Inter-echo time dependence of CPMG relaxation rate around capillaries in skeletal muscle tissue

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Target audience The present work targets investigators with an interest in quantitative CPMG measurements of capillary networks in muscle tissue.

Purpose Recently, remodeling of microcirculation due to skeletal muscle denervation or aging has been examined.[1] Also, blood transverse relaxation rate was shown to increase with inter-echo time τ_{180} of Carr-Purcell Meiboom-Gill (CPMG) sequences due to proton spin diffusion around capillaries that contain erythrocytes with paramagnetic deoxyhemoglobin.[2] The resulting susceptibility differences of capillaries and surrounding tissue are used to provide a means of quantifying microstructural parameters such as mean capillary radius and diffusion constant D.

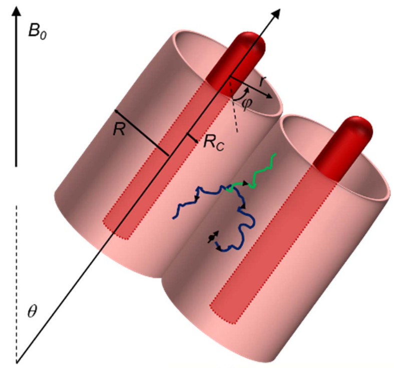

Fig.1: Schematic view of two parallel capillaries with supply areas and a spin trajectory (blue) that is replaced by a reflected version (blue-green).[3]

Methods Capillaries are considered in Krogh's supply model [3]: diffusion-dependent spin trajectories are restricted to a dephasing cylinder around each capillary where the radius is chosen such that the regional blood volume fraction $\eta=R_c^2/R^2$ remains constant (see Fig.1). Measured transverse relaxation rates $R_2=R_{2,0}+\Delta R_2$ with intrinsic and diffusion-dependent transverse relaxation rate $R_{2,0}$ and ΔR_2, respectively, where ΔR_2 can be expressed in terms of a correlation function that describes the diffusion process.[4] In close analogy to [5], the correlation function enables to quantify ΔR_2 through correlation time $\tau = R_c^2/D$ and susceptibility-dependent frequency shift $\delta\omega$.

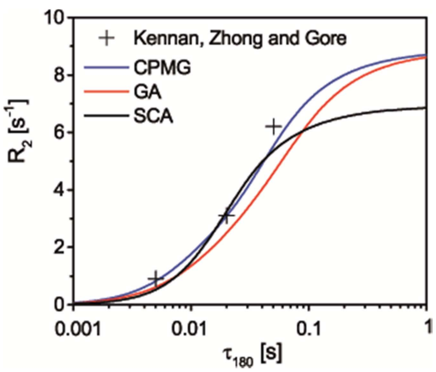

Fig.2: CPMG relaxation rate R_2 in dependence of inter-echo time τ_{180} for a single echo and parameters ($\eta = 0.05$, $R_C = 2.5\mu m$, $D = 1\mu m^2/ms$, $\delta\omega = 268 s^{-1}$) in comparison with Gaussian approximation (GA) and strong collision approximation (SCA) as well as experimental data from Kennan *et al.* [8] For small τ_{180}, ΔR_2 increases quadratically with τ_{180} to reach a plateau for large τ_{180} in accordance with previous results.[10]

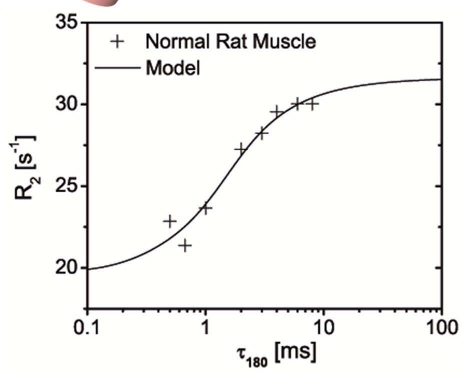

Fig.3: Comparison of model and experimental results for excised rat muscle.[6] Model parameters are $\tau = 0.42 \pm 0.7$ ms, $\delta\omega = 941.58 \pm 121.57$ s^{-1} and $R_{2,0} = 19.67 \pm 0.92$ s^{-1}.

Results To determine $T_2 = 1/R_2$ from a single spin-echo experiment, it is assumed that spin-echo magnetization M_{SE} decays mono-exponentially such that $R_2(\tau_{180}) = -\ln(M_{SE}(\tau_{180}))/\tau_{180}$. Figure 2 illustrates the dependence of R_2 on τ_{180} for CPMG signals for a specific set of parameters, and comparisons with results of the Gaussian approximation, [6] the strong collision approximation, [7] and experimental results from Kennan et al. [8] yield a good agreement. Furthermore, results for multi spin-echo R_2 were fitted to experimental data of Damon *et al.* [9] who examined excised plantaris muscles of Sprague-Dawley rats at $B_0 = 4.7$ T (Fig. 3). Resulting model parameters are given in the legend of Fig. 3 and, for $D = 2$ $\mu m^2/ms$, the capillary radius follows as $R_c = 0.92 \pm 0.08$ µm.

Discussion & Conclusion Model behavior of the CPMG relaxation rate and limiting cases agree well with approximations and experimental data from the literature (Fig.2,3) which, thus, support the validity of the model. However, predictions for rat muscle capillary radius underestimate the radius ~1.5-2.5 µm [11] most likely due to postmortal blood loss.[12] The presented model can be used to evaluate mean capillary diameters and/or proton spin diffusion constants around capillaries based on measurements of CPMG T_2 relaxation time.

References 1. Borisov, et al. Anat Rec 2000;285:292-304, 2. Gardener AG, et al. Magn Reson Med 2010;64:967-974, 3. Krogh A, J. Physiology 1919;52:457-474, 4. Jensen JH, et al. Magn Reson Med 2000; 44:144-156, 5. Ziener CH, et al. J Magn Reson 2010;202:38-42, 6. Sukstanskii AL, et al. J Magn Reson 2004;167:56-677, 7. Bauer WR, et al. Magn Reson Med 1999;42:1004-1010, 8. Kennan RP, et al. Magn Reson Med 1994;31:9-21, 9. Damon BM, et al. Proc. ISMRM 2002; 48:97-104, 10. Brooks RA, et al. Magn Reson Med 2001;45:1014-1020, 11. Sexton WL, et al. Am J Physiol 1994;266:H1502-11, 12. Kroeker RM, et al. Magn Reson Med 1985;2:1-13.