3D Segmentation and Quantification of the Aortic Arch for Endovascular Aortic Repair

Stefan Wörz[1], Hendrik von Tengg-Kobligk[2], Verena Henninger[2], Dittmar Böckler[3], Hans-Ulrich Kauczor[4], Karl Rohr[1]

[1]University of Heidelberg, BIOQUANT, IPMB, and DKFZ Heidelberg, Dept. Bioinformatics and Functional Genomics, Biomedical Computer Vision Group
[2]German Cancer Research Center (DKFZ) Heidelberg, Dept. Radiology
[3]University of Heidelberg, Dept. Vascular and Endovascular Surgery
[4]University of Heidelberg, Dept. Diagnostic Radiology
s.woerz@dkfz.de

Abstract. We introduce a novel model-based approach for the segmentation and quantification of the aortic arch morphology in 3D CTA images for endovascular aortic repair. The approach is based on a 3D analytic intensity model for thick vessels, which is directly fitted to the image. Based on the fitting results we compute the (local) 3D vessel curvature and torsion as well as the relevant lengths not only along the 3D centerline but particularly along the inner and outer contour. These measurements are important for pre-operative planning. We have successfully applied our approach using 3D CTA images and have compared the results with ground truth obtained by a radiologist. It turned out that our approach yields accurate estimation results.

1 Introduction

Aortic arch repair (AAR) poses a major challenge for cardiac and vascular surgeons as well as radiologists due to its tortuous anatomy (Fig. 1a). Since patients often have many comorbidities, more and more aortic arch pathologies are treated by minimal-invasive therapy using an endovascular graft (EVG, Fig. 1b). Endovascular aortic repair (EVAR) was initially used for the abdominal aorta but is currently also being explored for the thoracic aorta comprising the aortic arch (e.g., [1]). However, the EVGs currently used for AAR were designed for the abdominal aorta or are not yet optimized for the curved aortic arch. Therefore, these grafts fail to represent the tortuous anatomy of the arch, so misalignment of the EVG is often the case (Figs. 1c,d).

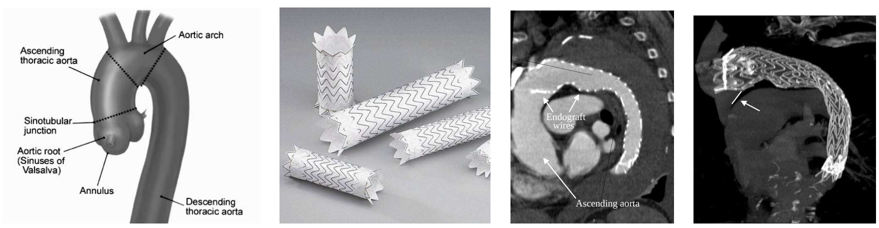
Since EVAR does not require opening the whole chest, pre-operative imaging is crucial to assess the vascular anatomy, for example, using 3D CT angiography (CTA). To choose the type of EVG for EVAR, morphological parameters need to be known such as aortic diameters, length of pathology along the centerline, and tortuosity of the aorta. In addition, we propose to choose an EVG also based on the relevant lengths along the outer and inner contours of the aortic arch. These measurements are important, for example, for planning the landing zone of the EVG, in particular, in case the landing zone is between two supra aortic branches. However, whereas in clinical practice the vessel diameters and lengths along the vessel centerline can be measured using commercial tools (e.g., [2]), the lengths along the inner and outer contour of the curved aortic arch as well as the (local) curvature and torsion are often not quantified at all, or only manually determined. Note that for the curved arch the lengths along the contour, in general, significantly deviate from the corresponding length along the centerline.

Previous work on the segmentation of the aorta from 3D images is often based on deformable models (e.g., [3, 4]). These approaches typically exploit contour information of vessel structures. Alternatively, deformable parametric intensity models have been suggested (e.g., [5, 6]). In comparison to contour-based models more image information is taken into account to improve the robustness and accuracy of the segmentation result. Concerning the segmentation of the abdominal aorta, i.e., the lower part of the aorta, contour-based approaches have been proposed (e.g., [3, 4, 7]). However, we are not aware of an intensity model-based approach which has been used to quantify the morphology of the aortic arch, i.e., the curved part of the aorta, for pre-operative planning of EVAR using grafts.

In this contribution, we introduce an approach based on a new intensity model for the quantification of the aortic arch morphology in 3D CTA images for EVAR. In contrast to previous work we quantify the (local) 3D vessel curvature and torsion as well as the relevant lengths not only along the 3D centerline but particularly along the inner and outer contour. Moreover, in contrast to previous approaches based on intensity models, our model is particularly suited for vessels of large widths such as the aorta, which is in contrast to, e.g., [5].

2 Materials and Methods

To quantify the aortic arch morphology, we have developed a 3D analytic intensity model, which represents the shape as well as the image intensities of the aortic arch within a 3D ROI. The parametric model is an ideal sharp 3D cylinder



(a) (b) (c) (d)

Fig. 1. Anatomy of the thoracic aorta (a), examples of endovascular grafts (b), as well as a 2D section (c) and a maximum intensity projection (d) of a 3D CTA of a patient after implantation of an EVG into the aortic arch. The EVG shows a significant misalignment w.r.t. the inner contour of the proximal aortic arch (see the arrow, (d)).

of radius R convolved with a 3D Gaussian (standard deviation σ) to incorporate the blurring effect of the image formation process. In particular, this model allows to represent the plateau-like intensity structure of thick vessels such as the aorta. Unfortunately, the exact solution of a Gaussian smoothed cylinder cannot be expressed analytically. In [6], an approximation of a Gaussian smoothed cylinder has been introduced, which uses two different approximations based on a Gaussian function and a Gaussian error function, and which employs blending functions to switch between both approximations. However, the application here concerns the segmentation of the aorta, which has a large width. Therefore, we here use a different approximation which is particularly suited for thick cylinders and which is computationally more efficient than the one in [6]. This 3D approximation is based on a 2D approximation of a Gaussian smoothed large disk using the Gaussian error function $\Phi(x) = \int_{-\infty}^{x} (2\pi)^{-1/2} e^{-\xi^2/2} d\xi$, and is defined as

$$g_{\text{Cylinder}'}(\mathbf{x}, R, \sigma) = \Phi(\rho_{\text{radial}}(r, R, \sigma)) \tag{1}$$

with $\mathbf{x} = (x, y, z)$ and $r = \sqrt{x^2 + y^2}$. Based on (1), the complete 3D intensity model is constructed by incorporating intensity levels a_0 (surrounding tissue) and a_1 (vessel) as well as a 3D rigid transform $\mathcal{R}$ with rotation parameters $\boldsymbol{\alpha} = (\alpha, \beta, \gamma)$ and translation parameters $\mathbf{x}_0 = (x_0, y_0, z_0)$. This results in the 3D intensity model $g_{M,\text{Cylinder}}(\mathbf{x}, \mathbf{p}) = a_0 + (a_1 - a_0)\ g_{\text{Cylinder}'}(\mathcal{R}(\mathbf{x}, \boldsymbol{\alpha}, \mathbf{x}_0), R, \sigma)$.

To segment the aortic arch we utilize an incremental process which starts from a given point D at the descending aorta and proceeds along the aorta until it reaches a given point A at the ascending aorta (Fig. 2a). In each increment, the parameters of a cylinder segment are determined by fitting the model $g_{M,Cylinder}$ to the image intensities $g(\mathbf{x})$ within a 3D ROI. Initial parameters for the fitting process are determined from the estimated parameters of the previous segment using a Kalman filter. To increase the robustness and accuracy of model fitting, we here apply a two-step refinement procedure. In the first step, we segment the aorta as described above using a larger size of the 3D ROI, i.e., we include more image information to robustly estimate the position $\mathbf{x}_0$ and orientation $\boldsymbol{\alpha}$ defining the centerline. In the second step, the remaining parameters such as the radius are refined by applying the model again but using a smaller size of the ROI in the direction of the centerline to increase the accuracy.

Applying our approach, we obtain estimates of the model parameters $\mathbf{p}$ for each vessel segment. In particular, based on the estimated radius R, position $\mathbf{x}_0$, and orientation $\boldsymbol{\alpha}$, we yield a 3D description of the shape of the aortic arch. For example, Fig. 2b shows the computed 3D shape overlayed with the original image data. To compute the (local) 3D curvature and torsion of the aortic arch, we apply a least-squares approach using cubic polynomials, which are locally fitted to a range of centerline positions. To visualize the results and to compute the lengths along the inner and outer contour of the curved aortic arch, we project the segmentation results onto a plane. This plane is specified by the centerline points A and D as well as the most anterior point along the centerline. For example, Fig. 2c shows the projected plane with the centerline (dashed), the inner and outer boundary (white), as well as the points *A*, *1*, *2*, *3*, and *D* where the points *1*, *2*, and *3* are distal to the three supra aortic branches.

3 Results

We have applied our approach to quantify the morphology of the aortic arch in ten 3D CTA images. The images consist of about $512 \times 512 \times 700$ voxels with a slice spacing of 0.8 mm and a within-slice resolution between 0.512 mm and 0.625 mm. In all ten 3D images the automatic segmentation and quantification of the aortic arch was successful. As an example, Fig. 2b shows the computed 3D shape for one 3D image and Fig. 2c shows the 2D projection of the segmentation result. To illustrate the application for pre-operative planning of EVAR, Fig. 2d shows a picture of a real graft, which has been (interactively) aligned in accordance with the segmented shape of the aortic arch.

To validate our approach, we compared the results with ground truth, which was manually obtained by a radiologist. In addition, we compared the results with results obtained using a workstation with a commercial vascular analysis software. Fig. 2e shows the estimated radius in *mm* along the aortic arch for the new approach (bold) and the segmentation results of the radiologist (small grey squares and grey line) as well as for the commercial software (dashed). It turns out that our approach yields a much better result w.r.t. the ground truth than the commercial software. The maximal difference of the estimated radius

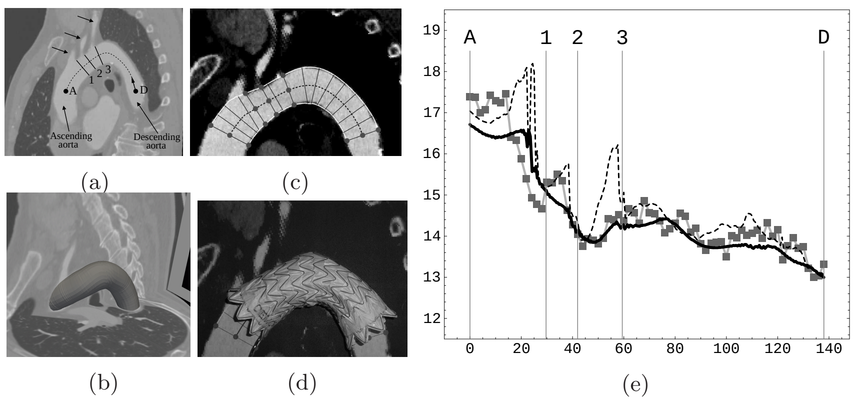


Fig. 2. 2D section of a 3D CTA showing the aortic arch (a), 3D segmentation result overlayed with two 2D sections of the 3D CTA image (b), a projected plane displaying the aortic arch and the segmentation result (centerline (dashed), inner and outer boundary (white), and several diameters) (c), as well as a picture (d) of a graft which has been aligned in accordance with the segmented shape shown in (c). The diagram (e) shows the estimated radius in *mm* along the arch for our approach (bold), the segmentation results of a radiologist (grey), and the result of the commercial software (dashed).

between our approach (bold) and that of the radiologist (grey) is 1.02 mm for all 70 measured radii, and the mean error is 0.34 mm. In contrast, the commercial software (dashed) yields a maximal error of 3.26 mm and a mean error of 0.44 mm. Moreover, for all ten 3D images we have compared the estimated radius of the aorta using our approach with the radius determined by the radiologist at the 3D points A, *1*, *2*, *3*, and D. It turned out that the results of our approach well agree with the ground truth with a maximal error over all points in all 3D images of 1.31 mm and a mean error of 0.38 mm.

4 Discussion

We introduced a new model-based approach for the segmentation and quantification of the aortic arch morphology in 3D CTA images for endovascular aortic repair (EVAR). The approach is based on a 3D analytic intensity model which is particularly suited for vessels of large widths. To increase the robustness and accuracy of model fitting we suggested a two-step refinement procedure. Based on the fitting results we directly compute the (local) 3D vessel curvature and torsion as well as the relevant lengths along the 3D centerline and along the inner and outer contour, which are important parameters for pre-operative planning in EVAR applications. We have successfully applied our approach to segment and quantify the aortic arch morphology using ten 3D CTA images.

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