# The susceptibility of dissolved oxygen

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**Target audience:** MRI researchers using gas challenges, particularly hyperoxia (or carbogen) and those who are interested in magnetic susceptibility calculations and theory.

**Purpose:** It has been predicted that, during hyperoxia, excess $O_2$ dissolved in arterial blood will significantly alter the blood's magnetic susceptibility, leading to non-negligible MR signal changes[1]. This would confound the interpretation of the hyperoxia-induced BOLD signal as arising solely from changes in venous and capillary deoxyhemoglobin (dHb), the implications of which are significant. This study, therefore, aimed to determine how dissolved $O_2$ affects the susceptibility of blood ($\chi_b$), both theoretically and experimentally, and, in turn, how this would affect the hyperoxia BOLD signal.

**Theory & Methods:** In the model for $\chi_b$ from [1], referred to here as the ideal gas model (IGM), the volume fraction of dissolved $O_2$ was given by the product $\varepsilon \cdot pO_2$, where $\varepsilon = 3.1\times10^{-5}$ mL $O_2$/mL blood/mm Hg $O_2$ is the solubility coefficient of dissolved $O_2$ in blood and $pO_2$ is the partial pressure of $O_2$. In a previous study, we showed that $\varepsilon \cdot pO_2$ significantly overestimated the true volume fraction of dissolved $O_2$ and we proposed an alternate model for $\chi_b$[2]. Briefly, our model is an extension of Spees et al.'s[3] formulation of $\chi_b$ that incorporates dissolved $O_2$ directly into the water compartments of blood (i.e. the water in plasma and red blood cells). This enables straightforward calculation of the volume fraction of dissolved $O_2$ in water and the calculation of $\chi_b$ for arbitrary hematocrit (a quantity that the IGM did not account for with respect to dissolved $O_2$).

To validate our model, long centrifuge tubes containing oxygenated samples of either distilled water or bovine plasma were placed one at a time along the centre of a large water phantom that was then placed in a 3 T scanner (Siemens Tim Trio) with the tube axis parallel to B0. A single-slice through the centre of the tube was imaged with a multi-echo gradient echo sequence and the phase images were subsequently processed to measure the field offset produced by the tube. After background field removal using a 6th-order 2D polynomial[4], the remaining field offset inside the tube was related to the susceptibility difference between the sample and the surrounding water using the infinite cylinder model[5].

Additional simulations were performed to compare the blood-tissue susceptibility difference and the BOLD signal across the vascular tree (arteries, capillaries, and veins) using three models: the IGM, our model, and ignoring dissolved $O_2$[3]. All three models used the same baseline value for $\chi$ of tissue when $pO_2 = 0$[1] but incorporated dissolved $O_2$ using their respective volume fractions[1-3].

**Results:** In distilled water and plasma, a linear fit to the measured changes in susceptibility gave excellent results ($R^2 > 0.97$), with identical slopes of 0.062 ppb/mm Hg of $O_2$ (SI units)(Fig. 1). This change is dramatically less than predicted using the IGM and is very close to that predicted by our model. The primary source of error in the IGM is the overestimation of the volume fraction occupied by dissolved $O_2$.

Further modelling of the blood-tissue susceptibility difference indicated that, while the contribution from dissolved $O_2$ to $\chi_b$ is small, it partially offsets the diamagnetic change in $\chi_b$ produced by the remaining ~2% dHb in arteries that converts to oxy-Hb under hyperoxia (Fig. 2). This was reflected in simulations of the BOLD signal from tissue occupied by arteries, where the relative signal change between 100% fixed inspired $O_2$ and normoxia was (2.8 ± 0.4)% using the IGM, (–0.54 ± 0.07)% using our model, and (–1.0 ± 0.1)% ignoring $O_2$.

**Conclusion:** We found that the change in susceptibility of distilled water and plasma was marginally less than predicted by our detailed model. Most importantly, in contrast to previous predictions, our results indicate that the BOLD signal from hyperoxia will have a negligible contribution from arteries under most physiological conditions.

**References:** [1] Schwarzbauer and Deichmann, *Neuroimage*. 2012;59(3):2401-12. [2] Berman et al., *ISMRM13*. 2013;0851. [3] Spees et al., *Magn Res Med*. 2001;45(4):533-42. [4] Langham et al., *Magn Res Med*. 2009;61(3):626-33. [5] Ogawa et al., *Biophys J*. 1993;64(3):803-12.

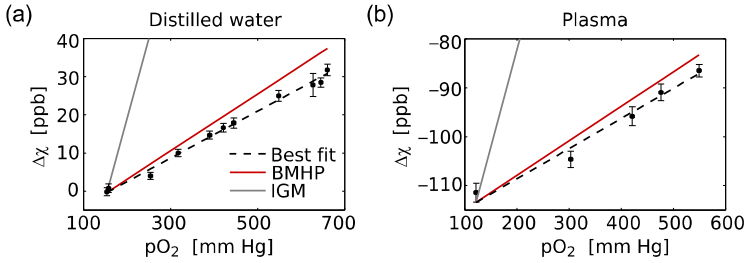


**Figure 1 (left):** Measured susceptibility differences in SI units (squares plus error bars) between oxygenated water (a) and bovine plasma (b) and the surrounding water in the phantom. Shown is the best linear fit to the data, our (BMHP) theory, and the IGM employed by [1]. The vertical offsets have been adjusted such that the lines intersect at normoxia.

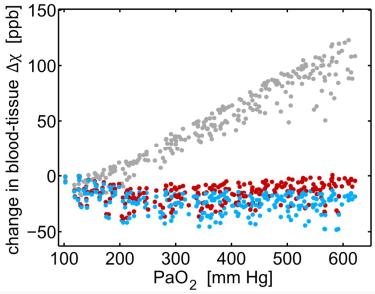


**Figure 2 (right):** Change in the arterial blood-tissue susceptibility difference (SI units) relative to normoxia for a range of hyperoxia levels as calculated when ignoring dissolved $O_2$ (blue), using our model (red), and using the IGM (grey). Each data point was produced using randomly selected baseline oxygen extraction fraction (0.1 – 0.55), arterial $pO_2$ ($PaO_2$) (90 – 130 mm Hg), Hct (0.35 – 0.5), and increase in $PaO_2$ (0 – 500 mm Hg).