129Xe Chemical Shift in Human Blood and Pulmonary Blood Oxygenation Measurement in Humans Using Hyperpolarized 129Xe NMR

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INTRODUCTION

Knowledge of tissue oxygenation can provide valuable insight into the pathophysiology of a spectrum of diseases. For example, in the discrimination of the penumbra following stroke (1) or identification of ischemia following myocardial infarction (2). Furthermore, hypoxia limits the efficacy of radiotherapy in the treatment of tumors (3). In lung diseases such as asthma and chronic obstructive pulmonary disease, hypoxia can influence the lifetime and the functionality of neutrophils that are associated with inflammation in the lungs (4). Surface blood oxygenation can be measured with an infrared finger probe, but this approach is depth-limited. The accepted gold standard method of determining deep tissue oxygenation is with polarographic electrodes, as pioneered in the late 1950s (5). This invasive method, however, samples only a small amount of tissue and is able to provide assessment of oxygenation for only limited tissue volumes. Owing to this limitation, oxygenation is usually estimated using surrogate techniques, such as the monitoring of mixed venous oxygenation, heart rate, blood pressure, and oxygen saturation at the jugular bulb. However, these estimates can prove inaccurate as distal tissue oxygenation is not necessarily well represented by the more proximal measurements, and vice versa (6).

MR perfusion imaging can be used to measure blood delivery to a tissue of interest, however, oxygen supply and demand can be independent of one another, e.g., revascularization of fibrotic tissue provides blood flow out of proportion to metabolic demand. Likewise, tissues with low levels of perfusion have an adequate oxygen supply while at rest, but an inadequate oxygen supply during periods of increased metabolic demand. Tissue perfusion alone, therefore, does not completely describe the underlying physiology of gas exchange (7) and thus direct, noninvasive measurement of blood oxygenation may be of interest in many clinical settings, as well as being of interest from a physiological perspective.

Several techniques have been developed to quantify regional oxygenation using MRI. A promising method is the use of blood oxygen level dependent (BOLD) MRI (8,9), where images that indicate impaired oxygen uptake can be generated, for example by cycling oxygen and carbogen levels (10). However, this technique provides only relative estimates of tissue oxygen partial pressure (11) because there are endogenous variations in magnetization relaxation parameters that can confound these measurements and thus make absolute oxygen concentration detection difficult. Moreover, BOLD signal response is governed by a mixture of T2 dephasing and diffusion due to microscopic susceptibility gradients, and is therefore very much
dependent upon the means of measurement, for example the choice of pulse sequence and field strength. Techniques that introduce exogenous tracers for MR oximetry, such as Overhauser-enhanced MRI of unpaired radicals (12,13) and 19F MRI (14), are promising for measurement of blood oxygenation; however, these tracers have yet to be applied in humans. In the lungs, the $T_1$ of inhaled hyperpolarized 3He gas in the airspaces (15,16) has been used to quantify regional alveolar oxygen concentration, but regional ventilation-perfusion mismatch and impaired gas transfer across the alveolar capillary interstitial barrier means this does not necessarily reflect the capillary blood oxygenation.

Xenon has been in routine clinical use for many years as a tracer of blood perfusion (17), and the physiological effects of xenon gas administration are well known and characterized (18,19). Hyperpolarized $^{129}$Xe MR has been shown in numerous studies to be a useful noninvasive probe of lung structure (20–22) and function (23–28). Physiologically important information about gas exchange can be derived from the xenon chemical environment: $^{129}$Xe nuclei exhibit a marked change in resonance frequency when dissolved in different biological fluids and tissues (29,30).

Three distinct NMR peaks are observed in vivo when $^{129}$Xe gas is inhaled into the lungs. The largest peak originates from $^{129}$Xe gas in the alveolar airspaces and the two other peaks, centered approximately 200 ppm away from the gas peak, have been attributed to $^{129}$Xe dissolved in lung parenchymal tissue/blood plasma (TP) and in red blood cells (RBCs) (31,32). Physiologically important information about gas exchange can be derived from the signal amplitudes and exchange kinetics of these distinct $^{129}$Xe resonances (20,33). Furthermore, the $^{129}$Xe resonance frequency in RBCs was shown previously by Wolber et al. to be sensitive to blood oxygen saturation, $S_{O_2}$ (34). Mechanisms underpinning the $^{129}$Xe chemical shift dependence on blood oxygenation are not yet fully understood, and the dependence is currently thought to be due to the conformational changes of hemoglobin as it binds and releases oxygen molecules (34).

In the study reported here, spectra of hyperpolarized $^{129}$Xe dissolved in samples of human blood were obtained to validate the previous in vitro work conducted at $B_0 = 1.5$ T by Wolber et al. (34). In so doing, we determine the relationship between the $^{129}$Xe-RBC resonance frequency and blood oxygenation, over the full oxygenation range at the two clinically relevant field strengths of 1.5 T and 3 T. Using this relationship, measurements of RBC $S_{O_2}$ in vivo in healthy human lungs were then derived using whole lung NMR spectroscopy measurements of lung oxygen desaturation during breath hold apnea. A technique for the noninvasive dynamic detection of RBC $S_{O_2}$ in vivo using hyperpolarized $^{129}$Xe is hereby demonstrated.

**METHODS**

**Hyperpolarized $^{129}$Xe Gas Preparation**

For in vitro and in vivo studies, a gas mixture of 3 % isotopically enriched xenon (86 % $^{129}$Xe), 10 % nitrogen and 87 % helium was flowed through a glass cell (volume 500 cm$^3$; temperature 373 K; total gas pressure 2 bars) on a home-built $^{129}$Xe spin-exchange optical pumping polarizer (35) at a flow rate of 300 sccm (standard cubic centimeters per minute). Upon exiting the cell, the hyperpolarized $^{129}$Xe was cryogenically separated in a liquid nitrogen-cooled distillator and collected in its frozen state over a time of ~20 min (xenon volume ~ 200 mL) for in vitro samples and ~60 min (xenon volume 600 mL) for in vivo samples.

**Blood Sample Preparation and Analysis**

Whole blood samples were withdrawn by a clinician from three self-consenting healthy male volunteers (two Caucasian, ages 23 and 27; one Asian, age 35) by venipuncture and transferred into lithium heparin vacuum containers approximately 2–3 h before the start of the NMR experiments. All blood samples were allowed to equilibrate to a temperature of 20 ± 2 °C (the temperature at which the scanner room is maintained). Before conducting the NMR experiments, the xenon was first dissolved in the blood. To ensure effective mixing, the xenon and blood were passed through an exchange module (25,36) (Superphobic MicroModule 0.5 X 1 G680 Contactor, Membrana, USA), which provided an exchange surface area of 100 cm$^2$. The exchange module was also used to control the oxygenation of the blood samples before they were mixed with xenon.

A clinical blood gas analyzer (Radiometer, ABL80, UK) was used to analyze each blood sample and determine the following physiological parameters: $S_{O_2}$ (fraction of hemoglobin molecules that are fully oxygenated), $pO_2$ (partial pressure of $O_2$ in whole blood), $pCO_2$ (partial pressure of $CO_2$ in whole blood), HCT (fraction of red blood cells within whole blood) and pH. Immediately after acquiring NMR spectra as described below, approximately 0.1 mL of blood was withdrawn directly from the NMR sample syringe and taken to the blood gas analyzer for analysis. Full experimental details of the xenon/oxygen dissolution method and RBC $S_{O_2}$ measurement technique have been described previously in a study reporting the $T_1$ relaxation behavior of $^{129}$Xe in blood (37).

**In Vitro NMR Spectroscopy**

A custom-built, eight-turn solenoid radiofrequency (RF) coil of 15 mm inner diameter was used for transmission/reception at the frequency of $^{129}$Xe dissolved in RBCs and plasma. The gas exchange membrane was positioned near the sensitive volume of the NMR coil to reduce the xenon-blood transit time to the coil and, thus minimizing $T_1$ relaxation. To calibrate the excitation flip angle, a small sample of the hyperpolarized $^{129}$Xe-blood mixture was placed within the active coil volume. Hard pulses of duration 500 μs were used to acquire spectra, and from these, the $^{129}$Xe-RBC signal decrease was fitted to $(\cos z)^n$, where $z$ is the flip angle to be calibrated and $n$ is the RF pulse number (37). The excitation flip angles used were calculated to be in the range 10–15°.

Spectra were acquired on both 1.5 T (GE, HDx, USA) and 3 T (Philips, Achieva, Netherlands) MR scanners. At both $B_0$ field strengths, 20 pulse-acquire measurements were made with 512 sample points, a receiver bandwidth of 2.5 kHz and a repetition time (TR) of 500 ms. Free induction decay data were imported into MATLAB...
(R2011b, MathWorks, USA) for spectral analysis. Zero-order phase corrections (on the $^{129}$Xe-RBC resonance), followed by first-order phase corrections (to phase the $^{129}$Xe-plasma resonance, using the $^{129}$Xe-RBC resonance as the zero frequency point) were performed on the averaged raw data, and absorption spectra, Re$L(\delta)$, were fitted in the chemical shift ($\delta$) domain to a linear combination of two Lorentzians

$$\text{Re}[L(\delta)] = A_r \frac{1}{(\delta - \delta_r)^2 + (\frac{1}{2} \Gamma_r)^2} + B_p \frac{1}{(\delta - \delta_p)^2 + (\frac{1}{2} \Gamma_p)^2}$$

where $A_r$, $B_p$ are the amplitudes of the RBC and plasma $^{129}$Xe resonances; $\delta_r$, $\delta_p$ are the maxima of the $^{129}$Xe-RBC and $^{129}$Xe-plasma resonances; and $\Gamma_r$, $\Gamma_p$ are the full width half maxima of the two respective peaks. Figure 1a shows an example of a fit to a typical in vitro 1.5 T $^{129}$Xe-blood spectrum.

**RESULTS**

**In Vitro Spectroscopy**

The relationship between the chemical shift of $^{129}$Xe and $\text{SO}_2$ of blood was calibrated in a controlled in vitro environment. The resonance frequency of $^{129}$Xe dissolved in plasma was used as a reference as it was found not to

![FIG. 1. a: Single-shot $^{129}$Xe-blood spectrum at 1.5 T. The measured absorption spectrum (blue line) was fitted to a linear combination of two Lorentzians (Equation [1], solid black line) to determine peak positions. b: Example $^{129}$Xe-blood spectra acquired at 3 T. With increasing oxygenation, the peak associated with $^{129}$Xe dissolved in RBCs is seen to shift measurably toward a higher resonance frequency.](image)

$^{129}$Xe-sequence with TRs of 100 ms (performed on the 28-year-old volunteer) and 800 ms (performed on both volunteers) were used, and the effective flip angle excitation on the $^{129}$Xe gas peak was determined to be ~2.5° (see Figure 2) for a 90° excitation of the dissolved phase $^{129}$Xe. For the TR = 800 ms breath hold experiments, 2048 samples were acquired at a bandwidth of 3 kHz, corresponding to a spectral resolution of 1.46 Hz (0.04 ppm). To achieve a TR of 100 ms at 3 kHz bandwidth, the number of samples was decreased to 128, reducing the spectral resolution to ~0.7 ppm. The spectra were phased and fitted to a double Lorentzian using the same method outlined in the previous section.

**In Vivo NMR Spectroscopy**

Whole-lung spectroscopy experiments were then performed at 3 T (Philips, Achieva, Netherlands) on two healthy male Caucasian volunteers (24 and 28 years old). All experiments were performed during breath hold apnea lasting 35–40 s. A 360 μs duration 90° hard pulse centered ~200 ppm downfield from the gaseous $^{129}$Xe resonance was used for excitation of the $^{129}$Xe dissolved in RBCs ($^{129}$Xe-RBC) and parenchymal tissue/blood plasma ($^{129}$Xe-TP) using a flexible quadrature transmit/receive RF coil tuned to 35.35 MHz (Clinical MR Solutions, USA). See Figure 2 for relative signal intensities corresponding to $^{129}$Xe-gas, $^{129}$Xe-RBC, and $^{129}$Xe-TP peaks in the lungs measured at 3 T.

Two separate pulse-acquire sequences with TRs of 100 ms (performed on the 28-year-old volunteer) and 800 ms (performed on both volunteers) were used, and the effective flip angle excitation on the $^{129}$Xe gas peak was determined to be ~2.5° (see Figure 2) for a 90° excitation of the dissolved phase $^{129}$Xe. For the TR = 800 ms breath hold experiments, 2048 samples were acquired at a bandwidth

![FIG. 2. Magnitude NMR spectrum of $^{129}$Xe acquired from the human lungs after a hard pulse excitation centered ~220 ppm away from the gas peak (depicted here as a large peak outlined in blue). Spectral peaks associated with parenchymal tissue/blood plasma (TP) and RBCs are an order of magnitude smaller and have broader linewidths (shorter $T_2^*$s) than the $^{129}$Xe-gas peak. Inset: $^{129}$Xe-gas resonance flip angle calibration for a hard pulse centered on the $^{129}$Xe-dissolved resonance.](image)
were fitted to a single empirical equation. Observations of Wolber et al. (34). 1.5 T and 3 T data fully oxygenated state. To approximately 25.5 ppm when the blood was in a completely deoxygenated state, the 129Xe peak separation increased from approximately 20.4 ppm, as a function of blood oxygenation in vitro. Increases RBC sO2 caused an increase in the resonance frequency of 129Xe dissolved in RBCs. The RBC-plasma peak separation increased from approximately 20.4 ppm, when the blood was in a completely deoxygenated state, to approximately 25.5 ppm when the blood was in a fully oxygenated state.

This observed chemical shift versus sO2 behavior was consistent at B0 magnetic field strengths of both 1.5 T and 3 T. To quantify the change in RBC-plasma peak separation, δ, as a function of sO2, the 129Xe-RBC and 129Xe-plasma peak locations, δ0 and δp, were determined by fitting the spectra to Equation [1]. Blood gas analysis was performed immediately after acquiring the NMR spectra to quantify the RBC sO2. The extracted peak separations are plotted as a function of sO2 in Figure 3, where it can be observed that the chemical shift of 129Xe in RBCs appears to be nonlinearly dependent on the measured sO2, which is consistent with the previous observations of Wolber et al. (34). 1.5 T and 3 T data were fitted to a single empirical equation

\[ \delta(sO_2) = \alpha \exp(\beta sO_2) + \delta_0 \]  

where, \( \alpha \) and \( \beta \) are empirical constants and \( \delta_0 \) is the RBC-plasma peak separation in fully deoxygenated blood (see Figure 3). The similarity in the measured 129Xe chemical shift values at 1.5 T and 3 T shown in Figure 3, therefore, suggest that the relationship between the 129Xe chemical shift and RBC sO2 is independent of the static magnetic field strength.

In Vivo Detection of Chemical Shift

To determine whether a similar shift in the resonance frequency of 129Xe in RBCs could be detected in vivo as a potential noninvasive probe for pulmonary blood oxygenation, a series of NMR spectra were acquired during breath hold apnea, which provides a simple model for blood oxygenation change. Figure 4 shows a waterfall plot of representative dissolved 129Xe spectra acquired as a function of time during one such experiment. The SNR of the spectrum at the beginning of the acquisition series was measured to be ~50, dropping to ~7 after 35 s of breath hold apnea. For these typical SNRs, it was possible to perform good Lorentzian fits on the data, enabling accurate peak assignment. The 129Xe resonance located at 0 ppm corresponds to the 129Xe-TP resonance and the resonance located downfield is from 129Xe dissolved in RBCs. For all datasets, an initial rapid drop in the 129Xe-RBC signal was observed, which we believe to be a result of RF-induced depolarization of the postcapillary signal from the 129Xe in the pulmonary veins for TRs shorter than (TR = 100 ms), or of the order of (TR = 800 ms), the RBC capillary transit time of ~750 ms (38).

For TR = 800 ms, the 129Xe-TP signal exhibited a monotonic decay over the breath hold time (Figure 5a). It was assumed that this signal decay follows the T1 of the 129Xe gas (dominated by dipolar coupling of the nuclear spin with paramagnetic oxygen in the lungs), which acts as a longitudinal magnetization reservoir, replenishing the 129Xe-dissolved magnetization in between RF pulses. With this assumption, a T1 fit (corrected for 129Xe-gas signal decay due to off-resonance RF excitations of 2.5° on the gas resonance, which result from the side bands of the hard RF pulses used) was performed on the decaying 129Xe-TP signal, resulting in an approximate 129Xe-gas T1 value of 18.8 s, which is in good agreement with previously measured 129Xe-gas T1 values of ~20 s (39). Although the 129Xe-RBC signal was observed to decay with the same overall rate as the 129Xe-TP signal, it did not decay monotonically; instead, the signal was observed to modulate periodically over the breath hold time (see Figure 5a).

To view this oscillatory decay behavior more clearly, the 129Xe-RBC signal was normalized to the T1 decay of the 129Xe-gas polarization reservoir (129Xe-RBC data were divided pointwise by the fitted T1 curve – see Figure 5b). For both volunteers, the 129Xe-RBC peak-to-peak signal variation varied as a function of breath oxygenation in vitro.

![Figure 3](Image 63x547 to 298x735)

**FIG. 3.** The 129Xe-RBC chemical shift plotted against the measured blood oxygen saturation, sO2, with the 129Xe-plasma peak as a 0 ppm reference peak. Data from the two field strengths are denoted by black open circles (1.5 T) and blue open squares (3 T). The black line is a fit to both the 1.5 T and 3 T data using Equation [2]. The grey triangle represents blood equilibrated with carbon monoxide (simulating the fully oxygenated conformation of hemoglobin).

![Figure 4](Image 315x154 to 550x261)

**FIG. 4.** Waterfall plot of a typical time series of in vivo 129Xe-dissolved spectra. The resonance at 0 ppm is from 129Xe dissolved in parenchymal parenchymal tissue/blood plasma (TP) and the resonance downfield is from 129Xe dissolved in RBCs. Each spectrum was acquired using a flip angle of 90° and a TR of 800 ms. The decay in both compartments follows approximately the T1 relaxation (due to the presence of oxygen in the lungs and RF excitation) of the 129Xe-gas, the magnetization reservoir that acts to replenish the 129Xe-dissolved signal between RF pulses.
The interval (i.e. modulation period) was measured to be 4–8 s (0.125–0.25 Hz).

Whereas the $^{129}$Xe-TP resonance was observed to remain fixed in position over the 35 s breath hold, the $^{129}$Xe-RBC resonance chemical shift was observed to decrease by approximately 1 ppm. The first observation of in vivo $^{129}$Xe-RBC resonance shifts with lung oxygenation was first reported in our preliminary work (40), and these findings have been recently confirmed by Kaushik et al. (41), who observed a decrease in the $^{129}$Xe-gas and $^{129}$Xe-plasma resonances were observed when the sample was heated from 20 °C to 37 °C. Albert et al. (42) previously measured a chemical shift difference of ~20 ppm between the $^{129}$Xe-RBC and $^{129}$Xe-plasma resonances in deoxygenated blood at a temperature of 8 °C, which is in good agreement with the chemical difference of 20.4 ppm we have observed at 20 °C. We therefore assume the $^{129}$Xe-RBC resonance is independent of temperature over the range 20 °C to 37 °C. For $TR = 100$ ms, both the $^{129}$Xe-TP and $^{129}$Xe-RBC signals exhibited oscillations with an approximately constant peak-to-peak signal interval (modulation period) of ~1 s over the breath hold duration.

In these calculations, it was assumed that the temperature difference in vitro (20 °C) and in vivo (37 °C) has a negligible effect on the $^{129}$Xe-RBC and $^{129}$Xe-TP resonances, i.e. the calibration curve in Figure 3 is valid for converting the in vivo $^{129}$Xe-RBC chemical shift to pulmonary $sO_2$. To test the validity of this assumption, NMR spectra of $^{129}$Xe dissolved in plasma were acquired at 20 °C and 37 °C with a $^{129}$Xe gas compartment as a 0 ppm reference. No differences in the $^{129}$Xe-gas and $^{129}$Xe-plasma resonances were observed when the sample was heated from 20 °C to 37 °C. Albert et al. (42) previously measured a chemical shift difference of ~20 ppm between the $^{129}$Xe-RBC and $^{129}$Xe-plasma resonances in deoxygenated blood at a temperature of 8 °C, which is in good agreement with the chemical difference of 20.4 ppm we have observed at 20 °C. We therefore assume the $^{129}$Xe-RBC resonance is independent of temperature over the range 20 °C to 37 °C. For $TR = 100$ ms, both the $^{129}$Xe-TP and $^{129}$Xe-RBC signals exhibited oscillations with an approximately constant peak-to-peak signal interval (modulation period) of ~1 s over the breath hold duration.
DISCUSSION

In Vitro Spectroscopy

The observation of a nonlinear dependence of $^{129}$Xe-RBC chemical shift on $sO_2$ has been reported in previous work by Wolber et al. (34), where it was concluded that bulk magnetic susceptibility differences between oxyhemoglobin (diamagnetic) and deoxyhemoglobin (paramagnetic) are not responsible for the $\sim 5$ ppm $^{129}$Xe-RBC chemical shift difference between oxygenated and deoxygenated blood. Instead, the authors hypothesized that the observed nonlinear relationship between blood oxygenation and chemical shift is the result of an oxygen-dependent hemoglobin affinity for xenon. To date, a total of 12 xenon binding sites have been located in deoxyhemoglobin using X-ray crystallography (43). To our knowledge, the binding sites of xenon in oxyhemoglobin have not been reported, making a quantitative description of the chemical shift mechanisms responsible for the observed nonlinear change in chemical shift with blood of oxygenation difficult at this time. Nevertheless, herein, we draw on the insights of Wolber et al. (34) to further understand the mechanisms governing the observed nonlinear relationship between the $^{129}$Xe-RBC chemical shift and blood oxygenation.

The resonance frequency of $^{129}$Xe in a solvent solution is determined by the local magnetic field experienced at the nucleus, which is mediated by the screening (or shielding) constant, $r$: 

$$\omega_{obs} = \gamma B_{eff}$$

$$B_{eff} = (1 - \sigma) B_0$$

$$\omega_{obs} = \gamma (1 - \sigma) B_0$$

where $\omega_{obs}$ is the observed resonance frequency, $\gamma$ is the gyromagnetic ratio, $B_0$ is the applied static magnetic field and $B_{eff}$ is the effective field at the nucleus. Following the pioneering work of Buckingham et al. (44), it is known that the screening constant, $\sigma$, of a nucleus can be expressed as the sum of the screening constant of the individual nucleus, $\sigma^0$, and a term arising due to the presence of the solvent medium, $\sigma_m$, thus 

$$\sigma = \sigma^0 + \sigma_m$$

$$\sigma_m = \sigma_a + \sigma_e + \sigma_w + \sigma_b$$

where $\sigma_a$ is a contribution from molecular anisotropy effects, $\sigma_e$ is the polar effect caused by an electric field, $\sigma_w$ is due to the van der Waals forces within the solute and solvent and $\sigma_b$ indicates the shielding arising from bulk magnetic susceptibility effects within the solvent, which we neglect as a significant contributor to $^{129}$Xe chemical shift changes with blood oxygenation from the conclusions drawn by Wolber et al. (34). For $^{129}$Xe dissolved in solution at 20 °C and at body temperature (37 °C), the anisotropic and electric field terms are zero (45), leaving only the van der Waals shielding term.

Stephen (46) has demonstrated that the van der Waals deshielding experienced by a nucleus within a solvent can be expressed as $-\sigma_w = BF^2$, where $F^2$ is the mean square electric field brought about by fluctuations among electrons located on the neighboring solvent molecules and $B$ is the “shielding hyperpolarizability” (47), which is significant for $^{129}$Xe, whose nucleus is surrounded by a large, easily-deformed electron cloud. As a result of this high shielding hyperpolarizability, the chemical shift of dissolved $^{129}$Xe in a solvent is very sensitive to small differences in the dispersion fields acting within liquid solvents. The most commonly used approach to correlate solvent-induced $^{129}$Xe chemical shifts with $F^2$ is to use a continuum model to describe the solvent (48,49). Specifically, $F^2$ is proportional to the square of the Bayliss-McRae function, $g(n)$ (49), i.e., 

$$F^2 \propto [g(n)]^2 = \left(\frac{n^2 - 1}{2n^2 + 1}\right)^2$$

where $n$ is the index of refraction of the solvent. The refractive indices of oxyhemoglobin and deoxyhemoglobin have been recently measured by Zhernovaya et al. (50), wherein no significant difference between the refractive index of deoxygenated and oxygenated hemoglobin (within the visible range of the spectrum) was reported. We therefore conclude that the observed $^{129}$Xe-RBC chemical shift change with blood oxygenation cannot be predicted using whole blood refractive index measurements.

Experiments using M"ossbauer spectroscopy (51) suggest that the electron cloud of hemoglobin is drawn toward the highly electronegative oxygen molecule in oxyhemoglobin, but is more evenly distributed in deoxyhemoglobin. Similarly, as $^{129}$Xe forms transient van der Waals bonds with hemoglobin, the net electron cloud of $^{129}$Xe is likely to be drawn to the more electronegative O$_2$ molecule in oxyhemoglobin. This would act to increase the deshielding of the $^{129}$Xe nucleus, thereby reducing $\sigma_w$, resulting in an increased $^{129}$Xe-RBC resonance frequency, which is in agreement with the observed data.

In addition to changes in the electronegativity of the hemoglobin molecules with blood oxygenation, the xenon-hemoglobin binding site locations may change as the hemoglobin makes transitions between oxy- and deoxy-conformations. As the extent of the shielding constant $\sigma_w$ is strongly dependent on the separation between a nucleus and the molecules giving rise to fluctuating electric fields (47), changes in position would greatly alter the magnitude of the mean square field, $F^2$, experienced by the $^{129}$Xe nucleus within the hemoglobin. Each RBC contains a large number of individual hemoglobin molecules, and the fraction of hemoglobin molecules in the oxy- and deoxy-conformations has been measured previously in horse hemoglobin to vary smoothly as a function of blood oxygenation (52). The intracellular environment experienced by $^{129}$Xe nuclei would thus be expected to vary smoothly as a function of blood oxygenation, which is consistent with the observation of a smooth nonlinear change in the $^{129}$Xe-RBC resonance with blood oxygenation.

Finally, to help determine whether the underlying mechanisms driving the change in $^{129}$Xe relaxation rate and $^{129}$Xe-RBC chemical shift with $sO_2$ are related, a correlation plot of the variation of the two NMR parameters was generated, as shown in Figure 7. The $^{129}$Xe-RBC relaxation rate data are taken from our previous study (37) in which the relationship between $^{129}$Xe-RBC relaxation rate and $sO_2$ was determined. The plot reveals that changes in $^{129}$Xe-RBC relaxation rate and $^{129}$Xe-RBC chemical shift are well correlated, with a coefficient of determination of $R^2 = 0.83$. This presents strong empirical evidence that the underlying physical mechanism driving these observed changes in chemical
shift and relaxation rate is the same. As the chemical shift and relaxation rate of $^{129}$Xe in solvents is strongly dependent on intermolecular separations, we therefore conclude it is likely that oxygen-modulated xenon binding is largely responsible for the observed $^{129}$Xe-RBC chemical shift and relaxation rate $sO_2$ dependencies.

### In Vivo Spectroscopy

As shown in Figures 8a and b, for TR = 800 ms, the $sO_2$ values calculated from the $^{129}$Xe-RBC chemical shift were shown to oscillate over the breath hold at the same frequency as the $^{129}$Xe-RBC signal amplitude modulation, but with a 180° phase difference; the $sO_2$ maxima were observed to coincide with the $^{129}$Xe-RBC signal minima, suggestive of a link between pulmonary oxygenation and $^{129}$Xe-RBC signal changes. The calculated $sO_2$ of ~0.87 for both volunteers at the beginning of the breath hold suggests that the observed $^{129}$Xe-RBC signal comprises $^{129}$Xe dissolved in blood containing RBCs with mixed $sO_2$ values; otherwise it would be expected that the calculated $sO_2$ would equal either 1.00 for fully oxygenated blood or ~0.75 for deoxygenated blood. Indeed, for TR values of 100–800 ms, the observed $^{129}$Xe-RBC signal should be constituted primarily by $^{129}$Xe nuclei dissolved in blood circulating in the alveolar capillary bed, which contains blood with a range of $sO_2$ values. Signal contribution from $^{129}$Xe dissolved in blood circulating in the pulmonary arteries (precapillary blood) is assumed to be negligible as a result of $^{129}$Xe polarization losses incurred during $^{129}$Xe transit in the systemic circulation. Signal from $^{129}$Xe in the pulmonary veins is also considered to be negligible, as the postcapillary $^{129}$Xe signal is destroyed by 90° RF pulses for TR values of 100–800 ms, which are of the order of the RBC capillary transit time of 750 ms.

A first-order estimate of the expected average $sO_2$ of RBCs which contribute to the observed $^{129}$Xe-RBC signal for TR = 800 ms can be derived using the following assumption: the average RBC oxygenation in the capillaries $sO_2C = 0.75$ (deoxygenated) + 1.00 (oxygenated)] / 2 = 0.88. This agrees well with the $sO_2$ value of 0.87 calculated from the ~22 ppm chemical shift observed at the start of breath hold apnea in both healthy volunteers for TR = 800 ms.

After 35 s of breath hold apnea, a decrease in the observed $sO_2$ of 7–10% was calculated for both volunteers. During breath hold the oxygen partial pressure, $pO_2$, in the lungs will decrease over time. Measurements of changes in oxygen partial pressure as a function of breath hold have been performed in both animal and human lungs using hyperpolarized $^3$He MR (16,53,54). It was shown in humans that over short breath holds (<40 s), the decrease in $pO_2$ can be approximated by a linear relationship (15,16,53)

$$pO_2(t) = p_0 - Rt$$

where $R$ is the rate of oxygen extraction by perfusion and $p_0$ is the initial $pO_2$. Previous studies involving $pO_2$ mapping with $^3$He in healthy volunteers (16,53,55) reported $R$ to decrease with decreasing $p_0$. This may be a result of the lower baseline $pO_2$ reducing the alveolar-capillary $pO_2$ gradient, and, therefore, decreasing the rate of diffusion of oxygen from the alveoli into the capillaries. It is worth noting that over long breath holds and/or large $R$ values, an exponential model of oxygen depletion should be used instead of Equation [8], which for small $t$ is the first term in the Taylor expansion of an

![FIG. 7. Correlation of $^{129}$Xe-RBC relaxation rate and $^{129}$Xe-RBC chemical shift in whole blood samples over the full (0.06–1.00) blood oxygenation range.](image7)

### FIG. 8. In vivo lung blood oxygenation and $^{129}$Xe-RBC signal changes over breath hold apnea measured from two healthy volunteers, (a) and (b) (28 and 24 years old, respectively). The blood oxygenation and $^{129}$Xe-RBC signal oscillate at the same frequency where the blood oxygenation maxima/minima coincide with $^{129}$Xe-RBC signal minima/maxima (i.e. a phase difference of 180°).
exponential function (54). Assuming a functional residual capacity of 3 L for the healthy male volunteers in this study and a resting \( p_{O_2} \) of 140 mbar (38), the \( p_{O_2} \) drop upon inhalation of 1 L of anoxic gas (Xe/N\(_2\)) can be estimated by scaling the \( p_{O_2} \) with the increase in lung volume to 4 L, i.e. \( p_b = 140 \times (3/4) \approx 105 \) mbar. The \( R \) value for \( p_b = 105 \) mbar has been reported to be \( R = 0.7 \) mbar/s (55). Inserting these values into Equation [8], the \( p_{O_2} \) is estimated to drop to \( p_{O_2} = 81 \) mbar at the end of 35 s of breath hold apnea, which corresponds to a saturation \( s_{O_2} \) value of 0.89 from the standard oxygen-hemoglobin dissociation curve (56,57). Using this value, the average alveolar capillary bed oxygenation can be calculated as \( s_{O_2}:c = [0.75 \text{ (deoxygenated)} + 0.89 \text{ (oxygenated)}] / 2 = 0.82 \), which is in reasonable agreement with the \( s_{O_2} \) estimates (measured from the \(^{129}\text{Xe} \) chemical shift) of approximately 0.80 for both volunteers after \( \sim 35 \) s of breath hold apnea.

For \( TR = 100 \) ms, both the \(^{129}\text{Xe}-\text{RBC} \) and \(^{129}\text{Xe}-\text{TP} \) signals were observed to oscillate at a frequency close to the cardiac pulsation frequency (Figure 9), suggesting that the lower frequency signal oscillation observed for \( TR = 800 \) ms (Figure 8) is actually an alias of the higher frequency oscillation observed for \( TR = 100 \) ms. The gray line in Figure 9b shows artificial signal sampling at a rate of 800 ms\(^{-1} \) to illustrate this effect. \(^{129}\text{Xe}-\text{RBC} \) and \(^{129}\text{Xe}-\text{TP} \) signal oscillations at similar cardiac pulsation frequencies were first observed by Venkatesh et al. (58) and have been more recently observed by Ruppert et al. (59), where the signal oscillations were attributed to changes in blood flux into the capillaries within the cardiac cycle.

For the faster-sampled experiment at \( TR = 100 \) ms, the spectral resolution was limited to 0.7 ppm, which was insufficient to spectrally discriminate changes in the \(^{129}\text{Xe} \) chemical shift over the breath hold. It is possible that the observed \( s_{O_2} \) for \( TR = 100 \) ms would be lower than that observed for \( TR = 800 \) ms; for short \( TRs \), the RBCs have less time to travel through the capillaries into the pulmonary veins in between RF pulses (i.e. it is possible that the observable pulmonary \( s_{O_2} \) varies as a function of the \( TR \) used). Cardiac-gated acquisitions may allow the probing of \(^{129}\text{Xe}-\text{RBC} \) chemical shifts (\( s_{O_2} \)) at specific time points in the cardiac cycle, opening up the possibility of using \(^{129}\text{Xe} \) NMR to quantify temporal blood oxygenation changes in the cardiopulmonary vascular circuit.

With the assumption that the \(^{129}\text{Xe}-\text{TP} \) signal modulation arises from blood plasma flux changes within the cardiac cycle, it is possible to compare the peak-to-peak \(^{129}\text{Xe}-\text{RBC} \) signal, amplitude, \( S_A \), with the \(^{129}\text{Xe}-\text{TP} \) signal amplitude, \( S_B \), to estimate the relative RBC and plasma concentrations in the blood circulating through the capillaries. Thus, by taking the average of the first five \( S_A \) and \( S_B \) values after steady-state was reached, \( S_A = 0.113 \pm 0.004 \) and \( S_B = 0.050 \pm 0.003 \), respectively, the HCT in the capillaries may be estimated from

\[
HCT_c = \frac{x}{x+1} \tag{9}
\]

where \( x = S_A \delta_B / S_B \delta_A \) and \( \delta_A = 0.27 \), \( \delta_B = 0.094 \) are the solubilities of xenon in RBCs and plasma at 37 °C (60). Inserting these values into Equation [9] gives \( HCT_c = 0.44 \), in good agreement with the Fähraeus effect which predicts \( HCT < 0.50 \) (61) for blood flowing in narrow vessels such as the pulmonary capillaries. This is potentially of interest clinically; however, further work is required to validate this technique for measurement of HCT in the pulmonary capillaries.

This dissolved \(^{129}\text{Xe} \) spectroscopy oximetry technique may also have applications outside of the lungs. For example, Mazzanti et al. (62) have recently shown that the signal of \(^{129}\text{Xe} \) dissolved in the rat brain can be modulated in a manner responsive to stimuli, suggestive that there is a significant contribution to the measured \(^{129}\text{Xe} \) signal from blood flow/perfusion. Moreover, dissolved \(^{129}\text{Xe} \) spectra from the human brain have been successfully acquired (63), suggesting that \(^{129}\text{Xe} \) can be detected in organs quite distal from the point of uptake in the lungs.

Finally, this work has implications for Dixon-based dissolved \(^{129}\text{Xe} \) imaging methods (64,65), which rely upon a fixed chemical shift difference between the target spectroscopic compartments; the frequency difference between compartments is encoded as a phase shift in a given echo time and the different echo times need to be
fixed in value. Therefore, drift in the $^{129}$Xe-RBC peak position would affect the intensity of the $^{129}$Xe-RBC phase image.

CONCLUSIONS

In this study, the feasibility of using hyperpolarized $^{129}$Xe as an exogenous NMR probe of pulmonary blood oxygenation in humans has been explored. A nonlinear relationship between the measured $\text{SO}_2$ values and the NMR resonance frequency of $^{129}$Xe dissolved in RBCs has been observed in vitro from blood samples at 1.5 T and 3 T. This relationship was evaluated over the entire range of possible blood oxygenation values and appears to be independent of magnetic field strength.

Furthermore, this relation has been used to derive lung blood $\text{SO}_2$ values by means of in vivo dissolved $^{129}$Xe whole-lung spectroscopy experiments conducted during apnea on a 3 T whole body system. To date, we are not aware of any other means of noninvasively measuring pulmonary blood oxygenation. The common modulation frequency of blood oxygenation and $^{129}$Xe-RBC signal change during breath hold is interesting and further work with cardiac-gated hyperpolarized $^{129}$Xe NMR is underway to help understand this newly observed phenomenon. Lastly, the HCT in the pulmonary capillaries has been estimated from $^{129}$Xe spectroscopic data. Further work is underway to validate hyperpolarized $^{129}$Xe NMR as a noninvasive technique for quantification of HCT in the pulmonary capillaries.

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