In Your Blood

Patient-specific simulation helps improve endovascular aneurysm repair.

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An aneurysm is a bulge in the wall of a blood vessel caused by a weakened vessel wall. As the aneurysm grows, the risk of rupture increases, and surgical repair may be recommended. The standard surgical method for treating an abdominal aortic aneurysm involves opening the abdominal cavity and removing the aneurysm. In the minimally invasive approach, called endovascular aneurysm repair (EVAR), the surgeon inserts a catheter into an artery in the groin and threads it to the aneurysm. Then using an X-ray imaging device to see the artery, the medical team inserts a guidewire into the artery and uses it to maneuver a stent graft to the aneurysm. The graft is then deployed inside the aorta and fastened in place to reinforce the weakened section, preventing the artery from rupturing. Compared to the traditional surgical method, EVAR results in a higher short-term success rate, less blood loss and faster recovery.

Planning for EVAR is based on pre-operative 3-D computerized tomography (CT) scans that are used to size and position the stent. With the newer capabilities of computer-assisted medical interventions, the 3-D scans could be overlaid on the 2-D images acquired during the operation to help guide the procedure. A key challenge is that introducing the stiff guidewire causes the artery to straighten and deform. Currently, surgeons estimate the amount of deformation when determining whether to recommend EVAR. However, since each patient is unique, the estimated amount of deformation might vary from actuality.

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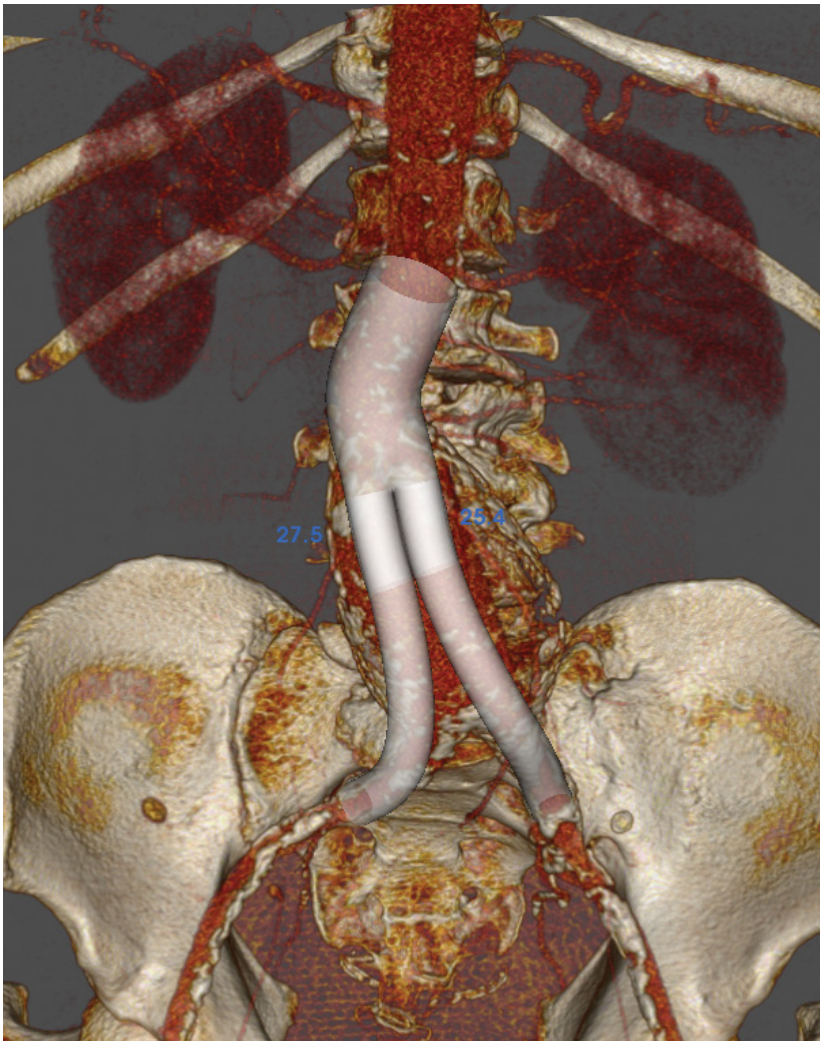


▲ Stent graft deployed inside artery during EVAR

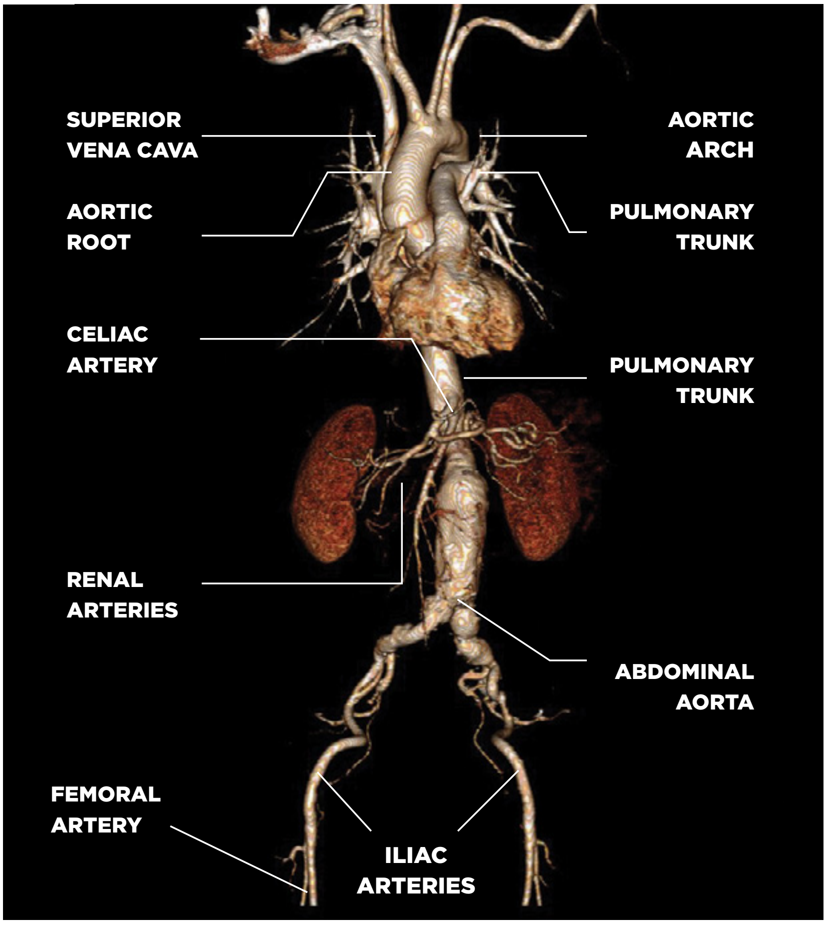
▲ Geometry extracted from CT scan with EndoSize™ software

This can make surgery more difficult, especially in challenging cases in which calcium accumulates in the artery wall. In other cases, if the patient's arteries are too calcified, it is simply not possible to navigate the EVAR tools in a too-rigid (calcified) cardiovascular system, and the surgeon may not discover this until the patient is in the operating room. "During an operation, time is critical; a surgeon needs to react quickly to any unexpected situation. If we have more information up front, we can better determine alternative strategies that are safer and more expedient for patient treatment. Simulation gives doctors the luxury of knowing what we will experience during surgery while the patient is still at home so that we are better prepared for surgical treatment," said Dr. Jean-Philippe Verhoye, full professor and cardiac, thoracic and vascular surgeon at the University of Rennes.

SIMULATING THE ARTERIAL SYSTEM

Researchers at the University of Rennes are addressing this challenge by using finite element analysis (FEA) to simulate the individual patient's arterial system under the influence of the guidewire. While finite element analysis has been greatly used with non-specific patient data to design endovascular devices and to study the behavior of aneurysms, this is believed to be the first time that FEA has been used on individual patients with the goal of improving surgical outcomes. The pre-operative CT data was analyzed using Therenva EndoSize™ software, which extracts vessel centerlines, contours and surfaces, and generates 3-D geometry. This geometry was imported into ANSYS DesignModeler software to re-create the complete aortic surface and produce a tetrahedral mesh with between 5,000 and 10,000 shell elements, depending on the individual patient.

A linear elastic model was used to describe the deformation properties of the arterial wall. Mechanical properties were based on the amount of calcification, which, in turn, was estimated based on analysis of the artery wall from the patient's pre-operative CT images. Young's modulus values defining elasticity were applied based on literature. Material properties of the guidewire were determined by physical testing. The upper extremity of the abdominal aorta is fixed by the aortic hiatus, while the femoral artery is fixed in the femoral triangle. Between the coeliac aorta and the femoral artery, there are no other strong anatomical structures to fix the arterial system. So the superior extremity of the abdominal aorta and the guidewire insertion site on the femoral artery were assumed to be fixed. Elastic supports were used to model the anatomical relation between the posterior side of the aorta and the anterior side of the spine.



▲ Structure of aorta

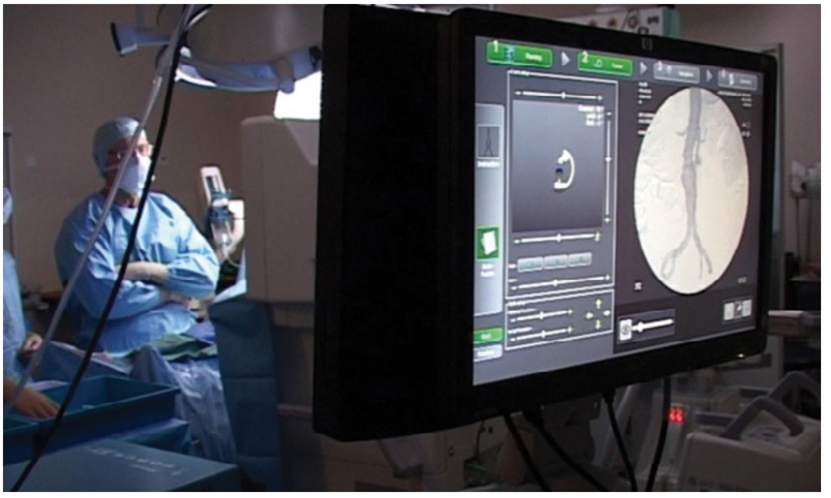
SIMULATION PROVIDES ACCURATE PREDICTIONS

Simulations were carried out using the ANSYS Mechanical FEA solver on a workstation with a six-core Xeon® processor. Researchers simulated placing the guidewire onto the centerline of the aorto-iliac arterial structure using pre-stress to initialize guidewire interactions. They then removed the pre-stress condition to initiate guidewire–artery contact. The end result was a deformed model that showed how the shape of the artery changed under the influence of the guidewire.

The team tuned model parameters by simulating 10 patients and projecting the

▲ Endovascular aneurysm repair surgery

The surgeon can more accurately determine the optimal size and position for the stent graft before surgery.



▲ Surgeon using simulation data for navigation during surgery

▲ FEA model created in ANSYS DesignModeler

▲ Deformed geometry after simulation of guidewire insertion

simulation results onto the intraoperative images that showed the actual deformation of the arteries. The model parameters were then adjusted independently for each patient to minimize errors. The mean simulation error was 0.8 mm with the model parameters tuned specifically for that patient. All simulation error measurements also include the error associated with registering the simulation onto the intraoperative image.

Based on these results, researchers established rules to set general simulation parameters based on patient data. The simulations were then rerun using the general rules to set model parameters. The mean simulation error was 2.3 +/− 0.6 mm, which is well within acceptable limits.

One patient's intraoperative data was used to match 3-D and 2-D data at two different incidence angles. The simulated guidewire was projected on two intraoperative images with different angles of incidence. The simulation error for this patient was 3.5 +/− 2.5 mm for the first image and 2.0 +/− 1.3 mm for the second image, which again was within acceptable limits.

Simulation was then applied to a test group of 12 patients. Mean simulation error including registration error was acceptable at 2.9 +/− 0.5 mm. Mean simulation calculation time was approximately 300 seconds. The time for the complete process was 10 minutes for data analysis and extraction, 10 minutes for preparation of simulation, five minutes for simulation, and two minutes for registration. Simulation results correlated well with fluoroscopy intraoperative images under several observation angles. Simulation was demonstrated to provide much more accurate predictions of the artery's deformed shape than could be achieved by the surgeons using their experience and intuition.

MORE ELABORATE SIMULATION FRAMEWORK

University of Rennes researchers and partners are currently working on the use of finite element analysis to study an elaborate simulation framework using a more accurate description of mechanical properties of arteries and endovascular devices. Assuming further developments, this method could be used pre-operatively to support decision-making in terms of navigability, access path, endovascular device choice, therapeutic strategy, aneurysm neck behavior, and evaluation of new devices. Additional evaluation and validation is required, especially in cases with complex anatomical configurations.

This new approach has the potential to provide several major improvements for EVAR. In the pre-operative phase, the surgeon might be able to more accurately determine whether EVAR is possible in difficult cases, such as when the patient's arteries are calcified; the team might more accurately identify the optimal size and position for the stent graft. During the operative phase, simulation can provide more-accurate 3-D images to guide the intervention. This method has been used as a secondary tool during a number of EVAR surgeries, but a clinical study will be required before it can be used as the primary method.

ADDITIONAL RESOURCES

NONLINEAR MODELING FOR HEALTHCARE APPLICATIONS
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