Mapping of Cerebral Blood Flow Directionality with Alternate Ascending/Descending Directional Navigation (ALADDIN)

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Introduction : Blood perfusion signals are commonly measured with arterial spin labeling technique and represented in a scalar quantity (rank 0). The directional property of perfusion has been rarely studied [1]. Alternate ascending/descending directional navigation (ALADDIN) is a new imaging technique in that perfusion-weighted images are sensitized to the directionality of local blood supply [2] and magnetization transfer asymmetry images can be acquired along with perfusion-weighted images simultaneously [3]. In ALADDIN perfusion-weighted imaging, *labeling* and *control* are determined by the direction of an individual blood spin movement rather than specific labeling and control scans. As such, blood spins moving in the same direction as imaging order are labeled, whereas those in the opposite direction are not labeled (control). In this study, we tested the feasibility of ALADDIN for mapping perfusion directionality in two different ways: one with vector mapping (rank 1) and the other with tensor mapping (rank 2) by acquiring imaging data at 3 and 6 different directions, respectively, similar to phase contrast (PC) MR angiography (MRA) and diffusion tensor imaging (DTI) [4], respectively.

Material and Methods : All experiments were performed on a 3T whole body scanner (Siemens Medical Solutions, Erlangen, Germany) with a body coil transmission and a 12-element head matrix coil reception. Five normal male volunteers were scanned in this study approved by the Institutional Review Board.

Perfusion-weighted images were acquired with ALADDIN [2]. Briefly, four different datasets were repeatedly acquired with alternate ascending/descending orders with positive slice-select gradients followed by the alternate orders with negative slice-select gradients. Imaging parameters were TR/TE = 4/2 ms, flip angle = 40°, matrix size = 128 × 128, FOV = 256 × 256 mm^2, thickness = 5 mm, gap = 7 mm, acquisition bandwidth = 575 Hz/pixel, scan direction = axial, PE order = linear, delay time between repetitions = ~1 sec, and scan time per dataset = ~2 min. Two datasets were acquired along each direction: one with number of slices 19 (odd) and the other with number of slices 18 (even) and then interleaved to each other to cover wider regions with the conventional gap value of 1 mm. Datasets were reconstructed as PSC between averaged ascending and descending images.

To map the perfusion directionality in a vector form, we acquired the data along three orthogonal directions of axial, sagittal, and coronal. To map the perfusion directionality in a tensor form (perfusion tensor imaging, PTI), we acquired the ALADDIN PW images along 6 different directions similar to DTI [4], as follows.

$$d = \left[\left(1/\sqrt{2}, 1/\sqrt{2}, 0\right)^T; \left(1/\sqrt{2}, -1/\sqrt{2}, 0\right)^T; \left(1/\sqrt{2}, 0, 1/\sqrt{2}\right)^T; \left(1/\sqrt{2}, 0, -1/\sqrt{2}\right)^T; \left(0, 1/\sqrt{2}, 1/\sqrt{2}\right)^T; \left(0, 1/\sqrt{2}, -1/\sqrt{2}\right)^T \right] \quad (1)$$

$$P = \begin{bmatrix} P_{XX} & P_{XY} & P_{XZ} \\ P_{XY} & P_{YY} & P_{YZ} \\ P_{XZ} & P_{YZ} & P_{ZZ} \end{bmatrix} \quad (2) \quad , \quad d^T P d = f \propto \left| \frac{\Delta M}{M_0} \right| \quad (3)$$

The perfusion tensor matrix (P) and the blood flow signals (f) along the specific unit vector can be described as Eqs. 2 and 3, where $\Delta M/M_0$ represents percent signal changes (PSC) between *labeling* and *control* images. Solutions of the 6 different equations from the combination of Eqs. 1–3 determine the 6 unknown parameters in the matrix P (Eq. 2).

The 3 orthogonal datasets for the vector mapping and the 6 oblique datasets for the tensor mapping were interpolated into nominal isotropic resolution of 2 × 2 × 2 mm^3 along the reference frame. For the tensor mapping, P and its eigenvalues and eigenvectors were calculated. The direction of the primary eigenvector was mapped in color.

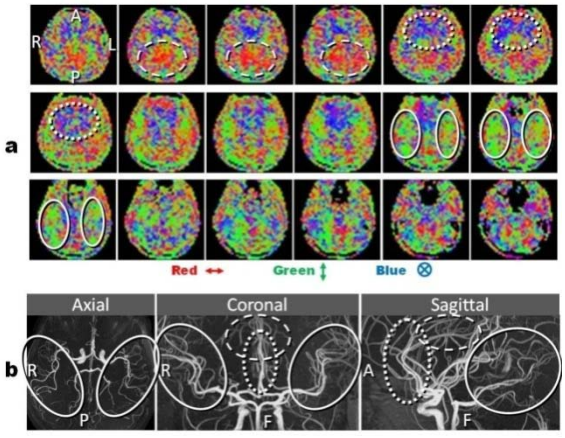

FIG. 3. Color mapping of the primary eigenvector direction of ALADDIN PTI (**a**) and corresponding time-of-flight (TOF) MR angiogram (**b**) in whole brain of a representative subject. The direction of each color in **a** is indicated at the bottom. The oval shapes with broken, dotted, and solid lines, represent exemplary clusters of the voxels with the same colors of red, blue, and green, respectively. Oval shapes in **b** represent the arteries that presumably contributed to the generation of the corresponding regional clusters in **a** with the same line types.

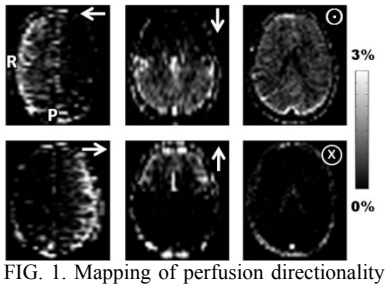

FIG. 1. Mapping of perfusion directionality with ALADDIN in a vector form. The perfusion directions are indicated on the upper right corner. Image locations are identical.

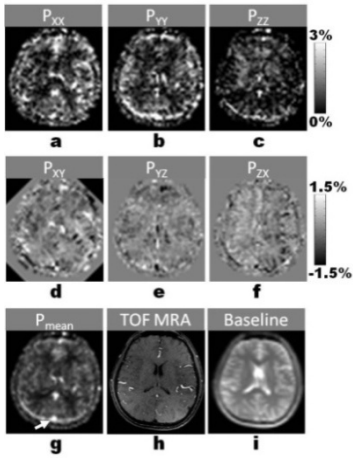

FIG. 2. Demonstration of ALADDIN perfusion tensor images. The diagonal terms (**a–c**), off-diagonal terms (**d–f**), and mean perfusivity (mean of eigenvalues = mean of diagonal terms) (P_{mean}) (**g**) of the tensor matrix are displayed in comparison with the corresponding time-of-flight MR angiogram (**h**) and the baseline image (**i**). The gray scale in **g** is from 0% to 3%. The arrow in **g** indicates the sagittal sinus vein.

Results and Discussion : Blood flow directions mapped with ALADDIN in the vector form was from brain center to lateral, anterior, and posterior (left two columns in Fig. 1) and from feet to head (right column in Fig. 1). For the tensor mapping, the signals of the diagonal terms were generally higher in GM than in WM. On the P_{ZZ} map, some strong signals were notable in WM regions (compared to GM regions) (Fig. 2c). The signals from the off-diagonal terms were smaller than those of the diagonal terms with distinct ranges in their signal distributions (Fig. 2d–f). Some bright spots and lines noted in the mean perfusivity map (Fig. 2g) corresponded to the arteries detected in time-of-flight MR angiogram (Fig. 2h), while other bright structures were presumed to be venous blood vessels (e.g., sagittal sinus vein indicated by the arrow in Fig. 2g). The directions of the primary eigenvector were heterogeneous between regions (Fig. 3a), the spatial distribution of these patterns was visually consistent across the subjects. Some of them exemplified as oval shapes in Fig. 3a might be partly attributed to the arteries detectable in TOF MR angiogram (Fig. 3b).

In ALADDIN, *labeling* and *control* scans spatially track imaging planes with the role of the scans alternating according to the direction of blood spin movement. This directional property allows mapping blood flow directionality. We have yet to investigate the dimension of blood vessels that are predominantly labeled and contribute to the directionality. Some measurement errors might arise from the non-isotropic scan resolution of the original 6 datasets. Further studies are necessary to assess the measured directionality of the primary eigenvector of ALADDIN PTI.

Acknowledgement : This work was in part supported by Competitive Medical Research Fund of the UPMC health system. **References** : 1. Frank et al, Magn Reson Med 2008;60:1284-1291. 2. Park and Duong, Magn Reson Med 2011;65:1578-1591. 3. Park and Duong, Magn Reson Med 2011;65:1702-1710 4. Le Bihan et al, J Magn Reson Imaging 2001;13:534-546.