Automatic extraction of blood vessel network using image processing based on Hessian matrix in ultrasonic volume

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1. Introduction

Recently, drug delivery systems (DDS), which aim to deliver and concentrate drugs to target areas in the human body, have been recognized as a new therapy method with reduced side effects. Our group has been developing a method of ultrasound DDS involving the physical control of microbubbles containing drugs through blood vessel in an internal organ using acoustic radiation force [1,2]. To apply this technique in a clinical situation, an intraoperative navigation system for the visualization of blood vessel network (BVN) in the body, as well as accurate positioning of ultrasound transducers on the body surface, is indispensable. Although many preceding studies have reported the reconstruction and classification of human blood vessels using CT or MRI data, the use of them is limited due to the deformation of the shape of BVN between the acquisition of images and the operation. Therefore, we have developed a therapeutic system using ultrasound alone, which includes the three-dimensional fusion imaging between B- and Doppler modes [3], and the spatial extension to obtain wider BVN using multiple volumes [4]. However, in our preceding research, because some procedures of region selection were manually required, there was a problem in computational time to provide reconstructed BVNs. Therefore, we have newly introduced an image processing method of Hessian matrix [5,6] to extract blood vessels according to their thickness. Because the output of Hessian matrix depends on the parameters, we attempt to reconstruct an appropriate BVN automatically by combining multiple procedures with various settings of parameters.

2. Methods

The principle to extract blood vessel is Frangi Filter based on Hessian matrix, which emphasizes the tubular or vessel-like structures in a three-dimensional volume data by referring the relationship between three eigenvalues. Before applying the calculation of Hessian matrix, a conventional Gaussian filter, which derives the result of blurring by a Gaussian function, with a parameter of the standard deviation of σ. By varying the value of σ, it is possible to emphasize the thickness of tubular structures in the following procedures.

Hessian matrix calculates second-order derivative in each direction of a volume *I*, which represents brightness in a three-dimensional ultrasound image, as shown in Eq. (1). Then, the derived eigenvalues were sorted as $\lambda_1, \lambda_2, \lambda_3 (|\lambda_1| \leq |\lambda_2| \leq |\lambda_3|)$. In case that λ_1 was smaller enough than other two eigenvalues, the point (x, y, z) was regarded to be included in a tubular structure [5].

$$H(x,y,z) = \begin{bmatrix} I_{xx}(x,y,z) & I_{xy}(x,y,z) & I_{xz}(x,y,z) \\ I_{yx}(x,y,z) & I_{yy}(x,y,z) & I_{yz}(x,y,z) \\ I_{zx}(x,y,z) & I_{zy}(x,y,z) & I_{zz}(x,y,z) \end{bmatrix} \quad (1)$$

Figure 1 shows examples of Frangi Filter applied to a blood vessel-like shape, where the original one was constructed in silico virtually as a straight line, which is continuously decreasing thicknesses, with four branches. After applying the Frangi Filter, higher value was enhanced to visualize as Fig. 1. It can be seen that only the structure with the thickness corresponding to the value of σ can be extracted. Meanwhile, all other structures except tubular structures are removed with this procedure.

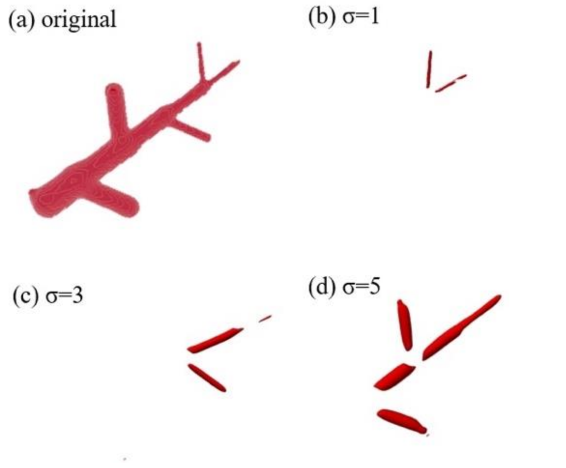

Fig. 1 Output of Hessian matrix applied to a blood vessel shape in silico.

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To reconstruct the BVN using multiple structures with various standard deviations σ of the Gaussian filter, we adopted to graft thinner structures on a thicker structure. Assuming two structures as V_p and V_q ($p < q$), first, superimposed structure was defined as V_{pq} ($= V_p \cup V_q$). Then, common connected structures between V_q and V_{pq} were remained, but others are eliminated. In the obtained structure, fine branches V_p were extended to V_q.

We used an echography (Philips EPIQ Elite) with a three-dimensional probe (X6-1). The imaging conditions for ultrasound volumes were B-mode gain = 60%, Doppler mode gain = 45%, depth = 100 mm, mechanical Index = 1.0.

3. Results

The subject was a healthy female of 52 y.o. and ordered to lie in dorsal position. The respiratory state is inhaling most deeply during the image acquisition time of about 10 seconds. In this report we used only B-mode image without Doppler mode image unlike our conventional method. **Figure 2** shows the results of the extraction of tubular structures from a three-dimensinonal B-mode volume according to the standard deviation σ.

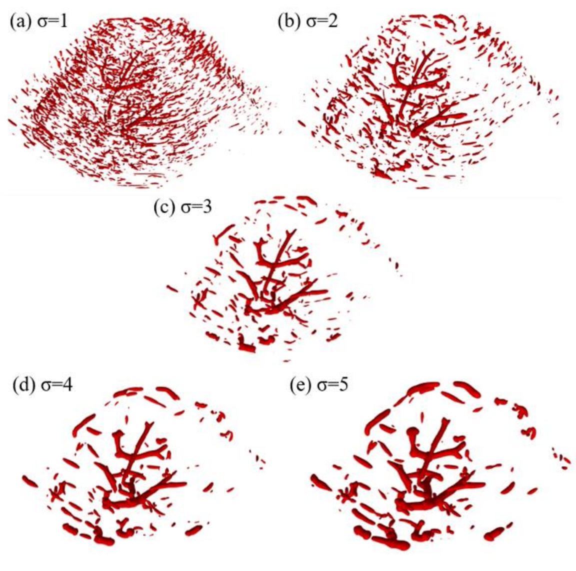

Fig. 2 Results of the extraction of tubular structure from a three-dimensinonal B-mode volume according to the standard deviation σ of the Gaussian filter.

To extend fine branches to the structure of σ = 5 (V_5), we grafted the structure of σ = 4 (V_4) to V_5, to obtain V_{45}. Similary, by continuing the procedure, we finally obtained the BVN of V_{12345}. **Figure 3** shows the comparison of reconstructed BVNs of liver between the proposed method (right) and the conventional method, which were processed from different part of the liver in the same subject. Compared with the conventional method, although the similar structures were obtained, noise and defects were distinct in the proposed method. However, near the tip of the blood vessel, wider blood vessels were obtained in the proposed method. Through those procedure, computational time was drastically improved from several 10 minutes to a few minutes.

(a) near region S6

(b) near region S8

Fig. 3 Reconstructed BVNs of liver by the propsed method (right) and comparison with the conventional ones (left).

4. Conclusions

In this study, we were able to obtain BVNs of a normal subject by combining multiple structures, which were obtained with different value of σ through a Frangi Filter based on the Hessian matrix, from B-mode volumes. Furthermore, by extending the structure based on the maximum σ to other networks with lower σ, we have succeeded to obtain BVNs with thinner branches and less noise than our conventional method. Because a series of the procedure was executed automatically, we confirmed the improvement of the computational time. In the future, we are going to consider to emphasize spheres at the bifurcation points with higher accuracy including machine learning method.

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