



Spatial Augmented Reality and Simulations to Improve Abdominal Aortic Aneurysm Diagnosis and Monitoring

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ABSTRACT

In this work we propose an approach based on IT tools to improve all the clinical activities related to Abdominal Aortic Aneurysm (AAA) detection and treatment. In particular, the approach is focused on a 3D CAD model of the AAA and CFD simulations to improve diagnosis by evaluation of rupture risk indicators and Spatial Augmented Reality (SAR) to simulate endovascular repair (EVAR) of the pathology. Geometric model of the vascular wall is build from Computer Tomography (CT) data by using and customizing algorithms and tools implemented in Vascular Modeling ToolKit (VMTK) software library. Four methodologies of geometry initialization are compared and we choose those able to describe the vascular disease excluding any foreign tissue (i.e., bones, internal organs, and muscles). An evaluation of the problems connected to the relative parameters of reconstruction, their influence for the correct geometry representation, focusing the attention on segmentation level and the smoothing of the surface, are presented. In particular, we point out the effect of the smoothing by the use of the Hausdorff distance. We propose a standardized process able to guide users in the modeling of this type of vessels; moreover, SAR can dramatically improve the efficacy of AAA visualization for some different clinical aspects. The 3D geometry of the AAA can be used to carry out CFD analysis, to calculate parameters of the blood flow and evaluate the rupture risk indicator, like Oscillatory Shear Index (OSI). The availability of risk indicators facilitates the physician in the diagnosis and prognosis. Finally, we present a methodology and tools to simulate EVAR on a specific patient based on geometry reconstruction and CFD simulations; this type of procedure can effectively improve training and facilitate endovascular surgery.

Keywords: spatial augmented reality, abdominal aortic aneurysm, CFD, computer-aided diagnosis.

1. INTRODUCTION

With the progress of technology and the increase of the computer power, there are increasingly more engineering virtualization practices such as virtual reality and augmented reality. The term “Virtual Reality” indicates a multi-sensorial simulation, which is totally immersive for the user. He is able to interact with it by the stimulation of different senses such as sight, hearing and touch [1]. However Augmented Reality differs from the previous technology as it is defined as a simulation that can add virtual information to the real environment, enhancing human perception through data generated and conveyed, in general, from electronic devices [11]. The most important point, which is necessary to generate the sense

of immersion of the user, is the interaction in real time.

In the medical field, these technologies are gaining importance. Here it is necessary to spend hours of trial and training which possibly do not endanger the patient; using virtual reality technologies, it is possible to get more knowledge on the procedure [4]. Information relating to medical imaging, such as computed tomography (CT) or Magnetic Resonance (NMR), allow the doctors to get a wide variety of data about the anatomy and physiology of the patients. It is possible, therefore, to use these data in Augmented Reality to gain additional information; other possible application of the Augmented Reality is the simulation of the real surgical experience.

Applications in surgical and minimally invasive field of virtual and augmented reality can be found in applications for:

- Pre-operative planning;
- Surgical training;
- Computer-Aided-Surgery (CAS);
- Diagnostics;
- Rehabilitation.

The simulators allow professionals to carry out a first training; it is repeatable and scalable according to the level of difficulty, allowing them to practice for the intervention of rare and serious diseases, and repeat the procedure several times without danger to anyone. These technologies are employed for student training or pre-operative planning. It will be possible to increase these potentials with augmented reality, projecting the anatomical structures on the actual patient, overlapping simulations and information previously generated and leading the operator during critical phases. These practices have already several uses, among which it can be found, regarding virtual reality, the Simbionix LAP Mentor [4], a simulator used for training and the simulation of operations laparoscopically performed, and the Vest System One, a simulator for endoscopic operations [4].

Other fields are, for example, those in which the augmented reality technologies were established, such as the project “Navigated Visualization Augmented Reality System (NARVIS)” in which images from CT are superimposed to the patient to guide the surgeon during the intervention [3]. This work is related to a technique that is becoming increasingly more popular for the treatment of abdominal aorta aneurysms, i.e., the Endovascular Aneurysm Repair (EVAR). This type of treatment is minimally invasive and concerns the endovascular surgery. In particular, it is stenting technique of the pathological area that is reached with minimally invasive instruments from an access to the vascular system. It raises the need to have a simulation tool capable to replicate the operation, in order to identify any issues or test alternative accesses to the vascular system, which may be more suitable.

EVEM (European Vascular and Endovascular Monitor) data, presented in November 2006 [5] at the Carpe Diem Vascular Meeting in Barcelona by Stephen Greenhalgh show a significant increase in EVAR procedures in recent years and in a growing trend of the same in Europe. This trend still not entirely convinces the scientific community because, although short term (30-day) mortality drops by two thirds, the long-term (1–4 years) remains unchanged, which is why the procedure has to be investigated and validated by scientific facts that allow it to become the standard in the repair of AAA.

One of the advantages of the procedure is certainly the possibility to intervene in an operating room or in

a catheterization laboratory and to perform it under local anesthesia. With the use of special tools for the endovascular surgery, and with the aid of X-ray images, a catheter containing a stent-graft is inserted through the femoral artery to the aneurysm site. A stent-graft is a component with a cylindrical structure consisting of a thin metal (stent), while the coupling part is made of various materials such as Dacron or polytetrafluoroethylene (PTFE) and may cover the stent.

The stent-graft is released by controlling the position at the site of the aneurysm and (in most cases) will be in contact with the aneurysmal wall by expanding itself. The aneurysm then collapses on the wall of the endoprosthesis.

In the literature, analyses have been already carried out relating the levels of risk which set the need to operate [1] and more complex models which simulate the behavior of the instrument are being introduced [14]. These, however, are far from allowing the usability of such information in a short time, even less if there is the need to do simulations for the pre-operative training. Therefore, there is the need to create simulators that can give a more accurate representation and allow real-time interaction at the same time. There are still few attempts to replicate this technique in virtual environment, particularly in the context of abdominal aortic aneurysms (AAA). Among them, it is worth mentioning the works of F. Wang and L. Duratti [17], which present a model for the representation and interaction in real-time of a physics-based wire, and a collision detection algorithm pretty quick that allows the high-frequency update of the behavior of the wire. Another work in this area is the study by Tang [16], in which it is presented a model for the interactive guide wire in which the wire is represented by flexible rods whose deformation is almost static.

It should be finally mentioned the work done by Ke Takashima M. Ohta [15], in which a system was developed to simulate a catheter and a guide thread for surgical planning in which the guide thread is made of soft and rigid elements. The model of the blood vessel, in this case, is an elastic cylinder, whose shape is defined by the central line and the respective beams, while the contact forces are determined according to the stiffness of the vessel wall.

The purpose of this work is to develop a simulation methodology in the field of virtual and augmented reality likely to be the repair method of abdominal aortic aneurysms. Moreover, this approach will allow the transition from an “in vivo” and “in vitro” test, currently used, to an “in silico” testing, certainly less economically onerous and less risky to patients. The interest is to generate an interface simulation that recreates the operating phase. The work will also deal with the construction of user interface system, suitable to simulate the use of surgical instruments. The perspective is to create, in the future, an

ad-hoc haptic system that gives the operator stimuli and feelings, as if he/she were in the operating phase.

The following work will examine medical tests, such as computed tomography (CT), generated by traditional diagnostic methods on patients which actually live or lived, thanks to the collaboration with the hospital “*Nuovo Ospedale di San Giovanni di Dio (TORREGALLI)*”, Firenze, Italy. It will also analyze the images and reconstruct geometries both useful for computational analysis and simulations suitable to be performed in real-time.

2. GEOMETRY EXTRACTION

As far as medical images concerns, it is difficult to reconstruct the geometry on the base of the gray levels of the same. Thus, segmentation models based on image features and partially dependent on the levels of gray are introduced: the deformable models.

2.1. Numerical Method

A useful multi-dimensional deformable model to segment the images is the Snakes model. Kass introduced the most interesting deformable model in 1988 [8]. A snake is a parametric curve that evolves based on the characteristics of the image and the inner contours. The same concept applied to the snakes, can be applied to their corresponding 3D known as balloons. Alternatives to parametric models are deformable implicit models such as those obtained with the Level Sets method. For the geometry extraction, the open source tool VMTK (Vascular Modeling ToolKit), based on Level Set method, was used. In 1988, Osher and Sethian [13] introduced the Level Set method for the study of moving fronts in physical problems such as the flame propagation. The basic concept of the level set function is to represent a contour as the intersection of a surface with the plane passing through its zero level: if the surface varies, the contour cut from the plane varies too; so it is possible to describe the movement of the contour evaluating the evolution of the surface.

It is defined a function dependent on space and time:

$$S(t) = \{x|F(x, t) = k\} \quad (2.1)$$

Since S is the k level set of F in time, the total derivative of F with respect to time of S must vanish. It is possible to rewrite the previous equation as the sum of several terms: the smoothing term, expansion term and convection term. The equation of evolution of the Level Sets for the function $F(x, t)$ becomes:

$$\frac{\partial F(x, t)}{\partial t} = -\alpha G(x)|\nabla F| + \beta(F_{uu} + F_{vv}) + \gamma \nabla P(x)\nabla F \quad (2.2)$$

where $G(x)$ is the speed of expansion, $P(x)$ the potential for attraction; α , β and γ respectively control the expansion, the curvature and the attraction of the model of the level set and the time step for which the function is decided to evolve. The Level Sets method can be successfully applied to three-dimensional modeling of blood vessels. To obtain a usable area in the virtual environment it is necessary to analyze triangulation algorithms: Marching Cubes (MC) [9] and its extension, the Marching tetrahedra (MT). The marching cubes algorithm, proposed by Lorensen and Cline (1987), aims at building 3D triangular mesh surfaces, and applied to a set of binary images, produces the triangulation of the surface of the object.

2.2. Initialization, Segmentation and Smoothing

For the reconstruction of blood vessels, libraries implemented in VMTK provide tools for medical image processing and elaboration of surfaces through the segmentation method based on the Level Sets (LS). To take advantage of the LS algorithm and extract the geometry by means of triangulation of the profiles at zero level, it is necessary to initialize the function $S(t)$ correctly. The initial value $F(x, t_0)$ defines the position of $S(t_0)$ and may be imposed by different techniques: Colliding Front (CF), Fast Marching (FM), Threshold (TH), and Isosurface (IS).

Figure 1 shows the effects of different imagine initialization techniques. The CF technique is particularly effective to exclude secondary branches from

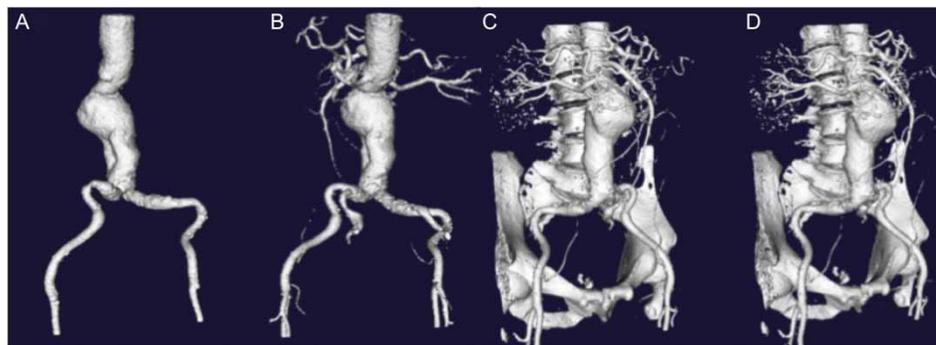


Fig. 1: Initialization of the geometry with different methods: CF (A), FM (B), TH (C) and IS (D).

reconstruction; it is not enough to generate a one-time initialization of branches whose morphology appears to be particularly convoluted and their diameter is very variable. The FM method allows the solution of this problem. However, the methods TH and IS are unsuitable for the purposes of this work, since they do not permit to eliminate the bony structures that have intensity levels close to those of the vascular tissue or to exclude secondary vessels, compromising the reconstruction.

In addition to the initialization technique, it is necessary to establish the threshold levels to limit the propagation of the wave within a well-defined intensity field. As can be seen from Fig. 2, aneurysmal geometry is initialized properly with a lower threshold that varies between 200 HU and 300 HU for a phase-contrast liquid CT scan. As far as the upper threshold concerns, this is free from the problems found in the lower one as long as the chosen value remains above 700 HU.

The triangulation by using the Marching Cubes algorithm, resulting in the segmentation of images, generates irregular geometries. The purpose of the smoothing phase is, therefore, to filter the noise from a mesh, just as it happens in the smoothing filters for the image processing. The choice of the smoothing level is fundamental to perform computational analysis on the structure, such as, for example, Computational Fluid Dynamics (CFD) analysis. Generally speaking, the most important and widespread smoothing methods, applied to polygon meshes, are Laplace [10] and Taubin [7,15] filters.

In this work, it was used a filter of the second type as less prone to shrinkage problems. The input parameters for the use of a Taubin filter are the number of iterations and the amplitude of

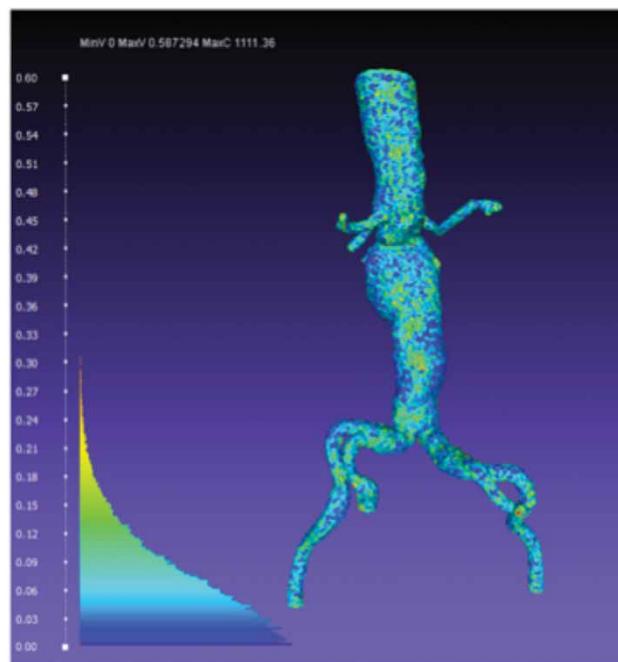


Fig. 4: Marching Cube mesh distance comparison between initialization with 150 iteration and bandwidth equal to 0.1.

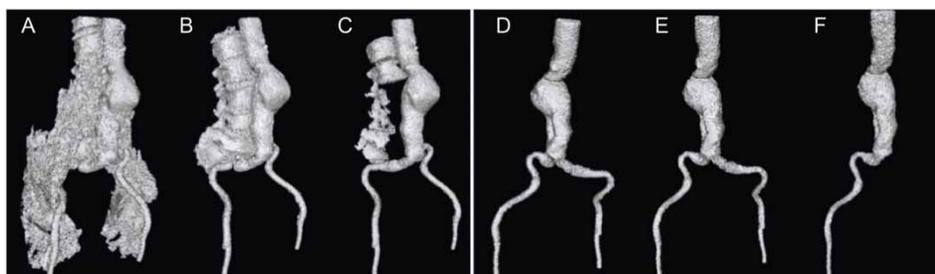


Fig. 2: Lower thresholds variations for the initialization: 50 (A), 100 (B), 150 (C), 250 (D), 300 (E), 350 (F).

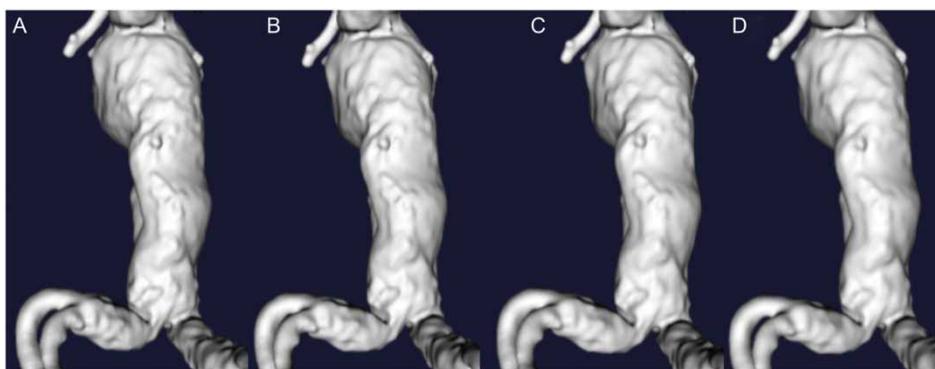


Fig. 3: Effect of the bandwidth with a fixed number of iteration (120): 0.1 (A), 0.08 (B), 0.06 (C), 0.04 (D).

the passing band. As an example, reconstructions obtained according to the changes of the bandwidth to a fixed number of iterations are shown in Fig. 3. For CFD analysis, for example, a number of iterations equal to 80 with a bandwidth equal to 0.1 may be a satisfactory, as a high level of detail of the morphology reconstructed is required [1]. A reliable evaluation of the error introduced in the smoothing process can be expressed by using the concept of distance of Hausdorff. The following algorithm, applied to two meshes, leads to an evaluation of the distance between the vertices of the mesh (Fig. 4).

3. VIRTUALIZATION

The term Virtual Reality indicates a simulated world. Its purpose is to recreate, through the aid of a computer, interaction and visual systems, worlds and objects that are the digital transposition of real environments or fantasy. In addition, this branch of engineering studies the methods of interaction between the real user and the virtual world, tools for three-dimensional viewing, tools for the manipulation of virtual objects, etc. It is a simulation that is completely perceived by senses, especially from the view, followed by hearing and touch.

3.1. Operating Tools

An EVAR operation for AAA can be summarized in four main phases, assuming that the patient is already catheterized with Seldinger technique and then there is access to the vascular system:

- Insertion of a guide wire required to reach the pathology;
- Insertion of a catheter, which carries the prosthesis to repair the damage;
- Release of the prosthesis in place;
- Extraction of the tools.

The tools useful in an EVAR operation of an AAA are mainly: a guide wire, a system to introduce the prosthesis (catheter and extractor) and an endoprosthesis (stent-graft). These components must be simulated in the virtual environment.

For the construction of the Augmented Reality environment and for the interactive prototype, these components are necessary:

- Software for the interaction;
- Hardware for interaction;
- Communication protocol between hardware devices and software;
- Manikin to simulate the real patient;
- CT Scans DICOM pack.

3.2. Interactive Prototype: Software

The most immersive viewing mode for the user concerns an approach relating the augmented reality, which is defined Spatial Augmented Reality (SAR) [3]. Regarding the SAR system, it has been prepared a manikin and along its hypothetical femoral area it is made to slide the wire of the interaction device. On him there is a sheet, representing the cloth used by physicians during the operations of surgical repair. Above it there is a projector, which reproduces the scene with which the user is able to interact through the use of the prototype.

A 3DVIA Virtools was chosen as a software environment, a blocks programming environment developed by Dassault Systemes SA that allows the creation of virtual or augmented reality applications. The communication protocol is enabled by the complete compatibility with a set of libraries, the VRPN (Virtual Reality Peripheral Network), which allows the exchange of data with devices through a Client/Server protocol. These libraries are open-source and freely extensible by programming in C++. As far as the input system concerns, an easily programmable system, able to ensure the possibility of future extensions regarding systems and mechanisms for input/output that can communicate with the protocol VRPN, was identified in Arduino microcontroller.

For the development of the application, and in particular for the characterization of the wire, it was employed the Physics Library that allows the interaction with objects in the scene whose behavior is related to the physical laws. In particular, this library allows experts to: specify the global physics of the scene (eg gravity), use the physics engine to calculate the movement, adding physical properties such as springs, motors, friction to the elements of the composition, control in a dynamic way the physical characteristics during the execution of the simulation, managing the interaction between the various elements of the SAR environment.

3.3. Interactive Prototype: Hardware

The endoprosthesis *E-Life [E-VITA] Abdominal XT of Jotec* company is the main hardware tool used for the setup of the Augmented Reality environment. This device is constituted of a guide wire, in the particular case of 0.87 mm. The platform Arduino Uno was used as the hardware environment of the user interface. The Arduino is a microcontroller that includes a hardware platform for physical computing. In addition, a potentiometer and a button allow the user-interaction software for the virtual implementation of the insertion of the guide wire.

3.4. Communication Protocol between Devices

For the communication between the software and hardware environment, the signal from the Arduino



Fig. 5: SAR system: setup of the environment and initial vision.

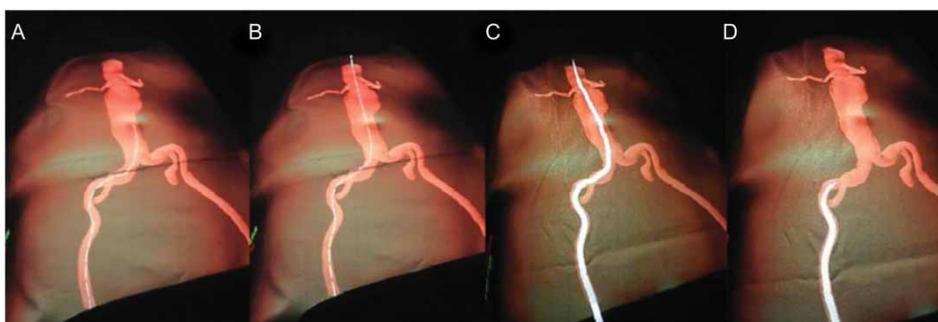


Fig. 6: Augmented reality process: A)-B) insertion of the guide wire, C)-D) insertion of the catheter.

environment is sent through VRPN (Virtual Reality Peripheral Network) libraries to Virtools [6]. These libraries are based on client / server architecture that can read the signal coming from a large number of input systems and allow the usability of these through the access to the server on which data are contained, by the Client, which in this case is the application developed in Virtools.

4. SIMULATION OF A REPAIR INTERVENTION ON AN AAA

The Augmented Reality environment is created by placing the manikin on a laboratory table that simulates the surgical table, Fig. 5 left. Over the manikin, a surgical sheet is placed, Fig. 5 mid. This sheet is necessary because a projector, placed above the manikin, projects on that the images from CT scan and from reconstructed CAD model. The reconstructed CAD model is strictly necessary because the interaction software needs to know the position of the vessel walls to take into account the walls-wire collisions. The interaction prototype is placed just behind the manikin, as visible on Fig. 5 left. Once the application is started and the procedure of reconstruction of the aortic tract is run according to the specifications previously seen, the scene shown in Fig. 5 right is presented.

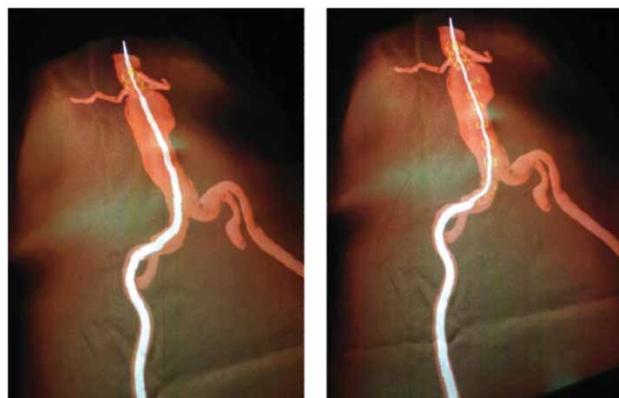


Fig. 7: Stent release.

4.1. Virtual Surgery Augmented Reality

It is now possible to interact with the prototype starting the insertion of the metal wire of the device, upon which the motion of the virtual guide wire depends, until the pathological area. The wire will follow a path dependent on the features of mass, stiffness and damping, and colliding with the wall of the aneurysm will dissipate energy in a manner dependent on the elasticity parameter which is set.

The following images show the various steps of virtual simulation of the repair. From the simulations carried out up using the SAR, it is possible to obtain

important information, having planned their automatic export from the program, such as the trajectory followed by the wire during the insertion (in particular the final part), and that of the wire and the catheter once the final position is chosen. The positions of the meshes of the stent on the catheter are also important, as these can be exploited as the starting point

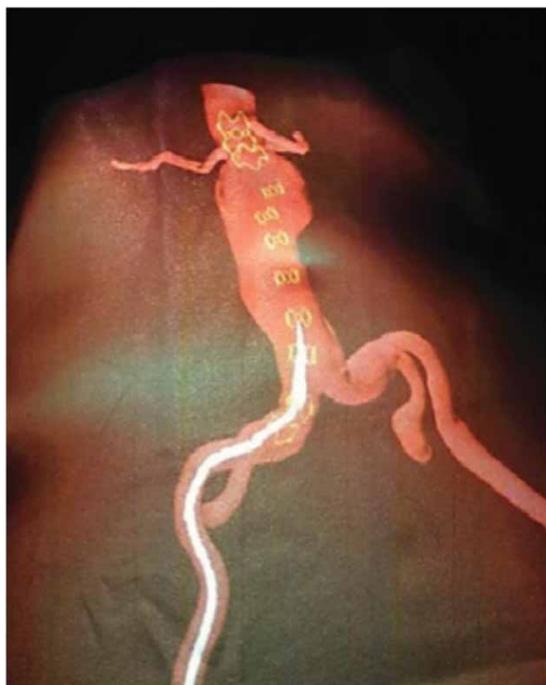


Fig. 8: Catheter extraction after stent expansion.

for CFD analysis relating the expansion of the stent within the vessel.

Figures 6-A and Figure 6-B represent two steps of the guide wire insertion. Figures 6-C and Figure 6-D represent two steps of the successive catheter insertion. Figs. 7-A and 7-B represent two steps of the stent release. In Fig. 8, it is visible the stent graft placed inside the AAA. Also it shows the last phase of the virtual surgery, the catheter extraction.

At this point, the interaction software has the information about the stent position. Using the embedded geometry extraction process, it can be possible to reconstruct the stent inside the previous AAA and to have a new CAD model.

4.2. CFD Simulation

Before and after the virtual surgery simulation, using a proper CFD-Embedded workflow, the mesh generation for the CFD simulations can be done in compliance to the geometric properties of the bifurcation. Meshes of 812.000 elements and 772.000 elements are then created for the before-stent situation and after-stent respectively. CFD simulations with unsteady formulation and custom boundary conditions (cardiac cycle) are implemented to analyze the fluid flow inside the vessel geometries. Cardiac cycle and blood properties are given by the clinical analysis, Nuovo Ospedale di San Giovanni di Dio (TORREGALLI), Firenze. Fig. 9 shows the OSI index for before and after stent virtual surgery, showing the better distribution of it after the stent placement.

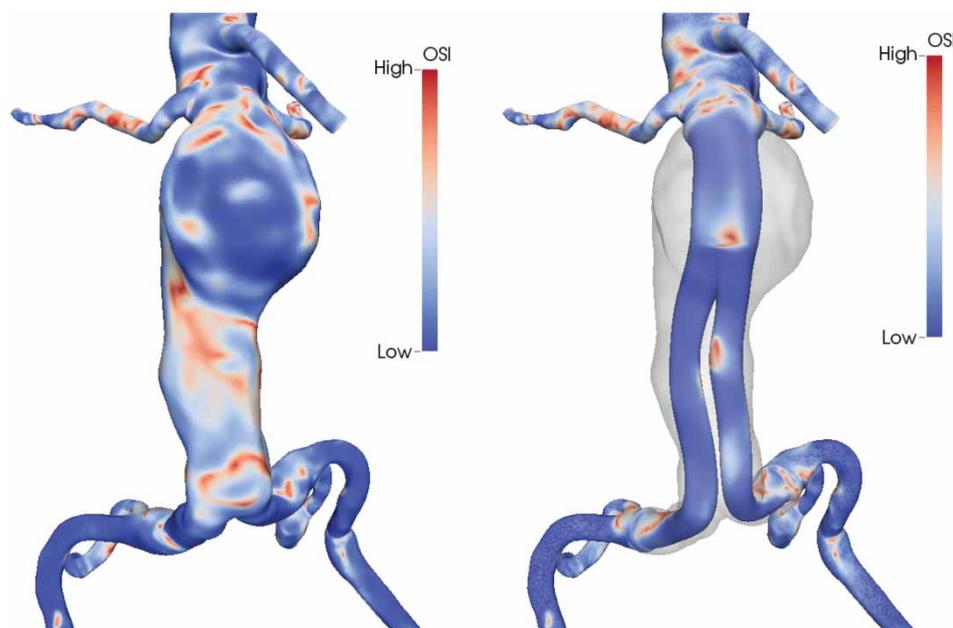


Fig. 9: CFD simulation of the AAA; OSI index distribution before (left) and after stent virtual surgery (right).

5. CONCLUSIONS

In this work we developed a SAR application able to generate an immersive environment for the users, without the need to wear any auxiliary system to analyze the information generated by the analysis taking the advantage of the system that generates information in 1:1 scale on a manikin of the patient. It was implemented the reconstruction technique, which results to be complete with all the features needed for the generation of aneurismal geometries usable both for computational analysis and virtual/augmented reality. It has been also paid attention on the reconstruction parameters, evaluating the goodness of different geometries.

The procedure analyzed is very efficient and automated in case small parts of vessels are reconstructed, but in the case of extended geometries and with variable sizes as well, the reconstruction is still strongly linked to the goodness of the images, the morphology of the vessels and skill of the operator. However, a guide on the process of reconstruction is provided.

The issue relating the implementation of the simulation control prototype has been investigated. The Arduino platform was proved particularly powerful for this type of applications. It was also implemented an augmented reality system for the simulation of a surgical repair of an AAA. From the geometrical reconstruction performed with the standardized process from the experimentation, it was possible to derive calculation grids for CFD simulations and therefore the calculation of the rupture risk based on hemodynamic indices which are the variation in the cardiac cycle of the WallShearStress.

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