material are known in advance. If the size of the artifact can be measured accurately, it will help us not only to know the target value of magnetic susceptibility required to reduce artifacts to within acceptable levels, but also to explain the exact range of device artifacts for patients and judge whether there are any possible problems with an MRI diagnosis. However, our study is limited in that other factors, such as imaging conditions, shape, orientation, and position of the object, were not investigated. These factors also affect the artifact volume and must be considered to predict it more accurately. Especially, previous studies have reported that artifacts appear larger under GRE than SE conditions. However, our results indicated that larger artifacts were generated under FSE than GRE conditions. Artifact range is affected by detailed imaging conditions, which means that some setting parameters could strongly affect the artifact volume. Thus, further study will be required to clarify the influence of detailed imaging conditions on the artifact volume. It has been reported that the range of artifacts is affected by the shape of high-magnetic-susceptibility materials; however, shape is not thought to be a factor for low-magnetic-susceptibility materials. Ernstberger et al. reported that artifact range was influenced by implant shape in titanium with high magnetic susceptibilities; however, when assessing carbon implants with low magnetic susceptibilities, the implant shape did not have any significant effect on the artifact behavior. Therefore, the effect of shape is decreased with the use of low-magnetic-susceptibility materials. Further study is required to more precisely predict artifact volume. Moreover, the development of new low-magnetic-susceptibility alloys is essential to suppress artifacts in MRI.

CONCLUSION

MRI artifacts generated by various spherical alloys with four different diameters were quantitatively evaluated. The analysis revealed that there were significant linear correlations of the artifacts with the mass, volume, and magnetic susceptibility of the alloy. The equations presented can serve as a useful guideline in clinical practice to predict the artifact volume. However, further studies are necessary to understand the influence of additional factors, such as imaging conditions, shape, orientation and the position of the object in MRI.

ACKNOWLEDGMENTS

This work was partially supported by a Grant-in-Aid for Fundamental Scientific Research (Nos. 17J10345 and 17K17152 and 17K17157) from the Ministry of Education, Culture, Sports, Science, and Technology of Japan.

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