Nonlinear pO_2 decay in human lungs during long-breath-hold ^{3}He MRI

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Introduction

The rate decay of hyperpolarized ^{3}He MR signal in the lungs during breath-hold is dominated by the polarization loss due to the presence of paramagnetic oxygen [1]. Measurements of oxygen partial pressure (pO_2) in both animal and human lungs using hyperpolarized helium MR have been proven to provide useful information on lung physiology. Most studies in humans assume that the decrease of pO_2 during the breath-hold is linear ($pO_2 = p_0 - R\,t$, where R is the rate of oxygen decrease and p_0 is the initial pO_2) [1].

The dependence of the MR signal decay on pO_2 is given by: $S(t) = S_0 \exp[-\xi^{-1}\int_0^t pO_2(t')dt']$, *where* $\xi = 2.6\ bar \times s$.

This is a good approximation for short breath-holds, before the alveolar pO_2 begins to decrease and approaches the mixed venous pO_2 (45- 60 s in humans) [1]. In animals with higher metabolic rate, this occurs in a few seconds. This has been shown in mice [2], where the pO_2 decay has been modeled by assuming a more general (and physiologically realistic) exponential time dependence ($pO_2 = p_0 \exp(-t/r)$, r is the oxygen depletion time constant). In this work, the global lung pO_2 decay is measured using hyperpolarized ^{3}He MR during prolonged breath-holds in human volunteers (up to 90 s). The decay data is analyzed with both the linear and exponential models. The effect of increased initial pO2 is also studied.

Methods

The MR experiments were performed on a 1.5T GE system using an asymmetric transmit-receive birdcage coil [4]. Hyperpolarized helium of polarization about 35% was obtained using a Helispin polarizer (GE). The inhaled gas consisted of 700 ml N_2 and 300 ml ^{3}He and was provided to the volunteer in a Tedlar bag. MR acquisition started immediately after inhalation. The work was performed with full regulatory and ethics committee approval. The effect of increased initial lung and arterial pO_2 were assessed by having the volunteer breathe pure oxygen for a few minutes before one of the breath-hold acquisitions. The breath-holds periods ranged between 40 and 90 seconds. MR acquisition was performed with a series of FID signals (2048 samples) acquired every 200 or 500 ms during the breath-hold, with constant flip angles ranging between 6 – 8° for the respective acquisitions and a bandwidth of 6 kHz. Arterial oxygen saturation was monitored at the left index finger using an MR compatible pulse oximeter (Maglife, Bruker). Data processing and fitting to the linear and exponential models were performed using Matlab (Mathworks, USA).

Results and Discussion

Figure 1 shows the results of one of the breath-hold experiments (~83 s). The signal decay has been fitted to both the linear and exponential models. The exponential model provides a much closer fit to the data over the whole time course up to the point of exhalation. The high temporal resolution (200 ms) and high SNR of the global FID data made possible the detection of the deviation of the data from the linear model. For shorter breath-holds (< 40 s) no significant deviation was detected. As expected, pre-washing the lungs with 100% O_2 resulted in increased initial levels of oxygen saturation in the blood (Fig. 2) and pO_2 in lungs (from 0.204 bar to 0.227 bar, for the data of Fig. 3). The start of the sharp drop in arterial oxygen saturation was delayed (Fig. 2), while the signal decayed at a faster rate (Fig. 3) due to the increased p_0. The decay of lung pO_2 and arterial oxygen saturation showed reasonable correlation, in that the lung pO_2 with air pre-wash falls faster (r = 52.9 s) reflecting the earlier dip in blood saturation whilst the pO_2 in the lungs with O_2 pre-wash changes less (r = 141 s) over the same time window.

The global nature of this method makes it susceptible to RF field inhomogeneity. Since the coil used in this work has a very high B_1 homogeneity (7% over the lungs) [4], inhomogeneity effects were neglected. The use of imaging methods to account for the spatial variations of pO_2 and the RF field may provide an improved ability to detect deviations from the linear model. However, the sensitivity of these methods may be affected by the reduced temporal resolution and SNR of the imaging data. To overcome these limitations a 32-channel receiver coil array will be used, which should allow the acquisition of regional pO_2, with temporal resolution and SNR comparable to global measurements.

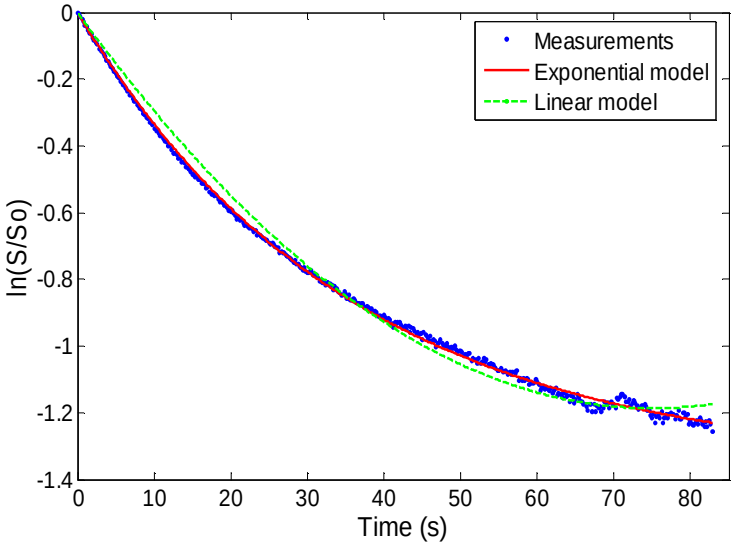

Figure 1. Fit of the linear and exponential models to breath-hold data. The exponential model provides a much closer fit to the data.

Conclusion

These results show that for long breath-holds it is possible to observe the non-linearity of the pO_2 decay in human lung using hyperpolarized ^{3}He. These measurements substantiate previous observations over shorter breath-holds in animal models. The data may be used to obtain useful information about the physiology of oxygen uptake in the lungs during apnea and provide a more realistic physical basis for imaging based models of pO_2 [3].

Acknowledgement

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References

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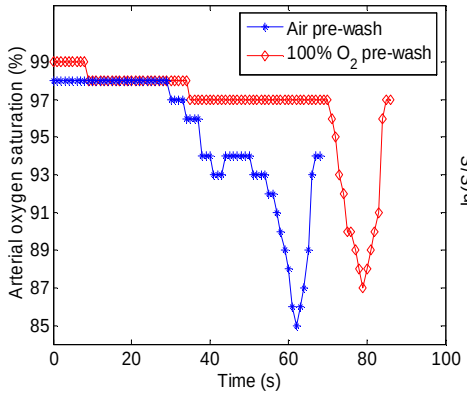

Figure 2. Arterial oxygen saturation measured with the pulse oximeter. The minima of the curves indicate the end of the breath-hold, when breathing resumes.

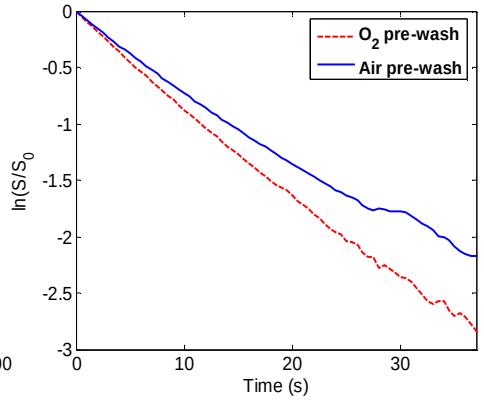

Figure 3. Signal decay in breath-holds after breathing air and 100% oxygen prior to the helium inhalation.