

Hyperpolarized ^{129}Xe Human Pulmonary Gas Exchange with 3-point Dixon Technique

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Introduction

In contrast with ^3He , which is most useful for imaging pulmonary ventilation, ^{129}Xe is soluble in tissue (20%). Previously we reported a saturation recovery method to measure gas exchange in porous polyethylene samples [1]. The dissolved state signal is quenched with a selective 90° pulse and then interrogated after a specified time that allows for exchange from the gas magnetization reservoir. For short times such that xenon only diffuses into the thin ($\sim 2\mu\text{m}$ thick) parenchymal layer between alveolar gas space and vasculature, diffusive accumulation in the dissolved state increases as the square root of time and is proportional to the local surface area per unit volume S/V [1]. Here we combine our gas exchange method with a 3-point Dixon method [2] to observe both gas and dissolved state signals simultaneously in a gradient echo imaging sequence. The ratio of the dissolved to gas signal is the % gas exchange and is proportional to S/V .

Methods

MR measurements were performed on a GE Profile IV MRI magnet (0.2T) that was interfaced with a broadband console (Tecmag Apollo) at Brigham and Women's Hospital, Boston, MA. A whole body RF coil (Q \sim 300) was constructed to operate at the ^{129}Xe frequency (2.361MHz). ^{129}Xe was polarized on site using a polarizer developed and built at University of New Hampshire [3] with typical polarization of 45% at a production rate of 1.2L/h. Polarized Xenon was frozen to separate from the buffer gases and then thawed into a tedlar bag (Welch Fluorocarbon, Dover, NH). Taking into account $T_1=20\text{min}$ for HP Xe measured in a bag, experiments were performed within 3 minutes after thawing. Human subject experiments followed an FDA IND and IRB approved breathing protocol which requires no less than 21% oxygen in the inhaled gas mixture and no more than 35% Xe in the lungs.

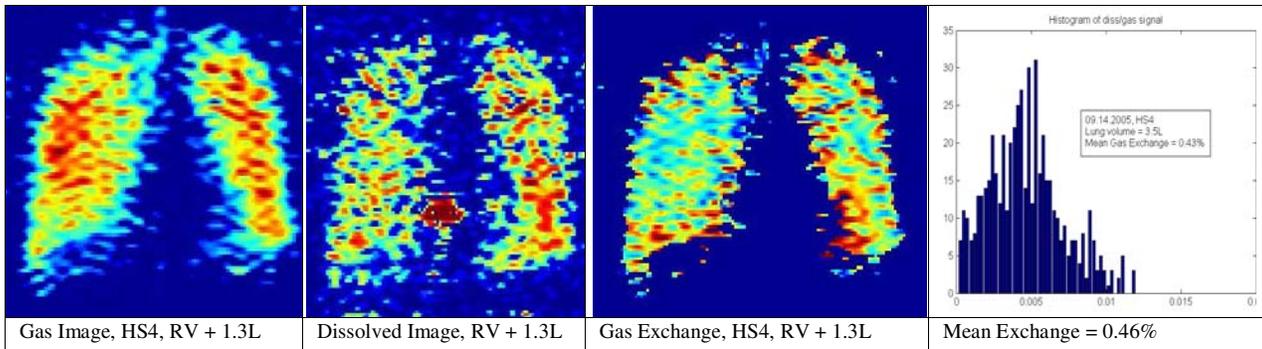
The observed frequency difference between dissolved and gas is $485\text{Hz} = \Delta\nu$. Gradient Echo projections were acquired at 3 TE times: 8.69ms, 9.72ms and 10.75ms, where $\Delta\text{TE} = 1/(2\Delta\nu)$. Exchange time was kept constant at 75ms. A 10ms frequency selective RF pulse was constructed from taking the Fourier Transform of a trapezoidal shaped pulse in frequency space. Centered on the dissolved state resonance, this pulse produced $<1^\circ$ flip in the gas state.

Experiments were performed on 2 subjects at 2 different lung volumes: RV+1.27L gas mixture (1L ^{129}Xe , 270 mL O_2), and RV+3L of gas mixture (1.8L ^{129}Xe and 1.2L O_2 and air). RV=residual volume. In all experiments 86% enriched ^{129}Xe was used. Because of the small value of the dissolved phase signal, phased reconstructions were performed, otherwise the "rectified" noise from an absolute value of the 2D FFT would result in a mean value similar to that obtained from exchange [5]. Using phased reconstructions, the mean value in noise only regions was ~ 0 .

Analysis and Results

The Fourier transforms of the collected signals are $S_1 = [D + Ge^{i\Delta\phi}]e^{i\phi_0}$; $S_2 = [D - Ge^{i\Delta\phi}]e^{i\phi_0}e^{i\phi}$; and $S_3 = [D + Ge^{i\Delta\phi}]e^{i\phi_0}e^{i2\phi}$, where D and G are the signals from Dissolved and Gas states, $\Delta\phi$ is the phase due to the chemical shift, ϕ_0 is some initial phase and ϕ is phase due to the dissolved signal being off-resonance, then $2\phi = \arg(S_3 / S_1)$. Correcting for this phase we have $S_1 - S_2e^{-i\phi} = 2Ge^{i\Delta\phi}e^{i\phi_0}$. Going back to time domain we can correct for the chemical position-shift artifact [4]. Then $S_1 - S_2e^{-i\phi} = 2Ge^{i\phi_0}$ and we can correct for the constant phase $\phi_0 = \arg(S_1 - S_2e^{-i\phi})$, i.e. for dissolved and gas states we get

$D = \frac{1}{2}[S_1 + S_2e^{-i\phi}]e^{-i\phi_0}$; and $G = \frac{1}{2}[S_1 - S_2e^{-i\phi}]e^{-i\phi_0}$. To calculate gas exchange values we account for flip angle differences experienced by each state. If α_D is the dissolved state flip angle and α_G is the gas state flip angle, then the fractional gas exchange will be: $R_{\text{exchange}} = D \sin(\alpha_G) / G \sin(\alpha_D)$.



Two gas volumes were inhaled starting at RV. Average gas exchange dropped from 0.46% for RV+1.3L to 0.26% for RV+3L. Similar behavior was observed on another healthy subject. Image reconstruction was implemented in Matlab. The amount of ^{129}Xe inhaled in the two breaths was 1.0L and 1.8L respectively.

Discussion

Ruppert et al [6] developed the XTC method to measure gas exchange and have demonstrated it in animals [6]. Their method probes the dissolved phase indirectly through changes in the gas signal following multiple applications of [dissolved phase 180 $^\circ$]-[exchange time] pairs. By contrast, the method described here is a direct measure of both the dissolved and gas phases, and is complementary to the approach of Ruppert et al [6]. We believe both techniques have great promise in detecting and quantifying early manifestations of parenchymally destructive diseases such as emphysema.

References

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