Dynamic oxygen-enhanced lung MRI: Cross-correlation analysis and oxygen-activated pixels

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Introduction: In oxygen-enhanced MRI (O_2-MRI) of the lung, 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 [1–9]. 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. It has been suggested to evaluate this time course by calculating the cross-correlation coefficient of each pixel response function and the ideal box-car waveform [3]. To quantitatively assess and compare the measured correlation coefficients, the fraction of oxygen-activated pixels has been defined as the fraction of lung pixels with correlation coefficients greater than 0.5 [7,8]. In previous studies [3,7,8], scanning was paused for 1 to 5 minutes after switching the gas supply until the new steady-state signal had been reached.

The purpose of the present study was to analyze the properties of the cross-correlation coefficient and of the fraction of oxygen-activated pixels in O_2-MRI with *continuous* scanning, i.e. with pixel time courses that contain the dynamic signal during the wash-in and wash-out periods.

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 80 acquisitions (20×air, 20×O_2, 20×air, 20×O_2) with ECG and respiratory triggering for acquisition in end-expiration. Lung tissue was segmented manually in all 11 data sets (44 slices).

We used two different reference functions to calculate the cross-correlation coefficient for each pixel time course: a box-car function as in [3,7,8] and a piecewise exponential function (cf. Fig. 1a,b); the wash-in and wash-out time constants of the exponential functions were set to 30 s in agreement with published data [2,4,6,9]. The cross-correlation was calculated for these two original functions and for a set of time-shifted correlation functions (Fig. 1c,d); in the latter case, the maximal correlation coefficient and the corresponding temporal shift over all shifted functions was pixelwise determined. We analyzed the mean values of the cross-correlation coefficients averaged over all volunteers and slices, the fraction of oxygen-activated pixels, and the mean temporal shifts. Cross-correlation coefficients and fractions of oxygen-activated pixels obtained with all reference functions were statistically compared with paired t-tests.

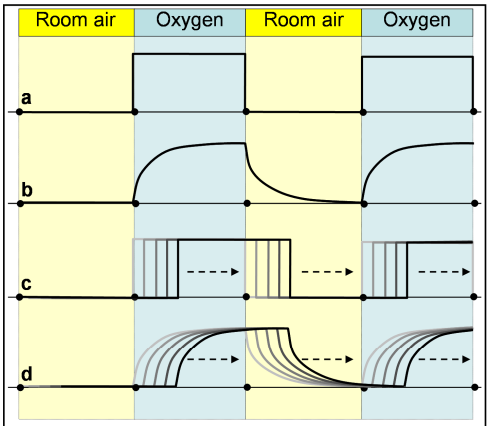

Fig. 1: Reference functions for cross-correlation analysis. (a) Rectangular box-car and (b) piecewise exponential functions, (c, d) same as above, but time-shifted.

Results: The results averaged over all 11 volunteers are summarized in Table 1. The correlation coefficients and the fractions of oxygen-activated pixels were significantly lower (p<0.01) with the fixed rectangular reference function than with all other functions. The highest correlation coefficients were found with the shifted exponential functions. Typical parameter maps are shown in Fig. 2.

Table 1: Cross-correlation coefficients, c_{cc}, fractions of oxygen-activated pixels, f_{OAP}, and temporal shifts, Δt; listed are mean values and standard deviations in parentheses

Correlation function	c_{cc}	f_{OAP} (%)	Δt (s)
Rectangular, fixed (Fig. 1a)	0.452 (0.141)	44.6 (31.3)	–
Exponential, fixed (Fig. 1b)	0.620 (0.148)	72.7 (22.4)	–
Rectangular, shifted to maximum, (Fig. 1c)	0.631 (0.120)	76.8 (20.5)	42.3 (12.9)
Exponential, shifted to maximum, (Fig. 1d)	0.650 (0.137)	76.9 (21.0)	22.7 (19.5)

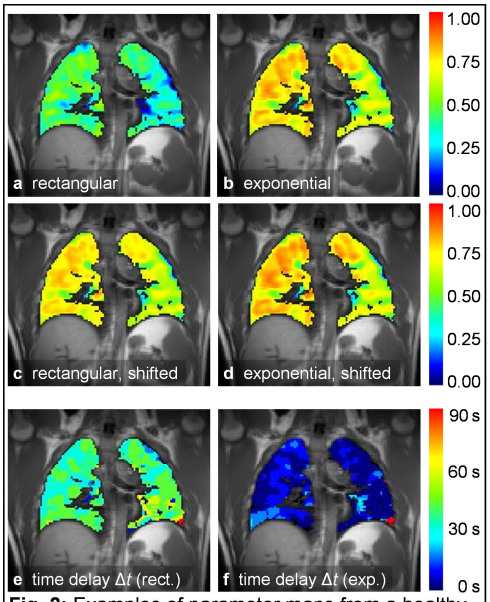

Fig. 2: Examples of parameter maps from a healthy volunteer showing (a–d) the cross-correlation coefficients corresponding to Fig. 1a–d, and (e, f) the time delay with maximal correlation.

Conclusions: We have shown that in dynamic O_2-MRI both the correlation coefficients and the fractions of oxygen-activated pixels depend significantly on the reference function used for correlation analysis. With a box-car waveform as in [3,7,8], the correlation parameters are substantially underestimated when the pixel time-course contains dynamic information from the oxygen wash-in and wash-out periods. If the maximum correlation coefficient of a set of temporally shifted correlation functions is determined, one has the further advantage that the temporal shift, Δt, can be obtained as an additional parameter, which might be useful in the characterization of diseased lung areas in patients. The observed difference of Δt of about 20 s between the rectangular and the exponential reference functions agrees well with the theoretical shift that is required for a maximum correlation of the ideal rectangular and exponential functions.

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]** Mai VM et al. Magn Reson Med 2003;49:591–4 **[4]** Arnold JFT et al. MAGMA 2004;16:246–53 **[5]** Dietrich O et al. Magn Reson Med 2005; 53: 1317–25 **[6]** Naish JH et al. Magn Reson Med. 2005; 54: 464–9 **[7]** Molinari F et al. Invest Radiol 2006;41:476–85 **[8]** Molinari F et al. J Magn Reson Imaging 2007; 26:1523–9 **[9]** Ohno Y et al. AJR Am J Roentgenol 2008;190:W93-9