Mapping cerebral blood flow territories using harmonic encoding pseudocontinuous arterial spin labeling, fuzzy clustering, and independent component analysis

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Introduction
Vessel-encoded pseudocontinuous arterial spin labeling (VEPCASL) (1) is a novel MRI technique with capability of differentiating flow territories of the primary arteries passing through a predefined tagging plane. As a derivative of ASL, VEPCASL inherits limited signal-to-noise ratio (SNR), which makes the classification method important in the determination of flow territories. While independent component analysis (ICA) is known as a data-driven method that separates multivariate data into subcomponents, fuzzy C-means (FCM) clustering is a soft classification method, which in our purpose provides for each pixel its probability of belonging to each flow territory. In this study, we implemented VEPCASL with harmonic encoding to expand feature dimension and employed ICA and FCM clustering for territory separation. Comparison was made with previously described K-means algorithms.

Materials and Methods
Four healthy subjects (2 females and 2 males, 22-28 yrs) were scanned under IRB approval and all gave written informed consent before partaking in the experiment. MR imaging was performed on a 3T scanner (Tim Trio, Siemens, Erlangen, Germany). The body coil was used for RF transmission and a 16-channel phased-array coil for reception. Scout scans were followed by whole-brain 3D magnetization prepared rapid gradient echo imaging for subsequent structure segmentation, and 3D time-of-flight angiogram for planning of VEPCASL. Two series of VEPCASL images were obtained by placing the tagging plane at different levels as shown in Fig 1 (α = tagging efficiency, L = spatial period of encoding) to include (A) left/right internal carotid arteries and vertebral arteries, and (B) anterior/middle/posterior cerebral arteries (ACA/MCA/PCA). Given that the tagging efficiency of PCASL is approximately sinusoidal in space (2,3), we applied harmonic encoding to generate varied degrees of tagging for multiple vessels at the same time. The black curves in Fig 1 indicate the originally proposed encoding scheme (1) while blue and red curves are the higher order encoding added in this study. Imaging parameters were: TR = 4 s, TE = 18 ms, labeling duration = 1.5 s, post-labeling delay = 1.2 s (Fig 1A) or 1 s (Fig 1B), matrix = 64x64, field-of-view = 22 cm, 11 (Fig 1A) or 5 (Fig 1B) axial slices, thickness = 5 mm, single-shot gradient-echo echo-planar readout. Scan time was 8 min for Fig 1A and 12 min for Fig 1B. VEPCASL images were grouped according to encoding steps, realigned separately for motion correction, and then co-registered between groups. The preprocessed images were averaged and subtracted to generate contrast which was converted to relative tagging efficiency (β) as described in Ref. 1. With harmonic encoding, multi-dimensional β was obtained. Flow territories were extracted with K-means, FCM, and ICA using homemade scripts and FastICA (http://www.cis.hut.fi/projects/ica/fastica/), respectively, in Matlab (www.mathworks.com). Analysis was performed within the gray matter mask created by segmenting anatomic images.

Results
Fig 2 shows the computed flow territories corresponding to the tagging plans in Fig 1. The components extracted by ICA and FCM were in continuous values and fed to K-means clustering to explicitly specify the flow territory of each pixel. As a whole, K-means alone and combination of K-means and ICA/FCM were able to distinguish principal flow territories such as the right/left internal carotid arteries and PCA in Fig 2A, and the ACA, PCA, and two branches of the M2 segment of the MCA on both sides in Fig 2B. However, applying K-means directly in the β space generated quite a few isolated blobs by mistake. Isolated pixels were noticeably reduced when K-means was applied to the components extracted by ICA and FCM. Specifically, ICA appeared to outperform FCM in terms of misclassification (see arrows). Highlighted in the rightmost image in Fig 2A is the area where no dominant FCM components were found (i.e., none accounted for probability larger than 0.5), which suggests the borderline of two or more flow territories and may provide useful information for clinical evaluation of watershed infarction.

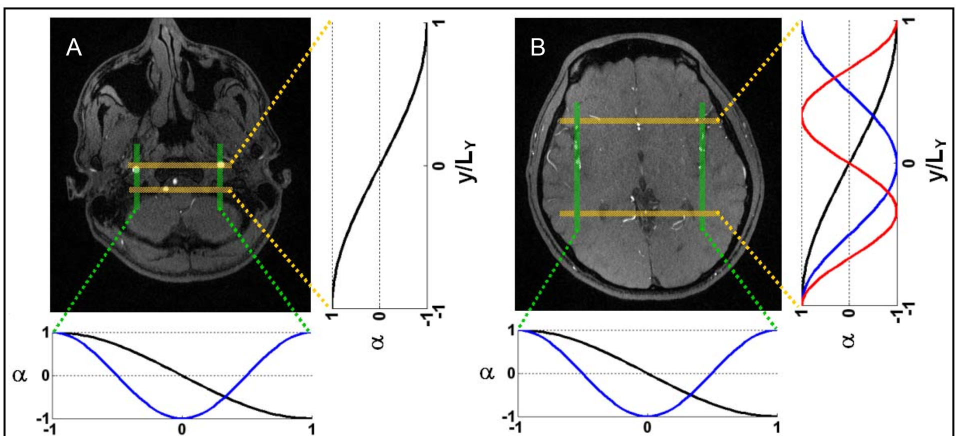

Fig 1

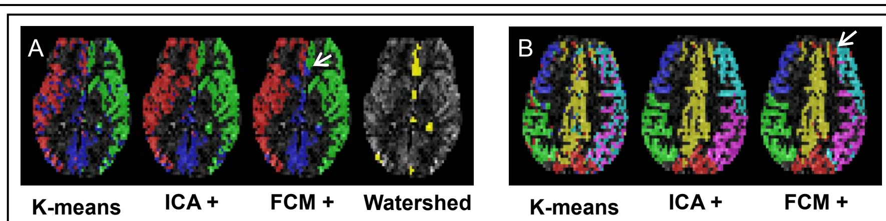

Fig 2

Discussion
Sine/cosine tag modulation (4) has been proposed to localize the position y of target vessels by $y = \tan^{-1}(S/C)\, L_Y/2\pi$, where S and C are the signal obtained with sine and cosine tagging, respectively, and L_Y is the spatial period of encoding. While simple, the method is unable to distinguish the phase imposed by encoding from that originating from B_0 inhomogeneity (i.e., $\tan^{-1}(S/C) = 2\pi y/L_Y + \phi(y)$). We have demonstrated that ICA and FCM can substantially improve the robustness of K-means clustering. Feature dimension can be efficiently expanded using harmonic encoding, especially along the direction where vascular branches are more complex.

References
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4. Wong and Kansagra, ISMRM 2008, p.182.