Transverse Relaxation of Cells Labeled with Magnetic Nanoparticels

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Synopsis

The NMR relaxation properties of magnetically labelled cells are discussed in this abstract. The cells are labelled with magnetic nanoparticles (SPIO, USPIO), which generate susceptibility contrast. The geometry of the labelled cells and the surrounding tissue is considered. We assume that the magnetic nanoparticles accumulate inside the cell. The dependence of the correlation time τ, which describes the motion of spins around this core, on the concentration of the nanoparticles is analysed. Using the *strong collision approach* [1], explicit expressions are given for the transverse relaxation rate $R_2^* = 1/T_2^*$ for tissue containing labelled cells as a function of the core radius, the diffusion coefficient, and the concentration of the nanoparticles. The predictions of this model agree well with numerical simulations and experimental data.

Model of the magnetically labeled cells

We model the situation in which small paramagnetic particles (SPIO, USPIO) have been incorporated into stem cells or macrophages. We assume that every cell contains approximately the same number of particles and that they form a spherical core with radius R. Diffusion is then restricted to the space between two concentric spheres with radii R_C and R (periodic boundary conditions assumed (figure 1)). The inhomogeneous field around this core is approximately that of a magnetic dipole, i.e. in spherical coordinates (r,θ,φ) by $\omega(\mathbf{r})$ where $\delta\omega = \gamma\Delta\chi B_0 /3$ is the characteristic equatorial frequency shift and $\Delta\chi$ is the susceptibility difference between the magnetic core and surrounding tissue. The volume fraction is given by $\eta = R^3/R_C^3$.

$$\omega(\mathbf{r}) = \gamma B(\mathbf{r}) = \delta\omega R^3 \frac{3\cos^2\theta - 1}{r^3}$$

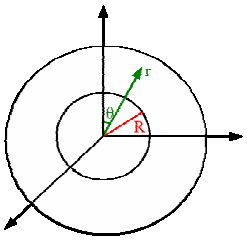

Figure 1: Geometry of the cell and the coordinate system.

Results

Using the *strong colission approximation* [1], we describe the time evolution of magnetization decay [2]. We obtain an expression for the correlation time $\tau = R^2/D\ (4/9 - 3/8\ \eta^{1/3})$ [3] and the transverse relaxation rate. Figure 2 shows that the results of the strong collision model are in close agreement with numerical simulations by Muller [4] and also with data obtained from the motional narrowing [5] and static dephasing [6] limits in the region where their approximations are valid.

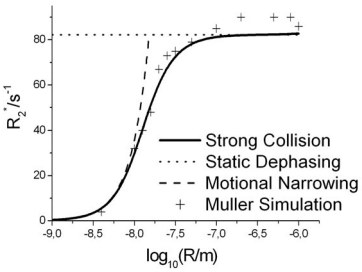

Figure 2: R_2^* dependence for different sphere radii R. The Crosses are the values obtained from the Muller Simulation.

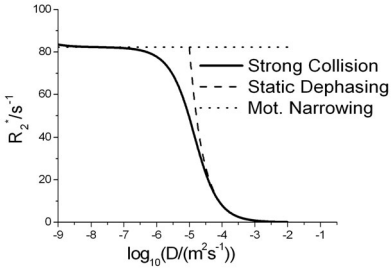

Figure 3: R_2^* vs. diffusion coefficient D for tissue parameters $\eta = 2{\cdot}10^{-6}$, $R = 1\ \mu m$, and $\delta\omega = 34{\cdot}10^6\ Hz$.

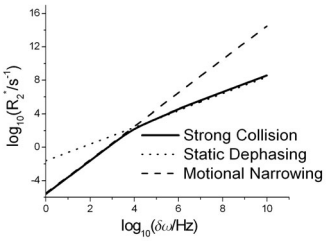

Figure 4: R_2^* dependence on the magnitude of the magnetic nano-particles ($\eta = 2{\cdot}10^{-2}$, $R = 1\ \mu m$).

Discussion & Conclusion

Based on a simple model geometry of magnetically labeled cells and surrounding tissue, we have derived an analytical expression for the transverse relaxation rate as a function of the concentration of the microspheres, the radius of the magnetic core, the magnetization difference, and the diffusion coefficient. The method that allowed this analytical approach was the application of the strong collision approach to the dynamics of spin diffusion. Based on the picture of spins diffusing around a sphere, two frequency scales characterising the underlying relaxation mechanism are present. The dynamic frequency scale τ characterises the stochastic process of diffusion using the correlation of moving spins, while the frequency shift $\delta\omega$ characterises the static scale. We are able to describe the relaxation process over the whole dynamic range, i.e. from motional narrowing to static dephasing.

Reference

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