

Development of a System for Endovascular Planning of AAA Interventions

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Abstract. Endovascular repair (EVAR) of Abdominal Aortic Aneurysms (AAA) requires a precise knowledge of the patient anatomy in order to choose or design the appropriate endovascular graft so as to avoid complications during and after intervention. We describe our *eVida Aorta* CTA-based system for EVAR planning, which includes a semi-automatic aorta lumen segmentation and advanced vascular analysis, intuitive 3D visualization tools, quantitative diameter and length estimation following different user-selected workflows and overall an intuitive interface allowing supervision of intermediate analysis and planning steps.

Keywords: aorta, Abdominal aortic aneurysm, AAA, endovascular aneurysm repair, EVAR, planning, endograft, stent, Computed Tomography Angiography, CTA, lumen, segmentation, quantification

1 Introduction

An Abdominal Aortic Aneurysm (AAA) is a localized dilation of the abdominal aorta, due to a weakening and ballooning of the vessel wall, exceeding the normal diameter by more than 50%. Surgery is recommended when the rupture risk is more important than the surgery risk. Current guidelines suggest intervention when the aneurysm diameter is >5.0 - 5.5 cm.

Endovascular Aneurysm Repair (EVAR) is a minimally invasive alternative to open surgical repair developed in the 1990s [1] involving the development and fixation of a stent-graft via catheterism. This excludes the damaged wall from circulation and creates an intraluminal thrombus which tends to shrink after a successful intervention. The intervention, not absent of risks, is much less

aggressive that open surgery and has significantly lower operative mortality [2]. However, the aneurysm, although excluded, is not eliminated and the technique has its own problems due to wrong fixation, recurrent flow into the thrombus area (endoleaks) or device wear, which may require a re-intervention. It is expected that improved pre-operative planning and patient-specific endograft design may reduce EVAR complications.

Pre-operative planning is performed on the basis of CTA imaging by performing patient-specific measurements (diameters and lengths) which allow the selection of the most suitable endoluminal device from a catalogue. However, the use of fenestrated endografts (f-EVAR) is proliferating, since they provide a better personalization and fixation, specially in cases of complex anatomies. These endografts are fixed suprarenally by providing fenestrations for involved subsidiary arteries in which auxiliary stents are fixed. Sometimes these endografts are designed specifically for a given patient, requiring precise design tools involving the definition of the size and position of the fenestrations based on quantitative image analysis. Apart from a few vascular modules in workstations, such as *Syngo CT Vascular Analysis* (Siemens AG, Erlangen, Germany) or *VessellQ Xpress CT* (General Electric, Fairfield, CN, USA) only very recently similar specific tools have been developed such as the *EndoSize* system (Therenva SAS, Rennes, France) or the *SOVA.evar* OsiriX plugin (SOVamed GmbH, Koblenz, Germany)

We describe our *eVida Aorta* (eMedica S.L., Spain) EVAR planning tool which, based on a preliminary aorta segmentation and vascular analysis allows to perform in a intuitive manner the quantitative measurements necessary for the selection and design respectively of standard and fenestrated endografts. It provides a combination of features not present in other softwares (although some of them exist individually), such as a complete aortic tree segmentation, an automatic centerline extraction with a single seed point, quantitative measurements at any point, three types of planning workflow (non-fenestrated, fenestrated and free), an almost fully 3D planning with visual cues and overall an intuitive user interface which also includes a supervision of the intermediate analysis steps and parameters with visual feedback for quality control of the final results.

2 Segmentation of Aorta and Branches

Lumen segmentation in contrasted images may seem a simple task. However, some difficulties arise when trying to develop a general system without special hardware requirements:

- *Non uniform contrast*: CTA contrast is not uniform along the aorta and branches due to their length which produces an intensity bias in the lumen.
- *Dataset size*: last generation scanners provide hundreds of slices for the volume of interest, which requires a method which is not too computationally expensive.
- *Tortuosity*: tortuosity of branches requires a fully 3D approach for the aorta versus slice-by-slice approaches.

- *Shape variability*: relevant vessels are of different size and the aorta lumen and specially the aneurysm may not locally be regarded as a tubular structure due to its large diameter.
- *Adjacent structures*: some adjacent structures of similar intensity may difficult segmentation, such as vertebrae or calcifications.
- *Noise and artifacts*: i.e. image noise and streak artifacts.

Different extraction methods may be considered for vascular structures [3]. For this application, we discarded centerline-based methods, which make use of multi-scale differential or integral operators, because they are too slow for such large vessels and fail to detect the boundary with precision. Active contours and deformable models were also discarded being computationally expensive and having a complex parameter setting for clinical users. A standard region-growing approach with fixed thresholds did not work due to the mentioned contrast inhomogeneities. Adaptive measurements based on confidence criteria as implemented in [4] were not successful either, since adaptive threshold recalculation was computed each time for even larger regions.

For this purpose, we developed a novel adaptive region-growing approach, which is an improvement of the method described in [5]. The inclusion criteria, based on a lower and upper limit for voxel intensities, is recalculated on the basis of the last voxels included in the segmentation and corresponds to the interval

$$[\tilde{x}(B)(1 - k\tilde{\sigma}(B)), \tilde{x}(B)(1 + k\tilde{\sigma}(B))] \quad (1)$$

where $\tilde{x}(B)$ is the median of the set B , $\tilde{\sigma}(B)$ its median absolute deviation (MAD) and k is a multiplying factor used as parameter. Median-based statistics were used since they are more robust against outliers. Furthermore, a conservative absolute upper threshold was set to prevent possible leaks to adjacent structures such as vertebrae. The approach provides the simplicity and speed of a standard region-growing approach with increased robustness.

3 Vascular Image Analysis

The objective of the vascular image analysis stage is to obtain a set of centerlines that can be the basis for obtaining quantitative diameter and length measurements, and to obtain high level information from the vascular topology.

First, an initial voxel-based set of centerlines is obtained by skeletonization via distance-based homotopic thinning. The resulting skeleton cannot be used directly since centerlines are noisy, due to the sensitivity of these methods to surface irregularities. Spurious branches and loops are also present, due to the non-tubular local nature at some parts of the aorta, but specially in the aneurysm region.

In order to solve these issues and perform high level analysis, such as automatic identification of branches, a vessel graph is created from the raw skeleton. Bifurcation points are identified and assigned a vertex on the graph and centerlines connecting vertices are assigned to edges of the graph. This requires

strategies for exploring the voxel-based skeleton and for grouping adjacent bifurcation points into single vertices.

Centerlines assigned to edges are then pruned, by setting a minimum branch length, and smoothed, by a simple averaging window of small size. Graph loops are identified and removed using a breadth-first-search algorithm where the most tortuous segment is removed in order to resolve the loop.

4 Quantification for Endograft Planning

Quantitative image analysis is performed on the basis of the extracted centerlines (Fig. 1). Length estimation is simple if there are no intermediate branches between the selected points and is performed by accumulating interpolated distances between centerline points. If a bifurcation is present, then the length estimation involves different centerline segments, and these have to be first identified, by using a breadth-first-search graph algorithm. Their corresponding centerline distances are then accumulated to obtain the final length.

Diameter estimation is problematic since the precise extracted section plane may be very sensitive to irregularities in the centerline, some of them not completely solved by the initial smoothing. In order to perform section estimation we locally adjust a third-order B-Spline that interpolates neighbour centerline points at the desired location. This allows us to compute the tangent to the centerline in a robust manner, which defines the local section plane. From this section plane, section boundaries are identified by a ray-casting strategy, outliers removed and the final diameters obtained (max, min, average).

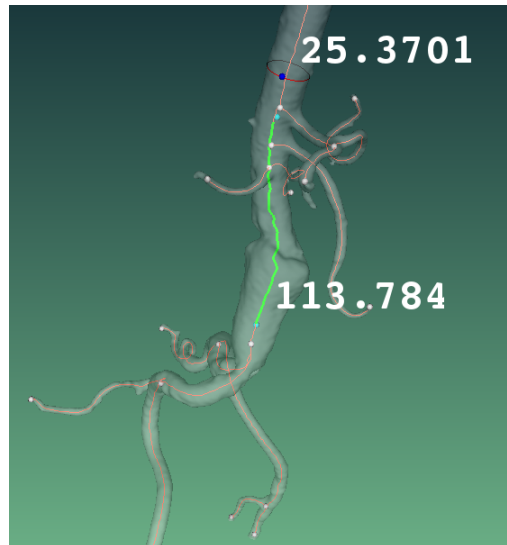


Fig. 1: Centerline-based diameter and length estimation.

5 User Interface

5.1 Segmentation Wizard

The *Segmentation Wizard* (Fig. 2) guides the user through the segmentation and vascular analysis stages. The user interface is intended to be as simple as possible, with minimal and intuitive parameter setting, but allowing for some fine grain control in order to improve the final result. Visual feedback is provided in all the stages for supervision of the intermediate results. The wizard consists on the following stages:

1. *Initialization*: the user is able to select some optional stages, such as VOI selection and image smoothing.
2. *VOI Selection*: reduces computational cost since datasets may be very large.
3. *Image Smoothing*: performs anisotropic smoothing for noisy dataset, but usually is not required.
4. *Lumen Segmentation*: the user selects a single seed point on the first slice. Additionally the user may select the multiplying factor k and the size of the buffer B if the default values are not optimal. Global thresholds may also be set to prevent leaks to adjacent structures, although this circumstance is not common. Segmentation results can be visualized and parameters re-adjusted.
5. *Post-processing*: a dilation of one voxel is usually required to refine the boundary and the user has the possibility of close the gaps up to a given size.
6. *Vascular Analysis*: the vessel graph is created and parameters for pruning and smoothing may be adjusted. The results are shown as 3D models of the aorta lumen and branches and corresponding centerlines.
7. *Conclusion*: resulting segmentation, centerlines and parameters can be saved for later use or directly used in the application.

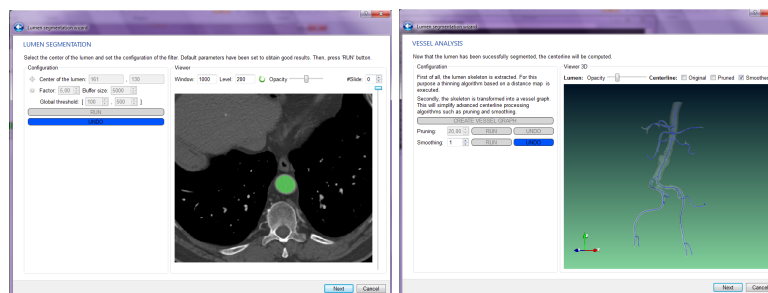


Fig. 2: Lumen segmentation (left) and centerline extraction (right) in *eVida Aorta Segmentation Wizard*

5.2 Endograft Sizing and Design

The *Endograft Sizing and Design Module* allows the user to perform the measurements necessary to choose or design an endograft based on the patient's specific vascular anatomy. Measurements are performed on a 3D model of the aorta and branches and corresponding centerlines. Different types of planes can be visualized for support, such as MPR planes in 3D space and sections normal to the centerline. The system is also able to reproduce the C-arm rotations.

Length measurements are performed by directly clicking on the surface of a 3D model of the aorta at the two desired locations. A highlighted centerline segment is displayed between the selected points. To perform diameter measurements, the user clicks on the 3D model which selects the closest centerline point and displays the estimated section. This position can be adjusted interactively. The estimated diameter is also displayed in a sectional view but the user may choose an alternative diameter interactively. This is useful for example in bifurcations where greater control may be desired. The process is guided by selecting any of three possible workflows:

- *Standard (endograft) mode* (Fig. 3): a standard non-fenestrated endograft is chosen because there is free space for fixation of the device in the infrarenal area. The application guides the surgeon for selecting the points at the aortic neck, bifurcation and iliac arteries and calculates length between these points. Diameters are automatically calculated at 5 and 10 mm. from each of these locations, in order to take into account diameter variations.
- *Fenestrated (endograft) mode* (Fig. 4): fenestrated endografts require the definition of the above standard diameters and lengths plus additional measurements that define fenestrations for the celiac trunk, superior mesenteric artery and renal arteries. Fenestrations are defined by measuring their height as measured from the top of the endograft, clock position and diameters of the fenestration and aorta at that location.
- *Free mode*: the user is allowed to perform any length and diameter measurements and these are recorded accordingly.

Finally, a report is generated with the relevant design parameters and visual information that can be handled to the endograft vendor for fabrication.

6 Initial Validation

One concern in this kind of complex vascular analysis is whether quantitative measurements are reliable and how each intermediate process affects the final result. For this purpose we have developed an initial validation methodology that takes into account the different image processes involved and their parameters, to estimate to which extent they contribute to the length and diameter estimation errors. The methodology is tested in synthetic datasets (i.e. cylinder, volumetric toroid or helix) where the centerlines and diameters are precisely known, since they are generated procedurally, and can be used as ground truth. The complete

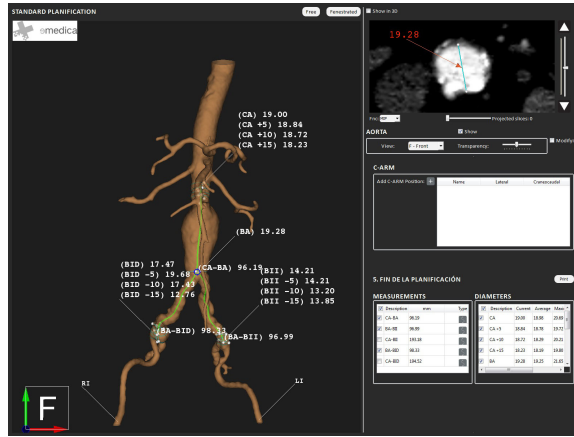


Fig. 3: Non-fenestrated endograft workflow in *eVida Aorta* application.

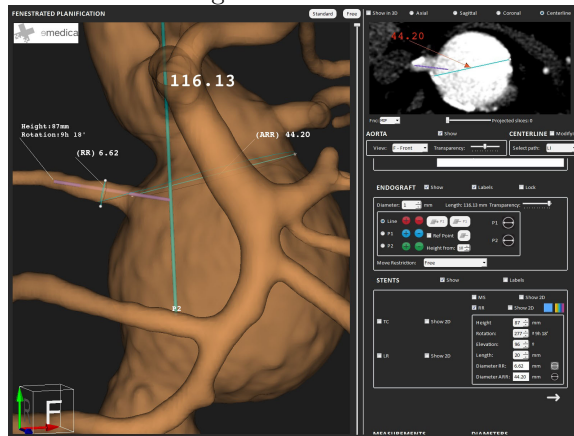


Fig. 4: Fenestrated endograft workflow in *eVida Aorta* application.

process is described in detail in [6], but we enumerate here to the possible sources of errors as a summary of the approach:

- *Segmentation Error*: depends on the segmentation approach. For a successful segmentation we assume an error of about one voxel. Although diameter estimation is performed directly on the source image at sub-voxel precision, the segmentation error affects subsequent processes such as centerline estimation which in turn determines diameter and length.
- *Centerline Error*: depends mainly on the rugosity of the segmented surface, on the image resolution, due to the voxel-wise nature of the extracted centerline, and on the size of the window used for centerline smoothing.
- *Length Estimation Error*: absolute difference in length between the measured and the ground truth length of the extracted centerlines in the synthetic dataset.

- *Diameter Estimation Error*: absolute difference in diameter between the measured and the ground truth diameters at each point of the extracted centerlines.

We tested the influence of image resolution, vessel curvature and centerline smoothing in the final measurements for volumetric cylinders, toroids and helices of different sizes, demonstrating the relevance of obtaining precise and smooth centerlines. Next steps will involve performing similar experiments in simulated and/or real CT data, possibly involving phantoms with known geometry.

7 Conclusions

We have developed the *eVida Aorta* CTA-based system for AAA EVAR planning which is able to guide the user in obtaining relevant vascular quantitative and qualitative information for the design of the most suitable endograft. It performs advanced vascular analysis of the aorta, provides an intuitive 3D visualization and interaction environment and a workflow that guides the user through all the process. The system is centered in providing the necessary usability and robustness, but allowing for supervision of the intermediate steps and results that leaves the final decision in hands of the surgeon.

The system is currently in the process of clinical validation that demonstrates its utility for planning of EVAR interventions. The ultimate long-term goal would be to demonstrate the hypothesis that a better customized stent selection may improve success and long term survival of EVAR interventions. Future work involves further validation, automating some parts of the design process, extending the system to handle the planning of EVAR interventions of Thoracic (TAA) and Thoraco-abdominal (TAAA) aortic aneurysms and trying to simulate the deployment of the designed endograft.

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