

Effect of Spatial Distribution of Magnetic Dipoles on Larmor Frequency Distribution and MRI Signal Decay - A Numerical Approach Under Static Dephasing Conditions

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PURPOSE Superparamagnetic iron oxide (SPIO) nanoparticles have been used to image cell migration with MRI by exploiting the capability of certain cell types to ingest small particles through phagocytosis [1]. Exposed to a strong magnetic field, cells loaded with SPIO produce strong dipolar fields around the cell such that diffusion has a minimal effect on the MR signal decay [2]. Theories describing static signal dephasing [2, 3] don't account for the relatively strong fields over fairly large distances of neighboring SPIO loaded cells, what causes very complex intravoxel magnetic field distributions and field superposition effects. In this study we treated this problem numerically and investigated the effect of spatial distribution of magnetic dipoles on the Larmor frequency distribution and related MR signal decay under static dephasing conditions. Our numerical studies are aimed towards deeper understanding of how the spatial distribution of SPIO loaded cells associated with physiologic and pathologic processes affects the MR signal formation. This fact is of critical importance to establish a reliable calibration standard for the in vivo quantification of local cell numbers.

METHODS The frequency distribution in presence of magnetic dipoles was studied using a 3D numerical model. The program flow chart is shown in Fig. 1 (right side). Varying numbers n_d of magnetic dipoles were randomly assigned to a 3D volume grid (size 10^6 computational units (c.u.)). The field perturbation δB_z in presence of a magnetic dipole was computed to $\delta B_z(r, \varphi) = (\delta\chi \cdot B_0 \cdot (3 \cdot \cos^2 \varphi - 1) \cdot a^3) / (3 \cdot r^3)$ for $r > a$ ($\delta\chi$ magnetic susceptibility, a radius, r distance from the dipole center, φ angle relative to the vector B_0). Computing the frequency $\delta\nu$ at each location demands summation over contributions from all magnetic dipoles. The related free induction signal decay (FID) was assessed by Fouriertransforming the computed frequency distribution. For all simulations the volume fraction (total volume of magnetic dipoles / 3D volume) was kept constant to 0.01 % and the number of magnetic dipoles in the 3D volume was varied from $n_d = 1$ to $n_d = 65536$ in logarithmic steps. The magnetic susceptibility $\delta\chi$ was 1300×10^{-6} [4] and the magnetic field strength was $B_0 = 1.5$ Tesla. For a single magnetic dipole ($n_d = 1$) the radius was $a(n_d = 1) = 2.8$ c.u. and for an increasing number of magnetic dipoles the radius $a(n_d)$ was given according to $a(n_d) = 2.8 / \sqrt[3]{n_d}$.

RESULTS 3D frequency distributions calculated for a constant volume fraction of magnetic dipoles, but for an increasing number of randomly distributed magnetic dipoles are summarized in Fig. 2a. Representative examples for the computed frequency distribution and signal decay are shown. For a small number of clusters ($n_d \leq 64$) the computed frequency distribution was neither symmetrical with respect to $\delta\nu = 0$ nor lorentzian distributed. The related signal decays are shown in Fig. 2b. Fouriertransforming those frequency distributions led to non-monoexponential signal decay forms for $n_d \leq 64$. Increasing the number of dipoles two observations can be made. First, this led to spectral broadening and hence faster signal decay. Second, increasing the number of magnetic dipoles led to a more symmetrical frequency distribution, which was found to be lorentzian distributed with respect to $\delta\nu = 0$ Hz. In that case monoexponential signal decay was observed.

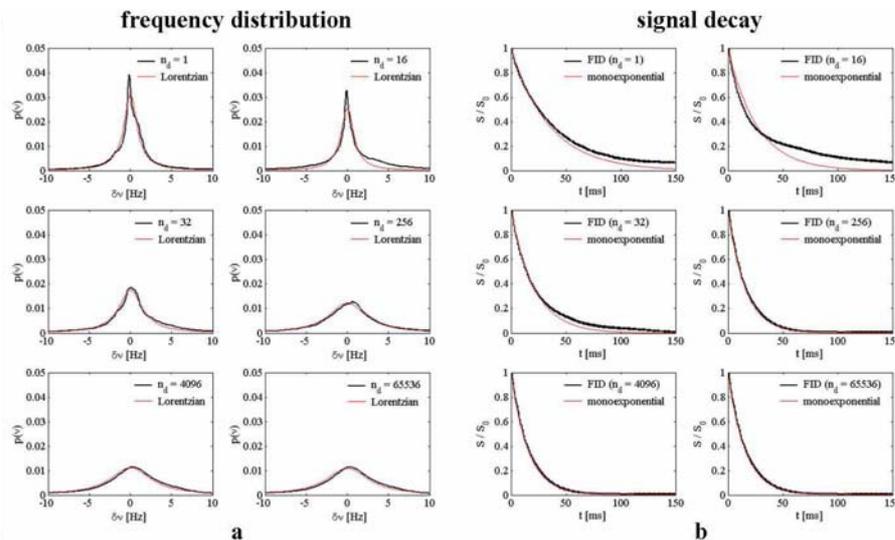
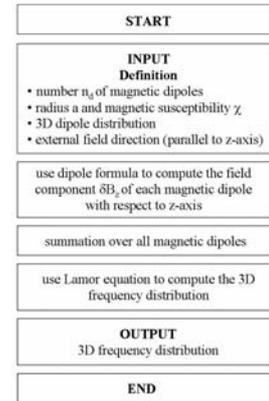


Fig. 2 (a) Spectral distribution of resonance frequencies, computed for a constant volume fraction (0.01%) but a different number n_d of magnetic dipoles, which were distributed randomly throughout the simulation universe. **(b)** Related signal decays. Lorentzian functions were fitted to the computed frequency distribution, while monoexponential functions were fitted to the calculated signal decay. Highly clustered magnetic dipoles showed non-lorentzian frequency distributions, what resulted in non-monoexponential signal decay.

DISCUSSION We have applied a numerical model and studied the effect of spatial distribution of magnetic dipoles on the Larmor frequency distribution under static dephasing conditions. We showed numerically, that in case of single labeled cells per MR imaging voxel [5, 6] the frequency distribution can be non-lorentzian, what lead to non-monoexponential signal decay. Our findings are important for the in vivo quantification of SPIO loaded cells, implying that in different tissues with different spatial distribution of the same concentration of SPIO labeled cells, different signal decays might be observed. The strong dependence of signal decay on spatial distribution of magnetic dipoles is likely to be of critical importance in optimizing and interpreting the results of iron-oxide contrast agents targeted to cells such as liver Kupffer cells [7]. In fact, non-monoexponential signal decay in liver tissue has been observed following the accumulation of iron oxide nanoparticles in liver Kupffer cells [8]. We demonstrated that the observed non-monoexponential signal decay is likely to be a direct consequence of the magnetic dipole clusters (i.e., SPIO loaded Kupffer cells) and the associated field inhomogeneities.

REFERENCES [1] Daldrup-Link HE, Radiology 2005;234:197 [2] Yablonskiy DA, Magn Reson Med 1994;32:749 [3] Bowen CV, Magn Reson Med 2002;48:52. [4] Josephson L, Magn Reson Imaging 1991;22:204. [5] Foster-Gareau P, Magn Reson Med 2003;49:968. [6] Dodd SJ, Biophys J 1999;76:103 [7] Tanimoto A, J Magn Reson Imaging 2001;14:72 [8] Briley-Saebo K, Cell Tissue Res 2004; 316:315.