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Accurate and sensitive measurements of magnetic susceptibility using echo planar imaging

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Abstract

Susceptibility differences are common causes for artifacts in magnetic resonance (MR); therefore, it is important to choose phantom materials in a way that these artifacts are kept at a minimum. In this study, a previously proposed MR imaging (MRI) method [Beuf O, Briguet A, Lissac M, Davis R. Magnetic resonance imaging for the determination of magnetic susceptibility of materials. *J Magn Reson* 1996; Series B(112):111–118] was improved to facilitate sensitive in-house measurements of different phantom materials so that such artifacts can more easily be minimized. Using standard MRI protocols and distilled water as reference, we measured magnetic volume susceptibility differences with a clinical MR system. Two imaging techniques, echo planar imaging (EPI) and spin echo, were compared using liquid samples whose susceptibilities were verified by MR spectroscopy. The EPI sequence has a very narrow bandwidth in the phase-encoding direction, which gives an increased sensitivity to magnetic field inhomogeneities. All MRI measurements were evaluated in two ways: (1) manual image analysis and (2) model fitting. The narrow bandwidth of the EPI made it possible to detect very small susceptibility differences (equivalent susceptibility difference, $\Delta\chi_e \geq 0.02$ ppm), and even plastics could be measured. Model fitting yielded high accuracy and high sensitivity and was less sensitive to other image artifacts as compared with manual image analysis.

Keywords: Susceptibility; MRI; EPI; Phantom; MRS

1. Introduction

Susceptibility differences in an object can cause many problems in magnetic resonance imaging (MRI) and magnetic resonance spectroscopy (MRS). Near interfaces, the magnetic field is disturbed; therefore, the spatial encoding in MRI is affected. The signal displacements can appear as high-intensity spots and spots with signal void in the image due to accumulation or subtraction of signal. In MRS, a magnetic field change can lead to a shift in resonance frequency and peak broadening.

If it is possible to determine the susceptibility of phantom and implant materials, then it is also possible to minimize the artifacts in advance by choosing materials with small susceptibility differences. This can become even more important as the trend for clinical MR goes toward higher field strength, 3 T and beyond, and higher field strengths lead to more pronounced susceptibility effects.

By means of MRS, a susceptibility-induced shift in resonance frequency can be used to determine the volume susceptibility of signal-giving liquids [1]. The method is accurate and easy to use. However, phantoms are often made of plastics or other solid materials, which is why the use of the MRS method is not always applicable. Beuf et al. [2] devised an MRI method that can be used for any sort of material because it is not the object itself but the effect it has on a reference liquid that is imaged. The susceptibility difference between an outer compartment and an inner compartment in a coaxial circular cylindrical phantom was determined by the size of the artifact in an MR image. For ordinary imaging sequences, the sensitivity was limited and the susceptibility differences caused by materials usually used in phantoms (e.g., plastics) were not detectable.

The aims of this study were (1) to increase the sensitivity of the MRI measurements of susceptibility differences to make it possible to also measure plastics and tissue-like

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materials, (2) to improve the sensitivity and accuracy in data evaluation by designing an automatic evaluation program based on model fitting and (3) to apply the improved method to measure the volume susceptibilities of polymethyl methacrlyate (PMMA) and polyethylene.

2. Materials and methods

2.1. Theory

Not only the artifacts but also the susceptibility parameter itself can be very confusing. Volume (χ), mass (χ_m) and molar (χ_M) susceptibilities, given in either SI or centimeter-gram-second (cgs) units, are all present in the literature. Volume susceptibility is defined as the dimensionless proportionality coefficient between magnetization, M, and magnetizing field strength, H; it describes the contribution to the magnetic flux density present, B, made by a substance when subjected to a magnetic field. Mass susceptibility and molar susceptibility are defined in terms of magnetization per unit mass or per mole of the material in reference to volume susceptibility: $\chi_m=\chi/\rho$ and $\chi_M=\chi*W_M/\rho$, respectively, where ρ is the density and W_M is the molar weight of the material. The molar susceptibility of distilled water at 17°C in cgs units is $-12.96*10^{-6}$ cm^3/mole [3] (in SI units, $-162.9*10^{-6}$ cm^3/mole). Schenck [4] gave some clarity to the different definitions and units; however, as in many other articles, the susceptibilities are given for 37°C and are not applicable in most phantom measurements. A temperature correction for volume susceptibility of water has experimentally been derived [5]. Using this correction, the molar, mass and volume susceptibilities of water at 37°C are $-164.2*10^{-6}$ cm^3/mole, $-9.109*10^{-6}$ cm^3/g and -9.049 ppm, respectively. These correspond well to earlier published values [1,2,4,6]. In the present article, SI units are always used and the measurements were performed at 20°C, at which the molar susceptibility of water is $-162.9*10^{-6}$ cm^3/mole [3] and the corresponding mass and volume susceptibilities are $-9.044*10^{-6}$ cm^3/g and -9.027 ppm, respectively.

The volume susceptibility of solutions can be calculated with the following equation [1]:

$$\chi = \sum_k C_k \chi_{M,k} \tag{1}$$

where C_k is the concentration in mole per cubic centimeters and $\chi_{M,k}$ is the molar susceptibility in cubic centimeters per mole for the constituent k of the solution. For $CuSO_4$, the molar susceptibility is $+1835*10^{-6}$ cm^3/mole [2].

The volume susceptibility of many solutions can be measured with MRS using two thin tubes that are filled with the same solution and arranged perpendicularly to each other, one parallel with the and one orthogonal to the static magnetic field. The liquid in the two tubes will affect the static magnetic field lines differently and will therefore result in two separate resonance frequencies for the solution. The difference in resonance frequency can be used to calculate the volume susceptibility of the sample inside the tubes according to Ref. [1].

$$\chi_i = \chi_e - 2\left(\delta_\top - \delta_\parallel\right), \tag{2}$$

where χ_i is the volume susceptibility of the liquid inside the tubes and χ_e is the volume susceptibility of the surrounding medium [in this case, the volume susceptibility for air (-0.36 ppm)] [4]. $\delta_\perp$ and $\delta_\parallel$ are the resonance frequencies in parts per million obtained from the measured spectra. The main uncertainties are the limited spectral resolution and the determination of the volume susceptibility of the surrounding medium.

For any type of sample, liquid, solid or gas, MRI can be used to determine volume susceptibility [2]. When imaging a coaxial circular cylinder containing an outer reference and an inner sample, the spatial encoding of the outer reference will be affected by the susceptibility difference between the sample and the reference. The shape of the artifact depends on the imaging technique. For two-dimensional Fourier transform (2DFT) and Cartesian/linear acquisition of k space, the signal is only misplaced in the readout direction and the artifact gets the shape of a spearhead. In contrast, a projection reconstruction imaging technique will result in an artifact shaped like a four-leaf clover [2]. The size of the artifact is proportional to the susceptibility difference between the inner and outer compartments. If the inner compartment is exchanged with an inner glass cylinder containing a liquid sample, the effective field disturbance, caused by both the sample and the inner glass cylinder (denoted as the equivalent solid sample), gives the resulting artifact in the reference liquid. The relation between the volume susceptibility of the equivalent solid sample χ_{2e} and the volume susceptibility of the inner glass and liquid sample [Eq. (3)] is derived from equations given in Ref. [7].

$$\chi_{2e} = \chi_1 \frac{a_1^2}{a_2^2} - \chi_2\left(\frac{a_1^2}{a_2^2} - 1\right) \tag{3}$$

where χ_n is the volume susceptibility and a_n is the outer radius for compartment n (Fig. 1B).

Beuf et al. [2] derived equations (Eqs. 4a and 4b) in which the volume susceptibility of the inner liquid sample can be calculated from the length of the artifact d:

$$\chi_1 = \left[\pm\frac{2}{a_2^2}\left(\frac{d}{2.829}\right)^3 \frac{G_r}{B_{30}} - (\chi_2 - \chi_3)\right] \times \left(\frac{a_2}{a_1}\right)^2 + \chi_2 \qquad \text{for } d \geq 2.305a_2 \tag{4a}$$

$$\chi_1 = \left[\pm 2\left(\frac{d - 1.383a_2}{1.707}\right)\frac{G_r}{B_{30}} - (\chi_2 - \chi_3)\right] \times \left(\frac{a_2}{a_1}\right)^2 + \chi_2 \qquad \text{for } d \leq 2.236a_2 \tag{4b}$$