Diffusion corrected reconstructions of partial pressure of oxygen using polarized gas MRI

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Introduction: In the presence of diffusion and the absence of wall relaxation effects, the measured MRI signal intensity, $S(r,t)$ as a function of position, r, and time, t, is governed by the diffusion equation. An integral representation for, $S(r,t)$, follows from time dependent perturbation theory and is of the form: $$-\ln\left(\frac{S(r,t)}{S_0(r,t)}\right)=\int d^3r''\nu_P(r'';r,t)P(r'')+\int d^3r''\nu_R(r'',r,t)R(r'')+\int d^3r''\phi(r'',r,t)\left(1-\cos(\alpha(r''))^N\right) \quad \text{(a), where}$$

$$\nu_P(r'';r,t)=\frac{1}{\xi S_0(r,t)}\int dt' G_0(r,r'';t')S_0(r'',t)'$$

$$\nu_R(r'';r,t)=-\frac{1}{\xi S_0(r,t)}\int dt' G_0(r,r'';t')(t-t')S_0(r'',t-t')'$$

$$\phi(r'';r,t)=\frac{1}{S_0(r,t)}\int dt' G_0(r,r'';t')S_0(r'',t-t')\sum\delta(t-t'-t_i)'$$

and

$$S_0(r,t)=\int d^3r' G_0(r,r';t)S(r',0)\cdot$$

$\alpha(r)$ is the position dependent flip angle, N the number of phase encodes used to obtain an image, ξ is a constant equal to 2.6 bar-sec at body temperature, $P(r)$ symbolizes the alveolar oxygen concentration at time zero while $R(r)$ denotes the oxygen uptake rate, t_i the time at which the i^{th} image is obtained, and $G_0(r,r';t)$, represents the free diffusion Green function. In the absence of diffusion equation (a) collapses to the following form,

$$S(r,t)=S_0(r,0)\exp\left(\left(1-\cos(\alpha(r))^N\right)\left(\sum\theta(t-t_i)\right)\right)\exp\left(-\frac{1}{\xi}\left(P(r)t-\frac{1}{2}R(r'')t^2\right)\right)'$$

which to first order in the flip angle term is identical to accepted behavior of an oxygen sensing HP ^{3}He MRI signal intensity in the absence of diffusion (1). In an oxygen sensing experiment integral equation presented above is numerically solved for the desired parameters.

Method: Spontaneously breathing New Zealand rabbits were sedated and maintained using ketamine anesthesia. They were placed in a supine position inside a solenoid coil. Oxygen experiments were performed using a multislice 2D GE pulse sequence with the following imaging parameters: FOV 160 mm; slice thickness 7 mm; T_R/T_E 6.2 s/2.8 s; resolution 64×64; interscan time 6 s. A tidal volume of 60 ml consisting of 12 ml O_2 and 48 ml HP ^{3}He gas (30% polarization) was administered to the rabbits.

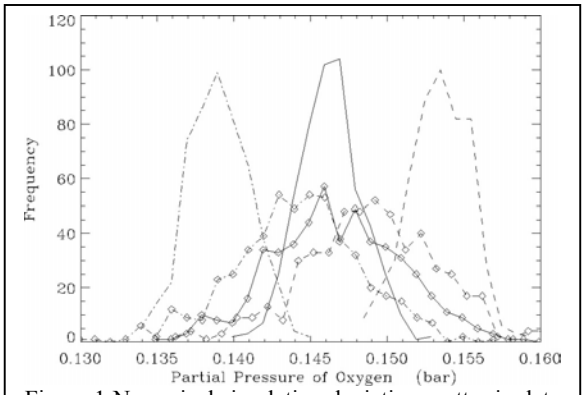

Figure 1 Numerical simulation depicting scatter in data for three oxygen values, 136 mbar- dashed dot line, 146 mbar, solid line, and 156 mbar, dashed line. The geometry, distribution of oxygen values, and conditions are as described for the rabbit experiment depicted in figure 2. The unlabeled lines represent the diffusion corrected results; the labeled lines the nondiffusion corrected, i.e., standard results. Note how the diffusion corrected results are significantly more accurate than the nondiffusion corrected results.

Results and Discussion: Figure 1 illustrates simulated results depicting the difference in accuracies between the traditional and diffusion corrected oxygen reconstructions. The diffusion corrected algorithm shows significantly better performance and is less susceptible to a regression to the norm effect. The scatter in the diffusion corrected data is due to the ill-posed nature of the inversion processes and the linearization of the diffusion kernel operator. Figure 2 depicts sample results with corresponding histograms. The mean values oxygen values were 105.1 ± 17.5 mbar. The average long time diffusion coefficient was 0.02 cm^2/sec (see insert)- calculated from series of striped images (2). Estimated error in these measurements based on simulations and necropsy phantom studies is less than ± 5 mbar.

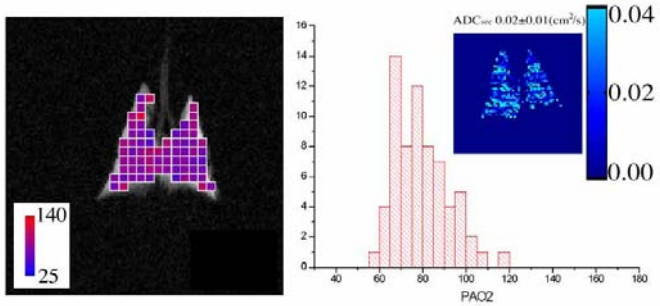

Figure 2 Partial pressure of oxygen as a function of position, for a sample coronal slice, on the left, histogram on right. Values in Torr. Long time diffusion coefficients used to construct the diffusion kernels were calculated from a time series of striped images (2) Long time diffusion coefficient used in calculation depicted in insert.

Conclusion: An integral representation of a HP MRI experiment can be used to reconstruct regional pulmonary oxygen tensions in the presence of a diffusing contrast agent. This approach corrects for a fundamental source of error present in previous oxygen reconstruction paradigms and gives significant improvements in measured oxygen tensions to a level approaching clinical interest.

References: 1. Fisher, MC, et.al., MRM, 52(4),766(2004), 2. Woods, JC, et.al., MRM 51, 1002(2004),