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A Flow-Diffusion Model of Oxygen Transport for Quantitative Mapping of Cerebral Metabolic Rate of Oxygen (CMRO₂) with Single Gas Calibrated fMRI

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Abstract

One promising approach for mapping CMRO_2 is dual-calibrated functional MRI (dc-fMRI). This method exploits the Fick Principle to combine estimates of resting CBF from ASL, and resting OEF derived from BOLD-ASL measurements during arterial O_2 and CO_2 modulations. Multiple gas modulations are required to decouple OEF and deoxyhemoglobin-sensitive blood volume. We propose an alternative single gas calibrated fMRI framework, integrating a model of oxygen transport, that links blood volume and CBF to OEF and creates a mapping between the maximum BOLD signal, CBF, and OEF (and CMRO_2). Simulations demonstrated the method's viability within mitochondrial oxygen pressure, P_mO_2 , and mean capillary transit time physiological ranges. A dc-fMRI experiment, performed on 20 healthy subjects using alternating O_2 and CO_2 challenges, was used to validate the approach. The validation conveyed expected estimates of model parameters (e.g., low P_mO_2), with stable OEF maps (grey matter, GM, OEF Standard Deviation ≈ 0.13). GM OEF estimates obtained with hypercapnia correlated with dc-fMRI ($r=0.65$, $p=2 \cdot 10^{-3}$). For 12 subjects, OEF measured with dc-fMRI and the single gas calibration method were correlated with whole-brain OEF derived from phase measures in the superior sagittal sinus ($r=0.58$, $p=0.048$; $r=0.64$, $p=0.025$ respectively). The simplified calibrated fMRI method using hypercapnia holds promise for clinical application.

Keywords: Calibrated Functional Magnetic Resonance Imaging (Calibrated fMRI), Cerebral Metabolic Rate of Oxygen (CMRO_2), Hypercapnia, Hyperoxia, Oxygen Transport Modelling

INSERT TABLE 1 HERE**1. Introduction**

Oxidative metabolism provides most of the brain's energy and is altered in a variety of pathologies such as neurodegenerative and neuroinflammatory diseases, stroke, epilepsy, and migraine¹. Magnetic resonance imaging (MRI) approaches for mapping baseline (₀) cerebral metabolic rate of oxygen (CMRO_{2,0})²⁻⁸ exploit the Fick Principle, that expresses CMRO₂ as the product of oxygen delivery (the product of oxygen concentration in arterial blood, C_aO₂, and cerebral blood flow, CBF) and oxygen extraction fraction (OEF) measured in either the macrovascular or the microvascular compartment. Macrovascular CBF₀ can be estimated from volume flow rate in large feeding arteries or draining veins using flow encoding sequences², whereas OEF₀ can be assessed in draining veins using sequences that measure magnetic susceptibility or blood T₂ predominantly affected by the presence of deoxyhemoglobin (dHb)^{8,9}. Since large vessels feed or drain significant portions of brain, such measures deliver global or regional information at best. Microvascular CBF₀ can be mapped using perfusion-weighted sequences such as Arterial Spin Labelling (ASL). One drawback of ASL is its low contrast in white matter (WM). Moreover, mapping microvascular OEF₀ is challenging because baseline magnetic susceptibility and MR relaxation parameters within a voxel with a small vascular compartment are not uniquely affected by dHb.

Among others^{10,11}, dual-calibrated functional MRI (dc-fMRI)^{4,12-15} is a promising approach for OEF₀ and CMRO_{2,0} mapping. While measuring CBF₀ with ASL, dc-fMRI estimates OEF₀ from the blood oxygen level dependent (BOLD) signal sensitivity to dHb₀. dc-fMRI uses BOLD-ASL recordings, biophysical modelling of BOLD signal¹⁶ and assumed isometabolic hypercapnic and hyperoxic modulations of CBF and C_aO₂ through respiratory stimuli. BOLD sensitivity to dHb₀ is encoded in the maximum BOLD increase, M, corresponding to complete dHb removal. The two respiratory stimuli decouple the contribution to M of OEF₀ and the dHb₀-sensitive cerebral blood volume, CBV_{v,0}, when Hb concentration in blood [Hb]^{4,14} is known. Although dc-fMRI has been applied in exemplar clinical studies¹⁷⁻²¹, its adoption is limited by the low signal to noise ratio (SNR)²² and by the complex gas challenge paradigm required.

Here, we introduce a new calibrated fMRI framework that estimates OEF₀ with only one measurement of M based on one manipulation of brain physiology and a flow-diffusion model of oxygen transport^{13,23,24}. The model

describes the steady-state oxygen diffusion from the capillaries into the tissue (equal to $CMRO_2$) as proportional to the product of the mean capillary transit time (mean CTT, MCTT) and the pressure gradient between the capillary bed and the mitochondria (where the proportionality constant is the effective tissue permeability to oxygen, k). Since MCTT can be expressed as the ratio between capillary blood volume (CBV_{cap}) and CBF, the flow-diffusion model can be incorporated in the formulation of M by substituting $CBV_{v,0}$ for an appropriately scaled $CBV_{cap,0}$ (with ρ being the scaling factor). This substitution replaces one unknown variable, $CBV_{v,0}$, with two unknowns, one proportionality constant, being a function of ρ and k , and the oxygen pressure at the mitochondria ($P_{mO_{2,0}}$). The advantage of the model lies in the tight distributions of the new parameters and on the reduced effect of their variabilities in the estimate of OE_{F0} , creating a probabilistic mapping of M , $C_aO_{2,0}$ and CBF_0 with OE_{F0} and $CMRO_{2,0}$ as the parameters to be inferred.

This manuscript reports the validation of the novel single gas approach. We term the new approach using a hypercapnic stimulus, hc-fMRI+, and that using a hyperoxic stimulus, ho-fMRI+. The report is divided into four sections. The first section, by exploiting simulations, describes the advantages, the validity, and the robustness to noise of the framework. The second section investigates the new model *in-vivo* using a dc-fMRI experiment, employing alternating hypercapnic and hyperoxic gas challenges in healthy subjects. We use a global estimate of OE_{F0} in the grey matter (GM), obtained with dc-fMRI analysis²², and we invert the single gas model using only the hypercapnic or the hyperoxic component of the experiment to investigate the distribution of the proportionality constant and $P_{mO_{2,0}}$ across subjects. The third section validates hc-fMRI+ and ho-fMRI+ against dc-fMRI²². To do so, the two parameters of the model are fixed to the average values obtained from the previous analysis, and the model is inverted to infer OE_{F0} . Finally, in the fourth section, GM OE_{F0} estimates from the different fMRI approaches are compared to whole-brain OE_{F0} inferred from a validated MRI sequence performing phase measures in the superior sagittal sinus (SSS) and conventionally termed 'OxFlow'^{2,25}.

2. Methods

2.1. Analytical Modeling

Here we summarize the analytical model derivation. Please refer to Supplementary Information for a more detailed description.

2.1.1. BOLD Model and the Dual-Calibrated fMRI Experiment

The rate of signal decay due to dHb, $R_2^*|_{dHb}$, within a voxel is represented by^{26,27}:

$$R_2^*|_{dHb} = A \cdot CBV_v \cdot ((1 - S_v O_2) \cdot [Hb])^\beta \quad (1)$$

where $S_v O_2$ is venous saturation, $[Hb]$ is the concentration of hemoglobin in blood and CBV_v is the BOLD sensitive blood volume. β ($\beta = 1.3$ at 3T) and A are field strength and vessel geometry dependent constants. For small perturbations of $R_2^*|_{dHb}$ and using the Grubb relation linking fractional changes in CBV_v and CBF, the steady-state BOLD signal can be expressed, within the Davis Model framework, as^{14,28}:

$$\frac{\Delta BOLD}{BOLD_0} = TE \cdot A \cdot CBV_{v,0} \cdot ((1 - S_v O_{2,0}) \cdot [Hb])^\beta \cdot \left\{ 1 - \left(\frac{CBF}{CBF_0} \right)^\alpha \cdot \left(\frac{1 - S_v O_2}{1 - S_v O_{2,0}} \right)^\beta \right\} \quad (2)$$

with the maximum BOLD signal M being equal to:

$$M = TE \cdot A \cdot CBV_{v,0} \cdot ((1 - S_v O_{2,0}) \cdot [Hb])^\beta \quad (3)$$

The subscript ₀ depicts baseline values, $\Delta BOLD/BOLD_0$ is the relative BOLD signal change, TE is the sequence echo-time and α is the Grubb exponent ($\alpha = 0.38$). During an isometabolic manipulation of brain physiology, Equation 2 can be expressed as a function of OEf_0 as:

$$\frac{\Delta BOLD}{BOLD_0} = TE \cdot A \cdot CBV_{v,0} \cdot \left(\left(1 - \frac{C_a O_{2,0}}{\phi \cdot [Hb]} \cdot (1 - OEf_0) \right) \cdot [Hb] \right)^\beta \cdot \left\{ 1 - \left(\frac{CBF}{CBF_0} \right)^\alpha \cdot \left(\frac{1 - \frac{C_a O_2}{\phi \cdot [Hb]} \cdot \left(1 - \frac{OEf_0 \cdot CBF_0 \cdot C_a O_{2,0}}{CBF \cdot C_a O_2} \right)}{1 - \frac{C_a O_2}{\phi \cdot [Hb]} \cdot (1 - OEf_0)} \right)^\beta \right\} \quad (4)$$

with $C_a O_2$ being the oxygen concentration in arterial blood and ϕ being the oxygen binding capacity of hemoglobin ($\phi = 1.34$ mL/g). Even when combining together A and $CBV_{v,0}$ in Equation 4, the equation still has two unknowns making it not possible to solve for OEf_0 through one manipulation of brain physiology. dc-fMRI solves this by performing two independent manipulations: hypercapnia and hyperoxia. However, the approach suffers from low SNR, a problem that has been addressed by regularizing the inversion procedure for OEf_0 ²⁹ and by using, simulation-trained, machine learning approaches applied to raw recordings²².

2.1.2. Flow-Diffusion Model of Oxygen Transport

A simple model can be used to describe the steady-state radial oxygen diffusion into the tissue along a straight cylindrical capillary of unit length²⁴:

$$\frac{dC_{cap}O_2(x)}{dx} = -k \cdot T_{cap} \cdot (P_{cap}O_2(x) - P_mO_2) \quad (5)$$

where $C_{cap}O_2$ and $P_{cap}O_2$ are the concentration and the partial pressure of oxygen at a relative position x along the capillary and T_{cap} is the CTT. k , the effective permeability, combines the effects of the capillary wall and the surrounding brain tissue into a single interface between the plasma and a well-stirred oxygen pool at the mitochondria at end of the diffusion path, at which the pressure of oxygen is equal to P_mO_2 ^{13,30}. CTT in the single straight capillary is then approximated by the MCTT in the capillary bed within the voxel. MCTT is expressed as the ratio between the capillary blood volume (CBV_{cap}) and CBF. Since $P_{cap}O_2$ and $C_{cap}O_2$ quickly equilibrate (less than a few milliseconds), depending upon the nonlinear nature of Hb binding to oxygen described mathematically by the Hill Equation:

$$SO_2 = \frac{1}{1 + \left(\frac{P_{50}}{P_{O_2}}\right)^h} \quad (6)$$

the following can be obtained:

$$CBF \cdot \frac{dC_{cap}O_2(x)}{dx} = -k \cdot CBV_{cap} \cdot \left(P_{50} \cdot \sqrt[h]{\frac{C_{cap}O_2(x)}{\varphi \cdot [Hb] - C_{cap}O_2(x)}} - P_mO_2 \right) \quad (7)$$

where P_{50} is the oxygen partial pressure when half of Hb is saturated (generally $P_{50} \approx 26$ mmHg; P_{50} can be inferred from a measure of end-tidal partial pressure of carbon dioxide, $P_{ET}CO_2$), and h is the Hill constant ($h=2.8$). An approximated closed solution to the differential Equation 7 can be made assuming a linear decrease of $C_{cap}O_2(x)$ and an average $C_{cap}O_2(x)$ equal to $\langle C_{cap}O_2(x) \rangle \approx \varphi \cdot [Hb] \cdot (S_aO_2 + S_vO_2)/2 = \varphi \cdot [Hb] \cdot (1 - OEF/2)$, where S_aO_2 is the arterial oxygen saturation. Integrating Equation 7 and equalizing the oxygen loss from the capillary to $CMRO_2$, the following is obtained:

$$CMRO_2 = CBF \cdot OEF \cdot CaO_2 = k \cdot CBV_{cap} \cdot \left(P_{50} \cdot \sqrt[h]{\frac{2}{OEF}} - 1 - P_mO_2 \right) \quad (8)$$

2.1.3. Integration of the Flow-Diffusion Model of Oxygen Transport into the BOLD Model for Calibrated-fMRI Quantification of CMRO₂

CBV_{cap} is here assumed to be a fraction of CBV_v, i.e., CBV_v = ρ · CBV_{cap}. Substituting CBV_{cap}, from Equation 8 into Equation 4, we obtain:

$$\frac{\Delta BOLD}{BOLD_0} = TE \cdot \frac{A \cdot \rho}{K} \cdot \frac{CBF_0 \cdot OEF_0 \cdot C_a O_{2,0} \cdot \left(\left(1 - \frac{C_a O_{2,0}}{\phi [Hb]} (1 - OEF_0) \right) [Hb] \right)^\beta}{\left(P_{50} \cdot \sqrt{\frac{2}{OEF_0}} - 1 - P_m O_{2,0} \right)} \cdot \left\{ 1 - \left(\frac{CBF}{CBF_0} \right)^\alpha \cdot \left(\frac{1 - \frac{C_a O_2}{\phi [Hb]} \left(1 - \frac{OEF_0 \cdot CBF_0 \cdot C_a O_{2,0}}{CBF \cdot C_a O_2} \right) \right)^\beta}{1 - \frac{C_a O_{2,0}}{\phi [Hb]} (1 - OEF_0)} \right\} \quad (9)$$

with the maximum BOLD signal M equal to:

$$M = TE \cdot \frac{A \cdot \rho}{K} \cdot \frac{CBF_0 \cdot OEF_0 \cdot C_a O_{2,0} \cdot \left(\left(1 - \frac{C_a O_{2,0}}{\phi [Hb]} (1 - OEF_0) \right) [Hb] \right)^\beta}{\left(P_{50} \cdot \sqrt{\frac{2}{OEF_0}} - 1 - P_m O_{2,0} \right)} \quad (10)$$

Equations 9 and 10 encode a non-linear mapping of measurable quantities M, C_aO_{2,0} and CBF₀ with OEF₀, enabling OEF₀ (and hence CMRO_{2,0}) to be inferred using a single manipulation of brain physiology. Apart from the constants that can be indirectly inferred (e.g., P₅₀, [Hb]), assumed (e.g., φ, β) or controlled (e.g., TE), the mapping depends on the non-measurable quantities: A, ρ, k and P_mO_{2,0}. A, having the same origins as β³¹, can be estimated assuming primarily an extravascular BOLD signal and assuming R₂*_{dHb} = R₂'^{32,33}. With an experimentally determined cortical R₂' of approximately 3 s⁻¹ at 3T³⁴, an average [Hb] of 14 g/dL, a S_vO₂ of 0.6, and a mean CBV_v of 2.5%, from Equation 1 we expect a value of A ≈ 14 s⁻¹g^{-β}dL^β at 3T. *In-vivo* variation in ρ has not been studied directly; we discuss this in the Supplementary Information. We expect ρ to be in the range 2 to 3, assuming a capillary blood volume between 20% to 40% of total blood volume, when the arterial contribution is assumed to be 20% to 30%³⁵. Moreover, we expect a value for the oxygen effective permeability k of around 3 μmol/mmHg/ml/min²². This value is derived from the literature using a different formalism where oxygen diffusion is assumed to happen at the endothelial wall of capillaries³⁶. In Equations 9 and 10, we create a practical grouping of A, ρ and k into one multiplicative parameter A·ρ/k. At a fixed field strength, all the three parameters are related to tissue structure and vessel geometry, which plausibly affects water and oxygen diffusion in the intravascular and extravascular spaces as well as the volumetric relationship between capillaries, venules and veins. We expect a

value of $A \cdot \rho / k$ of the order of $A \cdot \rho / k \approx 10 \text{ s}^{-1} \text{ g}^{-\beta} \text{ dL}^{\beta} / (\mu\text{mol}/\text{mmHg}/\text{ml}/\text{min})$. The mitochondrial oxygen partial pressure at rest, $P_{mO_{2,0}}$, must lie between 0 mmHg and the average oxygen tension of the capillary bed. Several in vivo studies suggest that oxygen tension at brain mitochondria is small in the healthy brain^{23,37}, and this theory is consistent with functional hyperemia in response to increased brain oxygen demand. However, departure from a negligible oxygen tension is plausible in the diseased brain.

In summary, the non-linear mapping in Equation 9 permits estimation of OEf_0 from one manipulation of brain physiology. Uncertainty in the mapping is driven by variability in two non-measurable quantities, a proportionality constant $A \cdot \rho / k$, that depends on tissue and micro-vessel structure at a fixed field strength, and $P_{mO_{2,0}}$. Importantly, these non-measurable quantities affect the non-linear mapping differently. The advantage of the new framework lies in the low variability of these parameters and their diminished influence on the OEf_0 estimation compared to $CBV_{v,0}$.

2.2. Simulations (Section 1)

We performed simulations to investigate the ability of hc-fMRI+ and ho-fMRI+ to infer OEf_0 . A forward model using Equation 9 was implemented to simulate the BOLD signal and was inverted to retrieve OEf_0 . In the forward model some variables were fixed (TE, α , β , h, ϵ , ϕ) (ϵ is the oxygen plasma solubility, $\epsilon=0.0031 \text{ mL}/\text{mmHg}/\text{dL}$) while others were simulated based on random sampling from physiologically and physically plausible distributions. When inverting the model, some random variables were unknown and were either fixed a-priori ($A \cdot \rho / k$, $P_{mO_{2,0}}$), or inferred (OEf_0 , $CBV_{cap,0}$ and $MCTT_{,0}$). Firstly, we ran the full forward and inverse analysis without measurement noise as a function of either the value chosen a-priori for the random variables that were fixed during the inversion or other parameters of interest ($P_{mO_{2,0}}$ and $MCTT_{,0}$). Secondly, we evaluated the effect of measurement noise, which was introduced on measures with lower signal to noise ratio (SNR), namely ASL CBF/CBF_0 and $\Delta BOLD/BOLD_0$. 10^7 simulations per condition were conducted; the non-linear inversions were performed through explicit search of OEf_0 that explained the measures. The explicit search was performed in the full OEf_0 space (between 0 and 1) with a resolution of 0.01. Constant parameters were set to $\alpha=0.38$, $\beta=1.3$, $h=2.8$, $\epsilon=0.0031 \text{ mL}/\text{mmHg}/\text{dL}$, $\phi=1.34 \text{ mL}/\text{g}$, TE= 30 ms, whereas random variables were simulated using either normal (N) or

gamma (Γ) distributions; additional physiological constraints were applied (please refer to the Table in Supplementary Information for additional information).

Figure 1 reports the distributions of the main random variables used in the forward model simulations. With respect to the parameters that were not measured for the inversion, $A \cdot p/k$ was simulated using a normal distribution with an average value of $10 \text{ s}^{-1} \text{ g}^{-\beta} \text{ dL}^{\beta} / (\mu\text{mol}/\text{mmHg}/\text{ml}/\text{min})$ and a coefficient of variation (CoV) of 0.3, whereas $P_m O_{2,0}$ was simulated using a gamma distribution, allowing variation between zero and $\langle P_{cap,0} \rangle$ to simulate a large variability in $P_m O_{2,0}$ that might be present in disease.

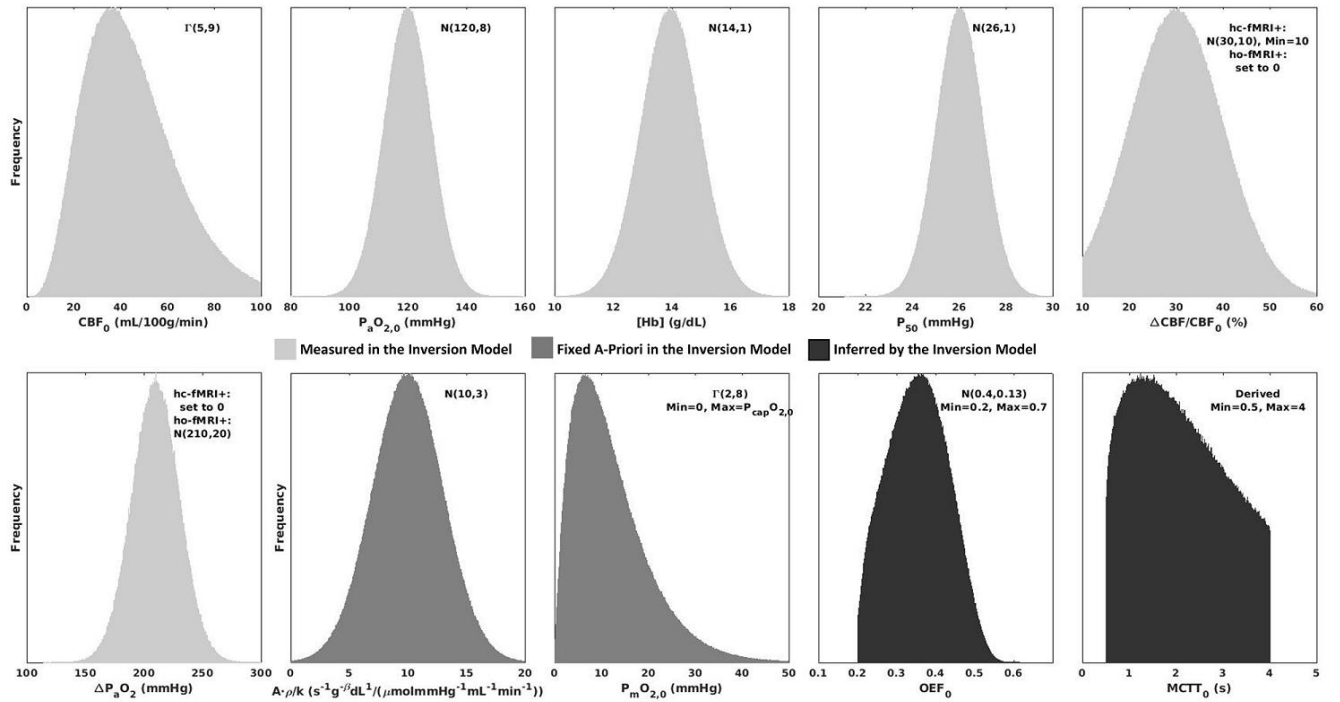


Figure 1: Random variables used to simulate BOLD and ASL signals using a hc-fMRI+ or ho-fMRI+ forward modelling framework. The variables reported in light grey were assumed to be measured for the hc-fMRI+ or ho-fMRI+ inversion model, those reported in medium grey were fixed a-priori in the inversion model and those in dark grey were inferred by the inversion model.

2.3. MRI Experiment (Sections 2-3-4)

Twenty healthy volunteers (13 males, mean age 31.9 ± 6.5 years) were recruited at CUBRIC, Cardiff University, Cardiff, UK. The study was in accordance with the Declaration of Helsinki and was approved by the Cardiff University, School of Psychology Ethics Committee and NHS Research Ethics Committee, Wales, UK.

Written consent was obtained from each participant. Data were acquired using a Siemens MAGNETOM Prisma (Siemens Healthcare GmbH, Erlangen) 3T clinical scanner with a 32-channel receiver head coil (Siemens Healthcare GmbH, Erlangen). A 18 minutes dc-fMRI scan was acquired with interleaved periods of hypercapnia, hyperoxia and medical air being delivered according to the protocol previously proposed^{13,29}. 3 periods of hypercapnic gas challenges and 2 periods of hyperoxic gas challenges were performed. CO₂ and O₂ in the lungs were evaluated from the volunteer's facemask using a gas analyzer (AEI Technologies, Pittsburgh, PA, USA).

Calibrated fMRI data were acquired during the gas challenge scheme using a pCASL acquisition with pre-saturation and background suppression³⁸ and a dual-excitation (DEXI) readout³⁹. The labelling duration (τ) and the Post Label Delay (PLD) were both set to 1.5 s, GRAPPA acceleration (factor = 3) was used with TE₁ = 10 ms and TE₂ = 30 ms. An effective TR of 4.4 s was used to acquire 15 slices, in-plane resolution 3.4 mm×3.4 mm and slice thickness 7 mm with a 20% slice gap. A calibration (S₀) image was acquired for ASL quantification with pCASL labelling and background suppression pulses switched off, with TR=6 s, and TE=10 ms¹³. A high-resolution whole brain structural image, used for GM identification in the fMRI space, was acquired using a 3D Fast Spoiled Gradient-Recalled-Echo T1-weighted acquisition (resolution = 1×1×1 mm³, TE = 3.0 ms, TR = 7.8 ms, TI = 450 ms, flip angle=20°).

For susceptibility-based oximetry, a transverse slice was acquired at approximately 15 mm above the confluence of sinuses (location at which the inferior sagittal, straight, and transverse sinuses join the SSS) using a T2*-weighted spoiled multi-echo gradient-recalled echo (GRE) sequence with: in-plane resolution = 1.6×1.6 mm², slice thickness = 5 mm, field of view (FOV) = 208×208 mm², bandwidth= 260 Hz/pixel, three echo times (TEs = 3.92, 7.44, and 10.96 ms), bipolar gradient readout, TR = 35 ms, flip angle = 25°, and acquisition time = 1 min and 7 s. This acquisition was performed in the framework of the OxFlow method, which previous studies have described in detail^{40–42}. For vessel identification purposes, two-dimensional T2*-weighted time-of-flight (TOF) images were acquired using a spoiled GRE sequence with: in-plane resolution = 0.86×0.86 mm², slice thickness = 2 mm, slice gap = 1.34 mm, FOV = 219×219×234 mm³, in-plane acceleration factor = 2, bandwidth = 220 Hz/pixel, TE=4.99

ms, TR =20 ms, flip angle=60°. Blood samples were drawn via a finger prick before scanning and were analyzed with the HemoCue Hb 301 System (HemoCue, Ängelholm, Sweden) to calculate [Hb].

2.4. fMRI Data Processing (Section 2-3)

2.4.1. Gas Recordings Processing

P_{ET}CO₂ and P_{ET}O₂ were extracted from CO₂ and O₂ recordings using in-house software in Matlab (Mathworks, Natick, MA). P_{ET}CO₂ and P_{ET}O₂ points were interpolated (cubic spline function), resampled to match fMRI, and shifted in time to maximally correlate with fMRI signals. P_{ET}CO_{2,0} and P_{ET}O_{2,0} were evaluated at baseline in the first 110 seconds. P_{ET}O₂ was assumed equal to PaO₂ for C_aO₂ computation whereas P_{ET}CO₂ was assumed equal to PaCO₂. P₅₀ was inferred from estimates of resting blood pH based on the Henderson-Hasselbalch Equation, assuming [HCO₃⁻]= 24 mmol/L⁴³:

$$pH = 6.1 + \log \left(\frac{[HCO_3^-]}{0.03 \cdot P_aCO_2} \right) \quad (11)$$

and calculating P₅₀ according to the linear relation, P₅₀ = 221.87–26.37·pH¹³.

SaO₂ was calculated from PaO₂ using Equation 6 and CaO₂ was inferred using the relation:

$$CaO_2 = \varphi \cdot [Hb] \cdot SO_2 + \varepsilon \cdot PO_2 \quad (12)$$

Finally, to highlight hypercapnic and hyperoxic modulations, P_{ET}CO₂ and P_{ET}O₂ traces were high-pass filtered with a 4th order Butterworth digital filter and a high-pass frequency of 1/600 Hz.

2.4.2. fMRI Processing

Both functional and structural MRIs were processed using FSL⁴⁴ and in-house algorithms implemented in Matlab. fMRI timecourses were motion corrected based on 6 degrees of freedom co-registration using MCFLIRT⁴⁵. High-resolution structural T1-weighted MRIs were skull-stripped using BET⁴⁶ and probability maps of Cerebrospinal Fluid (CSF), WM and GM, were computed using FAST⁴⁷. Motion-corrected fMRI timecourses and the skull-stripped T1-weighted MRI, together with tissue probability maps, were coregistered, relying on 12 degrees of freedom affine transformation, to the S₀ image⁴⁵. ASL control-tag difference perfusion data (ΔS) in S₀ space were obtained through surround subtraction of the fMRI timecourses at

TE₁, normalized with respect to S₀ and converted to CBF in quantitative units of ml/100g/min through the pCASL single compartment kinetic model of labelled spins and voxelwise signal normalization⁴⁸:

$$CBF = \frac{6000 \cdot \lambda \cdot e^{\frac{PLD}{T1_b}}}{\eta \cdot \eta_{inv} \cdot T1_b \cdot \left(1 - e^{-\frac{\tau}{T1_b}}\right)} \cdot \left(\frac{\Delta S}{S_0}\right) \quad (13)$$

where λ is the water partition coefficient ($\lambda = 0.9$ mL/g), T1_b is the T1 relaxation constant of blood, η is the tagging inversion efficiency ($\eta = 0.85$), and η_{inv} is a scaling factor to account for the reduction in tagging efficiency due to background suppression ($\eta_{inv} = 0.88$)⁴⁹. The T1_b was calculated from SaO₂ and PaO₂ measures using the experimental relation presented in⁵⁰:

$$T1_b = \frac{1}{1.527 \cdot 10^{-4} \cdot PaO_2 + 0.1713 \cdot (1 - SaO_2) + 0.5848} \quad (14)$$

CBF₀ was evaluated in the first 110 seconds. Finally, fractional CBF was high pass filtered with a 4th order Butterworth digital filter with a high-pass frequency of 1/600 Hz. BOLD T2*-weighted time-courses were obtained through surround averaging of the fMRI at TE₂ and they were expressed as relative BOLD changes with respect to the temporal average of the BOLD signal in the first 110 seconds (BOLD₀). BOLD relative changes were high pass filtered with a 4th order Butterworth digital filter with a high-pass frequency of 1/600 Hz.

Both processed CBF and BOLD volumes were masked with a GM mask at 50% probability threshold.

2.4.3. Dual-Calibrated fMRI Analysis

Firstly, OEF₀ maps were obtained with a dc-fMRI analysis. Because of the method's known low SNR, explicit inversion methodologies were avoided and a state-of-the-art method to analyze the data relying on a machine learning approach was used. The machine learning algorithm was fed with fMRI timecourses and, through a time-frequency transformation of fMRI signals to extract features of interest, directly mapped OEF₀ and CMRO_{2,0} relying on a pre-trained model based on simulated data. Please refer to²² for detailed information.

2.4.4. Single gas calibrated fMRI Analysis

Single gas calibrated fMRI analysis was performed on either the hypercapnic (using hc-fMRI+) or the hyperoxic (using ho-fMRI+) modulations within the dc-fMRI experiment. The evaluation of BOLD and ASL changes with physiological manipulations was performed using the general linear model (GLM)⁵¹. P_{ET}CO₂ and P_{ET}O₂ were

concurrently regressed on BOLD and ASL filtered modulations. The GLM β -weight delivered an estimate of BOLD or CBF modulation per unit of mmHg of $P_{ET}CO_2$ and $P_{ET}O_2$. The total modulation was then obtained by multiplying the β -weight with the maximum $P_{ET}CO_2$ or $P_{ET}O_2$ modulation. The SNR of the modulation was estimated by dividing the GLM β -weight by its confidence interval. In section 2 we focus on evaluating the between subjects distribution of the unknown parameters of the extended model, namely $A \cdot p/k$ and $P_mO_{2,0}$. This analysis was performed by extracting average BOLD and ASL modulations in the GM. These average estimates were used, together with a global estimate of GM OEf_0 obtained with the dc-fMRI analysis, to invert the model and estimate the unknown parameters. The inversion relied on Equation 9, which clearly could not be solved for the two unknowns; however, since $A \cdot p/k$ and $P_mO_{2,0}$ differently affect the non-linear mapping between BOLD and ASL modulations and OEf_0 , we were able to get insight into the average value of both parameters. In particular, we inverted the model assessing the proportionality constant $A \cdot p/k$ as a function of the a-priori fixed $P_mO_{2,0}$. We expected the $A \cdot p/k$ distribution to have a smaller CoV when $P_mO_{2,0}$ was closer to the correct average value. The non-linear inversion was performed through an explicit search in the range, for $A \cdot p/k$, between 0 and $40 \text{ s}^{-1} \text{g}^{-\beta} \text{dL}^{\beta}/(\mu\text{mol}/\text{mmHg}/\text{ml}/\text{min})$ with a resolution of $0.2 \text{ s}^{-1} \text{g}^{-\beta} \text{dL}^{\beta}/(\mu\text{mol}/\text{mmHg}/\text{ml}/\text{min})$ and, for $P_mO_{2,0}$, between 0 and 50 mmHg with a resolution of 1 mmHg. In section 3, the unknown parameters were fixed both spatially and between subjects to the optimal values derived in the first step and hc-fMRI+ and ho-fMRI+ inversion models were used for voxelwise estimation of OEf_0 and $CMRO_{2,0}$ and comparison with the estimates derived from the dc-fMRI analysis.

2.5. OxFlow Data Processing (Section 4)

In section 4 of the work, for a subset of twelve subjects, GM estimates of OEf_0 using single or dual calibrated fMRI approaches were compared to whole-brain estimates of OEf_0 from SSS derived using the OxFlow procedure. OxFlow images were processed using Matlab and code developed in-house. OEf_0 measurements were obtained based on the normalized difference in signal phase between the first and third TEs ($\Delta\phi/\Delta TE$), with acquisitions having equal gradient polarity⁴¹. The static background field inhomogeneity was removed using a second-order polynomial fitting⁴². The intravascular phase was measured as the average signal phase in a region of interest centered in the cross-section of SSS relative to the average signal phase in the tissue region surrounding the SSS. The angle (θ) between the SSS and B_0 was evaluated by comparing the slice acquired for OxFlow and the SSS

orientation in the slices immediately above and immediately below in the TOF image. Individual measurements of hematocrit (Hct, %) were obtained based on [Hb] assuming a ratio $Hct/[Hb]=3$ (%dL/g)⁵².

OE_{F0} was calculated using the infinite cylinder analytical model⁴¹:

$$OE_{F_0} = \frac{\frac{2\Delta\phi}{\Delta TE}}{\gamma \cdot \Delta\chi_{do} \cdot Hct \cdot B_0 \cdot \left(\cos^2 \theta - \frac{1}{3}\right)} \quad (25)$$

where γ is the proton gyromagnetic ratio ($\gamma=267.52 \cdot 10^6$ rad/s/T), and $\Delta\chi_{do}=4\pi \cdot 0.27 \cdot 10^{-6}$ is the magnetic susceptibility difference between fully oxygenated and fully deoxygenated red blood cells⁵³.

2.6. Statistical Analysis

Pearson's correlations and t-tests were performed to assess pairwise associations and biases between the different estimates. Null-hypothesis probabilities (p-values) were calculated using the Student's t distribution (using transformation of correlation for association testing). Normality evaluation was performed prior to statistical inference using the Kolmogorov-Smirnov test.

3. Results

3.1. Simulations (Section 1)

Figure 2 reports the outcome in estimating OE_{F0} when using hc-fMRI+ and ho-fMRI+ inversion models with fixed a-priori parameters. Figure 2a displays the OE_{F0} root mean square error (RMSE) obtained for hc-fMRI+ and ho-fMRI+ with $A \cdot p/k = 10 \text{ s}^{-1} \text{g}^{-\beta} \text{dL}^{\beta} / (\mu\text{mol}/\text{mmHg}/\text{ml}/\text{min})$ as a function of $P_{mO_{2,0}}$. A minimum RMSE of OE_{F0}=0.039 was obtained for hc-fMRI+ and a minimum RMSE of OE_{F0}=0.051 was obtained for ho-fMRI+, both at $P_{mO_{2,0}}=11$ mmHg. Figure 2b displays the scatterplots of the simulated OE_{F0} vs. the estimated OE_{F0} for hc-fMRI+ and ho-fMRI+ when marginalizing the other variables. The scatterplots reported were obtained using a close to optimal $P_{mO_{2,0}}$, $P_{mO_{2,0}}=10$ mmHg, and $P_{mO_{2,0}}=0$ mmHg. Figure 2c reports the OE_{F0} RMSE for the two methods evaluated as a function of two physiological parameters of interest in the forward model, namely MCTT₀ and $P_{mO_{2,0}}$, when fixing a-priori the non-measurable parameters analogous to Figure 2b. Importantly, when adding noise to

BOLD and fractional changes in CBF, the analysis highlighted the stability of the approach with respect to measurement SNR, with the OEF₀ RMSE reaching the OEF₀ RMSE related to model parameters uncertainty at BOLD and ASL SNRs around 4 (refer to Supplementary information for additional information).

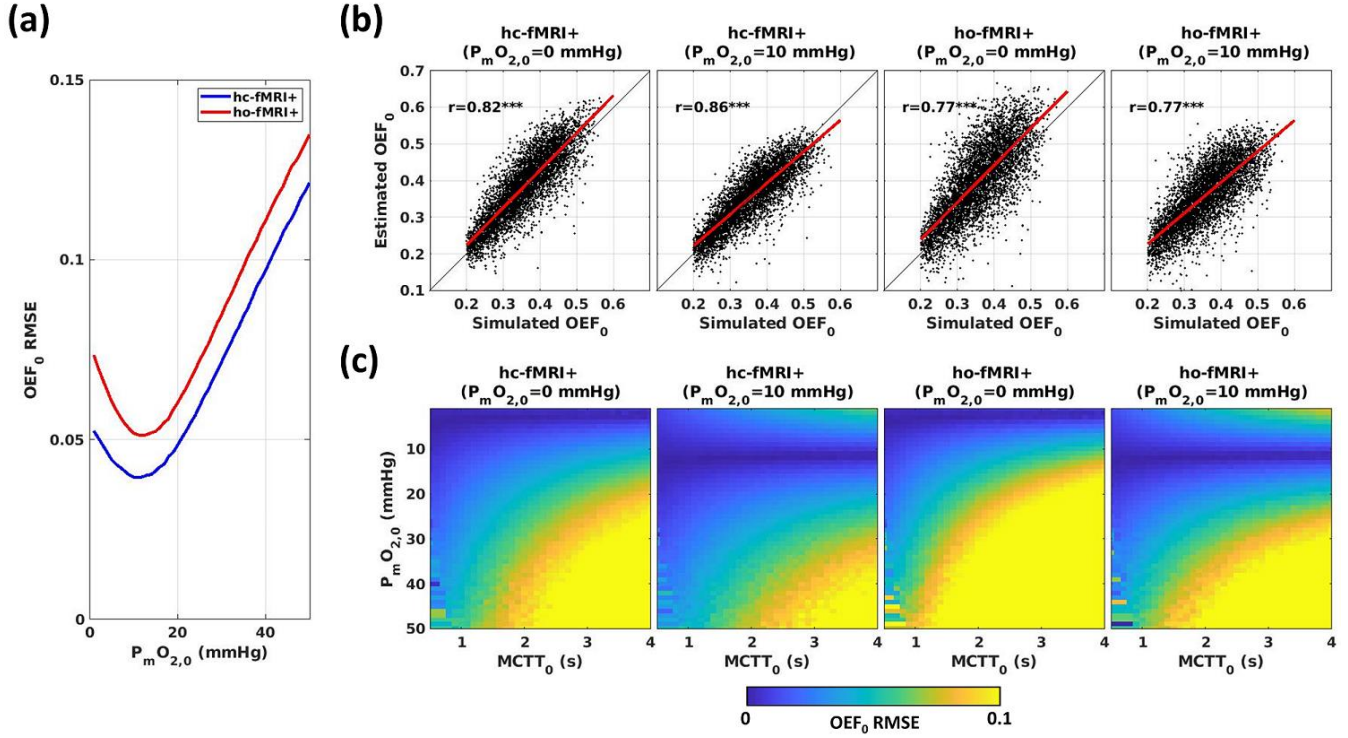


Figure 2: (a) RMSE in OEF₀ for hc-fMRI+ and ho-fMRI+ inversion models with $A \cdot \rho / k = 10 \text{ s}^{-1} \text{g}^{-1} \text{dL}^{\beta} / (\mu\text{mol}/\text{mmHg}/\text{ml}/\text{min})$ as a function of $P_{mO_{2,0}}$. (b) Scatterplots of the simulated and estimated OEF₀ for hc-fMRI+ and ho-fMRI+ inversion models assuming either $P_{mO_{2,0}} = 0$ mmHg or $P_{mO_{2,0}} = 10$ mmHg; (c) RMSE in OEF₀ as a function of the forward model MCTT₀ and $P_{mO_{2,0}}$ for hc-fMRI+ and ho-fMRI+ inversion models assuming either $P_{mO_{2,0}} = 0$ mmHg or $P_{mO_{2,0}} = 10$ mmHg. *** $p < 10^{-3}$

3.2. In-Vivo Evaluation of Gas, CBF and BOLD Modulations (Section 2-3-4)

Figure 3 reports the processing steps, in an exemplar subject, that were used to derive the hypercapnic and the hyperoxic CBF and BOLD modulations. Figure 3a shows O₂ signals acquired through the gas analyzer with the estimated P_{ETO_2} traces whereas figure 3b depicts CO₂ signals and P_{ETCO_2} traces. Figure 3c shows example of the ASL CBF/CBF₀ and the filtered and fitted P_{ETCO_2} . Figure 3d shows the relative BOLD change and the filtered P_{ETCO_2} and P_{ETO_2} traces fitted onto $\Delta\text{BOLD}/\text{BOLD}_0$. The GLM β -weight (in units of cerebrovascular reactivity, CVR, or in units of signal per mmHg of P_{ETO_2}) were multiplied by the maximum gas modulation to obtain the hypercapnic CBF/CBF₀ and the hypercapnic as well as hyperoxic $\Delta\text{BOLD}/\text{BOLD}_0$ modulations. Additional

information on gas and signal modulations are reported in the Supplementary Information. The GLM analysis delivered an SNR (evaluated as the statistical relevance of the β -weight) of $\text{SNR}_{\text{ASL}}=6.1$ ($\text{SD}=5.4$), hypercapnic $\text{SNR}_{\text{BOLD}}=16$ ($\text{SD}=12.7$) and hyperoxic $\text{SNR}_{\text{BOLD}}=8.6$ ($\text{SD}=7.52$).

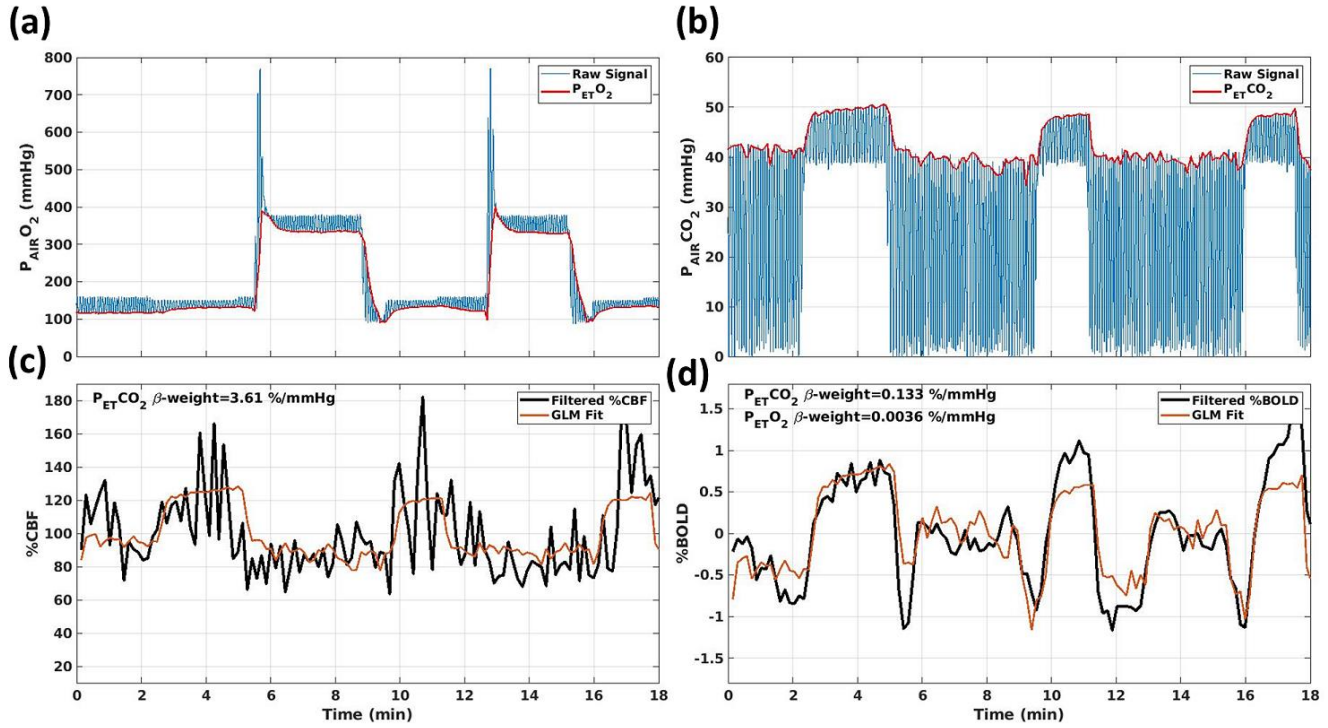


Figure 3: Example of: (a) O_2 and estimated $P_{\text{ET O}_2}$ traces; (b) CO_2 and estimated $P_{\text{ET CO}_2}$ traces; (c) GM CBF/ CBF_0 and fitted $P_{\text{ET CO}_2}$ trace. The β -weight of the GLM fit, with units of a CVR, $\text{CBF}/\text{CBF}_0/\text{mmHg}$, was multiplied by the maximum modulation $\Delta P_{\text{ET CO}_2}$ to obtain the hypercapnic CBF/CBF_0 . (d) GM average $\Delta \text{BOLD}/\text{BOLD}_0$ and fitted $P_{\text{ET CO}_2}$ and $P_{\text{ET O}_2}$ traces. The β -weights, with units of %BOLD/mmHg of $P_{\text{ET CO}_2}$ and $P_{\text{ET O}_2}$, were multiplied by the maximum modulation $\Delta P_{\text{ET O}_2}$ and $\Delta P_{\text{ET CO}_2}$ to obtain the hypercapnic and the hyperoxic $\Delta \text{BOLD}/\text{BOLD}_0$.

3.2. In-Vivo Estimation of Modeling Parameters (Section 2)

Figure 4 reports the analysis performed *in-vivo* to evaluate the modelling parameters. Figure 4a reports the subjects' average value (and standard error, SE) of $A \cdot \rho/k$ as a function of $P_{\text{m O}_{2,0}}$. The value is reported for both hc-fMRI+ and ho-fMRI+. In agreement with Equation 9, for higher $P_{\text{m O}_{2,0}}$ the estimate of $A \cdot \rho/k$ decreased. We obtained, for a $P_{\text{m O}_{2,0}}=0$, an average value of $A \cdot \rho/k=8.85 \text{ s}^{-1} \text{g}^{-\beta} \text{dL}^{\beta}/(\mu\text{mol}/\text{mmHg}/\text{ml}/\text{min})$ ($\text{SE}=0.58 \text{ s}^{-1} \text{g}^{-\beta} \text{dL}^{\beta}/(\mu\text{mol}/\text{mmHg}/\text{ml}/\text{min})$) for hc-fMRI+ and $A \cdot \rho/k=6.03 \text{ s}^{-1} \text{g}^{-\beta} \text{dL}^{\beta}/(\mu\text{mol}/\text{mmHg}/\text{ml}/\text{min})$ ($\text{SE}=0.41 \text{ s}^{-1} \text{g}^{-\beta} \text{dL}^{\beta}/(\mu\text{mol}/\text{mmHg}/\text{ml}/\text{min})$) for ho-fMRI+. Figure 4b reports the CoV of $A \cdot \rho/k$ for hc-fMRI+ and ho-fMRI+ as a

function of $P_{mO_{2,0}}$. The smallest CoV was obtained with a $P_{mO_{2,0}} \approx 0$ for both hc-fMRI+ (CoV=0.29) and ho-fMRI+ (CoV=0.31) with a monotonic CoV increase at increasing $P_{mO_{2,0}}$.

Figure 4c reports the comparison between hc-fMRI+ and ho-fMRI+ estimates of $A \cdot p/k$ for each subject, when fixing the $P_{mO_{2,0}}$ at the value of $P_{mO_{2,0}} = 0$ mmHg. A good correlation was obtained with a $r=0.71$, $df=18$, $p=4.2 \cdot 10^{-4}$, with a smaller hyperoxic estimate.

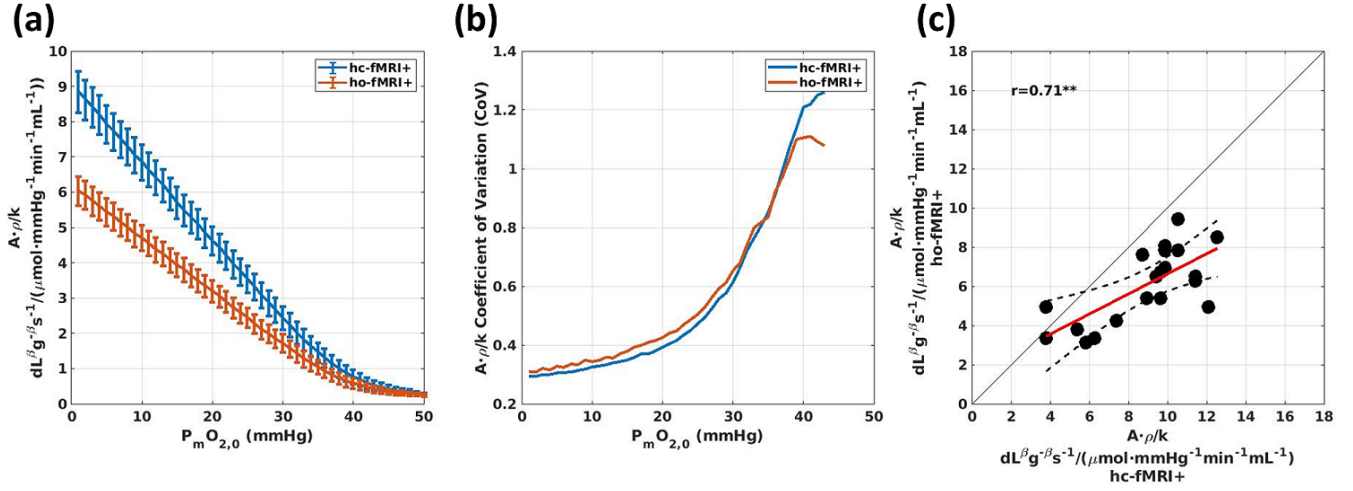


Figure 4: Results of the analysis evaluating the modelling unknown parameters that used hc-fMRI+ or ho-fMRI+ and the OEF_0 derived from the dc-fMRI analysis. (a) Subjects' average (and SE) estimate of the scaling parameter $A \cdot p/k$ of the model as a function of the $P_{mO_{2,0}}$ assumed. (b) Subjects' CoV of the scaling parameter $A \cdot p/k$ as a function of $P_{mO_{2,0}}$ assumed. (c) Comparison between hc-fMRI+ and ho-fMRI+ estimates of $A \cdot p/k$ for each subject, assuming a $P_{mO_{2,0}} = 0$ mmHg. $** p < 0.01$

3.3. In-Vivo Estimation of Oxygen Extraction Fraction: Calibrated fMRI vs. Dual-Calibrated fMRI (Section 3)

Figure 5a reports exemplar OEF_0 and $\text{CMRO}_{2,0}$ maps obtained with dc-fMRI, hc-fMRI+ and ho-fMRI+.

Notably, subjects' average spatial variabilities (estimated as standard deviation, SD) in the GM OEF_0 of $\text{SD}=0.17$ ($\text{SE}=0.003$), $\text{SD}=0.13$ ($\text{SE}=0.002$) and $\text{SD}=0.15$ ($\text{SE}=0.002$) were obtained for dc-fMRI, hc-fMRI+ and ho-fMRI+, respectively.

Figure 5b reports the scatterplots and the Bland-Altman plots comparing the average OEF_0 in the GM between dc-fMRI and the single calibration approaches. Average global GM OEF_0 ($\text{mean} \pm \text{SD}$) were 0.39 ± 0.04 , 0.39 ± 0.03 , and 0.40 ± 0.03 for dc-fMRI, hc-fMRI+ and ho-fMRI+, respectively. hc-fMRI+

OE_{F0} was significantly correlated with that of dc-fMRI ($r=0.65$, $df=18$, $p=2\cdot10^{-3}$, OE_{F0} RMSE=0.033) whereas that of ho-fMRI+ was not ($r=0.26$, $df=18$, $p=0.27$, OE_{F0} RMSE=0.044). No significant bias between the different approaches was found, but this was dependent on the proportionality constant calibration using dc-fMRI. A significant correlation, with no bias, was obtained between hc-fMRI+ and ho-fMRI+ ($r=0.50$, $df=18$, $p=0.02$).

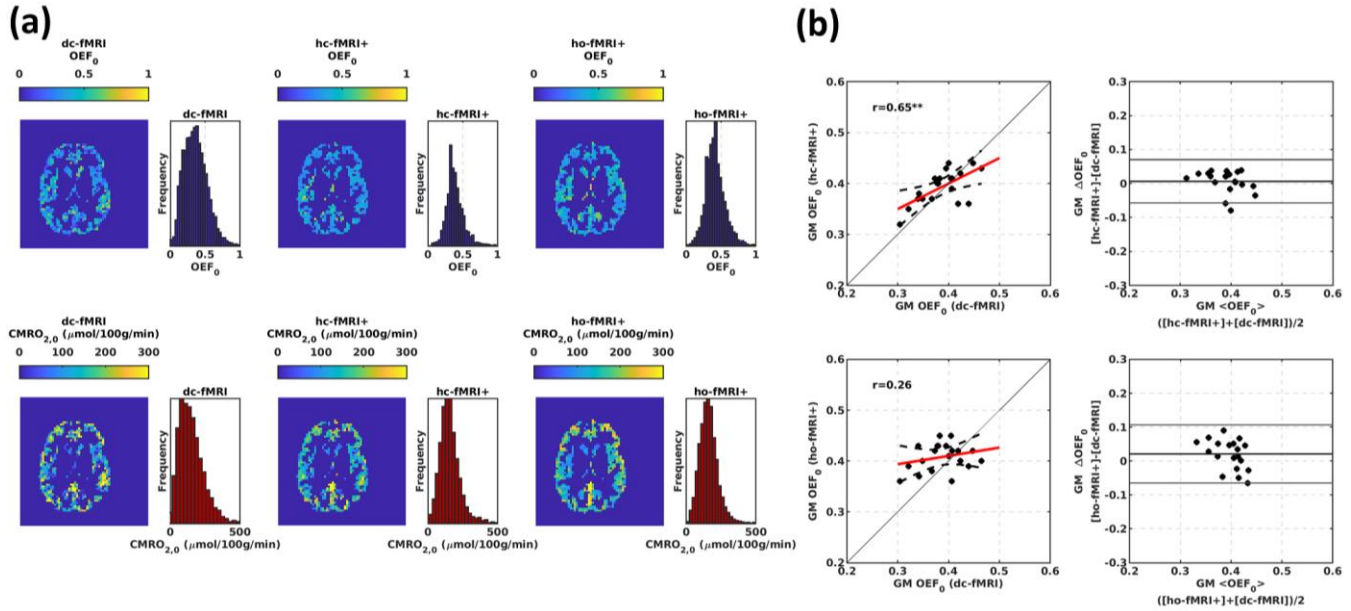


Figure 5: (a) Exemplar GM OE_{F0} and CMRO_{2.0} maps for a participant of the study obtained with dc-fMRI (left column), hc-fMRI+ (central column) and ho-fMRI+ (right column). (b) Scatterplots and Bland-Altman plots comparing the average OE_{F0} in the GM between the hc-fMRI+ (upper row) and ho-fMRI+ (lower row) and dc-fMRI. ** $p<0.01$; *** $p<10^{-3}$

3.4. In-Vivo Estimation of Oxygen Extraction Fraction: Calibrated fMRI vs. OxFlow (Section 4)

Figure 6 reports the scatterplots and the Bland-Altman plots comparing the global OE_{F0} of the fMRI approaches to the OE_{F0} estimated in the SSS using OxFlow in a subset of 12 subjects. Figure 6a shows, for one representative subject, the magnitude image and the processed phase image used to estimate OE_{F0} in the SSS within OxFlow. Average SSS OE_{F0} estimated using OxFlow was 0.31 ± 0.07 . Significant associations of the average OE_{F0} in the GM using a fMRI approach with whole-brain OE_{F0} retrieved using OxFlow were obtained for dc-fMRI ($r=0.58$, $df=10$, $p=0.048$, RMSE=0.034, Figure 6b) and hc-fMRI+ ($r=0.64$, $df=10$, $p=0.025$, Figure 6c,

RMSE=0.041). No significant association was obtained using ho-fMRI+ ($r=0.36$, $df=10$, $p=0.24$, Figure 6d, RMSE=0.066). A systematic bias was obtained with the OxFloW underestimating the OEF₀ with respect to fMRI. For the two fMRI approaches that delivered a significant association with OxFloW, an absolute difference between the dc-fMRI and OxFloW of $\Delta\text{OEF}_0=0.077$ with a $t=4.57$, $df=11$, $p=8\cdot10^{-4}$, and an absolute difference between hc-fMRI+ and OxFloW OEF₀ of $\Delta\text{OEF}_0=0.083$ with a $t=5.13$, $df=11$, $p=3.2\cdot10^{-4}$ were obtained.

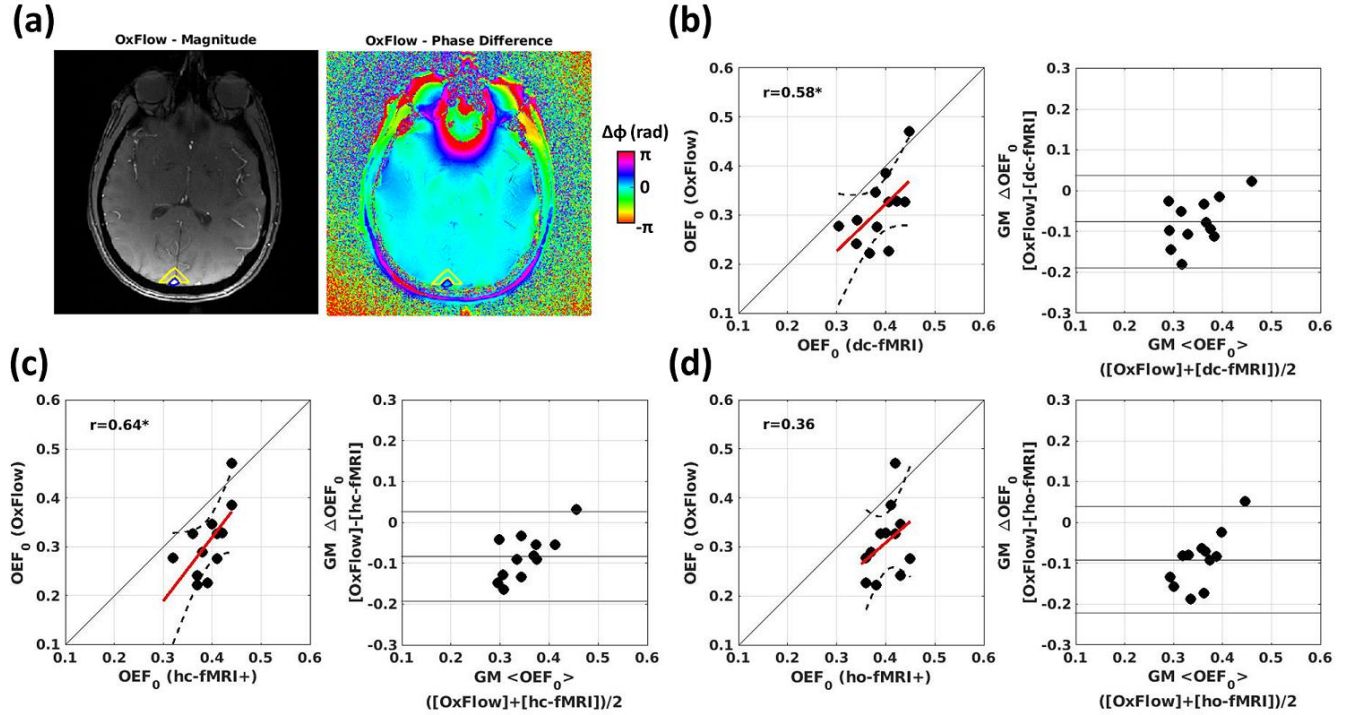


Figure 6: Scatterplots and Bland-Altman plots comparing the OEF₀ of the calibrated fMRI approaches and OxFloW in a subset of subjects. (a) Example of magnitude (arbitrary units) and processed phase images used to estimate OEF₀ in the SSS within the OxFloW method. SSS and the reference region are outlined in blue and yellow, respectively. OxFloW vs. (b) dc-fMRI; (c) hc-fMRI+; (d) ho-fMRI+. * $p<0.05$

4. Discussion

We introduced a framework for mapping OEF₀ and CMRO_{2,0} using single gas calibrated fMRI. The method integrates a flow-diffusion model of oxygen transport²⁴ with the steady-state BOLD signal model¹⁶. Simulations suggest the approach to be valid over a wide range of brain physiology. The new approach, when applied to hypercapnia, compared well with dc-fMRI and whole-brain OEF₀ assessed in the SSS using OxFloW. Compared to dc-fMRI, the novel method permits a simpler stimulation paradigm based on a single exogenous gas challenge²⁷ or,

presumably, on an endogenous challenge such as breath hold⁵⁴, and makes the approach robust to measurement noise.

4.1. Simulations

The simulations relied on a forward model assuming the new framework to be correct. When inverting the model, the unknown random variables were: (i) $A \cdot p/k$, a lumped parameter dependent on field strength, tissue structure and vessel geometry and (ii) the mitochondrial oxygen pressure at rest, $P_{mO_{2,0}}$. Variability in $A \cdot p/k$ (CoV=0.3) was based on in-vivo data (Figure 4), whereas the $P_{mO_{2,0}}$ was simulated in the range $0 < P_{capO_2}$ (Figure 1). When inverting the forward model with these parameters fixed, we obtained low OEf_0 RMSE (around 0.05) for both hc-fMRI+ and ho-fMRI+ when marginalizing all other variables, with slightly better performance for hc-fMRI+ (Figure 2a,b). This highlighted the unknown parameters' reduced effect on the mapping between the measurable variables and OEf_0 . In fact, when considering OEf_0 RMSE as a function of a wide range of two interesting physiological variables, $P_{mO_{2,0}}$ and $MCTT_0$, the OEf_0 RMSE was small. Only with very high $P_{mO_{2,0}}$ (>25 mmHg) and long $MCTT_0$ (>2.5 s) the RMSE increased significantly. Very high $P_{mO_{2,0}}$ and long $MCTT_0$, associated with low CBF_0 , are expected only in diseases that heavily alter oxygen supply, vasculature and mitochondrial function.

The simulations revealed the effect of BOLD and ASL measurement noise. For both BOLD and ASL modulations, the OEf_0 RMSE quickly reached the value caused by uncertainty in physiology at an $SNR \approx 4$. This is the SNR of the modulation estimate, not the temporal SNR of the raw signals. For example, when the modulation is estimated within a GLM framework regressing $P_{ET}O_2$ and $P_{ET}CO_2$ onto BOLD and ASL modulations (Figure 3), the SNR is the GLM β -weight divided by its confidence interval. Average voxel SNRs were between 6 and 16 in vivo for both signals and gas challenges. The robustness to noise of the approach is advantageous compared to dc-fMRI, that often relies on constrained inversion algorithms, trading off accuracy for higher stability²².

4.2. Modeling Parameters

Investigation of model parameters suggested an average value of $A \cdot p/k$ of the order of $10 \text{ s}^{-1} \text{g}^{-\beta} \text{dL}^{\beta} / (\mu\text{mol}/\text{mmHg}/\text{ml}/\text{min})$ when using hc-fMRI+, and an average value of $P_{mO_{2,0}}$ in the healthy population close to 0 for both hc-fMRI+ and ho-fMRI+ (Figure 4) both results agreed with expectations^{36,55}. In fact, the estimate of

$A \cdot p/k$ decreased beyond expectations at increasing $P_{mO_{2,0}}$ and increased its CoV as a function of the assumed $P_{mO_{2,0}}$, with a rapid increase above 20 mmHg. This work indeed suggests a particularly low average $P_{mO_{2,0}}$ in the healthy brain. However, it should be stressed that a strong increase in CoV of $A \cdot p/k$ was only observed at $P_{mO_{2,0}}$ above 20 mmHg. The confidence interval of the estimate still cannot provide a definitive answer on the average $P_{mO_{2,0}}$ within the range 0-20 mmHg. There is work suggesting the mitochondrial $P_{mO_{2,0}}$ is about ~12 mmHg^{56,57} which goes against the common assumption of $P_{mO_{2,0}}$ being near zero in the healthy brain³⁶ and, indeed, this is still an open debate. Nonetheless, the simulations of the study clearly demonstrate that the approach estimating OE_{F0} has limited sensitivity to the value of $P_{mO_{2,0}}$ if $P_{mO_{2,0}}$ and $MCTT_0$ are not both very high. The good correlation between the hypercapnic and the hyperoxic estimates indicated consistency. However, we obtained a value of $A \cdot p/k$ for ho-fMRI+ around 30% smaller than expected. This result might be a cross-talk effect of the hypercapnic on the hyperoxic BOLD modulations in the dc-fMRI experiment, or an overestimation of ΔPaO_2 .

4.3. Comparison with dc-fMRI and OxFlow

Spatial homogeneity of OE_{F0} in healthy subjects is often taken as an indicator of successful OE_{F0} mapping. hc-fMRI+ and ho-fMRI+ decreased OE_{F0} spatial variability in GM compared to dc-fMRI. The lower variability of hc-fMRI+ and ho-fMRI+ suggests a greater robustness, with respect to measurement SNR, compared to the dc-fMRI. Comparison of GM OE_{F0} estimates suggests that hc-fMRI+ is a valid alternative to dc-fMRI (Figure 5b). In addition, when comparing GM OE_{F0} of the different fMRI approaches with global OE_{F0} in the SSS through OxFlow, clear associations with the OxFlow OE_{F0} were obtained for both dc-fMRI and hc-fMRI+ (Figure 6). We identified a bias between the OxFlow and the fMRI estimates. In general, OxFlow OE_{F0} yielded a lower value. This is in accordance with the literature, where approaches using analytical modelling give higher estimates of venous saturation⁵⁸. The low performance of ho-fMRI+ is indeed a negative result of the study. Hyperoxia is generally better tolerated than hypercapnia¹⁹ and it would be more easily applicable in clinical settings. The lower performance of hyperoxia is plausibly related to the noisier estimate of M . Moreover, hyperoxic BOLD modulation is primarily sensitive to $CBV_{v,0}$ and largely insensitive to OE_{F0} ; in fact, hyperoxia can be used to estimate $CBV_{v,0}$ ⁵⁹. The oxygen saturation change due to hyperoxia stimulus is independent of the baseline oxygen saturation over most of the physiological range. In contrast, the oxygen saturation change to a hypercapnic challenge is linearly related

to the resting saturation. The sensitivity pattern of the hyperoxic modulation makes the estimation of OEF_0 with the new framework completely reliant on the flow-diffusion model approximations that link $\text{CBV}_{v,0}$ to OEF_0 . The model approximations are indeed less influential with hypercapnia, which has a larger sensitivity to OEF_0 with respect to $\text{CBV}_{v,0}$, making the hypercapnia approach less noisy and biased.

4.4. Limitations of the Method

The main limitations of the new method are mostly shared with dc-fMRI¹⁴. The approach using hypercapnia relies on a local CBF increase, a vascular reserve, which may be absent in diseases such as ischemic stroke, where vessels may be maximally dilated in an attempt to maintain perfusion. In addition, the method might be vulnerable to larger than expected changes in ρ or k , which are probably not independent. Although large changes in these parameters appear unlikely in many brain diseases, we might expect relevant tissue and vascular remodeling in some disease, such as brain tumors⁶⁰. The limitations of the approach in diseases with concurrent very high $\text{P}_{m\text{O}_2,0}$ and long MCTT_0 are noted earlier and should be assessed in future studies.

4.5. Study Limitations

The main limitation of the simulation study lies in the assumption of an exact analytical model with the error in the estimate of OEF_0 being introduced only by the limited number of measurable variables. The main simplifying assumption of the model was the replacement of the CTT in one straight capillary with the MCTT in the voxel capillary bed. This is an approximation, since, due to the non-linear mapping between CTT, OEF and oxygen diffusion between capillary and tissue, the complete CTT distribution within a capillary bed affects the macroscopic OEF ⁶¹. Without changing MCTT, OEF can be increased through homogenization of the CTT among capillaries. Future extension of the model might include the CTT heterogeneity (CTTH), a measure of the second moment of the CTT distribution within the capillary bed⁶².

With respect to the *in-vivo* validation using dc-fMRI, a limiting factor was related to the investigation of the proposed model proportionality constant $A \cdot \rho/k$ and $\text{P}_{m\text{O}_2,0}$. These estimates were evaluated assuming the OEF_0 derived from the dc-fMRI machine learning analysis²² to be exact. In fact, noise in the dc-fMRI OEF_0 limited our investigation of the model parameters to global evaluation within the GM. Moreover, another limitation was the problem of having two unknowns and one equation. By exploiting the different effects of these parameters on the

non-linear mapping between variables, we were able to get insight into both parameters, however only at a between subjects' average level. Alternative approaches should be used to investigate the different physiological parameters (e.g., ρ and k) contributing to the proportionality constant, which cannot be separately investigated using standard fMRI approaches. Comparison against non-MRI technology would be essential for definitive validation of the approach. Future validation is also necessary beyond the healthy controls involved in the study, to populations affected by diseases that might alter brain metabolism and for which the proposed model's validity might reduce.

5. Conclusion

We introduced a novel calibrated fMRI framework integrating a steady-state flow-diffusion model of oxygen transport in the BOLD signal model. The simple oxygen transport model assumes the rate of oxygen loss from the capillary is proportional to the $MCTT_0$ and the pressure gradient between capillaries and mitochondria. Since $MCTT_0$ can be expressed as a function of $CBV_{v,0}$ and CBF_0 , and capillary pressure can be expressed as a function of OEF_0 , the approach substitutes $CBV_{v,0}$ within the BOLD modelling with a function of CBF_0 and OEF_0 and allows us to estimate OEF_0 using a single manipulation of brain physiology.

Uncertainty in the integrated model was driven by variability in two non-measurable parameters, a proportionality constant $A \cdot \rho / k$, that depended on tissue and microvascular structure at a fixed field strength, and $PmO_{2,0}$. The advantage of the new framework lies in the low variability of these parameters and their limited influence on the OEF_0 estimation compared to $CBV_{v,0}$. Even by fixing these parameters to plausible values, the simulations showed the OEF_0 RMSE to be below 0.05 over a wide range of physiology meaning that the method may reliably identify OEF_0 modifications greater than approximately 10%. Only with concurrently very high $PmO_{2,0}$ (>25 mmHg) and long $MCTT_0$ (>2.5 s) the RMSE increased significantly. Importantly, the approach was highly robust to measurement noise. The method, when using hypercapnia in vivo, compared well with dc-fMRI and with whole-brain OEF derived from macrovascular susceptibility measures in the superior sagittal sinus using the OxFow method. Lack of positive results when using hyperoxia may be related to the high sensitivity to $CBV_{v,0}$.

and poor sensitivity to $OE\bar{F}_0$. The simplified calibrated fMRI method using hypercapnia has potential for application in clinical settings.

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Author contribution statement: AMC and MG developed imaging and analysis methods, and analyzed and interpreted the data. AMC, MG and RGW drafted the manuscript. FWW, RGW, KM and VT conceived the project. MG, HLC, RCS, EP, NS, SK, SJ, CF and KM set up and executed the experiment. DM, EB, AERS and EE contributed to data analysis. All authors revised and approved the final submission.

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Tables

Abbreviation	Meaning	Units	Abbreviation	Meaning	Units
θ	As subscript defines the physiological variable at baseline	/	[Hb]	Concentration of hemoglobin in blood	g/dL
α	Grubb exponent relating fractional change in CBV _v to fractional change in CBF	Dimensionless	β	Field strength and vessel geometry dependent exponent within the steady-state BOLD signal model	Dimensionless
β -weight	Coefficient of the GLM	/	γ	Gyromagnetic ratio of the proton	rad/s/T
$\Delta\chi_{\text{do}}$	Magnetic susceptibility difference between fully oxygenated and fully deoxygenated blood	Relative	$\Delta\text{BOLD}/\text{BOLD}_0$	Relative change in BOLD signal	Relative
ΔS	Tag-Control ASL image	Not defined	ε	Oxygen plasma solubility	mL/mmHg/dL
η	Tagging inversion efficiency of PCASL	Dimensionless	η_{INV}	Scaling factor accounting for reduction in tagging efficiency due to background suppression	Dimensionless
λ	Water partition coefficient of the tissue	mL/g	ρ	CBV _{v,0} /CBV _{cap,0}	Relative
φ	Oxygen binding capacity of hemoglobin	mL/g	Φ	Phase MRI image	rad
τ	Labelling duration of PCASL	s	A	Field strength and vessel geometry dependent proportionality constant within the steady-state BOLD signal model	$\text{s}^{-1}\text{g}^{-\beta}\text{dL}^{\beta}$
ASL	Arterial spin labelling	/	B_0	Static magnetic field	T
BOLD	Blood oxygen level dependent	Not Defined	$C_a\text{O}_2$	Concentration of oxygen in arteries	mL/dL
CBF	Cerebral blood flow	mL/100g/min	CBF/CBF_0	Fractional change in CBF	Relative
CBV _{cap}	Capillary blood volume	Relative (or mL/100g)	CBV _v	dHb-sensitive blood volume	Relative (or mL/100g)
CMRO ₂	Cerebral metabolic rate of oxygen	μmol/100g/min	$\text{CBV}_v/\text{CBV}_{v,0}$	Fractional change in CBV _v	Relative
CSF	Cerebrospinal fluid	/	CTT	Capillary transit time	s
CoV	Coefficient of variation	Relative	CVR	Cerebrovascular reactivity (CBF/CBF ₀ /mmHg of CO ₂)	%/mmHg
dc-fMRI	Dual-Calibrated functional MRI	/	dHb	Deoxy-hemoglobin concentration in tissue	g/100g
GLM	General Linear Model	/	GM	Grey matter	/
GRE	Gradient Echo Sequence	/	k	Effective permeability to oxygen of the capillary endothelium and brain tissue	μmol/mmHg/mL/min
h	Hill constant involved in the non-linear relationship between oxygen partial pressure and hemoglobin saturation in blood	Dimensionless	hc-fMRI+	Single gas calibrated fMRI using a hypercapnic modulation and the steady-state BOLD signal model extended with the proposed flow-diffusion analytical framework of oxygen transport	/

hc-fMRI	Single gas calibrated fMRI using a hypercapnic modulation and the steady-state BOLD signal model	/	Hct	Hematocrit	%
ho-fMRI+	Single gas calibrated fMRI using a hyperoxic modulation and the steady-state BOLD signal model extended with the proposed flow-diffusion analytical framework of oxygen transport		ho-fMRI	Single gas calibrated fMRI using a hyperoxic modulation and the steady-state BOLD signal model	/
MCTT	Mean capillary transit time	s	M	Maximum BOLD modulation	Relative
OxFlow	Validated macrovascular global measure of OEF ₀ , inferred through phase measures of the magnetic susceptibility of blood in the sagittal sinus relative to surrounding tissue	/	OEF	Oxygen Extraction Fraction	Relative
P₅₀	Oxygen partial pressure when half of hemoglobin is saturated with oxygen	mmHg	P_aO₂	Partial pressure of oxygen in arteries	mmHg
P_aCO₂	Partial pressure of carbon dioxide in arteries	mmHg	P_{cap}O₂	Partial pressure of oxygen in the capillary	mmHg
PCASL	Pseudo-continuous ASL	/	P_{ET}O₂	End-tidal partial pressure of oxygen	mmHg
P_{ET}CO₂	End-tidal partial pressure of carbon dioxide	mmHg	P_mO₂	Partial pressure of oxygen at the mitochondria	mmHg
PLD	Post label delay of PCASL	s	R₂* _{dHb}	Rate of free induction decay due to dHb	1/s
RMSE	Root mean square error	Variable	S₀	Proton Density Image for ASL normalization	Not defined
S_{cap}O₂	Capillary oxygen saturation of hemoglobin	Relative	S_aO₂	Arterial oxygen saturation of hemoglobin	Relative
SD	Standard deviation	Variable	SE	Standard error (standard deviation of the mean)	Variable
S_vO₂	Venous oxygen saturation of hemoglobin	Relative	SNR	Signal to Noise Ratio	Dimensionless
SSS	Superior Sagittal Sinus	/	T1_b	MRI longitudinal relaxation time constant of blood	s
TE	Time of echo of the MRI sequence	s	TOF	Time of flight MRI	/
TR	Time of repetition of the MRI sequence		WM	White matter	/

Table 1: Main variables and abbreviations used in the study, reported in alphabetical order.

Figure Legends

Figure 1: Random variables used to simulate BOLD and ASL signals using a hc-fMRI+ or ho-fMRI+ forward modelling framework. The variables reported in light grey were assumed to be measured for the hc-fMRI+ or ho-fMRI+ inversion model, those reported in medium grey were fixed a-priori in the inversion model and those in dark grey were inferred by the inversion model.

Figure 2: (a) RMSE in OEF₀ for hc-fMRI+ and ho-fMRI+ inversion models with $A \cdot \rho / k = 10 \text{ s}^{-1} \text{g}^{-1} \text{dL}^{\beta} / (\mu\text{mol}/\text{mmHg}/\text{ml}/\text{min})$ as a function of $P_{\text{mO}_{2,0}}$. (b) Scatterplots of the simulated and estimated OEF₀ for hc-fMRI+ and ho-fMRI+ inversion models assuming either $P_{\text{mO}_{2,0}} = 0 \text{ mmHg}$ or $P_{\text{mO}_{2,0}} = 10 \text{ mmHg}$; (c) RMSE in OEF₀ as a function of the forward model MCTT₀ and $P_{\text{mO}_{2,0}}$ for hc-fMRI+ and ho-fMRI+ inversion models assuming either $P_{\text{mO}_{2,0}} = 0 \text{ mmHg}$ or $P_{\text{mO}_{2,0}} = 10 \text{ mmHg}$. *** $p < 10^{-3}$

Figure 3: Example of: (a) O₂ and estimated P_{ET}O₂ traces; (b) CO₂ and estimated P_{ET}CO₂ traces; (c) GM CBF/CBF₀ and fitted P_{ET}CO₂ trace. The β -weight of the GLM fit, with units of a CVR, CBF/CBF₀/mmHg, was multiplied by the maximum modulation $\Delta P_{\text{ET}}\text{CO}_2$ to obtain the hypercapnic CBF/CBF₀. (d) GM average $\Delta\text{BOLD}/\text{BOLD}_0$ and fitted P_{ET}CO₂ and P_{ET}O₂ traces. The β -weights, with units of %BOLD/mmHg of P_{ET}CO₂ and P_{ET}O₂, were multiplied by the maximum modulation $\Delta P_{\text{ET}}\text{O}_2$ and $\Delta P_{\text{ET}}\text{CO}_2$ to obtain the hypercapnic and the hyperoxic $\Delta\text{BOLD}/\text{BOLD}_0$.

Figure 4: Results of the analysis evaluating the modelling unknown parameters that used hc-fMRI+ or ho-fMRI+ and the OEF₀ derived from the dc-fMRI analysis. (a) Subjects' average (and SE) estimate of the scaling parameter $A \cdot \rho / k$ of the model as a function of the $P_{\text{mO}_{2,0}}$ assumed. (b) Subjects' CoV of the scaling parameter $A \cdot \rho / k$ as a function of $P_{\text{mO}_{2,0}}$ assumed. (c) Comparison between hc-fMRI+ and ho-fMRI+ estimates of $A \cdot \rho / k$ for each subject, assuming a $P_{\text{mO}_{2,0}} = 0 \text{ mmHg}$. ** $p < 0.01$

Figure 5: (a) Exemplar GM OEF₀ and CMRO_{2,0} maps for a participant of the study obtained with dc-fMRI (left column), hc-fMRI+ (central column) and ho-fMRI+ (right column). (b) Scatterplots and Bland-Altman plots comparing the average OEF₀ in the GM between the hc-fMRI+ (upper row) and ho-fMRI+ (lower row) and dc-fMRI. ** $p < 0.01$; *** $p < 10^{-3}$

Figure 6: Scatterplots and Bland-Altman plots comparing the OEF₀ of the calibrated fMRI approaches and OxFlow in a subset of subjects. (a) Example of magnitude (arbitrary units) and processed phase images used to estimate OEF₀ in the SSS within the OxFlow method. SSS and the reference region are outlined in blue and yellow, respectively. OxFlow vs. (b) dc-fMRI; (c) hc-fMRI+; (d) ho-fMRI+. * $p < 0.05$