Blood Relaxation Properties at 3T -- Effects of Blood Oxygen Saturation

T. Lee[1], J. A. Stainsby[1], J. Hong[1], E. Han[2], J. Brittain[2], G. A. Wright[1]

[1]Sunnybrook & Women's College Health Sciences Centre, Toronto, Ontario, Canada, [2]GE Medical Systems, Menlo Park, California, United States

Abstract T2 values of blood vary characteristically with the amount of blood oxygenation ($\%O_2$) due to paramagnetic deoxyhemoglobin. This relationship has been well characterized at 1.5T as $1/T2=1/T2_o + K(1-\%O_2/100)^2$. At 3T, K increases and $T2_o$ decreases, resulting in lower blood T2s and greater variation with $\%O_2$ compared to 1.5T. These changes, together with increased SNR at 3T can yield more accurate $\%O_2$ measurements *in vivo*. The feasibility of using a 3T system for *in vivo* oximetry has been demonstrated through scans of the femoral vein in healthy subjects.

Introduction The MR signal of blood has been studied as a non-invasive method of diagnosis for diseases such as cardiac shunts and mesenteric ischemia, based on signal difference resulting from blood oxygen saturation levels. The T2 of blood ($T2_b$) is affected by the percent of hemoglobin (Hb) saturated with oxygen ($\%O_2$). Unbound hemoglobin is paramagnetic, causing local field inhomogeneities, which lower the T2 of deoxygenated blood. Previous studies [1] have shown the relationship between T2 and $\%O_2$ is well described by Eq. (1). Using the Luz-Meiboom approximation to describe the behaviour, we expect a quadratic dependence of

$$\frac{1}{T2_b} = \frac{1}{T2_o} + K\left(1 - \frac{\%O_2}{100}\right)^2 \qquad (1)$$

K on field strength, all else being equal. K is also sensitive to the time between refocusing pulses, t_{180}. Currently, *in vitro* calibration is used to determine $T2_o$ (T2 at 100% O_2) and K. These parameters have been well characterized at 1.5T. Measurements of blood T2s at higher field strengths have been presented by several researchers [2, 3], although detailed characterization as a function of oxygen saturation is limited. The studies by Thulborn, *et. al.* (1982) show that the constant, $T2_o$, varies with field strength, decreasing at higher field strengths [2]. Other effects of higher field strength on the blood signal include greater sensitivity to $\%O_2$. This study sought to perform more in-depth analysis to calibrate and determine the quantitative differences in MR signal dependence on $\%O_2$ from 1.5T to 3T.

Methods & Materials *In vitro* calibration was used to demonstrate the relationship between blood $\%O_2$ and T2. Human whole blood was drawn by venipuncture from 3 volunteers with informed consent, and mixed with anticoagulant (heparin). Various blood oxygen saturations (40-90%) were obtained by agitating blood with nitrogen gas or air (to lower or raise $\%O_2$, respectively), and sealed in syringes. Oxygen saturations used in the calibration were measured using an oximeter (Oxicom 2100, Waters Instruments) before and after MR scans. Syringes containing the blood samples were placed in a water bath (~37ºC), doped with manganese chloride to reduce the signal of the water. Scans were performed using a head coil on GE 1.5T Twinspeed and 3T VH/i scanners. A magnetization-prepared spiral sequence [4] was used on both systems to measure T2s with the following parameters: TR=2s, 20cm FOV, 1.1mm in-plane resolution, 2 averages and 6 TEs. Three refocusing intervals were considered (t_{180}=6, 12 and 24ms). The TEs used were 0, 24, 48, 72, 96 and 144ms at t_{180} = 6ms, and 0, 48, 96, 144, 192 and 240ms at t_{180} = 12 and 24ms. *In vivo* scans were also performed on the upper right thigh of the human volunteers, using an extremity coil on both systems. T1s were measured using a Look-Locker sequence where recovery following inversion is sampled every 100 or 150 ms with an excitation flip angle of 10º [5]. Both T1s and T2s were determined with weighted least squares fitting to signal behaviour.

Results The *in vitro* calibrations at 1.5T and 3T yielded the K values shown in Table 1 (mean ± std dev across subjects). K increased from 1.5T to 3T by a factor of 3.46 ± 0.15 for t_{180} = 6ms, 3.48 ± 0.36 for t_{180} = 12ms, and 3.42 ± 0.83 for t_{180} = 24ms. Average $T2_o$ values across refocusing intervals were 239.8 ± 11.7ms at 1.5T, and 165.4 ± 3.2ms at 3T. Fig. 1 shows the resulting changes in the T2-$\%O_2$ curve for t_{180} = 12ms, at 3 T versus 1.5T. T1 values were similar across blood samples at different $\%O_2$; average T1s at 3T showed an increase by a factor of 1.05 compared to those at 1.5T.

Table 1. K values at 1.5T and 3T at each t_{180}

T_{180}	1.5T	3T
6 ms	12.43 ± 2.34	42.90 ± 7.72
12 ms	22.23 ± 5.13	79.65 ± 18.81
24 ms	40.03 ± 7.28	135.47 ± 30.21

Using the calibration parameters for each subject, estimates of $\%O_2$ in the femoral vein of two subjects were 70.7 ± 3.4 $\%O_2$ at 1.5T and 70.9 ± 3.4 $\%O_2$ at 3T. No systematic variation was noted due to either field strength or t_{180}. The SNR *in vivo* of muscle signal at TE=0 was found to be 56.1 at 1.5T, and 75.6 at 3T.

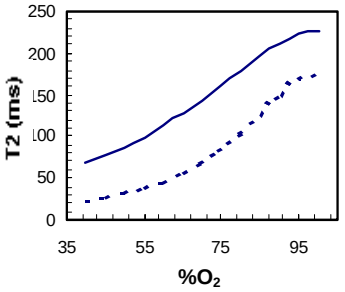

Fig. 1. T2-O_2 curve (t180 = 12ms) at 3T (--) (K = 100.0, T2o = 175.7ms) has lower T2 values than the curve at 1.5T (—) (K = 28.3, T2o = 225.8ms).

Discussion The drop in average $T2_o$ from 239.8ms at 1.5T to 165.4ms at 3T coincides with that predicted using data from the studies by Thulborn *et. al.* The slight increase in T1 and T1 insensitivity to $\%O_2$ also follows expectations. There is no significant effect of t_{180} on the ratio of K at 3T versus 1.5T; over all refocusing intervals, K increased from 1.5T to 3T by an average factor of 3.45 ± 0.03. This is lower than the predicted factor of 4, and is likely due to an increased contribution to signal decay at 3T of diffusional relaxation within the red blood cells relative to effects of water exchange between red blood cells and plasma [2].

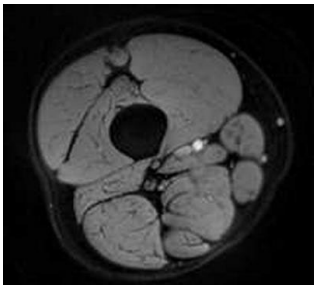

Fig. 2. *In vivo* scan of upper right thigh at 3T (t_{180} = 12 ms)

These results have a wide range of applications including optimizing artery-vein contrast for MRA at high field and determining the effect of field on the accuracy of $\%O_2$ measures by MR oximetry. Assuming the use of "optimal" TEs and constant error in estimating K and $T2_o$, the error in $\%O_2$ measurements made on an MR scanner is related to $(1/K*(SNR)^2)^{1/2}$ (2) at high $\%O_2$.[6]. There was an increase in SNR at 3T versus 1.5T by a factor of approximately 1.35 in our *in vivo* studies of the thigh using similar local birdcage coils. Comparing the expected relative error in $\%O_2$ measurement at 3T versus 1.5T (by using the ratio of K values and SNR), at high O_2, the error should be smaller by a factor of 2.5. That is, there should be an increase in sensitivity for blood $\%O_2$ measurements at 3T.

The feasibility of oximetry at 3T was demonstrated by comparing the *in vitro* calibrations with *in vivo* scans of the femoral vein in two subjects (Fig. 2). Peripheral venous blood in humans at rest is saturated to approximately 70% O_2, in agreement with blood saturations in the scanned femoral veins. This, combined with the higher levels of SNR and increased sensitivity at 3T, suggests that the use of 3T for oximetry is indeed feasible and perhaps advantageous.

References

[1] Wright, G.A., et. al., JMRI 1, 275, 1991.
[2] Thulborn, K. et. al., Biophys. Acta, 714, 265, 1982.
[3] Lee, S., et. al. MRM 42, 919, 1999.
[4] Brittain, J, et al., MRM, 33, 689, 1995.
[5] Wright , G.A., et al., Proc 4th SMR, 1474, 1996.
[6] Wright, G.A., et al., Proc. SMR 3rd Annual Meeting, 1995, p. 1052.