Characterization of Static Field Effects of Paramagnetic Molecular Oxygen on BOLD-Modulated Hyperoxic Contrast Studies of the Human Brain

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Introduction

The inhalation of hyperoxic gas mixtures is known to be an effective positive contrast agent in T_2^*-weighted images (1). Hyperoxic contrast has been demonstrated to be useful for a number of applications, including the calibration of quantitative BOLD fMRI (2), the quantitative measurement of regional capillary-venous cerebral blood volume (CBV) (3), and the characterization of altered metabolism in ischemic lesions (4). Although hyperoxic contrast produces physiological and biochemical alterations, its effects on CBV, cerebral blood flow, and metabolism have been shown to be negligible, given the sensitivity of MRI measurements (5). However, the quality of oxygen as an intravascular contrast agent depends not only on it having minimal effects on the underlying physiology, but also on it having minimal non-BOLD relaxation effects. An important effect in these experiments, which is not yet been considered in hyperoxic contrast studies of the human brain (2), is the disruption of the static magnetic field (B_0) in the frontal lobes of the brain due to the influence of paramagnetic gaseous oxygen in the nasal and oral cavities and the oxygen delivery mask. Since the magnetic susceptibility of gaseous oxygen is more than 300 times that of gaseous nitrogen (6), the magnetic properties of air are dominated by oxygen. If the fraction of inspired oxygen (FiO_2) is 1.0, the gas in the major airways will be five times more paramagnetic than air (FiO_2 = 0.21). This has the effect of further increasing the difference in magnetic susceptibility at the air-tissue interface, which will increase the static field inhomogeneity in surrounding brain regions leading to increased intravoxel dephasing and image distortions in echo-planar imaging (EPI) acquisitions. In this study, the effects of inhaled oxygen on the static field are characterized by the measurement of the difference in B_0 maps during normoxia and hyperoxia at high (3 Tesla (T)) and ultra-high (7T) field strengths. We hypothesized that the degree of static field inhomogeneity will increase with both the level of oxygen and with increasing field strength.

Materials and Methods

All experiments involving human subjects were done under protocols approved by our Institutional Review Board, and signed, informed consent was obtained. All images were collected on a whole-body clinical 3T MRI scanner (Siemens Trio; Siemens Healthcare, Erlangen, Germany) with a body coil transmitter and 8-channel receiver head coil, except for one dataset collected on whole-body 7T system (Siemens Magnetom) with a transmit-receive circularly-polarized head coil. For all experiments, medical grade air, oxygen, or hyperoxic mixtures were delivered to the subject with a nonrebreathing mask fitted tightly over the nose and chin, running at a flow rate of 40 L/min from an air/oxygen blending device capable of delivering precise FiO_2 values of 0.21-1.0 at high flow rates. An experimental paradigm lasting twenty-seven minutes was performed on one normal, healthy male volunteer (28 years old). A baseline three-minute period of normoxia (FiO_2 = 0.21) was followed by a six-minute mild hyperoxic stimulation period of FiO_2 = 0.5, a six-minute rest period of FiO_2 = 0.21, a six-minute hyperoxic stimulation period of FiO_2 = 1.0, and a second six-minute rest period of FiO_2 = 0.21. Continuous sagitally-oriented whole-brain dual-echo 3D GRE phase images were acquired at both field strengths. The total acquisition time of each 3D GRE image was 72 seconds, allowing five whole-brain B_0 maps to be acquired during each stimulation and rest period.

Results

Figure 1a shows a sagittal cut from calculated 3D relative B_0 maps in parts-per-million (ppm) at baseline at 3T and 7T. The difference in the relative B_0 maps between the hyperoxic states at 3T and 7T is shown in Fig. 1b,c; near the nasal cavity, there is more than 0.1 ppm increase in the B0 field during 100% oxygen inhalation at 3T in the frontal lobes. In this dataset, additional static field effects are observed at a distance from the nasal cavity during hyperoxia. During 100% oxygen inhalation at 7T, a large region of more than 0.1 ppm increase in the static field extends past the frontal lobes well into the parietal and temporal lobes. At each field strength, these effects remain present, but to a much lesser extent, during 50% oxygen inhalation (Fig. 1c). Fig. 1d,e shows that the B_0 values superior to the nasal and oral cavities changed approximately twice as much in FiO2 = 1.0 versus 0.5 at each field strength, and that relative B_0 changes are approximately twice as high at 7T versus 3T.

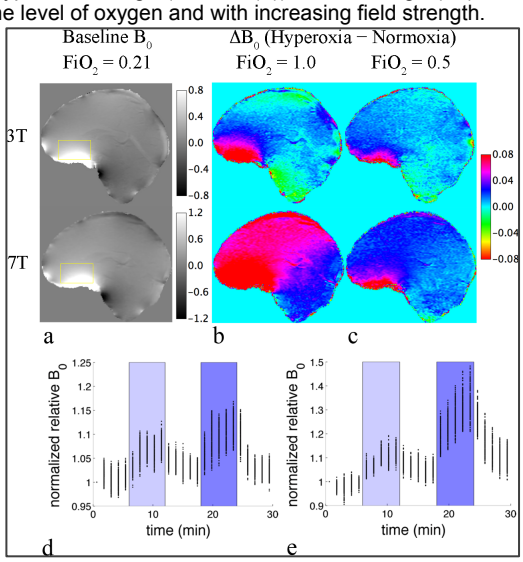

FIG.1. Baseline B_0 maps and change in B_0 after different levels of oxygen inhalation at 3T and 7T. Baseline relative B_0 maps (ppm) (a) during air breathing at 3T (top row) and 7T (bottom row). Change in the relative ΔB_0 (ppm) maps from baseline during FiO_2 = 1.0 (b) and 0.5 (c) at 3T (top row) and 7T (bottom row). The yellow boxes in the top and bottom rows of (a) mark rectangular regions of interest that are plotted in (d) and (e), respectively, as normalized relative B_0 values versus time for FiO_2 = 0.5 oxygen (light blue region) and 1.0 (dark blue region) epochs.

Discussion

In this study, hyperoxia was found to substantially increase the static field inhomogeneity across the brain. This effect was found to increase with increased FiO_2 and with static field strength. Based on the spatial distribution of the field changes, the main source of these field changes seems to originate in the oxygen gas in the nasal and oral cavities. Although it is possible that gas in the lungs could contribute to the field shift, the lack of global changes in the field indicates that the lungs likely play a minor role. The effect from the nasal cavity is large and will affect any imaging approach used in a hyperoxic contrast experiment, and it will have the most significant effects in gradient echo imaging acquisitions. In gradient echo EPI acquisitions, which are the most often used approaches in hyperoxic contrast experiments, these static field changes will manifest primarily as increased intravoxel dephasing and increased distortions, primarily in the phase encode and through-slice directions. While increased intravoxel dephasing will reduce voxel signal in these regions, it is possible that the image distortions can decrease or increase signals depending on the image orientation. These effects are very difficult to model and correcting them would require measurement of the EPI point spread function in normoxia and hyperoxia. However, it seems possible to minimize this effect but appear to be reducing the FiO_2 to a minimum and avoiding analysis in the frontal lobe regions adjacent to the nasal cavity.

References

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Acknowledgements

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