Automatic Segmentation of the Venous Vessel Network Based on Quantitative Susceptibility Maps and its Application to Investigate Blood Oxygenation

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TARGET AUDIENCE – Scientists with interest in image segmentation, three-dimensional data representation, and quantification of the cerebral venous vessel network.

INTRODUCTION – Three-dimensional angiographic imaging techniques in combination with sophisticated visualization tools and quantitative analysis methods are indispensable for diagnosis, treatment, and pre-surgical planning. A common method to assess the venous blood vessel network in high-spatial detail is susceptibility weighted imaging[1] (SWI). However, contrast on susceptibility weighted images may be non-local and there is a complex relationship between the orientation of venous vessel axis and the main magnetic field. To overcome this issue quantitative susceptibility mapping (QSM), a novel technique that enables conversion of gradient-echo phase images into maps of the magnetic susceptibility in vivo, can be applied.[2,3] Due to its quantitative nature, QSM also offers the possibility to estimate oxygen saturation within blood vessels. **In this contribution, we present an approach for automatic segmentation of venous vessels based on quantitative susceptibility maps to produce highly accurate 3D reconstructions of the cerebral venous network. This approach is also used to investigate blood oxygenation within the venous network.**

METHODS – *Data Acquisition:* Seven healthy subjects were measured with a fully flow compensated 3D single-echo gradient-echo sequence (TE/TR/FA/BW = 10.5ms/17ms/8°/140Hz/px, voxel size = (0.4 × 0.4 × 0.4) mm^3 on a 7 T MRI system. The scans were carried out with three different orientations of the head with respect to the magnetic field to enable computation of susceptibility maps using the COSMOS approach.[2]

Data Processing: The complex GRE data sets acquired in tilted head positions were registered to the data set acquired with normal head position. Phase aliasing was resolved by 3D phase unwrapping and background phase contributions were eliminated with the SHARP technique.[3] From the three background field corrected phase data sets susceptibility maps were computed using the COSMOS technique.[2,3] The susceptibility maps were normalized with respect to cerebrospinal fluid (CSF) and the susceptibility differences, $\Delta\chi$, in veins were converted to the underlying oxygen saturation, Y, according to $Y = 1 - \left(\frac{\Delta\chi}{\Delta\chi_{do} \cdot Hct}\right)$, where χ_{do}, the susceptibility difference between fully deoxygenated and fully oxygenated blood, is 3.39 ppm[5] and the hematocrit, Hct, was assumed to be 0.40. The susceptibility maps served as the basis for extracting the venous vessel network. To this end, firstly, vessel enhancing diffusion[6] (VED) was applied to the magnetic susceptibility maps to enhance the venous image contrast. VED involves computation of the second order tensor from the Hessian matrix in each voxel and uses the main direction of the tensor to smooth the vessel map. Secondly, a composite image, I_{comp}, was computed by weighted additive composition of the susceptibility map and the VED image ($I_{comp} = \alpha$*QSM+β*VED) using α=0.4 and β=0.6m determined empirically. Thirdly, a level set segmentation method was applied to the composite image. This level set approach[7] considered the principle direction of the vessel as given by the eigenvector and eigenvalue analysis of the Hessian matrix as well as local signal intensity changes to evolve the level set also along thin vessels. Based on the level-set results three-dimensional shaded surface representations of the venous network were created using the marching cubes technique. Finally, the oxygenation saturation was extracted within veins based on the segmentation result and mapped onto the extracted network.

RESULTS – The maximum intensity projection of the VED map (Fig. 1A) displays vessel structures from the main larger vessels to the smaller ones. The VED map was combined with the susceptibility map to enhance the vessels in the susceptibility map (Fig. 1B) while still keeping the valuable information of the susceptibility map required for segmentation. The whole venous network was reconstructed from the level set segmentation result of the acquired slab and allows following the vessels close to the basal ganglia (Fig. 1 B1) and cortical vessels (Fig. 1 B2). The entire venous vessel network of the acquired slab is presented in Fig. 1C using surface rendering showing the spatial organization of the cerebral veins. Finally, we mapped the blood oxygenation onto the extracted venous segments (Fig. 1D). The large sinuses show low oxygenation rates of about 60%: Interestingly, the blood oxygenation gradually increases along the vessels' path with larger distance from the sinuses to reach more than 80% in the small vessels.

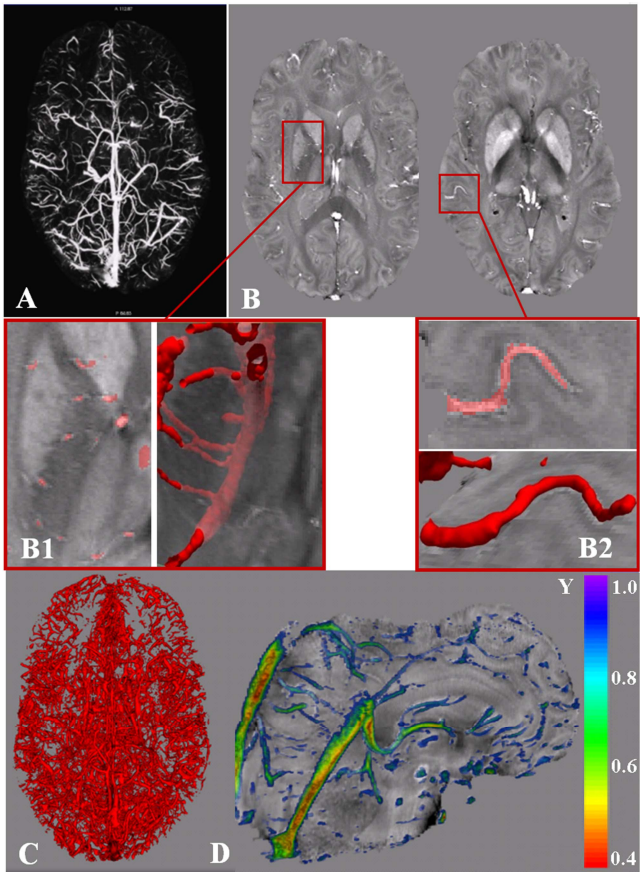

Fig. 1: The vesselness enhanced diffusion (VED) map is shown in (A). Composite image resulting from the fusion of the quantitative susceptibility map and the VED map (B) scaled between [-0.2, 0.2]. Inner vessels close to the lentiform nucleus (B1) and cortical vessels (B2) are segmented. The whole reconstructed venous vessel network is displayed in (C) and was used in combination with a volume rendering technique to display the blood oxygenation across the venous network (D).

DISCUSSION – We have presented a non-invasive approach for venous vessel imaging and 3D reconstruction of the cerebral network with an effective in-plane resolution of 0.4 mm. The presented approach was successful in segmenting vessels within the range of a single voxel allowing tracking the venous tree across several branches and providing access to a large proportion of the entire cerebral venous network. The overlay of the extracted blood oxygenation on the reconstructed venous network allows investigating blood oxygenation changes along the vessel course. The variance of the blood oxygenation observed in the sinus veins may be due to non-linear flow effects.[8] However, in contrast to previous work[9], we were able to reconstruct more complete vessel networks and to display the oxygenation inside the vessels continuously instead of a vessel segment based analysis.

CONCLUSION – Using quantitative susceptibility maps as the basis for vesselness enhancing diffusion (VED) filtering and level-set segmentation enables segmentation of vessels to create high resolution 3D reconstructions of the cerebral venous network. This opens the door to quantify parameters of the vessel network that could either be topological ones computed from the three-dimensional network model (radii, branching, tortuosity) or physiological parameters (e.g. blood oxygenation). In the future, studies investigating the possible correlations between these parameters will then be lead.

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