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Prediction of deformations during endovascular aortic aneurysm repair using finite element simulation

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ABSTRACT

During endovascular aortic aneurysm repair (EVAR), the introduction of medical devices deforms the arteries. The aim of the present study was to assess the feasibility of finite element simulation to predict arterial deformations during EVAR. The aortoiliac structure was extracted from the preoperative CT angiography of fourteen patients underwent EVAR. The simulation consists in modeling the deformation induced by the stiff wire used during EVAR. The results of the simulation were projected onto the intraoperative images, using a 3D/2D registration. The mean distance between the real and simulated guidewire was 2.3 ± 1.1 mm. Our results demonstrate that finite element simulation is feasible and appear to be reproducible in modeling device/tissue interactions and quantifying anatomic deformations during EVAR.

1. Introduction

The deployment of an aortic stent graft requires the introduction of rigid sheaths and guidewires via a femoral access, which then leads to deformations of the vascular structures, which by nature are soft. This is the main source of rigid registration errors when the preoperative 3-dimensional (3D) computed tomography angiography (CTA) is overlayed onto the 2-dimensional (2D) fluoroscopy images taken during endovascular abdominal aortic aneurysm (AAA) repair. When these intraoperative arterial deformations occur, they also lead to length changes, of the iliac arteries in particular. These arteries are measured at the time of sizing, in order to determine, from a limited catalog, which stent graft is the most suitable for the patient. This process leads to an obvious paradox: the deformations are not objectively taken into account at the time of sizing/planning and of guiding of the procedure, whereas the stent graft is deployed inside a deformed artery, which will not have the same length as that measured on the CTA. Currently, the physician anticipates such deformations, on the basis of his experience, but not on physical or statistical deformation data.

A few works have focused on computer aided navigation to assist endovascular repair of complex aortic aneurysms. Indeed, most of vascular surgeons work with a standard intra-operative 2D fluoroscopy-like imaging. For endovascular aortic aneurysm repair (EVAR), the best imaging to guide the intervention is the superimposition of the pre-operative CT volume onto the intra-operative imaging environment thanks to a registration process [1]. Intensity based [2,3] and feature based [4,5] 3D/2D rigid registration methods have been considered. Due to intra-operative deformations of vascular structures it is difficult to achieve an accuracy of about one millimeter. More recent works integrated non-rigid registration to take into consideration local deformations, of the renal ostia, observed between 3D CT pre-operative data and intra-operative images. The results reported from use of the image-guided surgery system during 23 procedures showed that the method was within a target accuracy of 3 mm in 78% of cases. The deformation of the iliac arteries caused by the introduction of stiff endovascular tools was not taken into account. Otherwise several works attempted to implement finite element methods (FEM) based simulation in the context of endovascular procedures. They were intended to deal with issues related to the understanding and the anticipation of aneurysm rupture risk, of strain, migration and endoleaks at

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the stent, in their pre-computed implementation [6–8] or to deal with catheterization simulation issues in their interactive/real time implementation [9,10]. With the extension of EVAR to more complex cases, in particular to the use of a fenestrated endograft in certain patients, the quantification of vascular deformations will become an important aspect in the planning and sizing of such devices. In addition, such deformations will need to be accounted for by the intraoperative imaging fusion system. The aim of this study was to assess the feasibility of finite element simulation to predict and quantify arterial deformations during EVAR.

2. Materials and methods

2.1. Patient and device data

From January 2011 to March 2011, CTA data was obtained from 14 consecutive patients (13 men) with an AAA who underwent EVAR in our department. The patients were operated when the aneurysm diameter exceeded the threshold of 50 mm. Their mean age was 73.5 ± 8.9 years. This study was approved by our hospital's ethics committee. The CTAs were performed using a 64-slice scanner (General Electric Medical Systems, Milwaukee, Wisconsin, LightSpeed16). The data acquisition parameters were: slice thickness = 1.25 mm, using a 215–260 mA, 120 kVp tube. 120 ml of a non-ionised iodine contrast medium (Hexabrix, Guerbet LLC, Bloomington, Ind) were injected via an antecubital vein with a 3.5 ml/s flow rate (iodine concentration of 320 mg/ml). The grayscale windowing of the tissue was 400 Houndsfield units (HU) at the periphery and 40 HU at the center. The one month postoperative CTAs were carried out according to this protocol, in addition to a delayed acquisition in order to detect any possible low flow-rate endoleak and so 2 CTAs were available for each patient.

The CTAs were analyzed using the Endosize® software [11] (Therenva, Rennes, France). The image analysis process combines contour-based and region-based segmentation algorithms including morphological operations to automatically remove connections between the vasculature of interest (aortoiliac structure) and bone structures (such as spine). The vessel centerlines and contours, as well as the surface description of the vascular lumen were extracted from the CTAs. The aorto-spinal distance was also considered. It was obtained by computing beforehand a Maurer distance map [12] from the bone structures. The vascular structures were described using active contours, and were represented by curves (B-spline type) in planes orthogonal to the centerline of each vessel. For each patient, 1 spline per cm (with 8 points/spline) was extracted, from the abdominal aorta to the femoral arteries. The 3D coordinates of three points defining each of the planes (one point along the centerline and two additional coplanar points) as well as the in-plane coordinates of the vessel lumen contour points were exported to the simulation software. For each patient, a complete sizing was performed according to the standards of the international society for vascular surgery [13]. P2 corresponded to the measurement point on the centerline immediately below the renal arteries, P3 to the end of the aortic neck, P4 to the aortic bifurcation, P5 and P6 to the left and right iliac bifurcations respectively (Fig. 1). P1, P7 and P8 corresponded to the extremities of the region of interest and were not considered as measurement points. On the post-operative CTA at 1 month, only the lengths were analyzed. They were measured using the same reference points (P2, P3, P4, ...) as on the preoperative CTA. In addition to these quantitative variables, the arterial wall quality (healthy wall, calcifications) was determined according to the grading system based on the recommendations of the international society for vascular surgery [13]. The grade 0 corresponded to a healthy wall and the (maximum) grade 3 corresponded to circular calcifications of the whole artery.

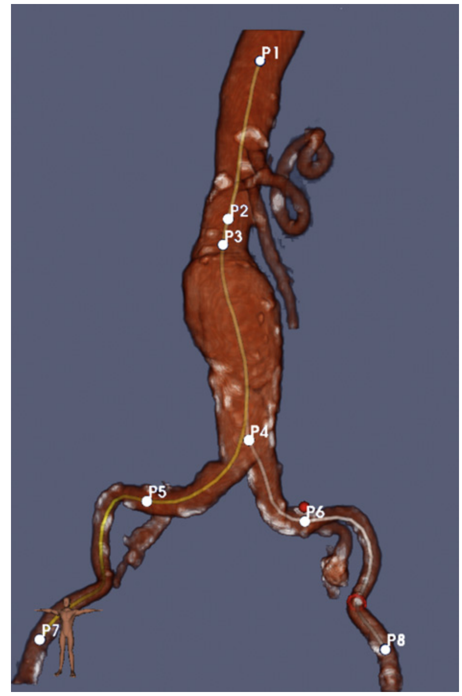

Fig. 1. Key points in the preoperative sizing.

2.2. Simulation

Reconstruction of the vascular geometry was achieved using the ANSYS DesignModeler software (ANSYS, Inc., Canonsburg, PA). The contours were imported from Endosize®, and by using a surface interpolation tool, the full aortic surface was recreated (Fig. 2). From this geometric model (Fig. 2), a triangular mesh was generated and contained (depending on the patient) between 5000 and 10,000 shell elements [14]. The thickness of the artery wall was 1.5 mm on the aorta and 1 mm on the iliac arteries. The vascular wall was considered to be homogeneous, isotropic and incompressible, with a Poisson's ratio of 0.45. A linear elastic model was used to describe the deformation properties of the arterial wall. The mechanical properties of the artery wall were determined from the calcification grade, determined from the sizing. Based on the literature [15–18] the values of Young's Modulus (defining the elasticity) were applied

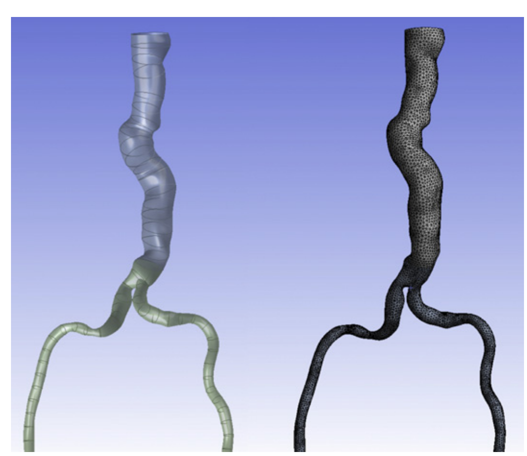

Fig. 2. Aortoiliac surface reconstructed (on the left) and aortoiliac mesh generated (on the right).