Magnetic microparticle size optimization for susceptibility contrast imaging

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Introduction

Superparamagnetic nanoparticles (SPIOs) and magnetic microparticles (MPIOs) are used as contrast enhancers in magnetic resonance imaging (MRI) [1, 2]. Compared to nanofabricated contrast agents, micrometer-sized agents can benefit from higher magnetic moments. As a result, susceptibility artifact (hypointense signal) is increased and visibility improves in MR images [3]. Magnetic moment of a micrometer-sized particle is a function of saturation magnetization and volume of the particle. Since MRI's external magnetic field (B_0) magnetizes ferromagnetic and superparamagnetic particles to saturation, the total magnetic moment and so the amount of the susceptibility artifact is determined by the volume of the particle. In the present work, a numerical simulation is used to investigate the behavior of the susceptibility artifact as magnetic microparticles are broken to smaller microparticles. Depending on the size of the constituent microparticles, different ensembles with identical total magnetic volume are considered.

Theory

The susceptibility difference created by the magnetic microparticles is the source of B_0 inhomogeneities (ΔBz) that cause geometrical image distortion and echo shifting in MR images. As opposed to spin echo (SE) imaging, the echo shifting results in signal loss in gradient echo (GE) imaging due to intravoxel dephasing. The susceptibility-based signal loss provides a mean to detect magnetic microparticles whereas their volume is largely inferior to the spatial resolution of the system [4]. For intravoxel dephasing the average signal within the volume of interest in GE imaging is given by: $S(t) = \int_V \rho(\vec{r})\, exp\left(-i\varphi(\vec{r},t)\right)dV$ with $\varphi(t) = \gamma B_z(\vec{r})t$, where φ is the phase dispersion across the voxel, *TE* is the echo time and γ is the gyromagnetic ratio for protons.

The field induced by sphere magnetic particles can be approximated by that of a dipole: $\Delta B_z(\vec{r}) = \sum_{i=1}^{N} \frac{\mu_0}{4\pi}\left(3\left(\frac{(\vec{m}.\vec{r_i})\hat{r}}{{r_i}^5} - \frac{\vec{m}}{{r_i}^3}\right)\right)$ with $\vec{m} = \frac{1}{6}\pi D^3 \vec{M}_{sat}$, where $\vec{m}$ is the net dipole moment, N is the number of the particles within the field of view (FOV) and $\vec{M}_{sat}$ is the magnetization saturation of the particle. The normalized signal from a particle of radius a and of homogeneous spin density is given by: $\frac{S}{S_0} = \int_V \rho(\vec{r}) \exp(-i\gamma \Delta B_z(\vec{r}) TE)\, dv$.

Materials and methods

The susceptibility artifact of *N* particles of diameter *D* was simulated based on the intravoxel dephasing resulting from the phase accumulation at the TE. MATLAB® programming language was used to model the normalized signal intensity of the ensembles of particles. The diameters of the particles were varied while keeping the total volume of magnetic materials constant($N\pi D^3/6$). The particles were distributed evenly in two fashions: on a line within the FOV and over a plane following a Fermat spiral to fill the FOV. The artifact was calculated for particles in both coronal and transversal planes. It was assumed that the microparticles are saturated at the magnetic field strength of 1.5 T. The imaging parameters were considered to be Pixel spacing = 0.04 mm, FOV= 2 × 2 cm and the echo time varied in the range of 10, 30 and 50 *ms*. The amount of the artifact was calculated by summing the in plane signal loss over the region of interest.

Results

The signal loss was calculated for different combinations of particle sizes and TEs in the coronal plane (Fig. 1). The images in Figure 2 show simulated noise free pixelized GE signals for particles of different diameters and at 400µm resolution. The signal loss in the transversal plane showed the same tendency as the coronal plane for both 2-D and 1-D distribution. Simulation results suggest that the amount of signal loss increases as the size of microparticles decreases (Fig. 2).

Discussion

The strong effective intravoxel dephasing caused by magnetic microparticles has made them promising candidates for MR tracking and contrast enhancement. Magnetic particles with identical volumes and magnetic moments produce equal amounts of signal loss in MR images. However, distribution of smaller magnetic particles over a surface creates a signal loss which is more pronounced than that created by larger particles on an identical total volume. Small particles provide a better contrast enhancement within the volume of interest yet the localization and tracking of individual particles is not feasible.

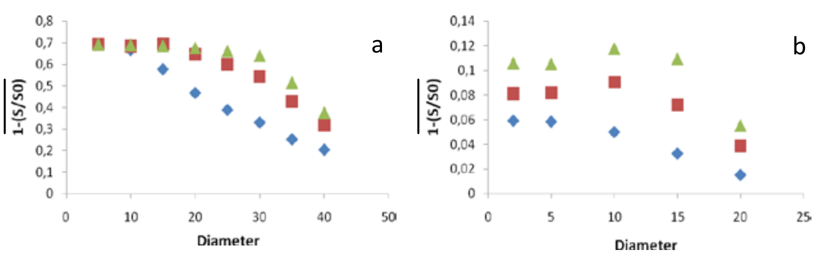

Fig. 1. Total image signal loss in coronal plane as a function of particle size in 2-D (a) and 1-D (b) distribution for TE=10 ms -♦- , 30 ms -■- and 50 ms -▲-.

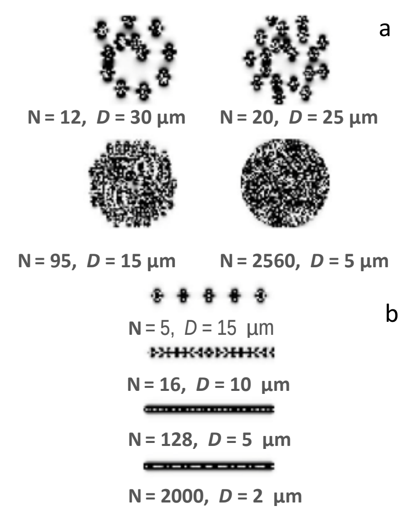

Fig. 2. Simulated GE noise-free MR images of magnetic particles with different diameters distributed evenly over the FOV (a) and distributed on a line within the FOV (b).

References

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