A simplified empirical model to estimate oxygen relaxivity at different magnetic fields

Emma Bluemke | Eleanor Stride | Daniel Peter Bulte

Institute of Biomedical Engineering, Department of Engineering Sciences, University of Oxford, UK

Correspondence
Emma Bluemke, Old Road Campus Research Building, University of Oxford, Headington, Oxford OX3 7DQ, UK.
Email: emma.bluemke@new.ox.ac.uk

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The change in longitudinal relaxation rate ($R_1$) produced by oxygen has been used as a means of inferring oxygenation levels in magnetic resonance imaging in numerous applications. The relationship between oxygen partial pressure (pO$_2$) and $R_1$ is linear and reproducible, and the slope represents the relaxivity of oxygen ($r_{1Ox}$) in that material. However, there is considerable variability in the values of $r_{1Ox}$ reported, and they have been shown to vary by field strength and temperature. Therefore, we have compiled 28 reported empirical values of the relaxivity of oxygen as a resource for researchers. Furthermore, we provide an empirical model for estimating the relaxivity of oxygen in water, saline, plasma, and vitreous fluids, accounting for magnetic field strength and temperature. The model agrees well ($R^2 = 0.93$) with the data gathered from the literature for fields ranging from 0.011 to 8.45 T and temperatures of 21-40 °C. This provides a useful resource for researchers seeking to quantify pO$_2$ in simple fluids in their studies, such as water and saline phantoms, or bodily fluids such as vitreous fluids, cerebrospinal fluids, and amniotic fluids.

KEYWORDS
longitudinal relaxation, oxygen, $R_1$, relaxivity, vitreous, water

1 | INTRODUCTION

Many researchers have investigated using the paramagnetic relaxivity effect of oxygen on longitudinal relaxation as a means of inferring oxygenation levels for applications ranging from cancer therapy to seawater analysis.$^{1-5}$ For example, measurements of the longitudinal relaxation rate $R_1$ ($1/T_1$) have been used to infer oxygen levels in vitreous fluid as a noninvasive alternative to the highly invasive oxygen electrodes used to measure retinal hypoxia,$^6$-8 bladder urine$^9$ and urine in the renal pelvis to create a noninvasive detection of renal dysfunction,$^5$ and cerebrospinal fluid,$^9$,$^{10}$ and this relationship between pO$_2$ and $R_1$ is also the basis for oxygen-enhanced MRI techniques.$^{11-13}$ In the linear relationship between pO$_2$ and $R_1$, the slope represents the relaxivity of oxygen, or $r_{1Ox}$, in that material. Unfortunately, however, there is considerable variability in the values reported for $r_{1Ox}$ from empirical measurements, and consequently reliable quantification of pO$_2$ from $R_1$ measurements presents a challenge.

This paper provides a summary of the empirical measurements reported in the literature, investigating the relationship between $R_1$ and the partial pressure of oxygen in phantoms, saline and water solutions, and vitreous fluid. These experiments have been performed using different equipment and field strengths and reported with a variety of units. For consistency, therefore, all $T_1$ values will be reported in ms, $R_1$ in s$^{-1}$, and relaxivity in s$^{-1}$/mmHg oxygen, with the corresponding field strength, temperature and material specified where these data are available. We then
propose a simplified empirical model for estimating $r_{1Ox}$ in water, saline, plasma, and vitreous fluids based on these reported literature values and report the resulting model parameters. Our aim is to provide a useful review and tool for researchers seeking to quantify pO$_2$ in simple fluids, such as water and saline phantoms, or bodily fluids such as vitreous fluids, cerebrospinal fluids, and amniotic fluids. This model does not represent the $r_{1Ox}$ in blood or tissue, due to the addition of proteins, structure, cells, lipids, and deoxyhemoglobin, which will affect the $R_1$-pO$_2$ relationship, to be addressed in a separate manuscript.

2 | METHODS

2.1 | Model theory

$T_1$ (measured in ms), and its inverse, $R_1$ (typically reported in s$^{-1}$), have both been used in the literature when reporting the relaxivity effect of oxygen. $R_1$ is linearly dependent on the concentration of paramagnetic particles$^{14,15}$ in this case dissolved molecular oxygen in the solution, with the following equation:

$$R_{1Ox} = R_{1,0} + r_{1Ox}C$$

where $R_{1Ox}$ is the relaxation rate in the solution with oxygen added, $R_{1,0}$ is the relaxation rate in the solution without oxygen, $C$ is the concentration or partial pressure of oxygen, and $r_{1Ox}$ is the relaxivity of oxygen in that solution (whose units depend on the oxygen measurement used in the constant $C$) (shown in Figure 1). Since the partial pressure of oxygen (pO$_2$) is a common measurement in biomedicine and clinical applications, in this manuscript, we report $C$ as pO$_2$ in mmHg and $r_{1Ox}$ in s$^{-1}$/mmHg. Conversion factors to other common units such as kPa, Torr, mmol/L, mg/L, and mL/L can be found in Supplementary Table S1.

Changes in both $T_1$ and $R_1$ have been used to report changes in pO$_2$ in the past$^{16}$ However, although an increase in oxygen could still qualitatively roughly be inferred from a shortening of $T_1$, it is important to note that the linear relationship exists with $1/T_1$ ($R_1$—not $T_1$—and

![Figure 1](image1.png)

**Figure 1** The relationship between $T_1$ and pO$_2$ (A) and $R_1$ and pO$_2$ (B) in a solution, with the initial $T_1$ of 3000 ms. The values are calculated using a range of $r_{1Ox}$ (relaxivity) reported in the literature at 1.5 T, in units s$^{-1}$/mmHg oxygen

![Figure 2](image2.png)

**Figure 2** The relationship between $\Delta T_1$ and initial $T_1$ (A) and $\Delta R_1$ and initial $R_1$ (B), for a $\Delta pO_2$ of 200 mmHg. The values are calculated using a range of $r_{1Ox}$ (relaxivity) reported in the literature at 1.5 T, in units s$^{-1}$/mmHg oxygen
therefore the change in $T_1$ caused by oxygen will be dependent on the original $T_1$ (shown in Figure 2). Therefore, for a quantitative inference of pO$_2$ change it is necessary to discuss changes with respect to $R_1$.

The $r_{1\text{Ox}}$, or relaxivity of oxygen, is affected by various experimental factors, including field strength. Equations already exist to determine the relationship between field strength and $R_1$; in 2001, Teng et al.\textsuperscript{17} measured the proton spin-lattice relaxation rate in water as a function of magnetic field strength at 1 atm of oxygen (approximately 760 mmHg) and found that the magnetic relaxation dispersion due to the paramagnetic contribution from molecular oxygen is well approximated by a Lorentzian shape, for which they proposed the following equation:

$$\frac{1}{T_{1\text{Ox}}} = A \frac{r}{1 + r^2 \omega_s^2} + B$$

where $A$ and $B$ are constants, $\omega_s$ is the electron Larmor frequency, and $r$ is the correlation time for the electron-nuclear coupling (empirically measured to be $6.8 \pm 0.5$ ps in water).\textsuperscript{17} One variable of particular interest for medical imaging research is field strength, which can be related to the electron Larmor frequency above ($\omega_s$) by the electron gyromagnetic ratio ($\gamma_e = 1.76 \times 10^{11}$ rad s$^{-1}$ T$^{-1}$) and Larmor equation $\omega_s = \gamma_e B_0$. By substituting $\omega_s = \gamma_e B_0$ into Equation 2, we can see that

$$\frac{1}{T_{1\text{Ox}}} = A \frac{r}{1 + r^2 \gamma_e^2 B_0^2} + B.$$  

From Equation 1 we know that $1/T_{1\text{Ox}}$ is proportional to the relaxivity ($r_{1\text{Ox}}$), and from Reference 17 we know that the Lorentzian magnetic relaxation dispersion is due to the paramagnetic contribution from molecular oxygen. Therefore, we propose that the relationship between $r_{1\text{Ox}}$ and field strength will be well approximated by a similar Lorentzian equation with new constants:

$$r_{1\text{Ox}} = \frac{C_1}{1 + C_2 B_0^2} + C_3$$

where $C_1$, $C_2$, and $C_3$ are new constants, and $B_0$ is the magnetic field strength (T). It is worth noting that in Equation 4 $C_1$ will not be equal to $A r$ as it is in Equation 3, since Equation 3 is calculating $R_1$ and Equation 4 is calculating $r_{1\text{Ox}}$—while $R_1$ and $r_{1\text{Ox}}$ should be proportional, there are additional multiplying or dividing factors that will be encompassed by $C_1$.

Finally, the relaxivity of oxygen is also reported to be affected by temperature, as seen in the varied relaxivity measurements reported by Muir et al.\textsuperscript{8} To account for this, we add a fourth constant ($C_{\text{Temp}}$), which represents the linear slope of relaxivity change due to temperature, resulting in the final equation:

$$r_{1\text{Ox}} = \frac{C_1}{1 + C_2 B_0^2} + C_3 + C_{\text{Temp}} \times T.$$  

### 2.2 Data collection and analysis

The 28 reported values for oxygen relaxivity were collected from the literature, and all units were converted to s$^{-1}$/mmHg oxygen, shown in Table 1 alongside the field strength and material used in each experiment. If data extraction from graphs was necessary, a digital plot analyzer was used to reliably extract values.\textsuperscript{25}

The SciPy optimize function for nonlinear least-squares fitting was used.\textsuperscript{26} Equation 5 was fitted using a randomized subset of 90% of the 28 literature data points in Table 1, fitting the $B_0$ and temperature values simultaneously. The dataset was split into randomized subsets for fitting using the sklearn train_test_split function with shuffling.\textsuperscript{27} This process was iterated 1000 times, and the median and 95% confidence interval of the distribution of fitted values for each parameter were used as the final parameters (listed in Table 2). Violin plots showing the distribution of parameter estimates from each iteration are shown in Supplementary Figure S1. Following the model fitting, all four final parameter values were substituted into Equation 5, and the accuracy of the model’s predicted $r_{1\text{Ox}}$ was compared against the ‘true’ $r_{1\text{Ox}}$ values, shown in Figure 3.
RESULTS

As shown in Table 1, we found 28 total measurements of $r_{1\text{O}}$, 7 measured in saline solutions,\textsuperscript{7,9,16,18,19} 18 in water,\textsuperscript{3,8,9,20–23} 1 in vitreous fluid,\textsuperscript{7} and 2 in plasma (ex vivo).\textsuperscript{16,24} The measurements were collected at field strengths ranging from 0.011 to 8.45 T and temperatures ranging from 21 to 40 °C. 12 additional values of $r_{1\text{O}}$, measured in blood (ex vivo\textsuperscript{16,24,28} and in vivo\textsuperscript{20,29}) and tissues (lung\textsuperscript{20} and brain\textsuperscript{21}), were also found.

| Reference | $r_{1\text{O}}$ ($\text{s}^{-1}/\text{mmHg} \times 10^{-4}$) | Field strength (T) | Temp. (°C) | Material |
|-----------|-------------------------------------------------|--------------------|-------------|----------|
| Matsumoto et al., 2006\textsuperscript{18} | 2.17 | 4.7 | 37 | Saline |
| Zaharchuk et al., 2005\textsuperscript{20} | 2.7 | 1.5 | 37 | Saline |
| d'Othée et al., 2003\textsuperscript{16} | 1.38 | 8.45 | 21 | Saline |
| d'Othée et al., 2003\textsuperscript{16} | 1.90 | 1.5 | 21 | Saline |
| Kramer et al., 2013\textsuperscript{19} | 2.82 | 1.5 | 37* | Saline |
| Kramer et al., 2013\textsuperscript{19} | 2.21 | 3 | 37* | Saline |
| Simpson et al., 2013\textsuperscript{7} | 3.6 | 1.5 | 35 | Saline |
| Pilkinton et al., 2012\textsuperscript{20} | 1.61 | 3 | 37 | Water |
| Vatnehol et al., 2020\textsuperscript{21} | 1.9 | 3 | 22 | Water |
| Nestle et al., 2003\textsuperscript{3} | 4.2 | 0.5 | 22 | Water |
| Hauser and Noack, 1965\textsuperscript{22} | 3.72 | 0.63 | 22 | Water |
| Zaharchuk et al., 2006\textsuperscript{9} | 2.49 | 1.5 | 37 | Water |
| Graf et al., 1980\textsuperscript{23} | 6.60 | 0.011 | 25 | Water |
| Graf et al., 1980\textsuperscript{23} | 6.60 | 0.031 | 25 | Water |
| Graf et al., 1980\textsuperscript{23} | 6.23 | 0.051 | 25 | Water |
| Graf et al., 1980\textsuperscript{23} | 6.60 | 0.137 | 25 | Water |
| Graf et al., 1980\textsuperscript{23} | 6.13 | 0.259 | 25 | Water |
| Graf et al., 1980\textsuperscript{23} | 5.18 | 0.525 | 25 | Water |
| Graf et al., 1980\textsuperscript{23} | 3.68 | 0.713 | 25 | Water |
| Graf et al., 1980\textsuperscript{23} | 3.89 | 0.159 | 25 | Water |
| Graf et al., 1980\textsuperscript{23} | 2.74 | 2.139 | 25 | Water |
| Graf et al., 1980\textsuperscript{23} | 2.51 | 4.387 | 25 | Water |
| Muir et al., 2013\textsuperscript{8} | 2.04 | 3 | 34 | Water |
| Muir et al., 2013\textsuperscript{8} | 2.05 | 3 | 37 | Water |
| Muir et al., 2013\textsuperscript{8} | 2.11 | 3 | 40 | Water |
| Simpson et al., 2013\textsuperscript{7} | 3.47 | 1.5 | 35 | Vitreous fluid |
| d'Othée et al., 2003\textsuperscript{16} | 1.11 | 8.45 | 21 | Plasma (ex vivo) |
| Hueckel et al, 2000\textsuperscript{24} | 3.38 | 1.5 | 37 | Plasma (ex vivo) |

*Temperature not reported, assumed to be 37 °C.

| Parameter name | Resulting value from fit (95% lower and upper confidence intervals) | Units* |
|----------------|-------------------------------------------------|--------|
| $C_1$ | 4.87 (4.70, 5.04) | $10^{-4}$ s$^{-1}$/mmHg |
| $C_2$ | 1.99 (1.59, 2.38) | T$^{-2}$ |
| $C_3$ | 0.844 (0.452, 1.24) | $10^{-4}$ s$^{-1}$/mmHg |
| $C_{\text{Temp}}$ | 0.0323 (0.0211, 0.0434) | $10^{-4}$ s$^{-1}$/mmHg/°C |

*If using temperature in Kelvin, subtract 273.15 to convert your temperature to °C.
The final values for the four parameters $C_1$, $C_2$, $C_3$, and $C_{\text{Temp}}$ (with lower and upper 95% confidence intervals) are listed in Table 2. The predicted versus true $r_{1\text{Ox}}$ values are plotted against the line of equality (solid black line) and a linear regression (dotted line, $R^2 = 0.93$) in Figure 3A, with a final mean squared error (MSE) of $0.19 \times 10^{-4}$ (s$^{-1}$/mmHg)$^2$. To examine bias in the model with respect to $r_{1\text{Ox}}$, $B_0$, and temperature variables, Bland-Altman plots are provided in Figure 3B-D. The performance of the model on the subsets of water measurements only ($R^2 = 0.94$) and saline measurements only ($R^2 = 0.73$) is provided in Supplementary Figure S3.

The modelled versus measured $r_{1\text{Ox}}$ values from the randomized unseen test set of each iteration is plotted in Supplementary Figure S2A alongside the line of equality and the linear regression ($R^2 = 0.90$, MSE = $0.26 \times 10^{-4}$ s$^{-1}$/mmHg)$^2$. The difference between the modelled and measured $r_{1\text{Ox}}$ values from the randomized unseen test set of each iteration is illustrated as Bland-Altman plots in Supplementary Figure S2B-D.

To understand the behavior of the resulting model, the effect of varying field strength on $r_{1\text{Ox}}$ is illustrated using synthetic data under varying temperatures (Figure 4), and the linear effect of varying temperature on $r_{1\text{Ox}}$ is illustrated using synthetic data under varying field strengths (Supplementary Figure S4). The resulting model prediction is also shown over a scatterplot of the $r_{1\text{Ox}}$ of the 28 literature points in Figure 5.

Since Equation 5 contains four parameters, the fitting process was repeated for all combinations of fewer parameters (e.g., removing $C_{\text{Temp}}$) and the Akaike information criterion (AIC) was calculated for each version of the model—the best-fit model according to the AIC is the model that explains the greatest amount of variation using the fewest possible independent variables. The AIC score, $R^2$, and MSE results of the different models tested are listed in Supplementary Table S3. The model with all four parameters scored the highest according to the AIC, and was therefore used in this manuscript. Removing only $C_3$ produced the second-highest AIC score, and removing only $C_{\text{Temp}}$ produced the third-highest AIC score. The resulting predicted versus true $r_{1\text{Ox}}$ values and parameter distributions from each model are shown in Supplementary Figure S5.

**DISCUSSION**

We have compiled empirical measurements of the relaxivity of oxygen over 50 years of MRI research in phantoms, saline and water solutions, plasma, and vitreous fluid, ranging from 0.011 to 8.45 T and 21 to 40 °C. While the reported relaxivity of oxygen varied greatly, we found that in the solutions of water, saline, vitreous fluid, and plasma the variance could largely be explained by the differences in field strength and
temperature, and that this variation was well approximated by a Lorentzian function and linear relationship with temperature. Therefore, while the table of reported empirical measurements can be referred to for future oxygen-MRI experiments, the \( r_{1Ox} \) can also be estimated using the proposed simplified model for estimating the \( r_{1Ox} \) in water, saline, plasma, and vitreous fluids that agrees well with the empirical measurements.

The relationship between longitudinal relaxation and the paramagnetism of oxygen has a long history in NMR, and there is a large body of both theoretical and empirical work.\(^1\)\(^-\)\(^{14}\)\(^-\)\(^{33}\)\(^-\)\(^{37}\) For materials containing paramagnetic contrast agents, there can be complex relationships between \( R_1 \) and field strength, and these relationships are affected by various factors inherent to the contrast agent.\(^{38}\) This relationship between contrast agent relaxivity and the magnetic field is important, as it can obscure the reproducibility of MRI-oxygen experiments if performed at different field strengths and temperatures.

The physical mechanisms that explain the relationship between field strength and relaxivity are complex, and although there are sophisticated explanations for specific contrast agents,\(^ {39}\)\(^-\)\(^ {42}\) much of the modelling of this relaxivity relies on empirical measurements.\(^ {43}\) While there has been previous evidence for modelling relaxivity-\( B_0 \) relationships as linear or logarithmic,\(^ {44}\)\(^ {45}\) one major limitation is that the majority of relaxivity measurements of contrast agents are performed at only two field strengths (1.5 and 3 T), which makes it difficult to properly describe the true relationship from empirical results. Interestingly, to address this issue, an experiment by Chou et al measured the relaxivity of a gadolinium-based contrast agent at a large range of field strengths, 0-12 T, revealing a curve that peaks around 1-2 T and drops off (in a Lorentzian shape) as field strength increases.\(^ {39}\) While these data are from a gadolinium-based contrast agent rather than oxygen, they suggest that the relationship of oxygen relaxivity and magnetic field strength may also follow a more complex curve than simply linear, or logarithmic. Therefore, for any modelling of relaxivity, it is important to state the range of field strengths over which the model is valid. The lowest field strength used to fit this model was 0.011 T, and below this field strength it is likely that the \( r_{1Ox} \) curves back down to zero as field strength approaches zero, in a similar manner to the pattern seen in Figure 4 of Chou et al,\(^ {39}\) which we have reproduced in Supplementary Figure S6.

4.1 | Limitations

The relaxivity values collected were from experiments performed over a timespan of five decades, with a huge variation in experimental equipment and temperature measurement techniques. Experimental measurement of \( r_{1Ox} \) can be difficult even within a relatively simple system
such as water, because the measurement accuracy depends on the proper selection of acquisition protocols and parameters (i.e., repetition and inversion times). For convenience, acquisition details from each experiment used in developing the present model are listed in Supplementary Table S4. MRI technology has advanced significantly since the measurements made in the 1980s, which account for the measurements made below 0.5 T, and low-field systems usually also suffer from poor signal to noise ratio. In addition, the values have often been extracted from original plots, some hand drawn, which is a source of error, and converted from the various original units to s\(^{-1}\)/mmHg, which can be another source of error. Finally, one experiment did not report the temperature of the solution during the experiment, and it was assumed to be 37°C. These limitations inevitably represent a large source of potential error in the accuracy of this model. It is hoped, however, that this can be addressed as the NMR community produces new measurements of \(r_{1\text{O}}\) at a range of field strengths and temperatures. As a future direction of this work, we have hosted the open-source model code and current \(r_{1\text{O}}\) measurements on GitHub (github.com/BulteGroup/OxygenRelaxivityModel) and invite the NMR community to share new \(r_{1\text{O}}\) measurement results and refit the model to improve the accuracy and enhance the utility of the model.

Furthermore, for the fitting of this model, we have combined values from water, saline, plasma, and vitreous fluids. In reality, there are factors that would cause the relaxivity in these solutions to differ, even amongst saline solutions with different compositions and concentrations. The decision to combine them was due to a lack of sufficient data points at a range of field strengths and temperatures in each solution; however, this is a considerable limitation, as it seems to fit more accurately to the water samples (\(R^2 = 0.94\)) than saline samples (\(R^2 = 0.73\)) alone (Supplementary Figure S3). Most importantly, values from the vitreous fluid and plasma would ideally be fit with separate models, as there are extra proteins in the plasma and vitreous fluid that have been shown to decrease the relaxivity slightly. However, this simply was not possible due to a lack of available data points in the literature. As above, we very much hope that this issue will be addressed as new data are acquired by future researchers.

Finally, this model does not represent the \(r_{1\text{O}}\) in blood and tissues, where the addition of proteins, lipids, and deoxyhemoglobin will affect the \(R_1\)-pO\(_2\) relationship; however, we have created a separate general model to calculate the \(R_1\) of blood, accounting for hematocrit, oxygen saturation, oxygen partial pressure, and magnetic field strength under hyperoxic conditions. For convenience, however, we have listed the reported literature values found in tissue and blood in Supplementary Table S4—nine values from blood and three from tissues. For the purpose of this model, only the 28 \(r_{1\text{O}}\) values in water, saline, vitreous fluid, and plasma were used.

## 5 | CONCLUSION

In conclusion, we have provided an overview of the literature reporting a relationship between longitudinal relaxation and oxygen in phantoms, saline and water solutions, and vitreous fluid ranging from 0.011 to 8.45 T and 21 to 40°C. In addition, we have provided a simplified model for estimating the \(r_{1\text{O}}\) in water, saline, plasma, and vitreous fluids that agrees well (\(R^2 = 0.93\)) with the empirical measurements. We hope that this will provide a useful resource for researchers seeking to quantify pO\(_2\) in simple fluids, such as water and saline phantoms, or bodily fluids such as vitreous fluids, cerebrospinal fluids, and amniotic fluids.

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## DATA AVAILABILITY STATEMENT

Data sharing not applicable to this article as no datasets were generated or analysed during the current study.

## ORCID

Emma Bluemke https://orcid.org/0000-0001-5970-9100

Eleanor Stride https://orcid.org/0000-0003-3371-5929

## REFERENCES

1. Mel’nichenko NA. The solubility of oxygen in sea water and solutions of electrolytes according to the pulse proton NMR data. Russ J Phys Chem A. 2008;82(9):1533-1539. https://doi.org/10.1134/S0036024408090239
2. Muir ER, Cardenas DP, Duong TQ. MRI of brain tissue oxygen tension under hyperbaric conditions. Neuroimage. 2016;133:498-503. https://doi.org/10.1016/j.neuroimage.2016.03.040
3. Nestle N, Baumann T, Niesner R. Oxygen determination in oxygen-supersaturated drinking waters by NMR relaxometry. Water Res. 2003;37(14):3361-3366. https://doi.org/10.1016/S0043-1354(03)00211-2
39. Chou C-Y, Abdesselem M, Bouzigues C, et al. Ultra-wide range field-dependent measurements of the relaxivity of Gd_{1-x}Eu_xVO_4 nanoparticle contrast agents using a mechanical sample-shuttling relaxometer. Sci Rep. 2017;7(1):44770. https://doi.org/10.1038/srep44770

40. Fischer HW, Rinck PA, van Haverbeke Y, Muller RN. Nuclear relaxation of human brain gray and white matter: analysis of field dependence and implications for MRI. Magn Reson Med. 1990;16(2):317-334. https://doi.org/10.1002/mrm.1910160212

41. Kirsch JE. Basic principles of magnetic resonance contrast agents. Top Magn Reson Imaging. 1991;3(2):1-18.

42. Koenig SH, Baglin C, Brown RD, Brewer CF. Magnetic field dependence of solvent proton relaxation induced by Gd\textsuperscript{3+} and Mn\textsuperscript{2+} complexes. Magn Reson Med. 1984;1(4):496-501. https://doi.org/10.1002/mrm.1910010408

43. Elster AD. How much contrast is enough? Dependence of enhancement on field strength and MR pulse sequence. Eur Radiol. 1997;7(Suppl 5):276-280. https://doi.org/10.1007/pl00006908

44. Hales PW, Kirkham FJ, Clark CA. A general model to calculate the spin-lattice (T\textsubscript{1}) relaxation time of blood, accounting for haematocrit, oxygen saturation and magnetic field strength. J Cereb Blood Flow Metab. 2016;36(2):370-374. https://doi.org/10.1177/0271678X15605856

45. Wang Y, van Gelderen P, de Zwart JA, Duyn JH. B\textsubscript{0}-field dependence of MRI T\textsubscript{1} relaxation in human brain. Neuroimage. 2020;213:116700. https://doi.org/10.1016/j.neuroimage.2020.116700

46. Bluemke E, Stride E, Bulte DP. A general model to calculate the spin-lattice relaxation rate (R\textsubscript{1}) of blood, accounting for haematocrit, oxygen saturation, oxygen partial pressure, and magnetic field strength under hyperoxic conditions. J Magn Reson Imaging. https://doi.org/10.1002/jmri.27938, In press.

SUPPORTING INFORMATION

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