Quantification of abdominal aorta and branches in CTA images for endovascular repair of aneurysms: a validation study.

Arenas María, Macía Ivan, Legarreta Jon Haitz, Graña Manuel, Rajasekharan Sabarinath
Vicomtech Foundation, IK4 Alliance
marenas@vicomtech.org

Abstract: EVAR require a precise quantification of key vascular structures for the design of the endorprosthesis. We provide an analysis of sources of errors during the quantification and an initial validation study of a semi-automatic algorithm.
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1. Introduction

Endovascular Aneurysm Repair (EVAR) is a minimally invasive endovascular surgery used by far to treat Abdominal Aortic Aneurysms (AAA) [1] since it results in reduced patient's recovery time and potentially improved survival rates [2].

EVAR requires a personalized endoprosthesis design to match the morphology and specific pathology of the patient, especially when the aneurysm is located at the height of other major arteries such as the renal arteries, since the endoprosthesis requires fenestrations to allow blood supply to these arteries. Thus, the quantification of abdominal aorta and branches is critical for the success of EVAR.

We perform semi-automatic diameter and length quantification on the basis of the estimated vessel centerline for the *eVida Aorta* medical software (eMedica S.L). The precise location of the centerline is unknown and to some extent depends on the extraction method used, but other sources of errors may difficult a correct estimation, for example, those due to the spatial image resolution, size of the tubular structures, tortuosity, or inherent image noise. In addition to this, centerline estimation based on skeletonization processes are very sensitive to surface rugosity [3]. Moreover, section estimation is more difficult in certain parts of the aorta, since having so large diameters, the apparent local shape differs somehow from being curvilinear In the current work, we identify the possible sources of errors to take into account during the length and diameter quantification, and provide an initial validation of our method on synthetic datasets of known geometry.

The structure of the paper is as follows: Section 2 provides a description of our semi-automatic quantification method, Section 3 describes our initial validation methodology, Section 4 shows the results obtained and Section 5 draws some conclusions and future work.

2. Semi-automatic Vessel Quantification Method

Our method consists of the following steps: (1) Semi-automatic vessel lumen segmentation based on a single seed point and an adaptive region growing algorithm; (2) Skeletonization via 3D distance-ordered homotopic thinning [4] on the mask obtained in the segmentation step; (3) Vessel graph creation with advanced vascular analyses such as pruning or automatic labeling and (4) Centerline smoothing using a simple averaging strategy and (5) Quantification of lengths and diameters based on the extracted centerline and B-spline interpolation. Following steps 4 and 5 are further explained, since they are the core of our work:

2.1 Centerline smoothing: Once the centerline is obtained, it has to be regularized in order to obtain a set of perpendicular vessel sections to the centerline, which will be the basis of diameter quantification. An initial smoothing is performed by simple averaging. The degree of smoothing is determined by the size of the window: large windows will offer large noise removal at the expense of missing valuable information related to intrinsic vessel curvature. The optimal smoothing parameter will be studied in the validation methodology.

2.2 Quantification of lengths and diameters: We assume that the centerline is composed of linear segments and that consecutive centerline points are close enough to each other. In this way, the estimation of the centerline length between two points is obtained as a simple sum of distances between consecutive points. On the other hand, diameter quantification is based on the estimation of the local vessel section perpendicular to the centerline, which requires a local estimation of the centerline tangent vector. For this purpose, we locally approximate a 3rd order B-spline at each point and compute its tangent, which corresponds to the section normal. Then, we obtain the section plane and estimate the profile by using a ray-casting approach on the mask.

3. Validation Methodology

Three synthetic data types with circular section that mimic the lumen will be explored in order to take into account different effects: a straight tube, a circular toroid and a circular regular helix. These synthetic data will be built upon their corresponding centerlines, which will serve as the ground truth centerline to validate our method.

We identify and estimate the following possible sources of errors in our semi-automatic method that may affect the final quantification result:

Segmentation error(ex): Inherent lumen segmentation error that depends on the method used. In most of our experiments we may assume that this error is about 1 voxel radially.

Skeletonization error (e_s): Centerline extraction method error that highly depends on surface rugosity and image resolution, due to the voxel-wise nature of the extracted centerline. It is computed as the distance deviation [mm] from each extracted centerline point to the rotation axis of the synthetic data. For the straight tube data, the ground truth centerline is the cylinder rotation axis. Thus, the skeletonization error at point *i* of the extracted centerline is computed as:

$$es[i] = |d(C, Pi)|, \qquad (1)$$

where *C* is the center point of the circular section of the tube *C(Cx,Cy)*, P_i is the extracted centerline point P_i $(P_i x, P_i y)$ and *d(C, Pi)* is the distance between these two points. For toroid and cylindrical helix synthetic data, this error is computed as:

$$es[i] = |R - d(C, Pi)|, \qquad (2)$$

where *R* is the radius of the toroid or cylindrical helix, *C* is the center of the toroid or the *x* and *y* coordinates of the rotation axis of the cylindrical helix. Based on the skeletonization errors computed at each point of the extracted centerline, the mean, standard deviation, median and median absolute deviation statistics are obtained for further analysis.

Length estimation error (e_L): Absolute length difference error between the ground truth and extracted centerlines lengths. This error is normalized by the ground truth centerline length in order to be able to compare different synthetic data.

$$e_L(\%) = 100 \times | l_{ground\_truth} - l_{measured} | / l_{ground\_truth} \qquad (3)$$

where *l* refers to the length. This error carries on the error due to the *skeletonization* and it is highly dependent on *image spacing* and vessel graph *smoothing* value chosen.

Diameter estimation error(e_D): Absolute diameter difference error between the ground truth and extracted centerlines diameters at each point of the extracted centerline. This error is normalized by the ground truth centerline diameter in order to be able to compare different synthetic data. Based on the diameter estimation errors computed at each point of the extracted centerline, the mean, standard deviation, median and median absolute deviation statistics are obtained for further analysis.

$$e_D(\%) = 100 \times | ø_{ground\_truth} - ø_{measured} | / ø_{ground\_truth} \qquad (4)$$

where ø refers to the diameter.

This validation process will serve to quantify the accumulative error of the vessel quantitative measures.

4. Results

First simulations were hold using the straight tube synthetic data with a fixed *height* of 50 mm and *tube radius* of

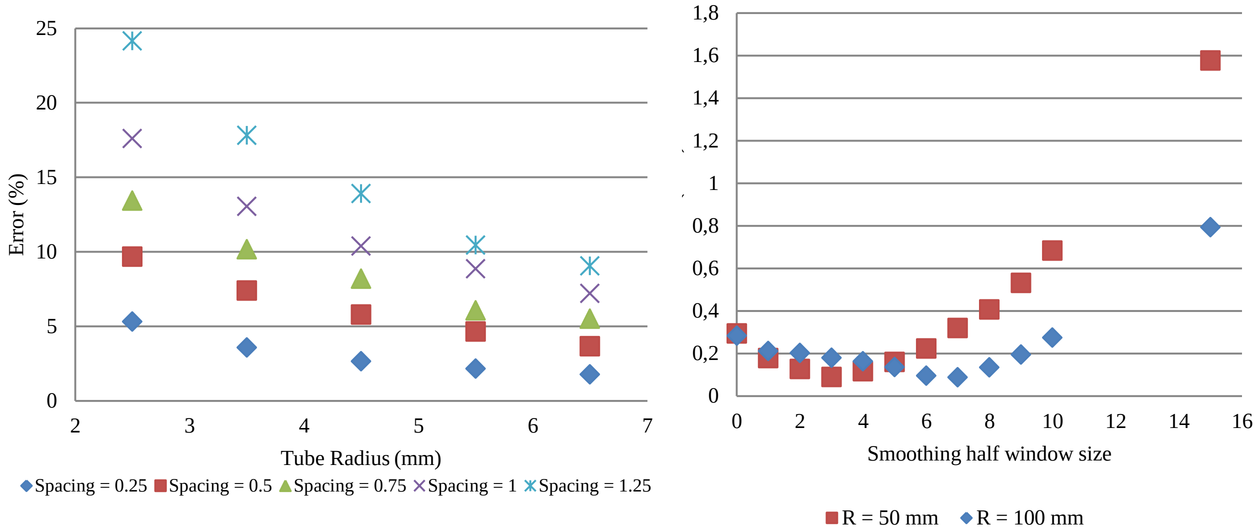

Figure 1: Left: Straight Tube Diameter Estimation Error (%)- Right: Smoothing influence in the Skeleton Error in two toroid configurations of tube radius = 6.5 mm

2.5, 3.5, 4.5, 5.5, 6.5 mm. It was concluded that the influence of *image resolution* in the range of [0.25-1.25] and *smoothing half window's* size of 0, 1, 2, 3 did not affect in the *skeletonization error* (e_s) neither the *length estimation error* (e_L). However, *diameter estimation error*(e_D) resulted to be highly dependent on the *image resolution* chosen as shown in Figure 1. Smaller the *tube radius*, the more significant will be to choose an appropriate *image resolution* to guaranty a minimum *diameter estimation error*. The maximum theoretical diameter error in a 3D image, assuming that *the image resolution* is enough to detect a given diameter, corresponds to the case when the contour point of the section lies on a voxel vertex, since it will be computed as if it were in the center of the voxel. For an image resolution value of σ, the maximum theoretical error is $\frac{\sqrt{3}}{2}\sigma$. Following, half toroid synthetic data with fixed *tube radius* of 6.5 mm and *toroid radius* of 50 mm and 100 mm with an *image resolution* of 1.0 was used to study the *smoothing* influence in the *skeleton error*. As shown in Figure 2 there is an optimal *smoothing half window size* for which the error is minimum and it depends on the curvature of the data: for large curvature (R = 50 mm) this optimal smoothing value is smaller than for smaller curvature (R = 100). Lastly, one complete cylindrical helix turn synthetic data with a fixed helix radius to 50 mm and tube radius of 4, 5 and 12.5 mm was studied with a fixed smoothing optimal value of 3 and *image resolution* of 1.0. Both *length* and *diameter errors* decreased for larger *tube radius*.

5. Conclusions

The influence of the *image resolution* and *the smoothing half window size* have been studied in different scenarios to estimate the *skeleton error, length estimation error and diameter estimation error* in known synthetic data. Further improvements of our method will include an adaptive smoothing filter that fits in different vessel curvatures, so as to be able to quantify not only the main aorta artery but also its branches.

4. References

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