3D WEIGHTED LEAST SQUARES ALGORITHM FOR PARTIAL VOLUME EFFECT CORRECTION IN ASL IMAGES

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Target audience: Physicians, radiologists, engineers and data scientists.

Purpose: Develop and compare a new method for partial volume correction for measurement of cerebral blood flow (CBF) using arterial spin labeling (ASL), by employing a 3D Weighted Least Squares (3DWLS) correction based on the ratio between grey matter (GM), white matter (WM) and cerebro spinal fluid (CSF).

Introduction: ASL has become a popular MRI technique for clinical and research-driven, non-invasive measurement of cerebral blood perfusion. The principle of ASL is to employ arterial blood water as contrast agent. For brain CBF this is obtained by tagging a bolus of arterial blood in the carotid arteries. The magnetization of inflowing blood water protons is inverted in the region of the carotid arteries by means of an external radiofrequency pulse. After a period of time (post-labeling delay), blood is delivered to the entire brain through the smaller arteries and capillaries. This labeled arterial blood signal gives a rise to a reduction in the image intensity when compared to a non-labeled (control) image. The difference between control and labeled images is proportional to the amount of arterial blood delivered to each voxel within the slice within the inversion time; and through the use of a suitable model, can be expressed in conventional physiological units of ml blood/100g tissue/min.

A consequence of limited spatial resolution (in ASL and other MRI techniques) is the presence of partial effects (PVE). The effect is significant in ASL, where the low signal-to-noise (SNR) ratio leads to the use of larger voxels, typically of the order of 3x3x6mm. Therefore, there is a need to perform PVE correction, as each voxel is likely to contain signal mixing of perfusion information from different tissue types. Due to the relative insensitivity of ASL in white matter at magnetic fields below 3T, the prime interest when using this technique is the study of pure GM perfusion. However, in voxels containing (for example) 50% WM, the CBF values could be significantly under-estimated. PVE is of paramount importance in the study of neurodegenerative diseases where GM atrophy significantly affects CBF quantification and therefore the comparison of patient data against control populations.

Several methods for PVE correction have been proposed[1, 2, 3, 4] but Asllani's linear regression algorithm[2] and the correction based on the overall brain ratio between GM and WM (PET Legacy[4]) are the most used. The method proposed by Asllani is based on the fact that a region within the 2D kernel should have the same CBF value.

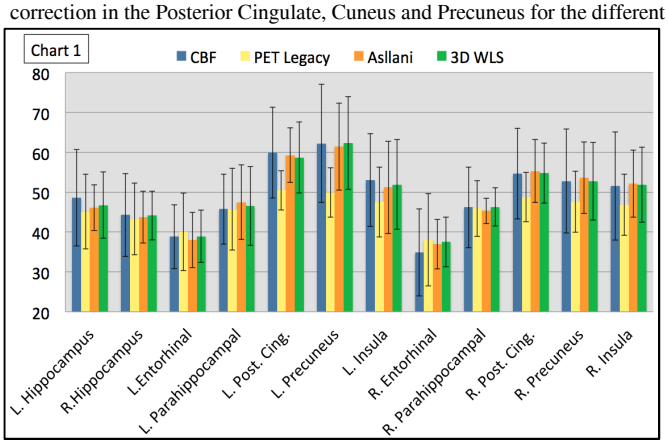
Methods: The algorithm proposed in this work explores the possibility of a 3D kernel and different weights for the voxels within that kernel. The first weighting matrix weights the distance to the kernel center using the inverse of the Euclidean distance. The second weighting matrix weights the confidence of that CBF measure computing the Fractional Aniso-probability (FA) of the tissue probabilities (GM, WM and CSF). The complete model is formulated below:

$$\begin{pmatrix} CBF_1 \\ \dots \\ CBF_N \end{pmatrix} = \begin{pmatrix} CBF_{Pure\,GM} & CBF_{Pure\,WM} & CBF_{Pure\,CSF} \end{pmatrix} * \begin{pmatrix} Prob_{GM,1} & \dots & Prob_{GM,N} \\ Prob_{WM,1} & \dots & Prob_{WM,N} \\ Prob_{CSF,1} & \dots & Prob_{CSF,N} \end{pmatrix} * W + \varepsilon$$

Where $W = W_E * W_{FA}$, both W_E and W_{FA} are diagonal matrices of NxN elements. For a specific voxel v, $W_E(v,v)=d(v,p)^{-1}$, with p denoting the voxel where the 3D kernel is centered and $d(v,p)^{-1}$being the inverse of the Euclidean distance between the centers of the voxels v and p. $W_{FA}(v,v)$ is defined as $\sqrt{\frac{1}{2}\frac{\sqrt{(Prob_{GM,v}-Prob_{WM,v})^2+(Prob_{WM,v}-Prob_{CSF,v})^2+(Prob_{CSF,v}-Prob_{GM,v})^2}}{\sqrt{(Prob_{GM,v})^2+(Prob_{WM,v})^2+(Prob_{CSF,v})^2}}}$. The resultant weight will give more importance to data from voxels that are closer to the center of the kernel and are more likely to be composed of one specific tissue.

The 3D weighted least squares algorithm was tested over a single healthy elderly subject, who underwent MRI examination in a 3T Signa HDx MR scanner (GE Healthcare, Waukesha, WI) using an eight-channel phased array coil. The first sequence was a 3D T1 weighted SPGR with a TR=10.024ms, TE=4.56ms, TI=600ms, NEX=1, acquisition matrix=288x288, resolution=1x1x1mm, FA=12. The second sequence was a 3D pCASL pulse sequence with matrix size= 128x128, resolution=1.875x1.875x4mm, flip angle = 155, labeling time 1.5s, post-labeling delay=2.025s, TR=4.733s, TE=9.812ms, NEX=3, acquisition time ~6min and was used to generate the regional cerebral blood flow (rCBF) maps. A segmented stack of spiral readout (8 arms, 512 points per arm) was employed. 3DT1 weighted images were segmented using SPM8 and also a cortical and subcortical parcelation was done using FreeSurfer. CBF maps were processed using Asllani's algorithm, PVE Legacy algorithm and 3D WLS with W, and W_E and W_{FA} separately.

Results: Chart 1 shows the changes in CBF (pure GM) values (ml/100g/min) for some selected regions (FreeSurfer labels). Figure 1 shows the effects of PVE correction in the Posterior Cingulate, Cuneus and Precuneus for the different PVE correction methods.



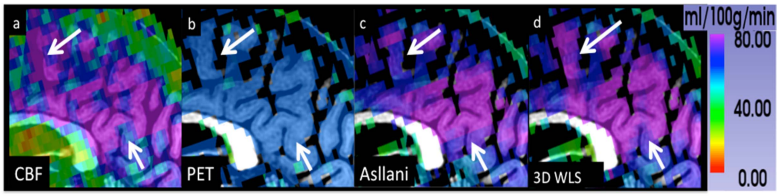


Fig. 1 Original CBF (a) and different PVE correction methods: PET Legacy (b), Asllani (c) and 3DWLS(d)

Discussion: The 3D WLS Fig.1 (d) achieves a more natural change in flow between slices (Z direction) than Asllani's 2D method. The PET Legacy method underestimates the CBF values in most of the regions. Whilst the data shows that in a single subject no statistically significant differences against Asllani's 2D method are found; we expect that our 3D WLS method is more robust due to a better modeling of anatomical differences and may provide superior in group comparisons with higher N.

Conclusion: We introduce a 3DWLS method that offers a more anatomically consistent formulation than current 2D-based linear regression algorithms[2]. The improvements are particularly evident in the slice direction. Our technique introduces the concept of weighting both distance and voxel composition based on Fractional Anisotropy Probability. Whilst at the single subject level it does not provide statistically significant differences against the 2D method, we are currently evaluating its effect in detecting statistically significant differences between groups of ASL data.

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