The use of *k*-means clustering and Bayesian inference framework for the processing of vessel-encoded p-CASL images as compared with super-selective p-CASL MRI

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Introduction Vessel-encoded (VE) pseudo-continuous arterial spin labeling (p-CASL) is a territorial ASL (T-ASL) technique to identify the perfusion territories of arteries.[1] The aim of this study was to compare the output of two VE p-CASL image processing methods, *k*-means clustering and a Bayesian framework, with the perfusion maps acquired with super-selective p-CASL.

Methods Fourteen healthy volunteers were investigated on a 3 T MRI scanner (Philips Healthcare). Two T-ASL techniques were performed: one planning-free vessel encoded (VE) p-CASL sequence[1,2] with 5 cycles, and four super-selective p-CASL sequences[3] for both internal carotid arteries (RICA, and LICA) and both vertebral arteries (RVA, and LVA). The VE p-CASL images were processed with both *k*-means clustering[2], resulting in 3 territories (RICA, LICA, and basilar artery [BA]), and a Bayesian framework[4], resulting in 4 territories (RICA, LICA, RVA, and LVA).

The territorial maps calculated with both VE techniques were compared to those acquired with super-selective p-CASL. The regions of the RICA, LICA, and BA were manually outlined by one observer (NH) and quantitatively compared using the Hausdorff distance and Dice similarity coefficient (DSC). The territorial maps calculated with the Bayesian framework were also compared using the modified DSC (mDSC) for a fractional comparison of the actual perfusion of the 4 territories.

The Hausdorff distance is a measure of error and is defined as the maximum distance between two regions.[5] The Dice similarity coefficient (DSC) is a spatial overlap measure and is defined as the ratio between the number of voxels in the intersection between two regions, and the mean volume of both regions.[6] Perfusion maps of the RICA, LICA, RVA, and LVA calculated with the Bayesian framework were examined with a DSC (mDSC) modified according to Crum et al.[7]

For a qualitative comparison of both VE processing methods, anatomical regions of the cortical anterior circulation, deep gray matter, cortical posterior circulation, and (for Bayesian framework only) the vertebrobasilar system (VBS), were scored by one observer (NH) for their agreement with the super-selective p-CASL perfusion maps as follows: excellent (agreement both of anatomical regions as well as mixed perfusion), good (anatomical regions agree but mixed perfusion is not detected), moderate (some boundaries are misclassified due to mixed perfusion), fair (boundaries of anatomical regions disagree), and poor (misclassification of an anatomical region).

Results Two cases are presented, in which there is mixed perfusion in the deep gray matter (figure 1) and in the anterior circulation (figure 2). The quantitative comparison of the entire group is summarized in table 1 and the qualitative comparison is depicted in figure 3.

	Territory				
Method	**RICA**	**LICA**	**BA**	**RVA**	**LVA**
Hausdorff distance (mm)					
k-means	10 ± 4	11 ± 4	10 ± 4		
Bayesian	11 ± 2	11 ± 2	11 ± 3		
Dice similarity coefficient {0-1}					
k-means	0.92 ± 0.02	0.91 ± 0.03	0.91 ± 0.03		
Bayesian	0.93 ± 0.02	0.92 ± 0.03	0.91 ± 0.03		
modified Dice similarity coefficient {0-1}					
Bayesian	0.93 ± 0.03	0.92 ± 0.04	-	0.75 ± 0.10	0.74 ± 0.12

Table 1. Hausdorff distance, DSC and mDSC for the perfusion territories of right and left internal carotid arteries (ICA), basilar artery (BA), and right and left vertebral arteries (VA), as calculated with both VE processing methods and compared with the super-selective p-CASL perfusion maps.

Discussion The results show that the territorial maps produced by VE p-CASL agree reasonably well with the perfusion maps acquired with super-selective p-CASL. Special consideration should be taken when using *k*-means clustering since it tends to fail in regions with high mixed perfusion, such as the deep gray matter. The Bayesian inference framework was superior in this regard; where it did not detect mixed perfusion it was found that the VE p-CASL source images had lower vessel selectivity between the different cycles. VE p-CASL with *k*-means clustering appears suitable as a general purpose T-ASL strategy, but the Bayesian framework is preferable since it can determine mixed perfusion. However, this is only reliable where the VE p-CASL images contain sufficient vessel selectivity, which was not always achieved using a planning free approach. To accurately determine the perfusion territories of a vessel, super-selective p-CASL is still recommended.

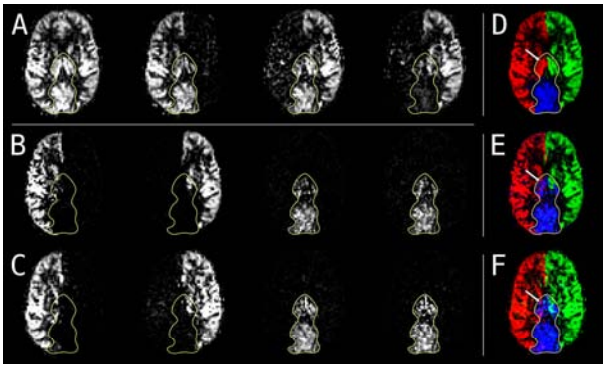

Figure 1. Perfusion maps of each VE p-CASL cycle (A), and the resulting *k*-means clustered territorial map (D). Perfusion maps of the RICA, LICA, RVA, and LVA generated with the Bayesian framework (B), and the corresponding superimposed territorial map (E). Perfusion maps acquired with super-selective p-CASL (C) of the RICA, LICA, RVA, and LVA, and the coressponding superimposed territorial map (F). This case illustrates mixed perfusion in the thalamic region (arrows), which is visible in the Bayesian generated maps, but is not shown in the *k*-means generated maps.

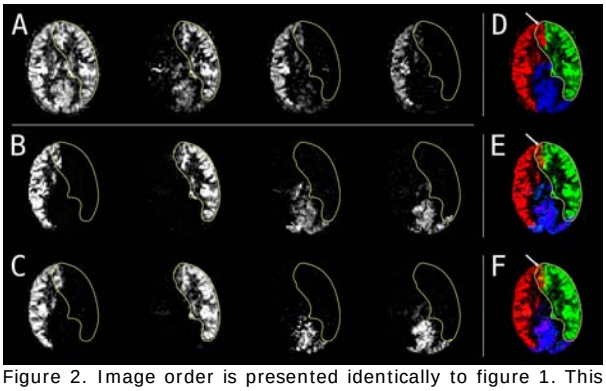

Figure 2. Image order is presented identically to figure 1. This case illustrates mixed perfusion in the anterior circulation (arrows), which is visible in the Bayesian generated maps, but is not shown in the *k*-means generated maps. The territoriy of the LICA is outlined on the super-selective p-CASL images and copied to the other territorial maps.

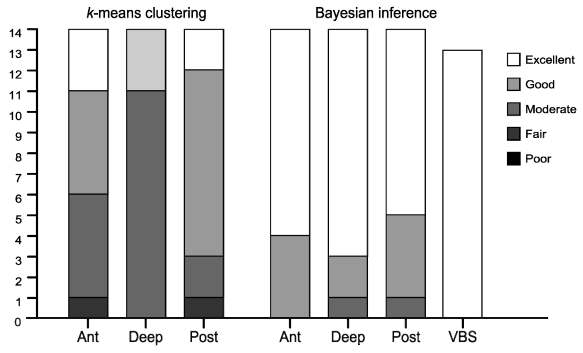

Figure 3. Qualitative agreement of *k*-means clustering and the Bayesian inference framework with super-selective p-CASL perfusion maps in the anatomical regions of the anterior circulation (Ant), deep gray matter (Deep), posterior circulation (Post), and the vertebrobasilar system (VBS).

References (1) Wong, Magn Reson Med. 2007:1086 (2) Gevers et al., AJNR. 2012:E21 (3) Helle et al., Magn Reson Med. 2010:777 (4) Chappell et al., Magn Reson Med. 2010:1529 (5) Huttenlocher et al., IEEE TPAMI. 1993:850 (6) Dice, Ecology. 1945:297 (7) Crum et al., IEEE TMI. 2006:1451