A Framework to calculate the IVIM signal for different diffusion gradient profiles

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Target audience: Researchers in diffusion MRI investigating intravoxel incoherent motion (IVIM).

Purpose: We recently introduced the concept of employing diffusion weighting gradients with different temporal profiles to extract estimates of the microscopic parameters of the IVIM model[1] (length of vessel segment l, blood flow velocity v, uncorrelated directional change after $\tau = l/v$) from in-vivo measurements at clinical MRI scanners[2]. To this end, the phase distributions of spin packets of the blood compartment are needed, whose calculation is a time consuming task that can only be performed numerically. The aim of this work is to provide the necessary functions and source codes to the community and provide some examples (code available at www.github.com/awetscherek/ivim_tools2) that show the potential usefulness of cosine oscillating gradients in the context of IVIM experiments.

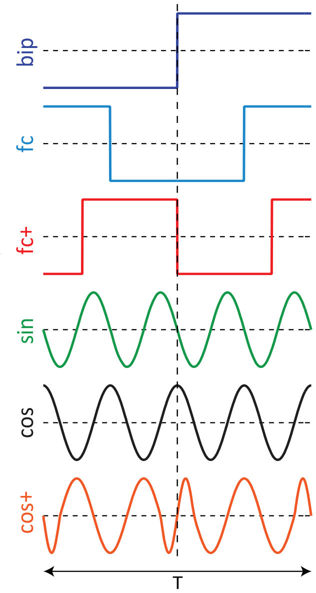

Fig. 1: Gradient profiles for which $\rho(\varphi, N)$ is available. Profiles labelled+ can be used symmetrically around a refocusing pulse.

Methods: The signal attenuation of the perfusion fraction undergoing incoherent motion is given by $F(b,T,l,v) = \int_{-\infty}^{\infty} \rho(\varphi, \frac{Tv}{l}) e^{-iv\sqrt{bT}\varphi} d\varphi$ with the normalized phase distribution $\rho(\varphi, N)$ that must be computed once for each gradient profile (Fig. 1) for sufficient values of the number of directional changes $N = \frac{Tv}{l}$. Computation of $\rho(\varphi, N)$ requires taking care of some subtleties like integrating over the time to the first directional change and is described in more detail in [2]. Knowledge of $\rho(\varphi, N)$ allows one to easily fit experimentally acquired diffusion data. Also flow velocity profiles like a parabolic one in case of laminar flow are readily taken into account by numeric integration over v.

Results: Two exemplary attenuation curves $F(b,T,l,v)$ for typical dimensions of capillaries and arterioles are shown in Fig. 2a and 2b, respectively, where laminar flow was assumed. The flow-compensated profiles (fc,fc+,cos) cause less signal attenuation than the non-flow-compensated profiles (bip,sin). The oscillating profiles (sin,cos) exhibit attenuation curves very similar to the standard bip/fc profiles for only 1 oscillation. Increasing the number of oscillations for the cosine and sine profile leads to reduced signal attenuation. For the signal in a network of arterioles (Fig. 2b), initial signal decay is so strong that changes with oscillation number are basically invisible for the sine profile.

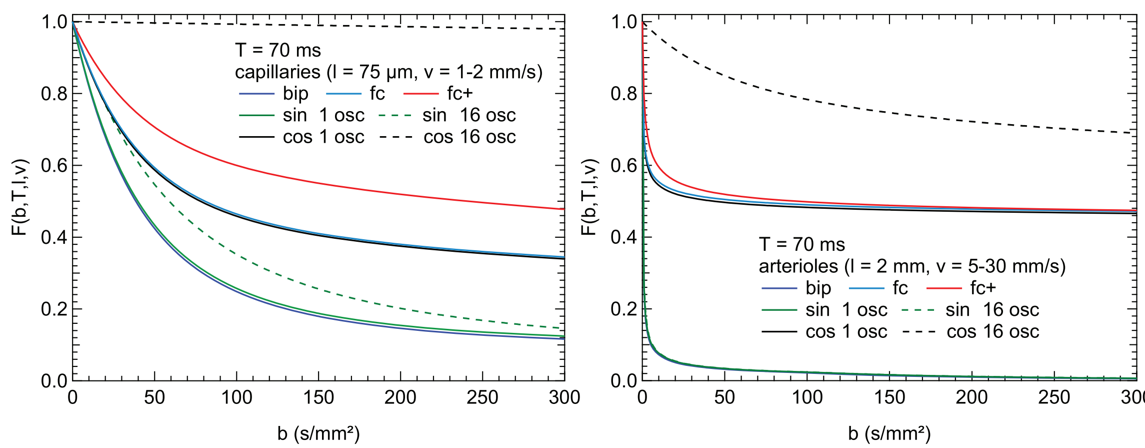

Fig. 2: Signal attenuation due to IVIM for typical capillaries (a) and typical arterioles (b). Flow compensated profiles exhibit less attenuation than bipolar ones. Increasing the number of oscillation reduces the signal attenuation. Signal attenuation curves for T=70ms and b=0-300s/mm² are calculated for capillary vessels (l=75µm, v=1-2mm/s)[1,3-5] and arterioles (l=2mm, v=5-30mm/s)[6]. Inside the vessels a parabolic velocity profile (laminar flow) was assumed.

Discussion: The large difference between attenuation curves for flow-compensated profiles (cos, fc, fc+) and non-flow-compensated (bip, sin) profiles is the basis of the method presented in [2] to obtain estimates of l and v. Fig. 2 shows that oscillating cosine gradients can in principle stabilize parameter estimation due to a further spreading of the curves, but the smaller b-value associated with higher oscillation number must be considered.

Conclusion: Matlab code to generate Fig. 2 and other figures is available at www.github.com/awetscherek/ivim_tools2 and may serve other researchers in the field applying oscillating or flow-compensated gradient profiles to calculate the resulting IVIM signal and extract the underlying parameters such as length of vessel segment l and blood flow velocity v.

References: [1]Le Bihan D et al. Radiology 1986;161:401-407. [2]Wetscherek A et al. Magn Reson Med 2014;10.1002/mrm.25410. [3]Klinke R et al. 6th ed. New York: Georg Thieme Verlag; 2010. 191 p. [4]Maki JH et al. Magn Reson Med 1991;17:95-107. [5]Pawlik G et al. Brain Res 1981;208:35-58. [6]Kunsch K, Kunsch S. Der Mensch in Zahlen 2nd ed. Berlin: Spektrum Akademischer Verlag; 2000. 64 p.