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Three-dimensional quantification of susceptibility artifacts from various metals in magnetic resonance images

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ABSTRACT

Susceptibility artifacts generated in magnetic resonance (MR) images were quantitatively evaluated for various metals using a three-dimensional (3-D) artifact rendering to demonstrate the correlation between magnetic susceptibility and artifact volume. Ten metals (stainless steel, Co–Cr alloy, Nb, Ti, Zr, Mo, Al, Sn, Cu and Ag) were prepared, and their magnetic susceptibilities measured using a magnetic balance. Each metal was embedded in a Ni-doped agarose gel phantom and the MR images of the metal-containing phantoms were taken using 1.5 and 3.0 T MR scanners under both fast spin echo and gradient echo conditions. 3-D renderings of the artifacts were constructed from the images and the artifact volumes were calculated for each metal. The artifact volumes of metals decreased with decreasing magnetic susceptibility, with the exception of Ag. Although Sn possesses the lowest absolute magnetic susceptibility (1.8×10^{-6}), the artifact volume from Cu (-7.8×10^{-6}) was smaller than that of Sn. This is because the magnetic susceptibility of Cu was close to that of the agarose gel phantom (-7.3×10^{-6}). Since the difference in magnetic susceptibility between the agarose and Sn is close to that between the agarose and Ag (-17.5×10^{-6}), their artifact volumes were almost the same, although they formed artifacts that were reversed in all three dimensions.

1. Introduction

Magnetic resonance imaging (MRI) is one of the essential diagnostic tools in various medical fields, especially in neurosurgery, orthopedics and stomatology. Moreover, MRI-guided neurosurgery and functional MRI applications for brain research are becoming widespread. MRI has great advantages in obtaining various cross-sectional views and precise anatomical detail of soft tissues without X-ray exposure. However, MRI diagnosis is often perturbed by artifacts when metals are implanted or fixed in the human body; examples of implanted metals include aneurysm clips, stents, orthopedic implants and orthodontic appliances [1–7]. In the static magnetic field of the MR scanner, new magnetic gradients are generated owing to the metallic device in the human body. Although differences in magnetic susceptibility exist in the human body, (such as at tissue–air or tissue–bone interfaces), the difference in susceptibility between metal and human tissue is much larger than the naturally occurring differences within the body. This large difference causes local field inhomogeneity, producing loss of signal from the object and geometric distortion. These effects are known as "susceptibility artifacts" and are observed in MR images as dark or bright areas caused by signal loss or excess signal, respectively. Susceptibility artifacts should be avoided as much as possible, because geometric accuracy is important in applications such as MRI-guided neurosurgery or planning of radiation treatment.

Various approaches for overcoming susceptibility artifacts have been discussed. Most of them are concerned with hardware-related techniques. Appropriate imaging conditions for MR scans such as strength of static magnetic field (B_0), imaging sequence, echo time (TE), slice thickness and bandwidth (BW) are important to decrease artifacts [8–13]. In addition, some numerical simulations and correction methods were developed to improve geometric accuracy, especially for MRI-guided neurosurgery and planning of radiation treatment [14–19].

On the other hand, decreasing the magnetic susceptibility of metallic devices is also an effective method to suppress the artifacts [20–22]. Susceptibility artifacts will decrease when metallic

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medical devices are substituted by ceramics or polymers. However, this is currently impossible in many cases, because the mechanical properties of metals, such as strength and toughness, are superior to those of ceramics and polymers. Among various metals, Ti and Ti alloys show low magnetic susceptibility compared with the other metallic biomaterials, but artifacts are still generated, even by Ti [7,21,22]. Recently, Zr-based alloys having magnetic susceptibility only one-third of that of Ti have been developed [23–26]. Although lower magnetic susceptibility leads to smaller artifacts, the relationships between the magnetic susceptibility and artifacts have not been reported quantitatively, and the target value of magnetic susceptibility required to reduce artifacts to acceptable levels is still vague; a clearly defined target would direct the design of novel metals.

The purpose of this study was, therefore, to quantify the artifacts from metals with different magnetic susceptibilities using a three-dimensional (3-D) artifact rendering, and to clarify the relationship between magnetic susceptibility value and artifact volume.

2. Materials and methods

2.1. Quantification of susceptibility artifacts from metals

Cylindrical specimens, 25 mm long and 3 mm in diameter, were prepared from ten different metals (316L type stainless steel (SUS), Co–Cr alloy (Co–29 Cr–6 Mo), Nb, Ti, Zr, Mo, Al, Sn, Cu and Ag). Metals employed in this study are generally used or contained in alloys used for medicine or dentistry. The magnetic susceptibility of each metal was measured using a magnetic balance (MSB-MKI, Sherwood Scientific Ltd, Cambridge, UK). Each metal was embedded in a nickel (Ni)-doped agarose gel phantom, consisting of a solution of 10 mM $Ni(NO_3)_2$ and 2% agarose, formulated to simulate the T_1 and T_2 characteristics of gray matter, as shown in Fig. 1a [27]. The long axis of the metal was set both parallel and perpendicular to the static magnetic field (B_0), using a positioning guide to achieve the same placement for every MR-imaging test. The magnetic susceptibility of the Ni-doped agarose gel phantom was also measured.

MR images were obtained using 1.5 and 3.0 T MR scanners (Signa-HDxt, GE Healthcare Waukesha, USA) with standard head coils. T_1-weighted sequences for fast spin echo (FSE) and gradient echo (GRE) were used with a frequency matrix of 512 voxels, a phase matrix of 512 voxels, a field of view (FOV) of 150 × 150 mm and 1 mm multislice acquisition without an inter-slices gap, resulted in a total of 50 slices; the frequency and slicing direction were parallel to B_0 (head to foot, HF). Sequence-specific parameters were as follows: for FSE sequences, BW 19.2 kHz, echo train length 2, TR 400 ms, TE 11 ms with full-Fourier acquisition, and NEX 3 times; for GRE sequences, BW 31.25 kHz, echo train length 2, TR 20 ms, TE 3.1 ms with half-Fourier acquisition at 1.5 T and 5.4 ms with full-Fourier acquisition at 3.0 T, NEX 4 times and flip angle 60°. Half-Fourier acquisition for 1.5 T GRE was used to examine the influence of acquisition method on susceptibility artifacts.

Images were transferred to a PC and analyzed using image-analyzing software (Ziostation, Ziosoft, Tokyo, Japan). To determine the artifacts caused by the metals in the MR images, the average signal intensity of the background was determined as follows: for each metal, a coronal slice that showed the center of the metal was selected as standard slice from the images. 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 (ROI), 10 mm in diameter, and tangential to both lines, were positioned where the lines intersected, as shown in Fig. 1b. The background signal intensity was obtained by averaging the signal intensities within the four circles.

According to ASTM F2119 [28], an artifact was defined as an area showing a signal intensity that differs by more than 30%, compared with the average signal intensity. The same threshold was used in this study and a 3-D rendering was constructed from all the slices. An example of the rendering is shown in Fig. 1c. Areas with signal intensity less than 70% or more than 130% of the average correspond to the dark (pink in Fig. 1c) and bright (green in Fig. 1c) artifacts, respectively. The dark and bright volumes (cm^3) were calculated from the 3-D rendering, and termed V_{70} and V_{130}, respectively. The total artifact volume (V) was determined as: $V = V_{70} + V_{130} - V_0$, where V_0 is the original volume of the metal.

2.2. Evaluation of signal intensity of the background

The signal intensity of the background should be determined before calculating the artifacts produced by the metals. The signal intensity values of a particular MR image varied depending on the area selected, because the intensity was affected by RF (B1) inhomogeneity, static magnetic field distortion and the influence of eddy currents. To determine an exact background, four ROIs were fixed around the metal specimens, as described above. The ROIs should be as near to the specimens as possible, without including artifacts. Although the specimen size was the same, the same ROI positions cannot be used for all specimens, because the artifact size may vary between specimens. However, this method may include some inaccuracies, because the tangential lines were determined visually. In addition, the size of the ROI may have an influence on the background signal. Therefore, the influences of ROI position

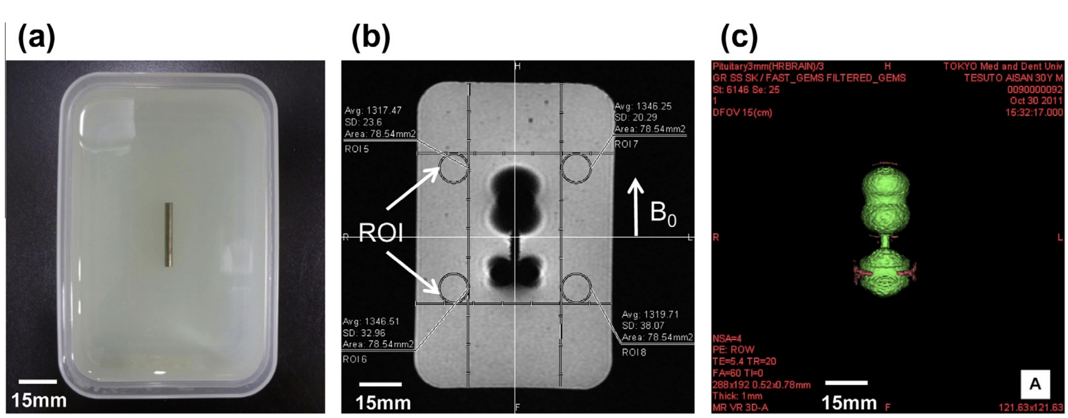

Fig. 1. Specimen prepared for MRI, its MRI image at 3.0 T and a 3-D rendering from the image. (a) Specimen embedded in a Ni-doped agarose gel phantom. (b) Standard slice of MR image for construction of 3-D rendering, showing four ROIs used to determine the background signal. (c) A 3-D artifact rendering indicating regions where the signal intensity is less than 70% (green) and more than 130% (pink) of that of the background.