Dynamic Characterization of Aorta Morphology and Function in Presence of an Aneurysm

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Abstract

Evaluation of aorta morphology and function in presence of aneurysms or dissection is crucial for a correct treatment choice between surgical resection and percutaneous stent-graft deployment. We developed and tested a new method for automated dynamic aorta segmentation from computed tomography (CT) images from which static and dynamic parameters of aortic morphology and function can be automatically extracted. To detect the aortic surface in a 3D domain we applied a level set segmentation scheme that incorporates gradient-based, weighted expansion and mean curvature dependent regularizers. Three subjects were imaged using a multi-detector CT scanner (Siemens, Sensation Cardiac): one normal and two patients affected by an aneurysm in the ascending and descending aorta respectively. Extracted parameters showed significant differences between them. This preliminary study proves feasibility for an accurate and dynamic aorta segmentation from which several indexes of aortic morphology and function can be automatically extracted. This may be of benefit to patients with aortic aneurysms and dissection.

1. Introduction

Aneurysm and dissection are the most dangerous diseases that affect the aorta. In presence of these pathologies the evaluation of aorta morphology and function is crucial for a correct treatment choice between surgical resection and percutaneous stent-graft deployment. In addition, in case of stent-graft deployment, imaging techniques such as computed tomography (CT) have the fundamental role in the search for anatomic details necessary to evaluate the most suitable anatomy for stent-graft and in the postoperative follow-up after stent graft placement. It is well known that this knowledge is crucial to improve its durability and results [1,2].

Since no analysis software is available on the CT imaging system to extract quantitative parameters that could be very useful to evaluate aorta morphology and function, in clinical practice, medical doctors usually perform manual measurements of aorta diameters in specific anatomical sites. This procedure is subjective and time-consuming.

Accordingly, our aims were to: (1) develop an automated technique for aortic surface detection throughout the cardiac cycle and (2) measure static and dynamic parameters characterizing aorta morphology and function.

As a first step, quantitative analysis of CT images requires segmentation of the aorta. Previous studies targeting aortic aneurysm segmentation employed a level set framework using either edge strength or region intensity information [3-5]. To extract the aortic surface in the 3D domain we applied a level set segmentation scheme [6-8] that incorporates gradient-based, weighted expansion and mean curvature dependent regularizers. The final results are the surfaces corresponding to the aortic vessel throughout the cardiac cycle. Once the vessel is segmented it is possible to calculate various descriptive indexes about it, including shape, size and its dynamic behaviour. Our segmentation method was implemented in the 3D domain and requires a simple definition of few reference points within the data as initial condition for the dynamic detection of the aorta boundaries throughout the cardiac cycle.

2. Methods

Three subjects were imaged using a multi-detector CT scanner (Siemens, SOMATOM Sensation Cardiac): one normal (NL) and two patients (PTS) affected by an aneurysm in the ascending (asc) and descending (desc) aorta respectively. Cine-loops were acquired during breath-hold and ECG-gating (1 mm slice thickness) with a temporal resolution of 10 frames per cardiac cycle, after beta-blocker and intra-vascular contrast injection.

2.1. Image analysis

The CT datasets were analyzed using custom software, which allows automated aorta surface detection by a level set approach [6,7]. This method uses an implicit representation of curves in the form of a partial differential equation to track boundaries, without geometrical assumptions or a-priori shape knowledge.

The classical level set formulation introduced by Malladi et al. [8] was implemented. This scheme incorporates gradient-based, expansion and mean curvature dependent regularizers. In our formulation the expansion regularizer was weighted by an additional term b that speeds up the expansion far from the real contours and slows it close to them. The resulting equation of the motion for the level set function is shown in equation (1):

$$\frac{\partial \varphi}{\partial t} = g\varepsilon K|\nabla \varphi| - gb|\nabla \varphi| + \nu \nabla g \cdot \nabla \varphi \qquad (1)$$

with the initial condition $\varphi(\mathbf{x},t) = \varphi_0$ and where $\varphi(\mathbf{x},t)$ is the level set function, the first term on the right hand is a curve tension force that depends on the Euclidean curvature K, the second term is the expansion force and the third term is a force that attracts the curve towards the boundaries and thus has a stabilizing effect. The edge indicator g, is a non-increasing function of the gradient of a smoothed version of the initial image [9]. The parameter ν is used to limit the regularization of the embedding controlled by the parameter ε.

The curve evolution will have a steady state solution when the geometry dependent term and the advection term balance the expansion term.

The initial curve is user-defined, and this initialization is required for the first frame for the entire cardiac cine-loop since the segmentation procedure takes the same initial condition for each frame throughout the cardiac cycle. Therefore the analysis has been performed automatically on the whole cardiac cycle. The operator selects few points along the vessel at different levels, in a long axis view. These points are the centers of spheres automatically generated that represent the initial condition for the evolution. An example of the steps required for the segmentation is shown in Figure 1.

Matlab 6.1 (The MathWorks Inc.) environment was used for software implementation. To speed up the segmentation procedure, the level set algorithm was implemented in the C++ language.

The segmentation procedure resulted in a dynamic representation of the aorta vessel, from which several static and dynamic indexes were extracted. The following parameters were evaluated: aorta mean radius D along the vessel for each frame, aorta volumes in the cardiac cycle, strain ($(D_{systole}-D_{diastole})/D_{diastole}$), vessel pulsatility (% radius change throughout the cardiac cycle) and tortuosity (vessel length/vessel height), aortic stiffness β ($\ln(P_{systole}/P_{diastole})$/strain, P: pressure) and elastic modulus Ep ($k*(P_{systole}-P_{diastole})$/strain, k=133.3).

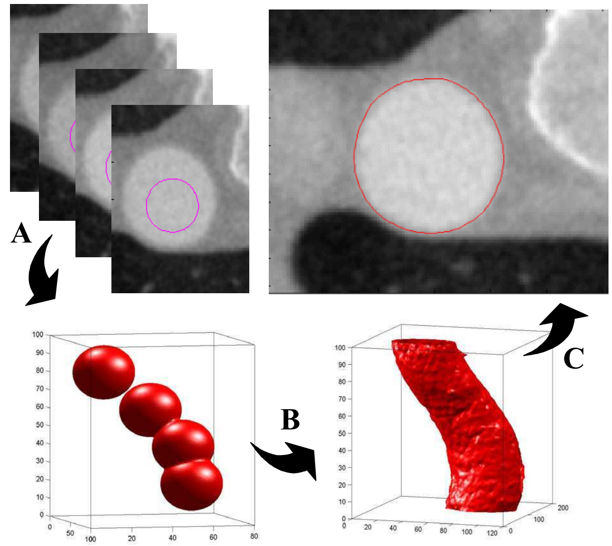

Figure 1. Steps required for the aorta segmentation: A. initial condition from which several spheres are automatically generated; B. final detected vessel surface after the evolution guided by the partial differential equation; C. 2D evaluation of the detected surface by superimposition of the anatomical data and the corresponding detected contour.

Radius measurements were validated against manual measurements (linear regression, Bland-Altman). All indexes were compared with those reported in literature and, in addition, between NL and PTS pre- and post-treatment.

3. Results

The aorta segmentation was completed in less than 2 min per frame on a personal computer (AMD Athlon XP 2800).

An example of the initial condition and the corresponding final detected contour on 2D images is shown in Figure 2.

We compared manual measurements of aorta radius in specific anatomical sites with radius measurements extracted by our technique. This comparison resulted in very good agreement with manual measurements (r: 0.98, bias: 0.01 mm, limits of agreement: 0.2 mm).

In a normal subject we compared the morphology and function of the ascending aorta versus the descending aorta.We found the maximum variation of the mean radius along the vessel is significantly greater in the ascending aorta (Figure 3, top panel) as well as the volume (Figure 3, bottom panel). In addition the mean radius maximum variation in the cardiac cycle was 5% for the ascending aorta and 0.5% for the descending one.

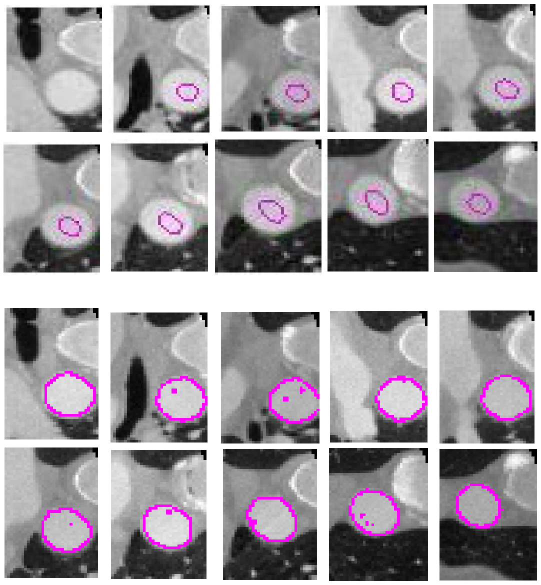

Figure 2. Example of the initial condition (top panel) and the corresponding final detected contour (bottom panel) on 2D images

This result was confirmed by the values we found for strain (asc: 0.113; desc: 0.013) and β (asc: 3.5; desc: 31.1). Ep showed a greater value for the descending aorta (asc: $2.16*10^5$ N/m^2; desc: $3.10*1010^5$ N/m^2).

The comparison between the ascending aorta of a normal subject and an ascending aorta of a patient of the same age and size, in presence of an aneurysm showed an increase radius along the vessel in correspondence of the aneurysm (Figure 4, top panel) and a significantly greater volume that did not change throughout the cardiac cycle (Figure 4, bottom panel).

The mean radius maximum variation in the cardiac cycle was less than 1% in presence of the disease. In addition in presence of the aneurysm the strain was smaller (0.007) and the stiffness significantly greater (55.7) compared to the vessel without the aneurysm. Ep showed similar values (asc: $2.16*10^5$ N/m^2; desc: $2.25*10^5$ N/m^2).

The comparison between the descending aorta of a normal subject and the descending aorta of a patient of the same age and size, in presence of an aneurysm resulted in significantly smaller pulsatility (0.2%), strain (0.0006), elastic modulus ($3.23 \cdot 10^3$ N/m^2) and greater mean radius (25.7mm) and stiffness (60.1).

In Figure 5 we show a tract of the segmented descending aorta we obtained post endograft insertion. The analysis of this data acquired post insertion evidenced just reduced radius in correspondence of the aneurysm location.

All these indexes had values comparable with those reported in literature.

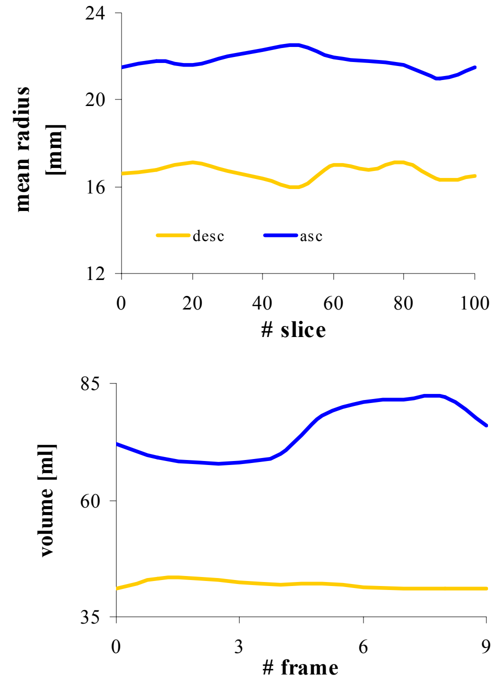

Figure 3. Mean radius along the vessel (top panel) and vessel volume (bottom panel), in a normal subject, in the ascending aorta (asc) versus the descending aorta (desc).

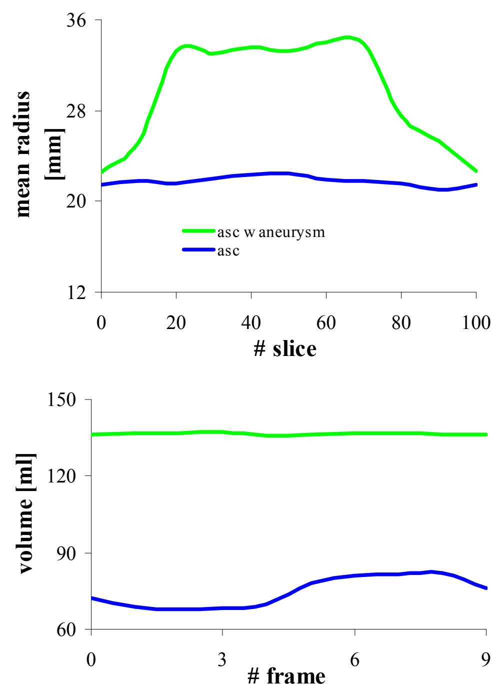

Figure 4. Mean radius along the vessel (top panel) and vessel volume (bottom panel), in a normal subject (asc) and in a patient affected by an aneurysm in the ascending aorta (asc w aneurysm).

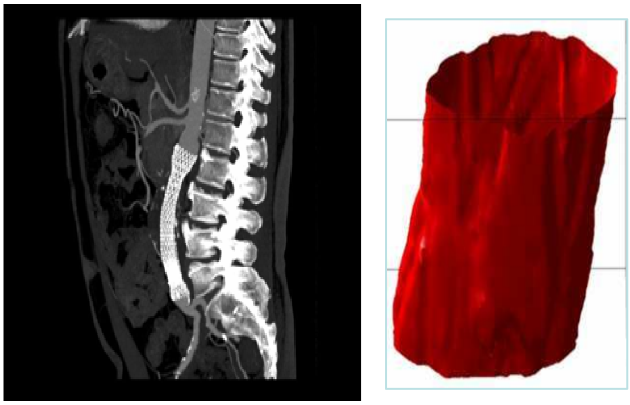

Figure 5. Anatomical data and tract of the segmented aorta post endograft insertion.

4. Discussion and conclusions

We presented an initial study for automated dynamic segmentation of aorta from CT images. The segmentation algorithm seems accurate and objective since almost no user interaction is required. Compared to conventional data navigation and manual measurements of aorta diameters in specific anatomical sites this procedure is fast and allows the extraction of new, volumetric and dynamic parameters for aorta morphology and function characterization. These parameters could be very useful for a correct treatment choice between surgical resection and percutaneous stent-graft deployment and, in case of stent-graft insertion they could help in the definition of the stent design and in the postoperative follow-up after stent graft placement.

In this preliminary research the proposed technique was able to quantitatively highlight the well known differences in morphology and function of the ascending and descending aorta in both normal and pathological conditions.

Further testing on a large number of patients affected by different pathologies is necessary to establish the clinical feasibility of this technique that may be of benefit to patients with aortic aneurysms or dissections

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