Analysis of signal dynamics in oxygen-enhanced MRI

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Introduction: Oxygen-enhanced MRI (O_2-MRI) has been successfully applied for the visualization and (semi-)quantitative measurement of pulmonary ventilation and lung function [1–6]. The inhalation of pure oxygen (O_2) decreases the longitudinal relaxation time, T_1, of blood, which can be detected by T_1-weighted MRI. Frequently, a block paradigm is used for O_2-MRI consisting of a series of T_1-weighted scans acquired during alternating blocks with inhalation of room air and O_2. This block design results in a signal-time course for each pixel that contains information about lung function as well as respiration and circulation parameters.

The purpose of the present study was to analyze the properties of this signal-time course of O_2-MRI in more detail by evaluating several model functions with different parameters.

Methods: We studied 11 healthy volunteers using a T_1-weighting multi-slice inversion-recovery half-Fourier-acquisition single-shot turbo-spin-echo (HASTE) sequence (TI=1300 ms, TE=11 ms, 4 slices, slice thickness 8 mm, slice distance 16 mm, matrix 128×128, FOV 400×400 mm², GRAPPA acceleration factor 2) implemented on a 1.5-T whole-body scanner (Magnetom Sonata, Siemens Healthcare, Erlangen, Germany) with an 8-channel phased-array thorax coil system. Each examination consisted of a series of 60 acquisitions (20×air, 20×O_2, 20×air) with ECG and respiratory triggering for acquisition in end-expiration. Lung tissue and the spleen were segmented manually in all 11 data sets (44 slices). We normalized all data pixelwise to their mean value over the 20 initial baseline (air) acquisitions to obtain relative enhancement data.

We compared six different model functions (a rectangular, a linear, and four exponential functions, cf. Fig. 1) for the evaluation of the signal-time course in all data sets. The model functions were fitted to the data from acquisitions 21…60, i.e. to the O_2 wash-in and wash-out periods; non-linear fitting was performed with a Levenberg-Marquardt implementation. The optimal fit function was determined by the corrected Akaike information criterion (AIC) [7], which is a measure based on the sum-of-squares difference (SS) between data and fitted function, the number, N, of data points, and the number, K, of free parameters: AIC = $N \ln(SS/N) + 2(K+1) + 2(K+1)(K+2)/(N-K-2)$. The optimal fit function (i.e. the one with the minimal AIC) was then used to calculate maps and median values of all parameters.

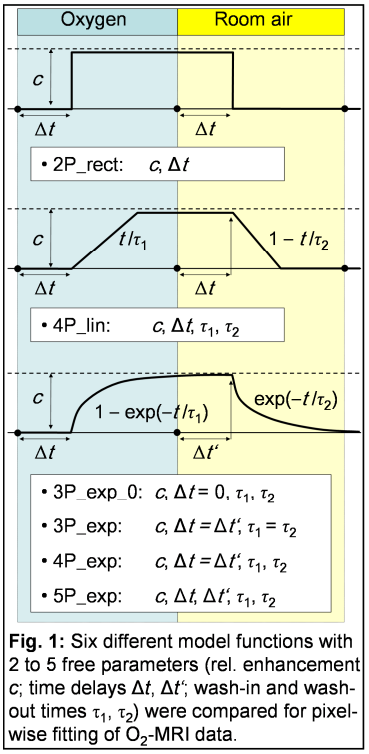

Fig. 1: Six different model functions with 2 to 5 free parameters (rel. enhancement c; time delays Δt, $\Delta t'$; wash-in and wash-out times τ_1, τ_2) were compared for pixel-wise fitting of O_2-MRI data.

Results: The model function with the minimal AIC (cf. Fig. 2) was the 4-parameter exponential model (4P_exp). The median values of the fit parameters in all 11 volunteers are summarized in Table 1. There is no position dependence of the parameters within the lung in anterior-posterior direction. Noteworthy are the substantial differences of the time delay, Δt, in the lung and the spleen as well as the prolonged wash-in time constant in the spleen. Typical parameter maps are shown in Fig. 3.

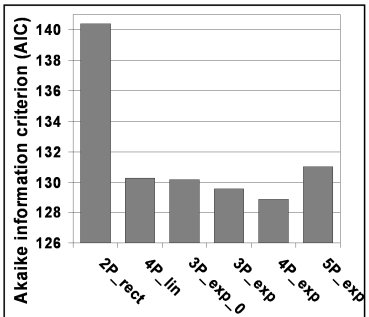

Fig. 2: Comparison of fit functions: minimal AIC indicates the optimal model function. AICs are averaged over all lung and spleen pixels of all volunteers.

Table 1: Parameters of oxygen dynamics in healthy volunteers (median values, 16th…84th percentile)

	c (%)	Δt (s)	τ_1 (s)	τ_2 (s)
Lung slice 1 (anterior)	16.3 (7.6…30.4)	6.3 (0.0…25.2)	33.8 (2.1… 96.0)	26.4 (0.5…92.5)
Lung slice 2	17.0 (9.2…29.9)	5.0 (0.0…25.3)	31.5 (3.4… 84.0)	26.7 (5.8…71.3)
Lung slice 3	15.9 (9.4…25.9)	6.5 (0.0…18.2)	28.8 (8.5… 71.7)	25.4 (3.8…61.2)
Lung slice 4 (posterior)	16.3 (10.7…27.8)	0.9 (0.0…13.6)	27.3 (10.7… 77.3)	23.3 (8.3…53.8)
Lung (all slices)	16.3 (9.5…28.1)	4.8 (0.0…18.9)	29.4 (6.9… 79.4)	25.1 (5.4…64.8)
Spleen (all slices)	14.8 (8.1…20.6)	24.5 (13.6…41.8)	72.7 (44.4…184.5)	29.6 (14.3…50.5)

Conclusions: We have shown that T_1-weighted O_2-MRI data is best fitted with a piecewise exponential function with different time constants, τ_1 and τ_2, for O_2 wash-in and wash-out. As a new parameter, our model function contains the time delay, Δt, that describes the interval between switching the gas supply and onset of the signal change in the considered organ. Further studies in patients with pulmonary diseases are required to investigate whether this time delay can help in the characterization of diseased lung areas; a preliminary result from O_2-MRI in a patient with bronchial carcinoma is shown in Fig. 4. Outside of the lung, e.g. in the spleen, Δt might be hypothesized to correlate to the global lung function. Pulmonary oxygen wash-in and wash-out times found in this study agree well with [2], and lie between lower values found in [5] and higher ones found in [3] and [6].

References: **[1]** Edelman RR et al. Nat Med 1996;2: 1236–9 **[2]** Hatabu H et al. Eur J Radiol 2001;37:172-8 **[3]** Arnold JFT et al. MAGMA 2004;16:246–53 **[4]** Dietrich O et al. Magn Reson Med 2005; 53: 1317–25 **[5]** Ohno Y et al. AJR Am J Roentgenol 2008; 190:W93-9 **[6]** Naish JH et al. Magn Reson Med. 2005; 54: 464–9 **[7]** Glatting G et al. Med Phys 2007; 34: 4285–92

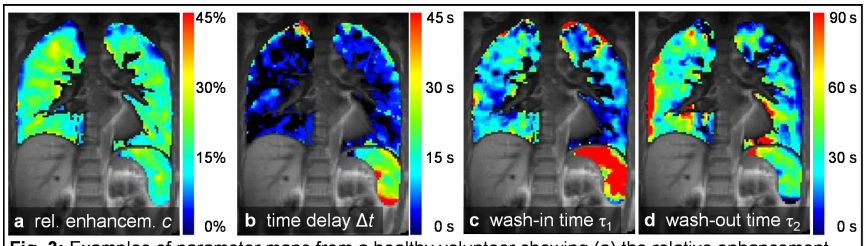

Fig. 3: Examples of parameter maps from a healthy volunteer showing (a) the relative enhancement, (b) the time delay between oxygen switching and the signal response, (c) the exponential wash-in time constant, and (d) the exponential wash-out time constant (fitted with the model function "4P_exp").

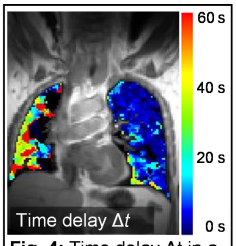

Fig. 4: Time delay Δt in a patient with bronchial carcinoma (in the right lung).