A Three-Dimensional Multi-Scale Line Filter Algorithm for Segmentation of Vein Vessels in Susceptibility Weighted Images

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Objective: To develop and validate an algorithm for the segmentation of venous vasculature in brain parenchyma on susceptibility-weighted imaging (SWI).[1]
Background: SWI is a MRI application that uses susceptibility differences between tissues as a new type of contrast that is different from spin density, T1-, or T2-weighted imaging and can directly image cerebral vein vasculature by using the phase information to enhance local susceptibility or contrast.[2,3] Through the application of a three-dimensional multi-scale line filter on SWI images it is possible to enhance curvilinear structures, such as vessels.
Material and Methods: Sixty-two (62) MS patients (44 relapsing-remitting and 18 secondary-progressive, 43.5 ± 11.8 yrs) and 33 age- and sex-matched HC were imaged on a 3T GE scanner using pre-contrast SWI. A subset of MS patients (50) and HC (7) obtained SWI post-gadolinium contrast sequence (0.1 mMol/Kg Gd-DTPA with 10 min delay). 3 subjects (2 MS patients and 1 NC) underwent two repeated scans within 7 days with and without contrast. A 3-D line enhancement based filter was developed for the discrimination of curvilinear structures and for recovering line structures of various widths. The 3-D line filter is based on a combination of the eigenvalues (λ_1, λ_2 and λ_3) of the 3-D Hessian matrix. For the discrimination of linear structures, λ_2 and λ_3 should be negative values with large absolute values while λ_1 should be as close as zero (Fig. 1). When signal loss occurs at a line structure, intensity values decrease as compared with surrounding parts. The line structure tends to be fragmented there. Thus, the second derivative along the line direction, λ_1, is positive at the corrupted parts. Based on the above consideration, we used a similarity measure to a line structure given by:

$$f(\lambda_1, \lambda_c) = \begin{cases} \exp\left(-\frac{\lambda_1^2}{2(\alpha_1\lambda_c)^2}\right) & \lambda_1 \le 0, \lambda_c \ne 0 \\ \exp\left(-\frac{\lambda_1^2}{2(\alpha_2\lambda_c)^2}\right) & \lambda_1 > 0, \lambda_c \ne 0 \end{cases}$$

where $\alpha_1 < \alpha_2$. Multi-scale integration is formulated by taking the maximum among single scale filter responses: we applied line filtering using several sets of parameter values followed by a threshold based growth process for edge correction. The aim of the experiment was to enable a comparison to be made among line-filtered images using different shapes of linearity measure, to generate reproducible vein vessel masks for quantifying vasculature (Fig. 2-a), classified according to diameter (D), and to generate vessel density maps (Fig. 2-b) for investigating diffuse venous damage in pathologies of the Central Nervous System (CNS).
Results: Visual comparison with Minimum Intensity Projections (MIPs) images confirmed that the line-filtered had high detection sensibility with respect to small vessels, vessel continuity, and the reduction of noise and artifacts, both pre- and post-contrast injection. However, the large vessel may result being thinned in the line-filtered images, making the combination with the threshold growth process a more accurate procedure for vein segmentation. In the comparisons between scan and rescan measures a relative variation of (6.19 ± 0.91)% in pre-contrast and (5.71 ± 0.80)% (Tab. 1) in post-contrast scans was observed.

	Pre-coontrast		Post-contrast	
	Total vein volume	**D < 0,3 mm vein volume**	**Total vein volume**	**D < 0,3 mm vein volume**
Subject 1	6.61%	6.72%	6.61%	6.72%
Subject 2	6.84%	7.41%	5.04%	6.50%
Subject 3	5.15%	7.99%	5.49%	7.29%
Absolute average variation	(6.19 ± 0,91)%	(7.37 ± 0,63)%	(5.71 ± 0,80)%	(6.83 ± 0,41)%

Tab. 1: Relative variation between scan and rescan measurements on three subjects pre- and post-GAD injection. Total vein volume and vein volume for vessel having D < 0.3mm are reported.

Discussion and Conclusions: We developed and validated a quantitative vein segmentation method based on a 3-D line enhancement filter that showed high sensibility with respect to small vessel in brain parenchyma; the resultant multi-scale line-filtered images provide significantly improved segmentation and visualization of curvilinear structures. The usefulness of the method is demonstrated by the segmentation and visualization of brain vessels from SWI scans.

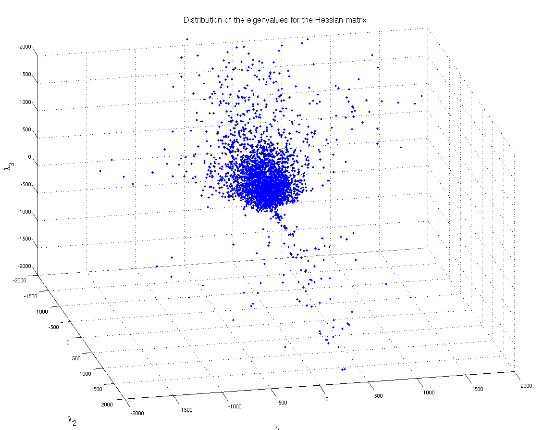

Fig. 1 3-D scatter plot for the eigenvalues of the Hessian matrix. The voxels belonging to linear structures are those for which λ_2 and λ_3 are negative while λ_1 is close to zero, giving the cluster in the bottom part of the plot.

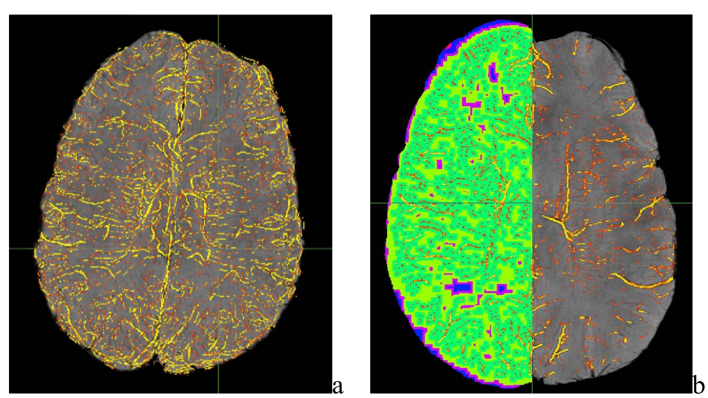

Fig. 2 Sample vein mask overlaid on the corresponding SWI image (a) and explanatory image (b) overlaying the distance-from-vein map on the corresponding vein and SWI map: the color coding expresses the distance-from-a-vein.

Bibliography
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