A Robust Semi-automatic Procedure for Motion Quantification of Aortic Stent Grafts using Point Set Registration

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Abstract. After endovascular aortic aneurysm repair, stent graft migration and kinking or buckling of the stent graft can cause the perilous risk of rupture. In a previous paper we presented an approach to analyze the migration of the stent by defining the spinal canal as a reference object and by investigating the movements relative to it. In this paper, we quantify also non-rigid deformations of the stent. A procedure is used based on the segmentation and extraction of surface points for stent and spinal canal and on point set registration. The sensitivity of the quantified values with respect to the choice of segmentation parameters is investigated as well. Results for 6 patients show that the procedure allows us to distinguish benign cases from dangerous changes in morphology even if segmentation parameters vary within a reasonable bandwidth.

1 Introduction

The enlargement of the aorta below the renal arteries due to its weakened walls is called an infrarenal or abdominal aortic aneurysm (AAA) [1]. From a diameter of 5 cm on, the AAA should be treated because of the perilous risk of rupture. Endovascular aneurysm repair is a treatment established in the early nineties in which a stent with a synthetic graft (stent graft) is placed inside the aorta to cover the weakened regions of its wall. However, the process of aneurysm shrinkage, ongoing aneurismal disease, and damage or fatigue of graft material may result in leakage, graft migration, and kinking or buckling of the graft, which can subsequently cause rupture or occlusion [2].

In order to assess the ruptur risk depending on the diameter of the aneurysm several methods for the segmentation of AAAs have been investigated [3]. Image processing methods have also been used for extracting and describing vessels from CT images to improve the design of stents [4]. Another study attempted to assess the rupture risk using hemodynamic modelling [5]. Several clinical papers are dealing with complications which appear after endovascular repair [2] or compare this approach with the classical open intervention [1].

Currently, few is known about the morphological changes and the migration of the graft as well as about those of the aneurysm after an endovascular stent

graft implantation, in particular their quantitative description is lacking. In a previous work [6] and [7] we proposed quantitative measures and an (implemented) procedure for this purpose, in particular we quantified the migration of the stent with respect to the spinal canal and to the aorta. In this paper, we investigate the robustness of the procedure and show that malign changes in morphology can be identified by the quantified parameters.

2 Methods

Our procedure for motion estimation is based on point set registration applied to the points of segmented surfaces, which have been extracted from the 3D-CT images of two different points in time. Hence, a reproducible determination of motion may depend on the chosen segmentation parameters and the user should be able to select each parameter in a range in which the resulting motion does not vary to a large extend. A reproducible motion determination is necessary if different users are applying the procedure (implemented as a software tool) and to get a comparable result if the motion of different patients has to be quantified.

Firstly, our procedure shall estimate the global rigid motion of the stent. Secondly, the non-rigid motion and deformation of the stent shall be determined and quantified. Finally, by varying a critical segmentation parameter within a certain bandwidth we analyse how the estimated motion depends on this parameter. In [6] we evaluated the first step on thoracic stents and the second step was performed on several abdominal stent devices in [7]. In [7], as well, the motion of the stent with respect to the aorta is analyzed. Here, we focus on the third step and detail the order of registration steps which we found out to be necessary for a robust behavior of the procedure.

As the pose of a patient in the CT device is different for two different points in time it is necessary, when tackling the first step, to define a fixed reference system. We found out the spinal canal to be well suited for serving as a object of reference: it deforms only little and it is relatively easy to segment it reproducibly. As described in [6] (see also [8] for the implementation) we used the "fast-marching-level-set"algorithm to segment the spinal canal. The stent could be segmented either by thresholding or using a "region growing"algorithm [6]. For the fast-marching-level-set and for the region growing algorithm seed points have to be set by the user. In the former case a parameter called "stopping value"exists responsible for the size of the segmented object.

To place the stent in the reference system defined by the spinal canal we register rigidly the spinal canal extracted for both points in time and transform the stent by the transformation matrix calculated during this registration step. A high registration accuracy is obtained by registration in both directions, time point one on two and vice versa, and by taking the result with smaller registration error ϵ_r. Here, ϵ_r is defined by

$$\epsilon_r(C_1, C_2) = \sum_{i=1}^{N_1} \Big(d\big(\mathbf{T}(\mathbf{c}_i), C_2\big)\Big)^2, \mathbf{c}_i \in C_1, \tag{1}$$

where C_1 (resp. C_2) is the point set of the spinal canal extracted at the first (resp. second) point in time; N_1 the number of points in C_1, $\mathbf{T}$ the transformation and $d(\cdot, C)$ is the Euclidean distance to point set C: $d(\mathbf{x}, C) = \min_{\mathbf{d} \in C} |\mathbf{x} - \mathbf{d}|$. The cost functional is optimized using the Levenberg-Marquardt algorithm and a pre-computed distance map.

After transforming the stent into this reference system we calculate its rigid motion by registration of the stent for both points in time as described above for the spinal canal. Now, we register the stent point sets also non-rigidly, first using an affine transformation, after with a thin-plate spline based algorithm [9]. Measuring the change in the residual error ϵ_r after each registration step (with an increasing number of degrees of freedom) represents an elementary possibility to quantify the amount of morphological change of the stent.

The stopping value during the segmentation of the spinal canal turned out to be a critical parameter for the size of the segmented objects. In order to determine the effect of this parameter we varied it and calculated its influence on the quantified motion parameters. We have chosen the parameter bandwidth such that a user can immediately see that a value below and above it would lead to an object which is too small or too large, respectively.

3 Results

In a clinical evaluation we investigated a sample of 6 patients all of which have been treated with the same kind of stent device (Zenith^{TM}). The corresponding CT image stacks consist of slices with 0.9 mm thickness, 0.5 mm x,y-spacing, 512 x 512 pixels per slice, and a number of 200 up to 250 slices, which we resampled to over 400 slices in order to obtain isotropic images with 0.5 mm thickness. The high accuracy demonstrated by the low residual error e_r $1mm$ for all patients after rigid registration of the spinal canal showed that the latter is well suited to establish a reference system. For its segmentation the stopping value in the fast-marching-level-set algorithm has been chosen such that, on the one hand, the segmented region is not leaving the domain of the spinal canal and that, on the other hand, no splitting in two not connected regions occurs (due to a too low stopping value). Inside of this range we varied the parameters and registered spinal canal and stent for different parameter combinations (see Table 1). Even though the motion parameters vary for the different combinations cases of high migration and deformation can still be identified. For two stents (patients 4 and 6 in Table 1) we quantified a large shape change (see Fig. 1) which also have been identified by the radiologists, however, only on later CT images. For these stents the initial transformation into the reference system of the spinal canal was helpful to obtain a good initial position for stent registration.

Table 1. Evaluation results. The residual registration error ϵ_r after registration of the spinal canal and after rigid and affine registration of the stent is shown for different stopping value combinations: 13 for both points in time, 11-15 and 15-11. For all combinations the two abnormal shape changes for patients 4 and 6 can be detected by a strong difference of ϵ_r after rigid and affine registration of the stent.

Patient	ϵ-Spinal Canal			ϵ-Stent			ϵ-affin		
	13-13	11-15	15-11	13-13	11-15	15-11	13-13	11-15	15-11
1	0.69	2.54	2.17	1.26	1.26	1.26	0.96	0.96	0.96
2	0.70	2.22	4.07	0.21	0.21	0.21	0.17	0.17	0.17
3	0.76	2.45	2.12	0.52	0.52	0.52	0.35	0.35	0.35
4	1.11	17.27	9.68	21.81	21.80	21.81	3.09	2.02	2.02
5	1.11	2.53	2.92	2.24	2.25	2.26	1.21	1.24	1.21
6	1.63	4.85	8.23	10.69	10.69	10.69	2.04	2.06	2.07

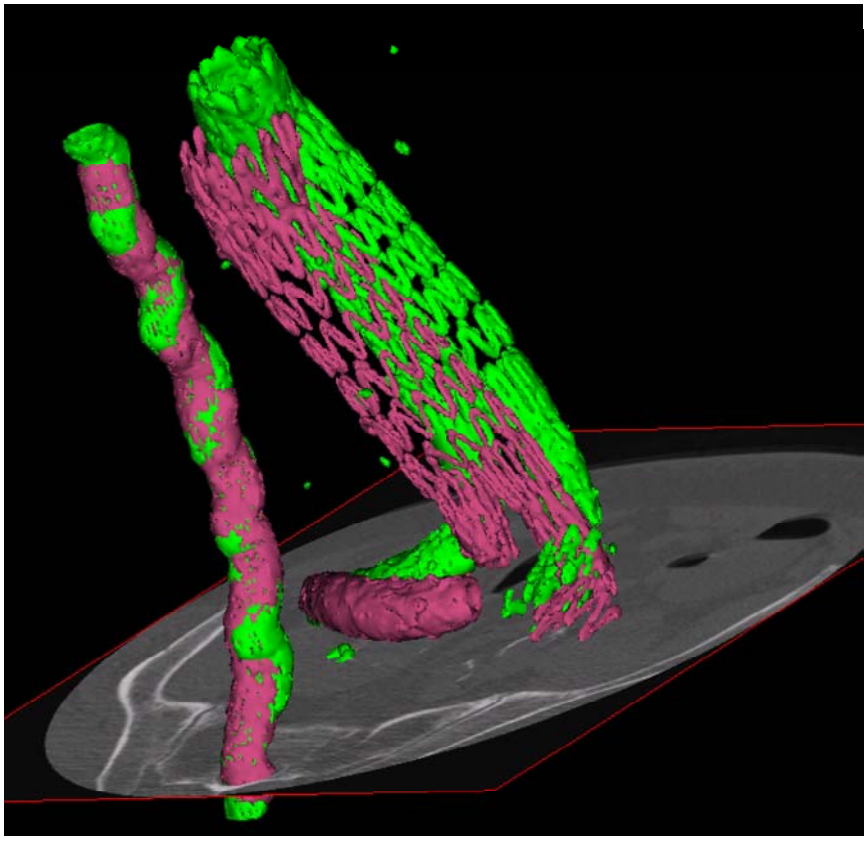

Fig. 1. *Patient 6: Spinal canal and stent surfaces extracted for two points in time (light March 2003, dark April 2004) after registration of the spinal canal's surface point sets and transforming the stent accordingly (reference system defined by the spinal canal).*

4 Discussion

We proposed a method to quantitatively describe disease patterns in the treatment progression of patients after endovascular AAA repair. The semi-automatic method is based on several segmentation and registration steps allowing to define a spatial reference system and to quantify the relative motion in this system. Here, we have shown that—for the small set of patient data investigated—the method is robust in the sense that the resulting description is largely user independent and reproducible. With the proposed procedure we could quantitatively distinguish cases where dangerous shape changes appeared and cases with benign treatment progression. In particular, we could identify an upcoming closure of one shank of a bifurcating stent in two cases where radiologists recognized this only on a later CT image. As shown in this paper, for the procedure's parameters the user can easily find a bandwidth inside which a clear decision is possible if an abnormal shape change occurred or not. This robustness allows also non-experts to obtain user independent results by the use of the implemented procedure. It represents a prerequisite to implement the method as a tool for clinical practice, together with a further automatization of the segmentation step, which shall be achieved in future work using a template based approach.

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