Optimization of phase-contrast MRI for the quantification of whole-brain cerebral blood flow

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TARGET AUDIENCE: Researchers and physicians interested in quantifying cerebral blood flow.

PURPOSE: Phase-Contrast MRI (PC-MRI) is a noninvasive MRI technique for quantitative flow measurements without the needs of exogenous tracers or assumptions associated with complex models. By measuring the flow flux at the main feeding arteries of the brain, including bilateral internal carotid arteries (ICAs) and vertebral arteries (VAs), one can quantify whole-brain cerebral blood flow (CBF) noninvasively with PC-MRI technique (1). The whole-brain CBF measured by PC-MRI not only provides an important index for brain function, but can also be used to normalize other regional CBF mapping techniques such as dynamic susceptibility contrast (DSC) techniques (2) or arterial spin labeling (ASL) (3). Therefore, optimizing the PC-MRI protocol for accurate quantification of whole-brain CBF is a critical step towards its wider applications in CBF mapping and brain function assessment. The present study aims to address two technical issues in PC-MRI. Since the PC-MRI measured velocity map is susceptible to partial voluming which could lead to biases in CBF estimation, the first component of this work aimed to optimize in-plane resolution of PC-MRI acquisition for CBF quantification by considering accuracy, precision, and scan duration. In the second component of this work, we assessed the detrimental effect of non-perpendicular imaging slice orientation on CBF quantification. Additionally, we evaluated the inter-rater reliability in PC-MRI data processing. This allowed us to obtain an optimized PC-MRI protocol for fast and accurate quantification of whole-brain CBF in adults.

METHODS: A total of 19 healthy subjects (12 males, 19-56 years old) were studies on a 3 Tesla MRI scanner (Philips). *Study 1: Effect of in-plane resolution on CBF quantification*. Resolution values of 0.4, 0.5, 0.6 and 0.7 mm were evaluated in 12 subjects. For each subject, a 3D time-of-flight (TOF) angiogram was first performed to visualize the feeding arteries of the brain (Fig. 1a). Next, CBF was measured on the targeted arteries using PC-MRI scans with various resolutions on ICA and VA, respectively (Fig. 1b). Due to time constraints, left ICA and left VA were chosen as the representative of the ICAs and VAs, respectively. The numbers of repetition were 11, 8, 7 and 6 for the resolution of 0.4, 0.5, 0.6 and 0.7 mm, respectively, assuring sufficient signal-to-noise (SNR) at each resolution. Other imaging parameters are: single slice, FOV=200×200×5 mm^3, maximum V_{ENC}=40cm/s. A smaller V_{ENC} was used to increase SNR of voxels near the edge of the arteries which have slow flow velocity, and any velocity aliasing was corrected in post-processing. To compare across resolutions, one-way ANOVA tests with repeated measures were performed on CBF value, Coefficient of Variation (CoV) of CBF, and artery area. *Study 2: Effect of slice orientation on CBF quantification*. To systematically evaluate the bias caused by imperfect slice orientation, we varied the angulation of the imaging slice from 0˚ to 30˚ at 5˚ step, with 0˚ represents the ideal positioning where the imaging slice is perpendicular to the targeted artery. A total of 28 PC-MRI scans (7 angulations x 4 repetitions, randomized) were performed on left ICA, and left VA, respectively. The optimal in-plane resolution determined from Study 1 was used. To compare the difference among imaging slice angulations, one-way ANOVA tests with repeated measures were performed on CBF values, CoV of CBF and artery area. *Inter-rater variability:* Since the CBF processing involves manual ROI drawing, we investigated the inter-rater reliability by comparing CBF values from studies 1 and 2 obtained by two raters.

RESULTS and DISCUSSION: *Study 1:* Figure 2 shows the effect of in-plane resolution on CBF quantification. One way ANOVA analysis showed that, the imaging resolution has a significant effect on CBF values for both left ICA (Fig. 2a, P=0.021) and left VA (Fig. 2d, P<0.001). CBF obtained with lower resolution would have higher values due to partial voluming. This partial voluming effect is more pronounced in VA than ICA. The CoV of the measured CBF tended to be slightly greater at higher spatial resolutions but the main effect did not reach a significance level (Fig. 2b and 2e). Arterial cross-sectional area was found to be significantly dependent on spatial resolutions for both left ICA (Fig. 2c, P<0.001) and left VA (Fig. 2f, p<0.001). To reach a tradeoff between accuracy, precision and time-cost, we recommend the spatial resolution of 0.5 mm for PC-MRI, and this was used in Study 2.

Study 2: Figure 3 shows the the effect of slice orientation on CBF quantification. The angulation of the imaging slice has a significant effect (p<0.001) on the measured area of the left ICA (Fig. 3c) and left VA (Fig. 3f). The angulation also showed a significant effect (p<0.01) on the CBF for both left ICA (Fig. 3a) and left VA (Fig. 3d). Compared to the ideal, perpendicular orientation (i.e., angulation of 0°), the angulations of 20° and larger showed a significant CBF overestimation (>8.9%, p<0.01) in ICA, and the angulations of 15° and larger showed a significant CBF overestimation (>10.1%, p<0.01) in VA. No significant CBF difference was found when the slice angulation was within 10° from the ideal orientation, for both left ICA and left VA, indicating that PC-MRI can tolerate certain degree of slice orientation imperfection. CoV of the PC-MRI scans was independent of the slice angulation for both left ICA (p=0.44, Fig. 3b) and left VA (p=0.82, Fig. 3e).

Inter-rater variability: In study 1, CBF values obtained by the two raters differed by 0.2±0.6% and 0.01±2.5% for ICA and VA, respectively. In study 2, CBF values obtained by the two raters differed by -0.45±2.1% and -2.4±3.7% for ICA and VA, respectively. The rater-effect is not a major contribution to the uncertainty in CBF quantification since inter-rater difference was <3%.

CONCLUSION: In conclusion, this work showed that PC-MRI scans applied on major feeding arteries of the brain with a spatial resolution of 0.5 mm could serve as an optimal protocol for the quantification of whole-brain CBF. In addition, non-perpendicular positioning of the imaging slice on the targeted artery could result in an overestimation in CBF. But if the slice orientation is within 10° of the ideal angulation, the bias is negligible.

REFERENCES: 1. Liu et al., MRM 2013; 69: 675-681. 2. Bonekamp et al., MRM 2011; 66: 54-66. 3. Aslan et al., MRM 2010; 63: 765-771

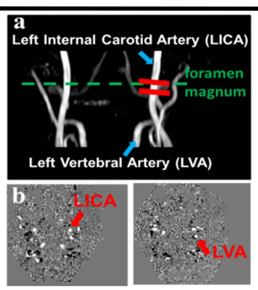

Fig. 1: Phase-contrast MRI. (a) position of phase contrast slice (red line) on a time-of-flight (TOF) angiogram. (b) phase image of phase-contrast MRI.

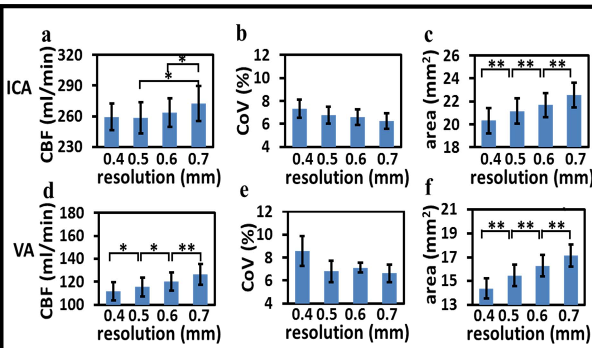

Fig. 2: Effect of in-plane resolution on CBF quantification. Mean CBF, CoV, and artery area obtained at different spatial resolution for (a)-(c) left ICA and (d)-(f) for left VA.

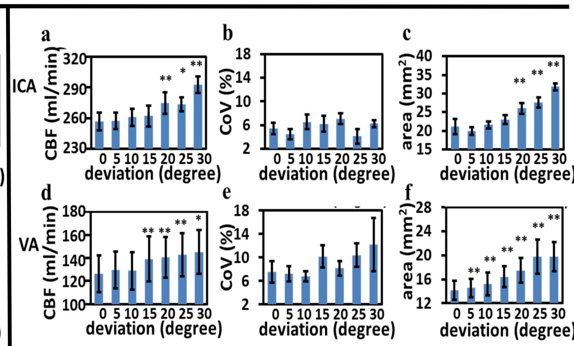

Fig. 3: Effect of slice orientation on CBF quantification. Mean CBF, CoV, and artery area obtained at different angulation for (a)-(c) left ICA and (d)-(f) for left VA.