Semi-automated approach to CTA based EVAR follow-up

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Abstract. Close follow-up is required after EVAR to assess the evolution of the aneurysm and detect possible complications such as endoleaks, which increase rupture risk and may lead to re-intervention. Correctly excluded aneurysms tend to shrink, which is usually measured by thrombus largest diameter or volume. However, thorough understanding and visualization of the aneurysm shape changes along time could provide valuable information for the clinicians. This work aims at developing a pipeline to assess the thrombus deformation at different time points, since a direct comparison is not feasible due to images located at different positions in space and deformations or displacements of the aorta. We propose a three-step workflow: I) vertebrae-based rigid registration to bring the data to the same space, II) Straightened Curved Planar Reformatting (s-CPR) to eliminate aortic displacement and deformation, III) s-CPR based deformable registration to evaluate changes intrinsic to the thrombus. Finally, we correlate the obtained deformation field with the presence and location of leaks.

Keywords: EVAR, Follow-up, thrombus, deformable, registration, leak, CPR

1 Introduction

An Abdominal Aortic Aneurysm (AAA) is a dilation of the abdominal aorta that, if not treated, tends to grow and rupture with high risk of mortality. Endovascular Aneurysm Repair (EVAR) is a minimally invasive technique involving the deployment and fixation of a stent via catheterization. This excludes the damaged wall from circulation and creates an intraluminal thrombus that shrinks after a successful intervention. The main advantages of this treatment are intervention time reduction, lower perioperative mortality, faster recovery times and improved post-operative pain control. Nonetheless, the long-term survival rate is almost equivalent to open surgery due to endoleaks [1], EVAR complications that may cause aneurysm growth and lead to re-intervention. Hence, close follow-up is required after EVAR by performing CTA examinations at least yearly. It would be very useful for clinicians to align and compare different post-operative time series to assess the morphological changes of the aneurysm during this follow-up. Preliminary studies have shown that this alignment is feasible [2], [3].

Hereby, we propose an AAA follow-up pipeline based on time-series registration for thrombus shape and deformation analysis, providing insight into the influence of the leaks in these shape changes. A three-step methodology is proposed: I) a landmark based 3D rigid registration of the vertebrae and co-registration of vascular structures, to eliminate patient position-related changes, II) a centreline based Straightened Curved Planar Reformation (s-CPR) of the aortic lumen and thrombus to remove aortic displacements and deformations, and III) a deformable registration of the thrombus.

The outline of the paper is as follows: in Sect. 2 materials and input data are presented. Sect. 3 describes the proposed follow-up pipeline. In 3.1 the landmark based 3D rigid registration of the vertebrae is explained. In 3.2 the s-CPR algorithm is presented and in 3.3 the thrombus s-cpr deformable registration step is described. Finally, in Sect. 4 some preliminary results are shown and Sect. 5 discusses the encountered problems and possible solutions for future work.

2 Materials

The main objective of AAA follow-up is to assess the evolution of the aneurysm across different post-operative series by providing qualitative and quantitative information. Such information, besides thrombus maximum diameter and volume measurements, could offer more insight into the progression and could help predicting complications and evaluating the rupture risk. Nevertheless, comparing time-series is hindered by I) the lack of robust thrombus automatic segmentation methods and II) patient position changes and aortic deformation and displacements. In this work the segmented thrombus is considered an additional source of information in order to focus on defining a pipeline for the follow-up.

The proposed methods are implemented with C++, using ITK [4] and VTK [5] libraries. We have evaluated the performance of the pipeline on 13 retrospective post-operative study pairs, taking the first post-operative image as reference. The datasets have been obtained with CT scanners from different manufacturers and have varying size and spatial resolution. All of them contain infrarenal thrombi that do not expand to the iliac arteries and only one of them presents leaks.

2.1 Input data for the follow-up pipeline

In the present work, segmentation of anatomical structures is considered as input for the registration pipeline. Aortic lumen segmentation and centreline extraction are obtained using the method proposed in [6]. The thrombi are isolated manually by an expert. Finally, vertebrae segmentation for the initial rigid registration is based on a simple connected components and thresholding approach.

This automatic segmentation approach is not intended to be precise, but it is sufficient for the registration, as shown in Fig. 2.

3 Methods

We present a three-step pipeline for the aneurysm follow-up evaluation by time-series registration. The proposed workflow is presented in Fig. 1. Each pipeline step deals with the removal of displacements and deformations coming from different sources, as explained in the following subsections. Note that our work is not focused on developing fine registration approaches, but rather at proposing a coherent pipeline that allows the comparison of thrombi at two time points.

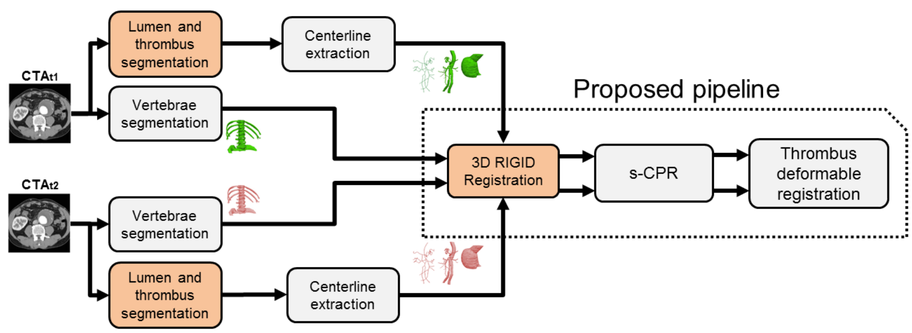

Fig. 1: Proposed pipeline for EVAR follow-up thrombus evaluation. Steps that require user input are highlighted in orange: for lumen segmentation a seed point is needed, thrombus segmentation is done manually and the rigid 3D registration starts from a user provided landmark in the renal artery. These segmentations serve as input for the proposed 3-step pipeline outlined by the dashed box.

3.1 Landmark-based rigid 3D vertebrae registration

The follow-up pipeline starts with the rigid 3D registration of the vertebrae to locate the datasets in the same space and minimize the patient position and orientation changes. We use the Versor Rigid 3D Transform [4] for volume registration. The transform is initialized with a landmark-based translation that roughly brings the second volume closer to the reference follow-up CTA, reducing the registration optimization time and ensuring convergence. This landmark is introduced by the user just below the lowest renal artery, which is a common anatomical reference for clinicians. We employ the Mean Squares Image To Image Metric [4] to evaluate the registration at each iteration. This metric is simple to compute and relies on the assumption that homologous points from both images have the same intensity. Since about 80% of the pixels correspond to the vertebral column and the hip, the metric will try to better match those structures than the remaining 20% pixels corresponding to the ribs. This is important because the positions of the ribs change with the respiratory cycle. The obtained transform is used to bring the vertebrae, as well as the lumen, the centreline and the thrombus of the moving dataset to new positions that are rigidly aligned with the reference. An example of the output of this first step is shown in Fig. 2.

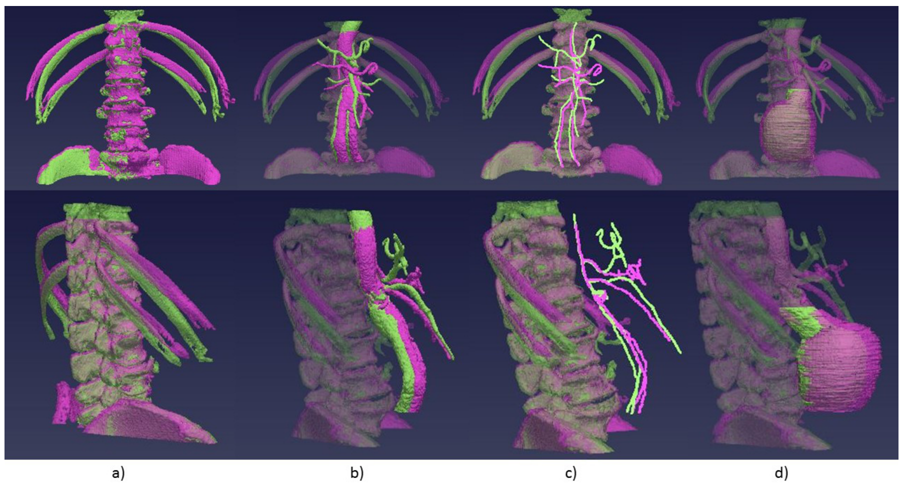

Fig. 2: 3D rigid registration, which brings fixed image (green) and moving image (pink) to the same space. a) Vertebrae registration, b) lumen co-registration, c) centerline co-registration, d) thrombus co-registration. Initially, the fixed image origin was (-184, -125, -829) and the spacing was (0.747, 0.747, 0.799), while the moving image origin was (-182, -149, 78) with a spacing of (0.86, 0.86, 0.625).

3.2 Straightened Curved Planar Reformation of lumen and thrombus

The vertebrae rigid registration and co-registration of vascular structures brings both datasets to the same space and eliminates the movements related to the patient's orientation, but does not account for the aortic deformations and/or displacements. In this second step we aim at removing the aorta-specific changes by applying a centreline-based Straightened Curved Planar Reformation (s-CPR) to the volume. Given the co-registered vessel centreline, the CPR works by resampling it and casting lines perpendicular to it, until the whole extent of the centreline is swept. The s-CPR fully straightens the aortic lumen, generating a linear representation of the vessel with varying diameter [7]. We employ a sampling distance of 1 mm along the centreline curve and the resulting slices have a height equal to the length of this equidistantly sampled centreline. The width of the slices is set to half the physical size of the initial image in the x coordinate, since it is a conservative value that always includes the thrombus extent.

The number of slices of the straightened volume is set to 200 and the projection direction is always sagittal (see Fig. 3). Since the thrombus is always located above the iliac arteries, we have developed a unique-path s-CPR algorithm, cutting the datasets before the iliac bifurcation. From the co-registered centreline we extract the main branch, i.e. the aortic centreline without considering the arterial bifurcations. In the lumen area restrained by the two stent modules we emulate a combined lumen and extract its centre point, which is depicted in Fig. 3a in yellow color.

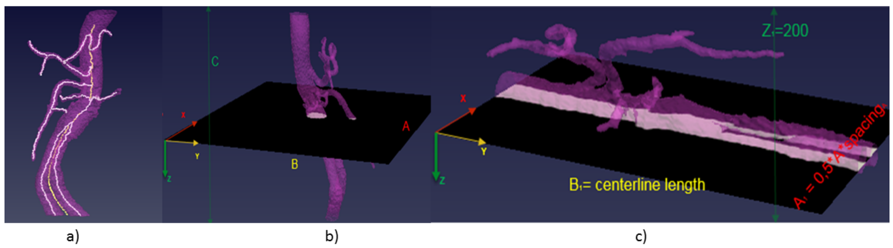

Fig. 3: a) Original centreline (white) and extracted main branch (yellow), b) original lumen segmentation, c) s-CPR of lumen with corresponding sizes.

Since the segmented lumen region/centreline size in both datasets may be different above the renal arteries, the height of the resultant s-CPR slices in each case varies. However, as we have equidistantly sampled the centreline curve, a translation-based registration in the straightened direction can be employed to align both s-CPR volumes. We apply the same s-CPR reformation to the anatomical landmark provided in the previous step and utilize it to match both volumes. Fig. 4 shows the obtained s-CPR volumes of the lumen and thrombus before and after registering them with the renal artery landmark.

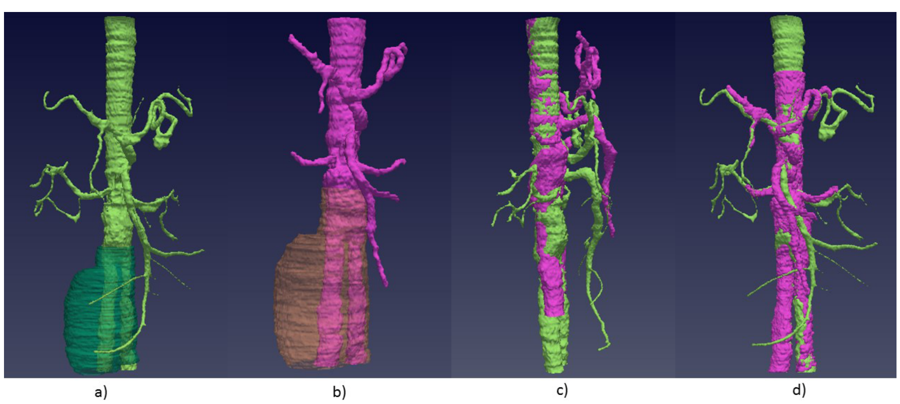

Fig. 4: s-CPR: a) fixed lumen and thrombus, b) moving lumen and thrombus, c) fixed and moving s-CPR of images with different size, d) renal based registration of the s-CPR volumes allows the comparison between them.

3.3 3D deformable registration of thrombus

Our final goal is the evaluation of the shape and deformation of the thrombus over time, for which we propose a deformable registration of the s-CPR volumes of the thrombi as the last step of the pipeline. This provides a deformation field representing how the thrombus in the second time point has changed with respect to the reference dataset and allows the correlation of these deformations with the appearance and location of leaks. We apply the Level Set Motion deformable registration algorithm [4], which relies on the assumption that pixels representing the same homologous point on an object have the same intensity in both the fixed and the moving image. The registration process is relatively fast, around 3'5 minutes per CTA on an Intel Core 3GHz desktop computer. We have set the number of iterations to 100 experimentally, since afterwards the error metric fluctuates around the minimum in most of the datasets.

4 Results

Aneurysm shape changes and deformations can provide additional information about the evolution of the patient besides the maximum thrombus diameter and volume. In this work, we aim at proposing a three-step pipeline for EVAR follow-up, taking as reference the first post-operative CTA. With an initial first rigid registration based on the vertebrae, which are the most invariable structures in the image, we place the datasets in the same space location and remove patient orientation related movements. Next, we apply s-CPR to eliminate the aortic deformation, since our goal is to study the thrombus intrinsic changes with respect to the centreline. Finally, a deformable registration of the reformatted thrombi provides a quantification of the produced shape changes and allows the visual inspection of the deformation fields.

We have validated the pipeline in terms of the deformable registration quality with the mean Dice similarity coefficient, which is widely employed to evaluate deformable registration results [8]. The mean Dice similarity coefficient of the deformable registration for the 13 datasets is 0.989 ± 0.015. Fig. 5 provides a qualitative evaluation of the registered thrombi in the unfavorable case.

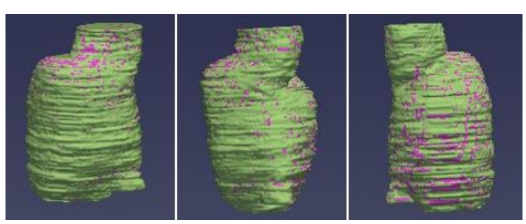

Fig. 5: Example of deformable registration output.

Besides, we have studied the ability to correlate the deformations with the appearance of leaks. Our hypothesis is that the occurred deformation strength and direction should match the location of the leak. We have been provided with a unique dataset that presents leaks and the obtained results seem to correlate this assumption, as shown in Fig. 6. The deformation field depicts how the s-cpr thrombus in the second time point has changed with respect to the reference reformatted thrombus. The arrows indicate the direction of the deformation and the color represents the magnitude of the vector, being red the highest deformation, visible around the leaks.

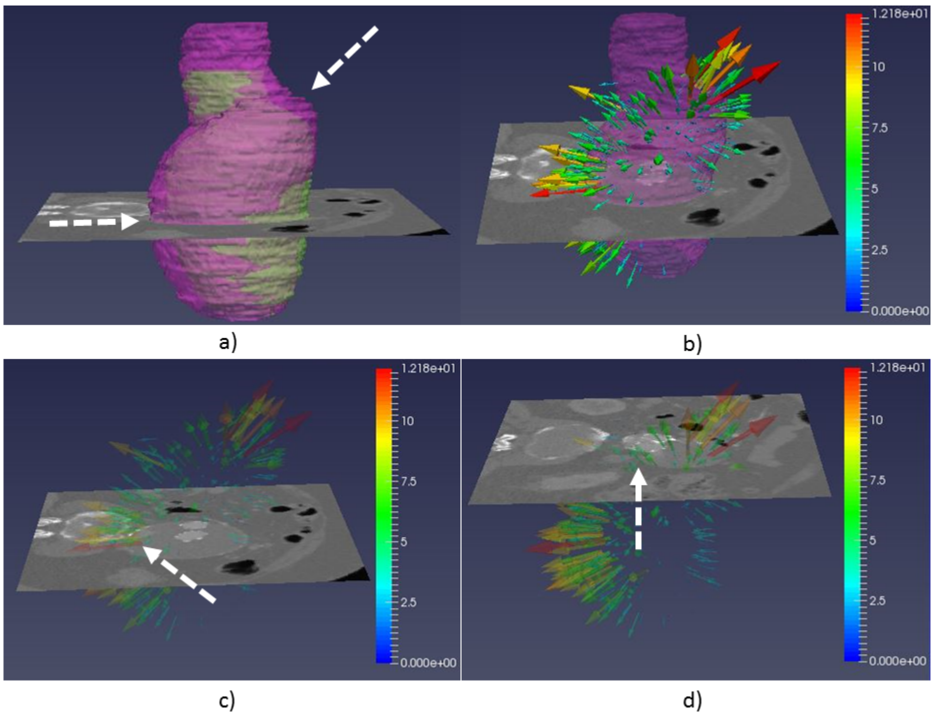

Fig. 6: a) Registered s-CPR of the thrombi, where white arrows point to the location of the leaks, b) deformation field overlapped with the second post-operative volume s-CPR and thrombus s-CPR, c) the white arrow points to a type II endoleak, where the deformation vector magnitude increases, d) the white arrow indicates a type Ia proximal endoleak, where the deformation vector also increases.

5 Discussion and Future Work

This paper presents a novel pipeline for the assessment of the aneurysm evolution after EVAR. The reference dataset is always the first post-operative CTA. We do not study the pre-post deformation, since the lumen and centreline in these cases are not easily comparable due to I) the presence of the stent in the post-operative and II) the centreline displacement caused by the aneurysm in the pre-operative. After applying the proposed pipeline to a post-operative CTA pair, the resulting reformatted and registered thrombi are comparable using a deformable registration algorithm. Results have shown that a possible correlation exists between how a thrombus deforms and the presence and location of leaks. However, these conclusions must be validated with a larger number of cases and with more clinical involvement. Besides, a rupture risk predictive model based on this analysis of the deformation should be considered as future work. Endotension cases could be evaluated with this pipeline to infer information of these less-understandable situations. Although the results of the work seem encouraging, the process has some drawbacks. On one hand, the input thrombi has been manually segmented, which includes some user-variability. A semi-automatic thrombus segmentation method may provide robustness to the whole process. Additionally, the initial rigid registration of the vertebrae is based on a rough segmentation. On the other hand, the extraction of the s-CPR volume is built upon a single-path CPR. We emulate a combined lumen where the prosthesis separates the lumen in two regions, which is a good approximation but reduces the precision of the reformatting. A multi-path s-CPR should be considered. Finally, all the stages of the pipeline should be integrated into a user- friendly, intuitive workflow for clinical usage.

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