Quantitative MRI of Cerebral Arterial Blood Volume

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Abstract: Baseline cerebral arterial blood volume (CBV_a) and its change are important for potential diagnosis of vascular dysfunctions, the determination of functional reactivity, and the interpretation of BOLD fMRI. To quantitative measure baseline CBV_a non-invasively, we developed arterial spin labeling methods with magnetization transfer (MT) or bipolar gradients by utilizing differential MT or diffusion properties of tissue vs. arteries. Cortical CBV_a of isoflurane-anesthetized rats was 0.6 – 1.4 ml/100 g. During 15-s forepaw stimulation, CBV_a change was dominant, while venous blood volume change was minimal. This indicates that the venous CBV increase may be ignored for BOLD quantification for a stimulation duration of less than 15 s. By incorporating BOLD fMRI with varied MT effects in a cat visual cortical layer model, the highest ACBV_v was observed at layer 4, while the highest BOLD signal was detected at the surface of the cortex, indicating that CBV_v change is highly specific to neural activity. The CBV_v MRI techniques provide quantified maps, thus, may be valuable tools for routine determination of vessel viability and function, as well as the identification of vascular dysfunction.

Keywords: Arterial blood volume, venous blood volume, BOLD, cerebral blood flow, CBF, arterial spin labeling, ASL, fMRI, brain mapping.

INTRODUCTION

The adult human brain represents ~2% of body weight, but receives ~15% of total cardiac output. Cerebral blood flow (CBF) is closely related to cerebral blood volume (CBV), which can be divided into arterial and venous blood volume. Arterial vessels including arteries, arterioles and pre-capillary small arterioles dilate and constrict actively responding to internal and external perturbations, while venous vessels including veins, venules and post-capillary small venules respond passively. Vascular volume changes in the brain are important for regulation of blood flow under conditions of both normal and abnormal physiology. It is generally thought that dilation and constriction of arterial blood vessels is the major mechanism that maintains CBF within an autoregulatory range [1], and that adjusts blood flow to perturbations such as those induced by CO2 changes and neural stimulation. Thus, arterial CBV change is expected to be more sensitive than total CBV change in assessing cerebrovascular regulation, as well as in identifying regions of abnormality. For example, in ischemic regions, arterial blood vessels dilate to compensate for reduced blood pressure, making quantitative mapping of CBV_a more promising diagnostic tool. However, CBV_v has rarely been investigated, possibly due to difficulties involved in compartment-specific blood volume measurements and the lack of gold-standard methods for comparison.

Arterial CBV can be mapped with arterial spin labeling (ASL). ASL is achieved with endogenous magnetic labeling by either virtually continuous (i.e., long duration) application of radiofrequency (RF) labeling between acquisitions (referred to as “continuous ASL”) [2, 3] or by short RF pulse(s) (referred to as “pulsed ASL”) [4-6]. Labeled spins will reside mostly in arterial vessels and tissue due to short half-life (spin-lattice relaxation-time) of labeled spins. For the quantification of CBF, it has been of great interest to remove the contribution of arterial blood signals, which can be achieved by using a post-labeling delay time [7] or by employing small bipolar gradients [8] (referred also to as diffusion gradients), which dephase rapidly moving spins [9]. Conversely, these arterial contributions can be exploited to quantitatively map CBV_v. In studies without the removal of arterial signals, the ASL signal is a sum of arterial blood and tissue signals, which can be deconvoluted with dynamic ASL models [10, 11]. Thus, CBV_v may be determined from ASL data obtained at multiple spin labeling times. Alternatively, arterial and tissue ASL signals obtained at a single spin labeling time can be separated with diffusion gradients [12] or the magnetization transfer (MT) effect [13], rendering simultaneous measurement of CBV_v and CBF.

Since significant increase in CBF during stimulation is highly associated with arterial dilation, functional change in CBV_v is expected. However, CBV_v comprises ~60-80% of total CBV under normal baseline conditions [14-17], thus vascular responses assume the dominance of CBV_v changes during stimulation - with minimal CBV_a changes in biomechanical models of functional MRI (fMRI) (such as the balloon model) [18, 19]. According to vascular physiology studies, however, local and upstream arterial vessels rigorously dilate during increased neural activity [20]. Thus, it would be valuable to know the portion of CBV_v change that contributes to overall stimulus-induced CBV_v change to gain insight into neurovascular control.
mechanisms. Therefore the measurement of CBV_{arterial} vs. CBV_{venous} change is helpful to understand BOLD signals and could quantify the vascular responses of neural activity. Thus, we measured total and arterial CBV using contrast agent and ASL with MT effect, respectively, and compared CBV_{arterial} vs. CBV_{venous} (= CBV_{arterial} – CBV_{venous}) changes during stimulation. Since the most widely-used BOLD signal is closely dependent on CBF and venous (not total) CBV [21], the relationship between CBV_{arterial} and CBV_{venous} changes makes a major impact to BOLD quantification. In order to further obtain functional CBV_{arterial} response with high temporal resolution, a new MT-varied blood oxygenation-level dependent (BOLD) fMRI technique was developed to determine both ΔCBV_{arterial} and BOLD fMRI responses [22]. From fMRI data acquired at multiple MT levels, MT-independent arterial signal can be separated from MT-dependent tissue (and venous) signals.

In this review article, we present the theoretical basis of quantitative CBV_{arterial} measurement with MT-varied ASL and MT-varied BOLD fMRI techniques, and summarize our lab’s findings of CBV_{arterial} measurements obtained from isoflurane-anesthetized rats and cats at 9.4 T. Arterial vs. venous CBV changes during stimulation were measured to determine relative contribution of CBV_{arterial} to CBV_{venous} change. Then, the implication of our finding for BOLD quantification was discussed. To further examine the importance of functional CBV_{arterial} mapping, the spatial specificity of CBV_{arterial} change was also examined.

THEORETICAL BASIS OF ARTERIAL CBV MEASUREMENTS

It is assumed that MRI signals in a given pixel originate from four compartments including extravascular tissue, arterial blood, capillary, and venous blood. Under the assumption that water in capillary blood freely exchanges with tissue water, the spin status in venous blood could be similar to those in tissue generated by upstream free exchange, therefore components from tissue, capillaries and venous vessels will be indistinguishable, thus these are treated together as one compartment. Arterial spin fraction \( v_a \) can be determined by separating arterial blood from tissue signals (see below), then converted to physical volume CBV_{arterial} considering differences in spin density between tissue and blood pools; CBV_{arterial} values (units of ml blood/g tissue) can be obtained from \( v_a \) by multiplying a tissue-to-blood partition coefficient. It is noted that the tissue-to-blood partition coefficient of 0.9 ml/g for the entire brain [23] was used in our studies. Thus, the CBV_{arterial} value in gray matter is ~0.9 s [25] and ~1.4-1.9 s [25, 26], respectively. Based on the central volume principle, arterial CBV can be determined from CBF and transit time of (\( \tau_a - \tau_v \)) [26]. \( \tau_a \) and \( \tau_v \) can be measured without and with magnetic field gradients, respectively, since the ASL signal originating from arterial blood can be suppressed by employing small bipolar gradients. Although this bipolar gradient approach with multiple spin labeling times has been successfully implemented in humans [26], determining \( \tau_a \) and \( \tau_v \) accurately is not trivial. Thus, we propose a simple method to use one spin labeling time longer than \( \tau_v \) with and without the suppression of arterial blood signals [12]. When diffusion-weighted gradients are applied, ASL signal (\( \Delta S \)), as a function of the diffusion-weighted gradient factor \( b \), at echo time \( TE \), is described as

\[
\Delta S(b) = (1 - v_a) \cdot \Delta M_{tissue} \cdot e^{-b \cdot R_2(c)} \cdot e^{-TE \cdot R_2(c)} + v_a \cdot \Delta M_{artery} \cdot e^{-b \cdot D^*} \cdot e^{-TE \cdot R_2(c)},
\]

where \( v_a \) is the fraction of spins in the arterial blood pool (units of %); \( \Delta M_{tissue} \) and \( \Delta M_{artery} \) are changes in magnetization induced by ASL in tissue and in arterial blood, respectively; \( D^* \) is the water diffusion coefficient in the tissue pool, and \( D^* \) is the pseudo-diffusion coefficient, where it is assumed that \( D^* \) arises from arterial spins only [12]. With rectangular-shaped gradient pulses, \( b \) (in units of s/mm²) can be expressed as \( b = (\gamma \cdot \delta \cdot G)^2 (\Delta - \delta / 3) \), where \( \gamma \) is the gyromagnetic ratio of proton nuclei, \( \delta \) is the duration of each gradient, \( G \) is the diffusion-weighted gradient strength and \( \Delta \) is the time between gradient onsets [9]. When bipolar gradients of \( b \geq 70 \) s/mm² are applied, then only tissue signal remains [12], while both arterial and tissue signals exist when no bipolar gradient is used. The difference between ASL signals with and without bipolar gradients is related to arterial blood volume. The fraction of arterial spins is

\[
v_a = \frac{[\Delta S(0) / S(0)] - [\Delta S(b) / S(b)]}{2 \cdot \alpha \cdot \tilde{\xi} - [\Delta S(b) / S(b)]},
\]

where \( S(0) \) and \( S(b) \) is the signal intensity of unlabeled images without and with bipolar gradients, respectively; \( \alpha \) is the spin-labeling efficiency; \( \tilde{\xi} = e^{TE \cdot (R_{2,tissue} - R_{2,artery})} \), where \( R_{2,tissue} \) and \( R_{2,artery} \) are the \( 1/T_2 \) values of tissue and arterial blood water, respectively. If \( T_2 \) values of blood and tissue are similar (such as at 9.4 T [27]) or TE is short, then \( \tilde{\xi} = 1.0. \)
Alternatively, arterial blood from tissue in ASL signal can be separated with independent modulation of tissue and vessel signals (MOTIVE) with different MT effects in tissue and blood [13]. When protons in tissue macromolecules are saturated by long off-resonance RF pulse(s), their magnetization is transferred to tissue water protons [28, 29], thereby selectively reducing the ASL signal originating from tissue water. However, the signal from the arterial blood pool is minimally affected due to its small macromolecular content and the inflow of fresh spins from outside the RF coil’s sensitive region [28, 29]. Thus, arterial blood and tissue signals can be differentiated with MT effects. The MR signal intensity from tissue decreases with an increase in MT level; but the MT effect on arterial blood signal is insignificant. Schematic diagram is shown in Fig. (2). The normalized ASL signal (the difference between the “unlabeled” signal and “labeled” signal), $\Delta S_{MT}/S_0$, can be written as

$$\Delta S_{MT}/S_0 = C \cdot (S_{MT}/S_0) + v_c \cdot \xi + (2\alpha - C) \tag{3}$$

Where $S_{MT}$ and $S_0$ is the signal intensity with and without MT effect, respectively; $C$ is a constant related to tissue perfusion, which is $2\alpha f/\lambda / (1/T_1 + f/\lambda)$ where $f$ is cerebral blood flow (ml/100 g tissue/min), and $T_1$ is $T_1$ of tissue without MT effects. By fitting a linear function to $\Delta S_{MT}/S_0$ vs. $S_{MT}/S_0$, the intercept represents MT-insensitive arterial blood signals. In our case, we assumed $\xi \approx 1.0$. If the arterial oxygen saturation level is much less than 1.0, CBV$_a$ is under-estimated by $1/\xi$.

The example of isoflurane-anesthetized rat brain for CBV$_a$ measurement is shown in Fig. (3). The normalized ASL signals were calculated at each MT level (e.g., Figs. 3A and 3B), then were fitted against normalized unlabeled images at corresponding MT level (not shown here). CBV$_a$ maps (Fig. 3C) can be easily achievable by calculating with intercepts, slopes, and arterial spin labeling efficiency (see Eq. [3]). Similarly, ASL signals without bipolar gradient (Fig. 3A) were compared with those with bipolar gradients (Fig. 3E). Then, CBV$_a$ maps were calculated using Eq. [2] (Fig. 3F).

**Functional CBV$_a$ Measurements: MT-Variated BOLD**

As mentioned previously, extracranial vascular and intravascular venous blood pools will be considered together as one MT-dependent compartment. In contrast, the arterial blood pool experiences only a minimal MT effect. In order to separate MT-dependent tissue and MT-independent arterial signals to BOLD fMRI, functional experiments can be performed with different MT levels [22]. Schematic diagram is same shown in Fig. (2) except ASL signal ($\Delta S$) is replaced with stimulus-induced signal change ($\Delta S$). The stimulus-induced signal change in the presence of MT ($\Delta S_{MT}$) normalized by $S_0$ is

$$\Delta S_{MT}/S_0 = - (\Delta v_a + \Delta v_{2,flow} \cdot TE) \cdot (S_{MT}/S_0) + \Delta v_a \cdot \xi \tag{4}$$

when $\Delta S_{MT}/S_0$ is linearly fitted against normalized baseline signal $S_{MT}/S_0$, an intercept is $\Delta v_a \cdot \xi$ and a slope is $[22, 30]$. When gradient-echo data collection is used instead of spin echo, $R_2$ terms in Eqs. [1] to [4] should be replaced with $R_2^*$. It should be noted that BOLD fMRI with diffusion gradients can separate only extra- vs. intra-vascular (arterial + venous blood) functional signals [31], thus can not be used to measure $\Delta CBV_a$ if the intravascular venous blood signal contributes to BOLD fMRI.

**BASELINE CBV$_a$ QUANTIFICATION**

In order to determine quantitative CBV$_a$ map, continuous ASL techniques with either MT or bipolar gradient approaches were implemented in isoflurane-anesthetized rats at 9.4 T [12, 13]. All coronal images were acquired using a single-shot echo planar imaging (EPI) sequence with spin preparation time $= 8$ s, spin echo time (TE) = 36 ms, repetition time (TR) = 10 s, slice thickness = 2 mm, and in-plane resolution = $0.47 \times 0.47$ mm$^2$. To vary a level of MT effects without changing arterial spin labeling efficiency, we used two actively-detunable surface coils: one in the neck for generating arterial spin labeling in the carotid arteries, and the other in the brain for generating MT effects and collecting images. A pair of pulses, a 100-ms spin labeling pulse in the neck coil followed by a 100-ms MT-inducing
pulse in the head coil, was repeated during a spin preparation period (see pulse sequence in [13]). Two CBV\textsubscript{a} measurement approaches were compared: ASL with MT and bipolar gradients. MT pulses with +8,500 Hz off-resonance frequency were applied during the spin labeling period for achieving MT ratios (MTR = 1 – S\textsubscript{MT}/S\textsubscript{0}) of 0 - 0.6 without the use of bipolar gradients [13]. The average CBV\textsubscript{a} obtained from ASL with MT (without bipolar gradient) (Fig. 4A) was 1.0 ± 0.3, 1.0 ± 0.3 and 1.7 ± 0.6 ml/100 g tissue (n = 10) in the cortex, caudate putamen and a region containing a large artery, respectively [13]. ASL images with bipolar gradients, b = 0 and 104 s/mm\textsuperscript{2} with each MT level were also obtained for CBV\textsubscript{a} mapping (Fig. 4B-D). The CBV\textsubscript{a} values measured by both methods agree well [12]. Cortical CBV\textsubscript{a} values in anesthetized rats were 0.6 – 1.4 ml/100 g (n = 12).

Since both the MT and diffusion-weighted methods can determine CBV\textsubscript{a} from ASL measurements, it is important to critically evaluate properties of both methods (see details in [12]). Although the arterial blood volume fraction is on the order of 1% of total brain volume, quantitative CBV\textsubscript{a} values were robustly measured because in ASL studies, the ratio of signal originating from arterial blood relative to tissue is much greater than the actual arterial blood volume fraction. In our studies, signals originating from arterial blood are typically 10 - 15% of ASL signal (ΔS\textsubscript{0}). In humans, the arterial blood signal contribution can be >50% of ΔS\textsubscript{0} when the spin labeling time < 2.0 s [8]. If the tissue signal is further suppressed by MT effects, the relative contribution of arterial signals is accentuated. Differences between the diffusion-weighted and MOTIVE approaches with ASL are:

i) Only two measurement points (with and without
suppression of arterial signals) are obtained in the diffusion-weighted method, while more points at multiple levels of tissue signal intensity can be obtainable with MOTIVE. The large dynamic range afforded by multiple MT saturation levels in the MOTIVE method may potentially yield more accurate CBVa than obtained from a simpler two-point approach. ii) Implementation of the diffusion-weighted technique is simple both for continuous and pulsed ASL. The MOTIVE method with continuous ASL requires two coil system (two RF amplifiers) for modulation of MT levels without changing the arterial spin labeling efficiency. But, the MOTIVE approach could be implemented with pulsed ASL by applying variable MT-inducing RF pulses during the spin labeling period (e.g., inversion time in FAIR [5]). iii) MT-inducing RF pulses in the MOTIVE approach can cause significant power deposition, especially at high magnetic fields. Based on our experience in rat studies, the MOTIVE technique is more robust than the bipolar gradient method. However, since the MOTIVE approach with MT can not easily apply to human studies due to a concern of power deposition, the bipolar gradient CBVa approach is more appealing.

Similar diffusion-weighted ASL approaches were used to determine absolute CBV in humans. Peterson et al. [11] and Brookes et al. [10] proposed to acquire labeling time-dependent ASL images by repetitive data acquisitions after pulsed arterial spin labeling. Non-exchangeable and exchangeable ASL signals can be de-convoluted with dynamic perfusion models, thus CBVa can be quantified from the non-exchangeable ASL signals. To obtain multiple labeling time-dependent ASL signals quickly, Look-Locker acquisitions were implemented after pulsed ASL [10, 11]. Small flip angle excitations were repeated with an inter-pulse interval after one ASL pulse, consequently the signal intensity is closely dependent on excitation flip angle and time interval between data collection. Thus, flip angle and inter-pulse delay should be optimized. Petersen et al. measured CBVs in humans to be 0.9% for gray matter and 0.3% for white matter [11]. Similarly, Brookes et al. found human CBVs of 1.7 – 2.2% (n = 6) in gray matter and 9 - 10% in area with large arterial vessels [10]. The CBV obtained with dynamic ASL model turned out to be zero when arterial blood signals were suppressed with the b-value of 4.4 mm²/s [10], indicating that the proposed dynamic ASL model with two compartments is valid. The multiple spin-labeling time approach [10, 11] is effective to simultaneously measure CBV and CBF, and arterial and capillary transit times can be additionally determined. Disadvantages of this approach are to select the proper time-interval between repeated data acquisitions, to measure excitation flip angles accurately, and to use complex dynamic ASL models. If the time interval is too short relative to the arterial blood travel time (τc - τa) in the imaging slice, the blood signal is partially saturated during repeated RF pulsing. When CBF, τc, and τa are obtained from ASL data with multiple spin labeling times, CBV can be also calculated using the central volume principle. Recently, Liu et al. found CBV of human gray matter to be 1.18 ml/100 g [25]. These measured human CBV values [10, 11, 25] agree with those reported by Ito et al. of 1.1 ± 0.4 % in humans [32], in which a dynamic blood and tissue compartment model was used in conjunction with 11CO and time-dependent H215O PET studies. Compared to multiple spin labeling time studies, our bipolar gradient ASL approach with one spin labeling time is simple and has high sensitivity due to the use of 90° excitation pulse (rather than small flip angle pulses). However, the spin-labeling time should be selected longer than τc, which may not be straightforward in abnormal vascular conditions.

Recently, inflow-based vascular-space-occupancy (iVASO) technique was proposed to measure CBVa [33]. This approach is similar to the ASL method with an inflow time of τc. In this approach, two images are subtracted to
obtain only arterial blood signals; one image is acquired at a
blood nulling inversion time after a non-slice selective
inversion pulse followed by a slice-selective inversion pulse,
so spins within the imaging slice are un-perturbed, while
inflowing blood spins will be initially inverted. The other
image is obtained at the same inversion time after a slice-
selective inversion pulse followed by a slice-selective
inversion pulse, so both tissue and arterial blood spins are
un-perturbed. Gray matter CBV\textsubscript{a} is reported to be 1.6
ml/100 g in humans. Although this approach is similar to
other ASL CBV\textsubscript{a} methods, only one inversion time is used
without the use of bipolar gradients. Thus, this is the most
simple among all currently available CBV\textsubscript{a} measurement
methods. The major drawback of this approach is to
carefully select an inversion time to null blood signals, while
the inflowing blood during the inversion time fills up only
arterial vasculature. This condition is not easy to be met.

**ARTERIAL VS. VENOUS CBV CHANGE DURING STIMULATION**

Significant CBV changes induced by various neural stimuli have been observed using CBV-weighted fMRI and
intrinsic optical imaging studies [34-36]. The separation of
total CBV change into CBV\textsubscript{a} and CBV\textsubscript{v} changes is helpful
for understanding basic vascular physiology and properly
interpreting BOLD signals. We therefore investigated the
relationship between CBV\textsubscript{a} and CBV\textsubscript{v} in isoflurane-
anesthetized rats during 15-s forepaw stimulation [37].
Although most fMRI studies have been performed with \textalpha-
chloralose anesthesia, we instead chose to use isoflurane
because it provides stability of anesthetic depth coupled with
simple noninvasive induction; these benefits enable us to
maintain consistent animal physiology during the long
duration of these experiments [38, 39]. CBF and CBV\textsubscript{v} were
simultaneously determined by the MOTIVE technique [13],
while CBV\textsubscript{t} was determined by following intravascular
infusion of a susceptibility-based contrast agent [40, 41]. The
difference between CBV\textsubscript{a} and CBV\textsubscript{v} was considered to be
CBV\textsubscript{v}. Baseline vs. stimulation values in the somatosensory
cortical region (see Fig. 5) were: CBV\textsubscript{a} = 0.83 ± 0.21 vs.
1.17 ± 0.30 ml/100 g, CBV\textsubscript{v} = 3.10 ± 0.55 vs.
3.41 ± 0.61 ml/100 g, and CBV\textsubscript{a}/CBV\textsubscript{v} = 0.27 ± 0.05 vs.
0.34 ± 0.06 (n = 7, mean ± SD) [37]. Absolute changes in
CBV\textsubscript{a} (0.34 ± 0.16 ml/100 g) and CBV\textsubscript{v} (0.31 ± 0.11 ml/100
g) due to activation are similar (see Fig. 5). In our 15-s
somatosensory stimulation studies in rats, the blood volume
changes during neural stimulation occur mainly in arteries
rather than in veins [37]. Direct optical measurements of
vessel diameters show the similar finding that arterial blood
vessels dilate, while venous vessels do not change much
during 20-s neural stimulation [42]. Arterial vs. venous CBV
changes can be dependent on stimulus parameters such as
strength, spatial extent, and duration [30]. If the stimulus
duration is short, venous CBV change will be minimal due to
its passive responsiveness. If the stimulation duration is long,
then venous CBV contribution is larger [43]. Nonetheless,
arterial CBV change is highly significant, and can be used
for functional brain mapping.

The implication of our CBV\textsubscript{a} findings have been
discussed previously [37]. The BOLD effect depends on
alterations in venous oxygenation level (\textgamma) and CBV\textsubscript{v} in
response to increased neural activity [21]; an increase in
venous oxygenation level increases BOLD signals, while an
increase in venous blood volume decreases the BOLD effect.
It should be noted that an increase in CBV\textsubscript{a} in itself does not
contribute to BOLD signals significantly. Generally, the
CBV\textsubscript{v} change has been estimated directly from total CBV\textsubscript{t}
measurements or indirectly from CBF changes using Grubb’s
equation [44-47] under the assumption that CBV\textsubscript{a}
changes are dominant. Since our results show that venous
blood volume changes are minimal during short stimulation,
BOLD fMRI signals will derive mostly from changes in venous oxygenation. Thus, the biophysical model for BOLD can be simplified as

$$R_2^* = M \cdot CBV \cdot \Delta Y,$$

where $R_2^*$ is the stimulus-induced relaxation rate change, $\Delta Y$ is the change in venous oxygenation level, which is caused by the mismatch between CBF and cerebral oxygen consumption (CMRO$_2$) changes, and $M$ is a constant closely related to many biological and MR parameters, including vessel size, magnetic field, and pulse sequence. To show the importance of functional CBV$_a$ contribution, relative CMRO$_2$ changes were estimated from the human visual cortex data reported in Kim et al. [46], which are $\Delta$CBF/CFB and $\Delta R_2^*$ of 47% and -0.45 s$^{-1}$ during hypercapnia, and 44% and -0.11 s$^{-1}$ during visual stimulation, respectively. i) When it is assumed that the relative CBV$_a$ (rCBV$_a$) change = the relative CBV$_t$ change obtained from $\Delta$CBF/CFB using the Grubb’s equation for both hypercapnia and visual stimulation, which has been widely used in the fMRI community, the relative CMRO$_2$ change is 17%. ii) If the rCBV$_a$ change = the relative CBV$_t$ change in hypercapnia, but rCBV$_a$ change = 0 for visual stimulation, then the relative CMRO$_2$ change is 38%. iii) If the rCBV$_a$ change = 0 for both hypercapnia and neural stimulation, then the relative CMRO$_2$ change is 30%. The ratio of relative CMRO$_2$ to CBF change is 0.39, 0.86, and 0.68, depending on the different rCBF vs. rCBV$_a$ conditions. When the commonly-accepted assumption of significant CBV$_a$ changes is used (case #1), $\Delta Y$ will be overestimated as determined from the measured BOLD response, and consequently the CMRO$_2$ change is underestimated significantly. Thus, the proper estimation of rCBV$_a$ change, which is indirectly determined from arterial and total CBV changes in our laboratory, is important to quantify relative CMRO$_2$ change from BOLD signals.

**SPATIAL SPECIFICITY OF ARTERIAL CBV CHANGE**

One of important questions is whether the functional CBV$_a$ response is specific to sites of neural activity. To evaluate spatial specificity of fMRI signals, the cat cortical layer model with full-field visual stimulation can be used [36]. If the fMRI signal is specific to neural activity, the highest change should occur within layer 4, which has the highest density of capillary mesh and synapses, and which has the highest changes in neural activity, metabolism, and blood flow during sensory stimulation [48]. Layer 4 is roughly located at the middle of the cortex (hyperintensity area in T1-weighted image indicated by black arrows in Fig. 6D). Full-field visual stimulation activates the entire visual cortex, so blood containing stimulus-induced deoxyhemoglobin changes travels far downstream to large draining veins, thus it is ideal to examine spatial specificity.
of fMRI signals. Note that the rat forepaw stimulation model used in Fig. (5) is not ideal for investigating spatial specificity due to small activation area and consequently minimal draining problem. To obtain both BOLD and CBVa changes, MT-varied BOLD fMRI [22] was used on a well-developed cat visual cortical model due to its higher sensitivity and temporal resolution over ASL approaches. BOLD fMRI with three MT levels was acquired across cortical layers of isoflurane-anesthetized cats during visual stimulation with a single-shot gradient-echo (GE) EPI technique with slice thickness = 2 mm, in-plane resolution = 0.31 x 0.31 mm², TE = 20 ms, and TR = 1 s. In conventional GE-BOLD fMRI (i.e. without MT effect), the highest percentage signal changes occur above the surface of the cortex (green contour area in Fig. 6A), within the subarachnoid space containing cerebrospinal fluid (CSF) and numerous large vessels (including pial veins). Stimulus-induced changes normalized by S₀ (ΔSᵣ/S₀) were linearly fitted against corresponding normalized baseline signals (Sᵣ/S₀) (refer to Fig. 2 schematic). When intercepts were computed from BOLD data acquired at three different MT levels, positive values were observed within the cortex, while negative values were detected mostly from the cortical surface (Fig. 6B). Since arterial vessels dilate during stimulation, only positive intercept values are shown in the ΔCBVa map of (Fig. 6C). Within the cortex (within the green contours), the highest change was observed at the middle of the cortex (indicated by white arrows in Fig. 6C), where average ΔCBVo and BOLD responses without MT effects (n = 7) were 0.33 ± 0.02 ml/100 g and 1.16 ± 0.44%, respectively [30]. Negative changes observed in the surface of the cortex (purple pixels in Fig. 6B) are likely due to a decrease in MT-insensitive CSF volume [30], which was experimentally proven using T₁rho-based fMRI [49]. This clearly demonstrates that arterial CBV fMRI will improve spatial specificity to sites of neural activity relative to BOLD fMRI.

Since CBVo response is more specific to neural activity relative to BOLD fMRI, it can be used for high-resolution fMRI. Functional CBV measurements with endogenous contrasts have been shown by i) arterial spin labeling with varied MT effect (i.e., MOTIVE) [37] and Look-Locker EPI [10], ii) vascular space occupancy (VASO) [50], and iii) apparent diffusion coefficient (ADC) [51]. ASL with LL EPI was used in humans for fMRI studies; baseline CBVo in the motor cortex was 3.7% and increased to 4.9% during finger tapping [10], and baseline CBVo in the visual cortex was 0.88 ml/100 g and increased to 1.44 ml/100 g during visual stimulation [52]. Functional CBVo maps appear to be more localized than BOLD fMRI [10]. The VASO technique has been used to determine temporal dynamics of functional CBV change, but its sensitivity is quite poor, especially at high magnetic fields. Since T₁ values of blood and tissue converge at high fields, the suppression of blood signals with the non-selective inversion recovery technique results in low tissue signals. To overcome this issue, inflow-enhanced slab-selective VASO approach was proposed [53], which can also improve spatial resolution [53]. However, the VASO technique is difficult to the quantification of absolute or relative CBV changes, and also sensitive to CSF contributions. Functional ADC changes with small b-values are heavily weighted by ΔCBVo if venous blood signals are suppressed [31]. The venous blood signal can be suppressed at setting TE >> T₂*, which can be achieved at high fields. In fact, this bipolar gradient BOLD approach has been extensively used to separate intra- and extra-vascular functional signals [27, 54].

Based on our animal studies at 9.4 T, we found that MT-varied BOLD provides the highest sensitivity and temporal resolution among available techniques in our laboratory, ASL with MT (MOTIVE), VASO, and ADC. The MT-varied BOLD technique provides simplicity, high temporal resolution and high sensitivity for the quantification of ΔCBVo, thus is the choice of non-invasive CBV-weighted fMRI methods in animal studies with a surface coil. Drawbacks of the MT-varied BOLD technique are many folds. i) Additional MT-inducing pulse is required, consequently concerning SAR at high magnetic fields. ii) Since inflow spins should not experience MT-inducing pulses, the surface coil is preferable. When a homogeneous coil is used, then inflowing arterial blood also have up to 40% of tissue MT effects [55]. iii) In MT BOLD fMRI, the venous CBV contribution is assumed to be minimal. If MT effect in tissue and venous blood is similar due to free water exchange, then both venous blood and tissue signals are MT-dependent, while the arterial signal is MT-independent. This assumption is valid when MT pulses are long enough (≥ water exchange time). Otherwise, the venous blood signal is suppressed by setting TE >> T₂* of venous blood, which can be achievable at high fields. iv) MT BOLD fMRI requires two fMRI runs with or without MT effect. Due to head motions between fMRI runs, MT-varied BOLD fMRI is not easy to be implemented for human fMRI studies.

CONCLUSIONS

Quantitative CBVo and its functional changes can be determined non-invasively with MRI. The CBVo response shows dominant to total CBV change during neural activation and well-localized to neural activity, and also provides the quantification of functional activity. Therefore, the CBVo MRI techniques may be valuable tools for routine determination of vessel viability and function, as well as the identification of vascular dysfunction.

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REFERENCES


