Automatic Carotid Centerline Extraction from Three-Dimensional Ultrasound Doppler Images

S. Parrini, L. Zhang, S. Condino, V. Ferrari, D. Caramella, and M. Ferrari

Abstract— **Vessel lumen centerline extraction is an important issue for the intra-operative guidance of endovascular instruments; furthermore, vessel centerline is often used as a reference position in many hemodynamic studies, especially in carotid arteries. In this work we propose an innovative method for the extraction of carotid vessels centerline from three-dimensional Color Doppler ultrasound images. The method was tested on carotid Color Doppler images of eighteen healthy subjects and validated by calculating the Euclidean distances between the centerlines detected by the algorithm and those manually annotated by two experts in the corresponding original US volumes. The results show that the proposed approach can accurately estimate the actual centerline with an average error of 1.08 ± 0.54 mm. Furthermore, the method is completely automatic and therefore suitable for the aforementioned purposes.**

I. INTRODUCTION

A real-time knowledge of vessels lumen centerline (the points set defining the center of the vessel lumen) is extremely important for traditional and innovative diagnostic and therapeutic procedures. In hemodynamic studies, the centerline of a vessel is always used as a reference position to determine blood velocity and volume flow profiles [1]. Furthermore, the centerline is a very powerful feature in image guided surgery (IGS), as it can be used for navigation and registration purposes [2]. In particular, we have already presented [3] and validated [4] an endovascular navigation platform based on the electromagnetic localization of endovascular instruments. This platform, however, uses static 3D images of the vessels, so, to date, it cannot account for breathing and cardiac cycle movements. Deformations due to the interaction of the endovascular instruments with blood vessels cannot be compensated too. Modern 3D Ultrasound (US) scanner, permitting the real-time acquisition of volumetric images of the area of interest, could represent the optimal solution for vessel movement tracking. To this end, an efficient, fast and automatic algorithm to determine vessels centerlines by 3D US images could therefore permit to compensate these movements during surgery.

Centerline extraction from 3D US has been reported in literature [5, 6]. We previously presented a method based on a combination of snake and gradient vector flow field to extract and track liver vessels centerlines from 3D US images [2]. These methods are sufficiently robust and almost completely automatic; however, centerline extraction from US images remains challenging due to the speckle noise and the shadowing characterizing such images [7]. To overcome these difficulties, a smart solution could be the use of the Doppler modality. US Doppler is the most commonly used imaging technique for hemodynamic studies. It is particularly used for the diagnosis of the carotid stenosis [8]. US Doppler permits to assess whether blood is moving towards or away from the probe, and its relative velocity [9]. In Color Doppler (CD) imaging this information is displayed as a colored image, with vessels voxels in red or blue depending on the direction of the blood flow. This enhances the visibility of blood vessels over other anatomical structures and could therefore be used as a good starting point for the automatic identification of the vessels and for the extraction of their centerlines.

Despite the automatic extraction of the centerline from CD images appears to be straightforward, to the best of our knowledge a very few studies have already addressed this issue. In [8] the centerline is obtained in a semiautomatic manner. At first, a volume of interest is selected to reject non-vessel voxels and to consider only straight vessel regions, avoiding the most tortuous ones; then the centerline is automatically extracted with a spline interpolation algorithm based on the detection of peak flow velocity in every slice of the CD volume. However, in a second phase the operator has to manually adjust the position of the centerline until he considers it acceptable. This second step is very time-consuming. In [10] a method for extracting blood vessels and airways from different modalities (CT, MR and 3D Doppler US) by exploiting the computational power of graphic processing units (GPUs) is presented. This method is robust and fast enough to extract centerlines from different modalities, even if it suffers by the limited memory on the GPU, that causes large datasets not to be processed.

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In this paper we propose a novel algorithm for the extraction of carotid arteries centerlines from 3D US CD images. Taking advantage of the different coloration of a vessel in respect to the background tissues, we have developed a completely automatic method for extracting carotid centerlines; no manual interaction from the user is required. Furthermore, differently from other methods, the extraction does not depend on the relative orientation between the US transducer and the carotid (i.e., the algorithm does not need to work with slices orthogonal to the vessel of interest). The "Materials and Methods" paragraph provides an overview of the adopted experimental setup (section II A) and of the algorithm (section II B); the "Results" paragraph shows algorithm performances in terms of centerline extraction quality. Finally, the results are discussed and conclusions are given.

II. MATERIALS AND METHODS

A. *Experimental setup*

We used a 3D US transducer (VL13-5) and a Philips iU22 ultrasonic system (Philips Medical Systems, N.A.; Bothell, WA), which allows us to fully sample the volume of interest [11] employing a motorized linear array to acquire US CD images of carotid arteries. Our ultrasonic scanner produces DICOM files that can be easily read by the Matlab® *dicomread* function of *Image Processing Toolbox*. The dimensions of acquired volumes in our experiments were 38.30 mm x 28.80 mm x 28.65 mm, with a resolution of 0.11 mm, 0.09 mm and 0.11 mm for the x-axis, y-axis and z-axis, respectively. Every dataset is composed of two subsequent parts: the first 256 slices are US B-mode images (Fig. 1a), the next 256 are the corresponding CD images (Fig. 1b). CD images are grayscale images with black background/non-vessel voxels, while vessel voxels have different gray tones, depending on the corresponding flow velocity value. Our algorithm works only on this second segment.

B. *Algorithm description*

We propose an algorithm for the automatic detection of carotid arteries centerlines in CD dataset. It is based on the extraction of the carotid center of mass in every slice of the CD dataset. This intrinsically assumes that the vessel is perfectly parallel to the probe scan direction. Despite the great care in orienting the probe scan direction parallel to the principal axis of the vessel, misalignments can arise. To account for the various orientations of the carotid in the US volume, we firstly rotate the volume to make the vessel axis parallel to the scan direction. In this way, less care has to be taken in acquiring carotid volumes and every slice contains the actual axial vessel lumen. To do this, we first collect in a vector all the coordinates of the points whose intensities are above an empirically predetermined threshold; as said above in fact, in a CD dataset the vessels are represented with gray tones, thus they have higher intensities values than the black background voxels. We then calculate the covariance matrix of this points set. The eigenvector with the highest eigenvalue gives an estimate of the vessel principal axis direction. Exploiting this information, we can therefore rotate the volume to make the slicing direction parallel to the vessel axial direction. After the rotation, the slicing of the volume along its z-axis allows us to obtain 2D images containing the actual axial lumen of the vessel. The algorithm starts by finding the first slice with a vessel region. Every slice is analyzed until the first center-point is found. As it can be seen in Fig. 2a, the identification of a vessel in Doppler images is not straightforward, due to the intrinsic noise that afflicts this kind of images. Several non-vessel regions can be present in addition to the actual vessel lumen. However, they have a smaller size and can be rejected by applying an empirically estimated threshold. Moreover, noise also warps vessel shape; since we choose the center of mass of a region as center-point, these disturbances can influence the correct selection of a center. To remove possible extroflessions and/or to separate connected regions, an opening filter is used. Being the shape of the lumen comparable to a circle, a circular structuring element is used for the implementation of the filter. Various radii of the structuring element have been tested, and a value of 0.25 times the region radius was found to give the best result (Fig. 2b).

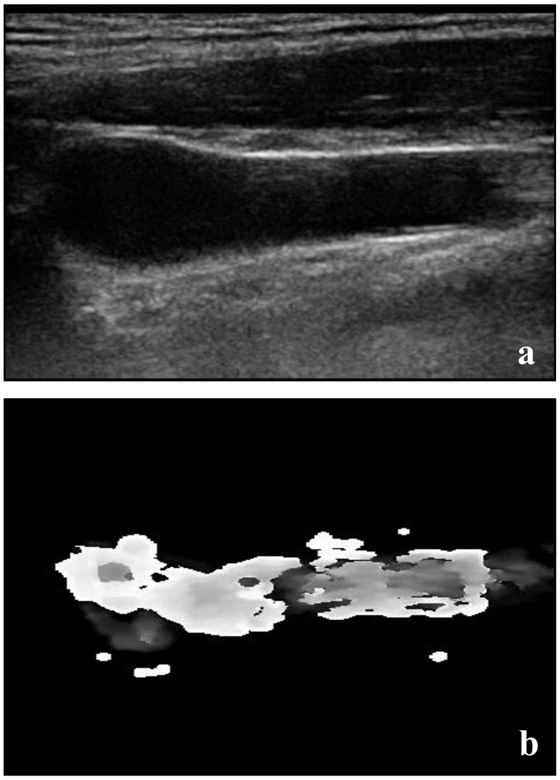

Figure 1. Two illustrative slices showing the composition of a complete CD dataset for a carotid artery: a) standard US B-mode image; b) the corresponding CD image of a): it is possible to see that only the carotid has non-black voxels.

After the extraction of the first center-point, one image in every five is analyzed to reduce the computational burden, as we can assume with safety that there is continuity between adjacent images. To identify actual vessel regions the same aforementioned strategy is used. If no regions in a new image

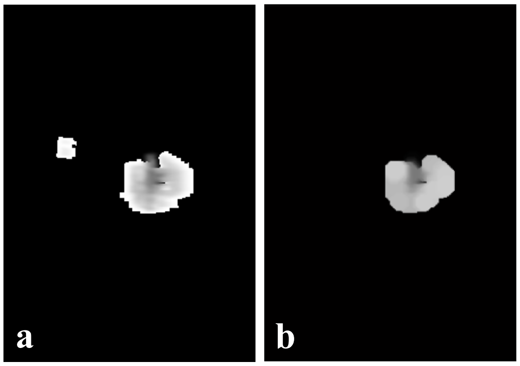

Figure 2. a) Example of CD image after rotation containing the actual axial vessel lumen. It is possible to see a second noisy region in addition to the carotid. b) The same image after the discard of the smallest region and the application of the opening filter: it can be seen that only the actual vessel is now present in the image; moreover, the lumen shape is less irregular with respect to fig. 2a.

meet the established requirement, no center-points are extracted and the next image is analyzed. Once all the CD dataset has been considered, a cubic polynomial interpolation of the extracted center-points is performed to obtain a continuous and smooth centerline. The flow chart in Fig. 3 resumes the overall algorithm organization.

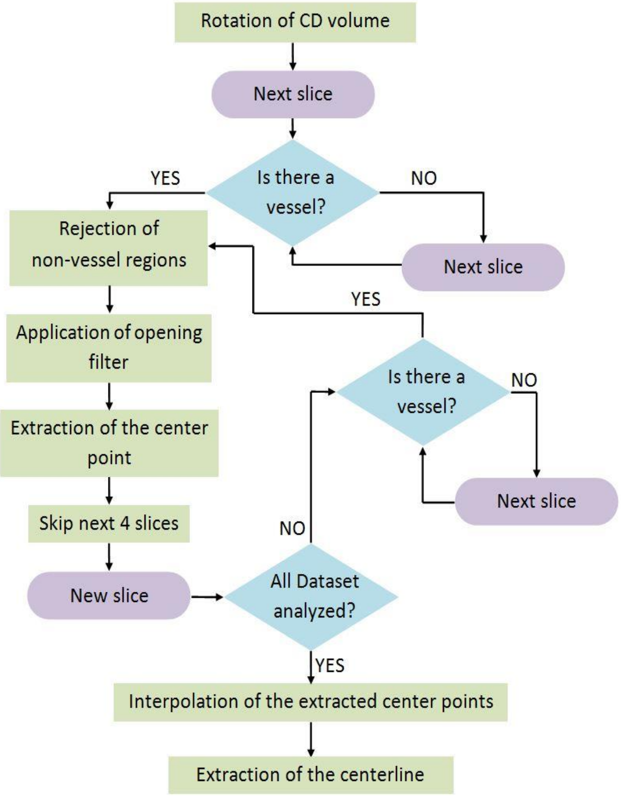

Figure 3. Algorithm flow chart.

C. *Algorithm evaluation*

To test the accuracy of our method in estimating the carotid centerline, we compared the centerlines extracted using our algorithm with those manually extracted by two experts in the B-mode US volumes after the application of the same rotation described in section II B. For every B-mode US volume, the experts sliced all images annotating in every slice the center-point of the vessel of interest. Then for every volume we computed the minimum, maximum, and mean Euclidean distances between the two centerlines.

III. RESULTS

We tested our algorithm with eighteen CD volumes acquired from young healthy subjects to detect carotid centerlines. As said above, the algorithm is fully automatic and no manual interaction is required. Every CD volume is used as an input to our algorithm and the corresponding centerline is obtained. Fig. 4 reports the result of centerline extraction for a CD dataset.

To test the validity of our method, we calculated the minimum, maximum and mean Euclidean distances between the center-points extracted using our algorithm and manually extracted ones by two experts in the B-mode US volumes after the application of the same rotation described in section II B. The two centerlines can have different numbers of samples: the establishing of a perfect biunivocal correspondence between their points is not therefore possible. For this reason, for every point of a centerline, we first found the corresponding nearest point on the other centerline, and vice versa, and then computed the minimum, maximum and mean Euclidean distances between the two evaluations. In Table 1, we report the results among all the datasets and the two observers.

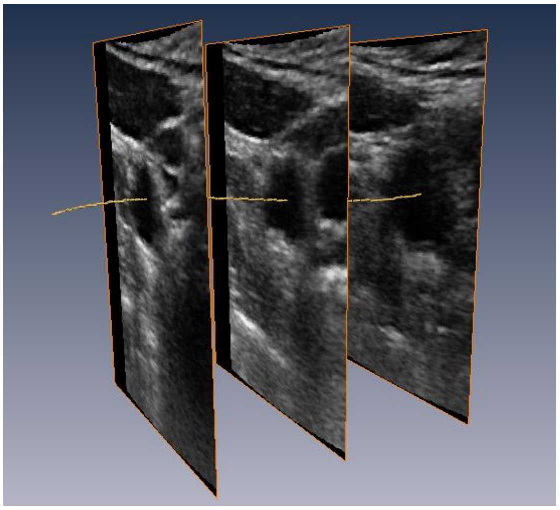

Figure 4. An example of centerline detection result for a CD dataset. It is possible to see the obtained centerline (yellow line) and 3 illustrative slices to demonstrate centerline extraction accuracy.

TABLE I. DISTANCES BETWEEN MANUAL AND AUTOMATIC CENTERLINES

	Average distances ± standard deviation (mm)
Min	0.11± 0.13
Max	3.51 ± 1.94
Mean	1.08 ± 0.54

IV. DISCUSSION

The centerline is a powerful means to describe a vessel and it is therefore used in many clinical studies. In this paper an algorithm to determine carotid vessel centerline from 3D CD dataset is proposed.

The algorithm has been developed with the intention of applying it in endovascular procedures for carotid artery; however, it is general and may be applied to other domains and interventions in which the vessels of interest present a suitable Doppler response, after an adequate tuning of its parameters. Our algorithm is fully automatic and it is based on the determination of the center of mass of the vessel in every slice of the CD dataset. To the best of our knowledge, a few studies have already addressed the automatic extraction of centerline from CD volume.

As it is possible to see in Fig. 4 and in Table 1, our algorithm is able to accurately extract centerlines: the mean, minimum and maximum Euclidean distances between manually extracted centerlines and those obtained using our method, among all the datasets and the two observers, are, respectively, 1.08 ± 0.54, 0.11± 0.13 and 3.51 ± 1.94 mm. The results are acceptable, and the obtained accuracies adequate for the carotid mean diameters (approximately 8 mm), considering the maximum error of the algorithm.

Our algorithm requires on average 7.78 s to extract the entire centerline from a single dataset. All the measures were performed in MATLAB® using an Intel® Core™ i7-3700 CPU 3.4GHz, RAM 8GB. Speed requirement is not essential when the centerline is used for hemodynamic studies; on the contrary, it becomes crucial when the centerline has to be used for navigation and registration purposes. Though these speeds are not compatible in the latter case, the computational burden can be highly reduced optimizing the hardware components and the algorithm implementation (e. g. taking into account only a region of interest containing the vessel under examination).

V. CONCLUSIONS

We presented a novel and simple algorithm for the automatic extraction of carotid artery centerline from 3D CD datasets. The algorithm is completely automatic, thus avoiding the operator to manually select the points in every slice of a volume. In this way, the needed time and the errors related to a manual extraction can be drastically reduced. The algorithm is also sufficiently accurate in estimating the carotid centerlines, that are therefore suitable to be used for navigation purposes and in hemodynamic studies.

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