Contrast Agents: The Effect of Relaxation on Magnetic Particle Imaging

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Introduction: Magnetic particle imaging (MPI) is a new tomographic method [1] based on the nonlinear response of super-paramagnetic iron oxide (SPIO) nanoparticles. It has promise for fast imaging in the submillimeter range with some advantages in sensitivity, contrast, and cost in comparison with MRI. A static but spatially inhomogeneous field (selection field) and homogeneous oscillating field (drive field) are applied for spatial encoding. The selection field has a very strong gradient in order to saturate nanoparticle domains outside the field-free-point (FFP). The oscillating drive fields can move the FFP around the whole field of view by using different driving frequencies in different directions. The FFP region yields the detectable signal. The average magnetization has been assumed to respond immediately to changes in the applied field. However, delays due to magnetization relaxation lead to limitations on the response time and it is the purpose of the present paper to augment previous simulations [2, 3] by taking into account relaxation time effects.

Methods and Model: Our simulation is based on two Bloch-like relaxation terms, $-\vec{M} / T_N$ and $\left(\vec{M}_L - \vec{M}\right) / T_V$; a general reference is [4]. The latter term involves the Langevin equilibrium limit for temperature T, $\vec{M}_L\left(\vec{r},t\right) = m\, c(\vec{r})\, [\coth\left(m\, |\vec{B}\left(\vec{r},t\right)| / k_B T\right) - k_B T / m\, |\vec{B}\left(\vec{r},t\right)|\,]\, \hat{B}\left(\vec{r},t\right)$, yielding the nonlinear function of the magnetic field crucial to the MPI idea. Here, the particle concentration is $c(\vec{r})$, the particle magnetic moment $m = M_S V$ for spherical particle volume $V = 1/6\ \pi D^3$. The saturation magnetization is $M_S = 0.6T / \mu_0$ for magnetite (Fe3O4). [2] Thus we consider two major mechanisms corresponding to the Neel relaxation time of the magnetization within the particle domain, $T_N \propto \exp\left(K_N V / k_B T\right)$, and the Debye/viscosity relaxation time, $T_V = \pi D^3 \eta / 2 k_B T$. With V entering the exponent, the Neel relaxation time is ultra-sensitive to particle diameter D (K_N is a constant). We use the viscosity η=1.03mPa·s for Resovist in our simulation. [5] For our particular case, particle diameters in the tens of nm lead to $T_N >> T_V$, the interior magnetization is considered constant and changes in relaxation effects are mainly determined by T_V . A slice with a dimension of 1 mm × 32 mm × 16 mm is used as the phantom. It is divided into a 64 × 32 matrix so the size of each pixel is 1 mm × 0.5 mm × 0.5 mm. A Maxwell coil pair is placed along the y-axis, which provides two selection fields with a gradient of 1.25 mT/mm μ_0^{-1} in the y-direction and 2.5 mT/mm μ_0^{-1} in the z-direction. The two corresponding drive fields have the same amplitude of 20 mT μ_0^{-1} and different frequencies of 25.51 kHz and 25.25 kHz separately, as in [2]. The total duration of the scan is 3.88 ms and the sample frequency is 2.5 MHz. Two receiving coils are oriented with y-direction and z-direction axes. The sensitivities of the recording coils are taken to be perfectly uniform over the whole field of view. The final signal is the sum-of-squares of the signal from the two coils. In the original simulation [2], the sensitivity and hence the resolution was seen to be significantly improved by considering larger diameters in the 30-50 nm range. Including relaxation, the relaxation time varies from 10^{-6} s to 10^{-4} s, as the diameter of the particles is changed from 10 to 50 nm.

Results and Discussion: With the increase in the total relaxation time, which is dominated by T_V, the SNR and spatial resolution drop dramatically. The 50-nm particles, which by simulation have the best spatial resolution with no relaxation, actually give a significantly poorer quality image when relaxation modeling is included. The figure shows the pattern used in [1], albeit here standing for Physics, for different relaxation times corresponding to different diameters, as indicated in the caption. It is seen that larger particles lead to relaxation blurring; smaller particles lead to poorer resolution with some optimal size between. The underlying physical principle is when the FFP is moved to a previously saturated point, the particles at the original or final FFP do not respond quickly enough to the change at the frequency of the driving field f_0 if $1/T_V$ is much smaller than f_0. The signal from the final point will be reduced by the factor of $1/T_V$ and the signal surviving from the original point will blur the image. From our simulation results, we find that images from large particles provide high spatial resolution but are badly blurred by the relaxation time. While a growing number of interesting experimental results and theoretical studies can already have be found for MPI [1-3, 6-10], we conclude that relaxation should be taken into account in modeling, especially for a reliable interpretation of which particle size is dominating the imaging signal.

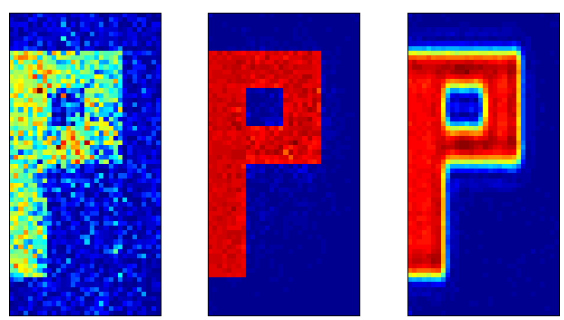

Fig. 1 (a) 50 nm particles with relaxation time = 10^{-4} s (b) 25 nm and $1.25 \cdot 10^{-5}$ s (c) 10 nm and $0.8 \cdot 10^{-6}$ s

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