Correction of Errors due to RF Field Inhomogeneities in Hyperpolarized 3He Measurement of Alveolar Oxygen Partial Pressure in Human Lung

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INTRODUCTION: Measurement of the spin-lattice relaxation time of hyperpolarized ^{3}He due to oxygen in the lung (T_1,O_2) has been proposed as a method for estimation of the regional alveolar oxygen partial pressure, p_AO_2 (1). However, the use of inhomogeneous RF coils leads to variations in flip angle across the lung which can propagate into T_1 (2) inaccuracy. This is especially apparent for clinical ^{3}He RF transceive coils which conform to the thorax and may have inhomogeneities in excess of 10% or more over the entire lung volume. In this work, simulation of the effects of RF field inhomogeneities are performed. The simulations place limits on the accuracy of T_1 results in the presence of RF field inhomogeneity and this is confirmed in human subjects. A properly calibrated variable flip angle (VFA) approach is demonstrated to reduce error in T_1 due to RF field inhomogeneities compared to a conventional constant flip angle (CFA) method. For RF field inhomogeneities in excess of 2%, a B_1 mapping approach is proposed and demonstrated for correction of p_AO_2 inaccuracies.

METHODS: The signal dependence for hyperpolarized ^{3}He measurements due to p_AO_2 and flip angle can be written as (3):

$$S = \text{const} \cdot \sin(\alpha) \exp\left(-\frac{1}{\xi} \int_0^t p_A O_2(t) dt \right); \qquad 1.$$

where ξ is the inverse T_1 relaxivity of oxygen (= 2.6 bar s) and α is the first flip angle in a CFA or VFA (4) centric phase ordering acquisition scheme. In order to theoretically investigate the sensitivity of VFA and CFA to RF field non-uniformity, eight different amounts of RF field inhomogeneity up to 15% were simulated by increasing the flip angle systematically for both VFA and CFA methods. T_1 values were then calculated using 10 simulated T_1-weighted images with a 2 s delay between each for both VFA and CFA using Eqn. [1] with cos α = 1 for VFA and α_{opt} = 3.19° for CFA ($\alpha_{opt} = \tan^{-1}[1/\sqrt{N/2}]$, where N is total number of RF pulses).

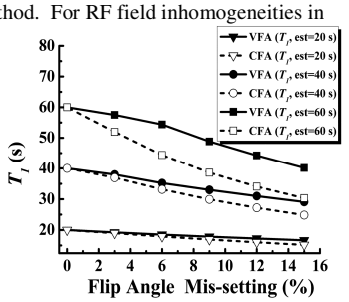

Fig. 1. Simulated T_1 estimates using VFA (solid lines) and CFA (dashed lines) approaches in the presence of fixed RF field inhomogeneities.

^{3}He MR imaging was performed at 3T (GEHC, Excite 12.0) corresponding to a frequency of 97.32 MHz. Clinical whole-body gradients and a commercial, rigid elliptical chest RF transceive coil (Rapid Biomedical, Wurzberg, Germany) was used for human measurements. Hyperpolarized helium (polarization ~ 35%) was provided by a turn-key spin-exchange polarizing system (Helispin®, GEHC). Five healthy volunteers were imaged following a protocol approved by the UWO Standing Board of Human Research Ethics. Two 14-slice, 2D FGRE VFA acquisitions (5) with 7 seconds delay between each were obtained in the coronal plane during one breath-hold (14 sec) of ^{3}He following normal breathing of room air. FOV was40 x 40 cm, matrix was 128 x 128, TE was 1.1 ms and TR was 4.6 ms and slice thickness was 1.5 cm. For calculation of p_AO_2, the two images were analyzed on a pixel-by-pixel basis using Eqn. 1. For VFA calibration (5), a 1-D acquisition (with the phase-encode gradients turned off) was chosen for convenience and to minimize acquisition time and avoid any effect due to diffusion between slices. Variable flip angles were calculated using $\alpha_i = \tan^{-1}[1/\sqrt{N-i}]$ (where N is total number of RF pulses) and calibrated by ensuring a constant signal (<2% change) as a function of RF pulse number for a sample of pure hyperpolarized ^{3}He from a syringe placed on the subject's chest. RF pulse amplitude was calibrated by scaling the power to the RF coil. To quantitate the actual RF field inhomogeneity, a B_1 field map was obtained with 3D FGRE VFA sequence (FOV was 35 x 35 cm, matrix was 64 x 64 x 36 slices, TE was 0.35 ms, TR was 3.1 ms, slice thickness was 1 cm, with 5 seconds delay between two 3D data sets) using a chest-sized balloon phantom containing a mixture of ^{129}Xe (10 l) and HP ^{3}He (0.25 l) in order to provide long T_1 (~1 hr) and ADC similar to lung (~0.2 cm^2/s). For this phantom, VFA based p_AO_2 measurements (5) permitted calculation of a B_1 field map as all signal variation is due solely to the RF coil inhomogeneities.

RESULTS: Simulation confirmed that a calibrated flip angle is very critical for p_AO_2 measurements. Fig. 1 shows that the presence of B_1 inhomogeneities may lead to significant underestimation of T_1, particularly for the CFA method. Table 1 shows the p_AO_2 (in atm.) results for right and left lung (slice number 4) from all subjects. Fig.2 shows a typical p_AO_2, map (slice number 3), calculated based on Eq. [1], and assuming no RF field inhomogeneities. While p_AO_2 values for the right lung are approximately those expected following normal breathing of room air (0.09–0.18 bar (6)), p_AO_2 in the left lung is consistently overestimated. B_1 mapping confirmed that the very high p_AO_2 values found for the left lung were due to RF field inhomogeneities. Table 1 also shows the p_AO_2 values obtained for the left lung of all subjects using Eqn. [1] and the actual flip angles based on the B_1 mapping of the phantom. Correction for RF field results in significantly better agreement between the two lungs and the physiological expectation. Fig. 3 confirms that B_1 field corrections can be routinely applied to any slice with indication of RF field inhomogeneity.

Table 1. p_AO_2 values (in atm.) and standard deviations for human subjects.

	1		2		3		4		5	
	mean	**σ**	**mean**	**σ**	**mean**	**σ**	**mean**	**σ**	**mean**	**σ**
p_AO_2 (right)	**0.15**	**0.08**	**0.19**	**0.06**	**0.14**	**0.05**	**0.16**	**0.09**	**0.21**	**0.05**
p_AO_2 (left)	**0.32**	**0.07**	**0.32**	**0.06**	**0.25**	**0.09**	**0.26**	**0.15**	**0.31**	**0.09**
p_AO_2 (left cor.)	**0.14**	**0.10**	**0.19**	**0.06**	**0.14**	**0.08**	**0.16**	**0.12**	**0.22**	**0.04**

DISCUSSION: Our results indicate that the VFA calibration can be a simple test for the presence of significant RF field inhomogeneities. In general, VFA cannot be properly calibrated if RF inhomogeneities are more than 2%, which is typical when using a chest-sized RF transceiver coil. In such cases, a flip angle map using a phantom of known (and large) T_1, such as the balloon containing a mixture of ^{129}Xe and HP ^{3}He can be very helpful. In this work, knowledge of the B_1 field was used to correct p_AO_2 map to significantly improve the accuracy of T_1 (and p_AO_2) estimates in human subjects. Results of B_1 field corrections for the five human subjects suggest that once found, the B_1 field map for the RF coil in the magnet can be used to correct p_AO_2 maps from any subject in any position, provided that the coil is re-positioned identically in the magnet for each subject. Although this work describes correction of 2D images, the 3D B_1 map can be used generally for correction of p_AO_2 maps obtained at any slice location and with 3D pulse sequences.

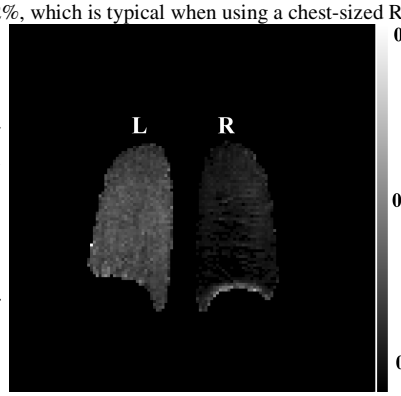

Fig. 2. p_AO_2 map obtained for human subject.

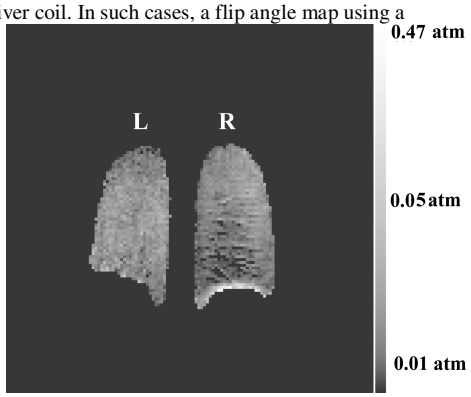

Fig. 3. Corrected p_AO_2 map from Figure 2.

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