Accuracy and Precision of MR Blood Oximetry Based on the Long Paramagnetic Cylinder Approximation of Large Vessels

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Introduction

An accurate non-invasive method to measure hemoglobin oxygen saturation (HbO_2) of deep-lying vessels without catheterization would have many clinical applications. Quantitative MRI may be the only imaging modality that can address this difficult and important problem. Here, accuracy and precision of MR susceptometry-based oximetry [1 - 3] was investigated theoretically on the basis of an analytical expression for the arbitrarily oriented cylinder serving as a model approximating a vessel segment, as well as experimentally in phantoms and *in vivo* in the femoral artery and vein at 3T field strength. *In vivo*, consistency of HbO_2 measurement was evaluated at successive femoral vessel segments which differ in eccentricity and tilt but constant HbO_2.

Methods

The incremental field, ΔB, inside a cylinder tilted at an angle θ relative to B_0 is given as $\Delta B = \frac{1}{2}\,\Delta\chi B_o(\cos^2\theta - 1/3)$, where $\Delta\chi = \Delta\chi_{do}Hct\cdot(1 - HbO_2)$ is the susceptibility difference (in SI units) between the intravascular blood and that of its surrounding muscle tissue, $\Delta\chi_{do} = 4\pi\cdot(0.27$ ppm) [4] is the susceptibility difference in SI units between fully deoxygenated and fully oxygenated erythrocytes, HbO_2 represents the fraction of the oxygenated hemoglobin (*Hb*) and hematocrit (*Hct*) is the fractional volume of the packed erythrocytes in the whole blood. ΔB can be quantified from a phase difference, $\Delta\phi_{map} = \gamma\Delta B\cdot\Delta TE$, where ΔTE is the time duration between two successive gradient echoes. Potential sources of error: 1) If vein is approximated as an elliptic cylinder, the incremental field is $\Delta B_v = -e\Delta\chi B_o\sin^2\theta\cos 2\psi + \frac{1}{2}\Delta\chi B_o(\cos^2\theta - 1/3)$. Eccentricity is defined as $e=a/(a+b) - \frac{1}{2}$, where a and b are the major and minor axes of an ellipse, respectively, and ψ is the angle between major axis a and the component of B_o that lies in the cross-sectional plane of the elliptic cylinder. 2) The dipolar field outside the vein may affect the effective field outside its boundaries, e.g. artery due to its close proximity to the vein. The incremental field at a *point in the artery* is [5] $\Delta B_a = \frac{1}{2}\,\Delta\chi_a B_o(\cos^2\theta - 1/3) + \Delta\chi_v B_o(r_v/\rho)^2 \sin^2\theta\cos 2\psi$. $\Delta\chi_a$ and $\Delta\chi_v$ are the relative susceptibilities of the arterial and venous blood, ρ is the distance measured from the center of the vein to a point in the artery, and r_v is the "radius" of the vein. 3) The most significant source of error results from low-frequency modulations of static magnetic field produced by the interface between air and tissue or between adjacent tissue types. Details of an effective method to remove the slowly-varying part of the field inhomogeneity have been discussed previously [6].

In phantom studies, errors associated with vessel tilt, non-circularity and contamination in the arterial blood from the proximity of a vein phase was investigated with tubes of circular and elliptic cross-section containing 1 mM Gd-doped water. Tilt angles θ from 0° to about 30° and eccentricities e ranging from 0.0 to 0.11 were evaluated (values found to be typical of those of the femoral and popliteal veins). For non-circular tubes the cylindrical container was also rotated to vary ψ. For *in vivo* reproducibility evaluation, the experiment conducted on each of two healthy subjects (33 yrs-old male and 23 yrs-old female) was repeated on three different days and measurements taken at three locations along the femoral vessels. The data acquisition during a session took less than two minutes once the desired axial slices were identified; hence, possible temporal variation of HbO_2 could be assumed to be negligible. On the other hand, intra-individual variations between different scan sessions could be expected [7]. All images were acquired with a multi-echo RF-spoiled GRE sequence programmed with SequenceTree™ [8]. The pulse sequence included fat suppression and first-moment nulling along the slice (i.e. blood flow) direction. All phantom and *in vivo* experiments were performed on a 3T Siemens Trio scanner using an eight-channel knee array coil (Invivo Inc., Pewaukee, WI) with the following parameters to: voxel size = 1 x 1 x 5 mm^3, FOV = 128x128 mm^2, BW = 488 Hz/pixel, TE1 = 3.75 ms, inter-echo spacing = 2.32 ms, TR = 39.1 ms and flip angle = 13°.

Results and Discussion

Due to space limitations phantom data are not shown but the average standard error and coefficient of variation of measurements were found to be less than 2% with tilt correction, suggesting that high accuracy and reproducibility can be achieved even when ignoring non-circularity for tilt angles up to about 30°. Magnitude and phase difference images acquired at three axial locations during the same scan session are shown in **Figure 1 (a – f)**. In all three slices the femoral artery is circular whereas the vein's eccentricity is a function of the slice location. Pulsatile flow artifacts were found to be minimal and did not interfere with the phase measurements. For each scan session $\%HbO_2$ values from the three distinct slices separated by about 20 mm are listed, along with eccentricity and local vessel tilt angles, in **Table 1**. Only the data from one subject is shown but the coefficient of variation was less than 5% between the values that were measured during the same scan session for each subject.

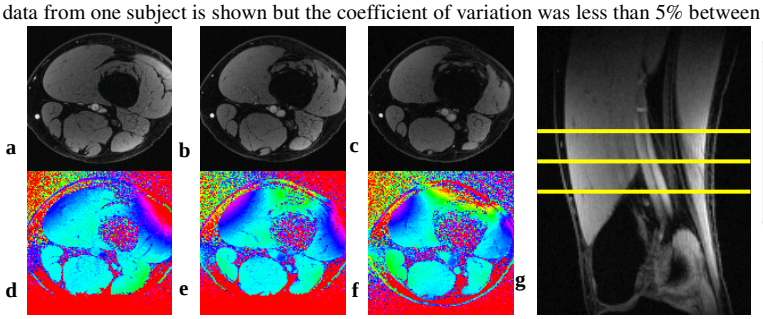

Figure 1 Corresponding magnitude (a – c) and phase difference (d – f) images of three axial slices. The locations of the corresponding axial locations are shown in the oblique sagittal image (g). The window level of the phase difference images was set at -1.7 to +1.7 rad to enhance the contrast between the femoral artery (circular in all three slices) and vein.

Subject 1	Session1				Session 2				Session 3			
Slice	1	2	3	Avg (Std)	1	2	3	Avg (Std)	1	2	3	Avg (Std)
e	0.12	0.09	0.11		0.06	0.07	0.17		0.21	0.15	0.05	
θ(deg)	21	23	21		21	26	23		13	20	20	
$\%S_aO_2$	98	97	96	97 (1)	97	100	96	98 (2)	94	96	94	95 (1)
$\%S_vO_2$	69	69	68	69 (1)	69	72	67	69 (3)	69	66	67	67 (2)

Table 1 Quantified arterial and venous saturation ($\%S_aO_2$ and $\%S_vO_2$, respectively) in three different femoral vessel segments and imaging sessions for one of the volunteers. Derived oxygen saturation levels were corrected for tilt angle. Similar performance was achieved in the second volunteer (data not shown due to space limitations).

Conclusion

The data suggest that HbO_2 can be measured reliably *in vivo* in large vessels of the peripheral circulation on the basis of the paramagnetic cylinder approximation of the incremental field. Reproducibility of *in vivo* HbO_2 quantification was on the order of 5% in the femoral vessels and the data indicate that non-circularity, although corrigible, can be ignored even at 30° with tilt correction alone. Finally, the MR oximetry-derived $\%HbO_2$ values are in good agreement with those determined from blood sampled directly from the femoral vein [8].

References: [1] Weisskoff et al., MRM 1992; 24(2):375-383. [2]Haacke et al. Human Brain Mapping 5:341-346 (1997); [3] Fernandez-Seara et al. MRM 55:967–973 (2006); [4] Spees et al MRM 45: 533 – 542 (2001); [5] Schenck JF, Med Phys 1996; 23(6):815-850; [6] Langham et al., MRM (In press) [7] Keys A, Am J Physiol 1938; 124(1):13-21; [8] Magland et al. Seattle, WA. Proc. ISMRM.2006, p 578.

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