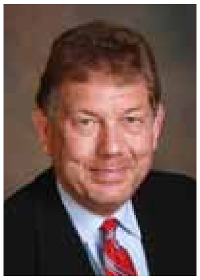
ADVANCED AORTIC IMAGING: FUTURE DIRECTIONS



A.B. Lumsden, M.D.

Alan B. Lumsden, M.D.; Christof Karmonik, Ph.D.; Christopher J. Smolock, M.D.; Jean Bismuth, M.D.

Methodist DeBakey Heart & Vascular Center, The Methodist Hospital, Houston, Texas

Abstract

There have been dramatic advances in aortic imaging over the last decade. Some of these capabilities have been driven by the development of aortic endografts, the need for accurate measurement of aortic dimensions, and capabilities for simulating endograft placement. The development of three-dimensional (3D) reconstruction has rapidly moved from being an additional luxury item to a commodity, either packaged into advanced imaging systems or freely available as downloadable, highly advanced software such as OsiriX for the Macintosh computer. Other advances such as dynamic magnetic resonance angiography (MRA) have resulted from continuous improvement in the hardware (acquisition of signal) and software (post-processing capabilities) of these imaging systems. We are particularly intrigued by the ability of these capabilities to improve the diagnosis and treatment of aortic disease. Furthermore, there is a rapidly emerging field of creating a 3D image in the interventional suite, which can potentially be used to steer catheter-based robots in a manner never before conceived. These various components will be described below.

The Basics

Interventional imaging has to include four features in order to be of great promise in the endovascular arena: 1) the equipment must have adequate definition and thereby be able to characterize tissues and define boundaries between anatomic structures; 2) the system must be interactive and intuitive; 3) three-dimensional capabilities are necessary when navigating vascular anatomy; and 4) the system must include a fourth dimension, the ability to evaluate motion. The vascular bed is a dynamic one, and therefore not including motion could allow for misinterpretation. Motion occurs with the cardiac cycle, respiration, and aortic pulsation. Deformation also occurs when stiff devices are advanced through blood vessels. Both motion and deformation can affect the accuracy of procedure performance. The ability to compensate for both motion and deformation are currently being developed.

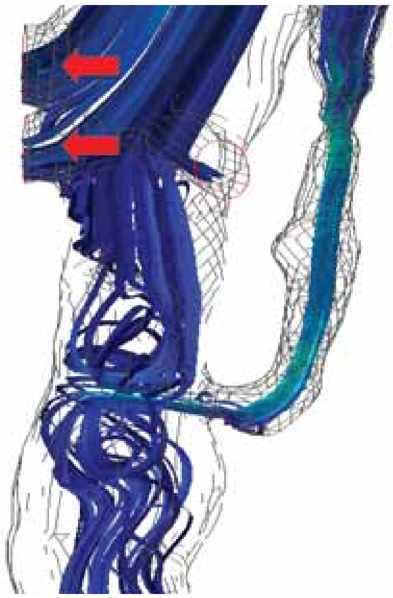


Figure 1. Computational fluid dynamic analysis of re-entry points of a type B dissection distal to the celiac and superior mesenteric arteries (arrows).

Dynamic Magnetic Resonance Angiography

Although the resolution of 3D computed tomography (CT) scans is optimal, magnetic resonance imaging (MRI) has the added advantage of providing additional physiologic data. We utilize dynamic 3D MR reconstruction in all patients with aortic dissections, often with computational fluid dynamics (CFD) overlay (Figure 1). Dynamic MRA has also been very useful in demonstrating mobile aortic thrombi when searching for an embolic source (Figure 2). While computational simulations in general, and of blood flow in human arteries in particular, have been the topic of research in the last decades,[1, 2] only recently with the introduction of advanced clinical imaging techniques and progressed computing power has it been possible to tailor these simulations towards the conditions found in a particular individual.[3-6] Initially, CFD simulations were restricted to 2D models and idealized geometries. Solutions even for these simplified geometries could only be obtained after many hours or even days. Continuous technical advances, however, have now made it possible to convert information from images acquired during a routine clinical exam into 3D complex mathematical

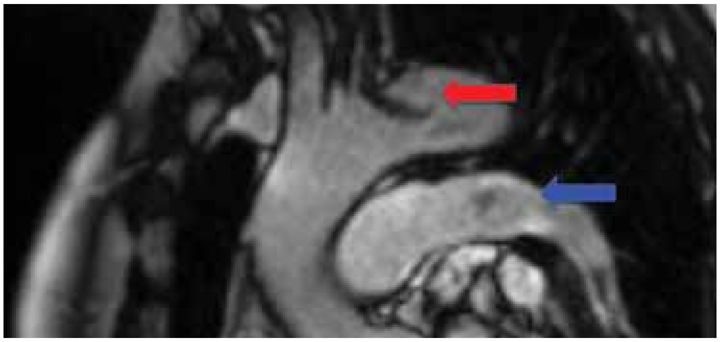


Figure 2. There is a large mobile embolus lodged in the orifice of the left subclavian artery (red arrow) and a second embolism in the left pulmonary artery (blue arrow). This patient had a patent foramen ovale and was suffering from paradoxical emboli. Both these lesions were highly mobile on the dynamic study.

Figure 3. Robotic hybrid room that permits angiography and the acquisition of a fluoro CT scan.

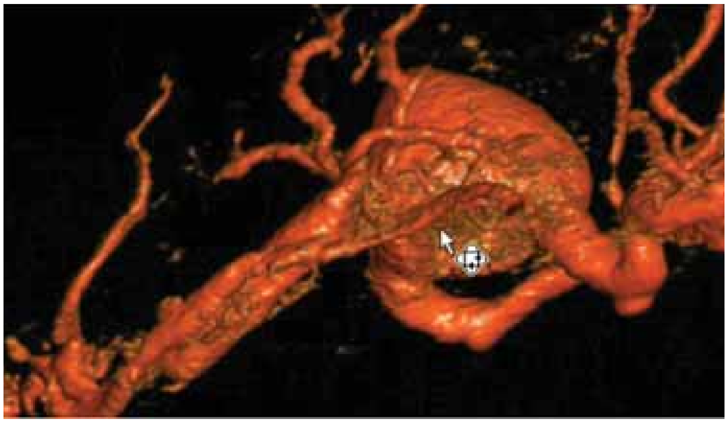


Figure 4. 3D reconstruction of a splenic artery aneurysm showing 2 large branches arising from the aneurysm. In the aortogram, it appeared that this was a simple saccular aneurysm that would have been amenable to stent grafting.

meshes consisting of hundreds of thousands of small-volume elements for transient simulation of the hemodynamics in human artery segments, either in health or in disease.[7] The results of these simulations provide access to hemodynamic parameters that are currently not reliably measurable with clinical imaging methods. Arguably, one of the most important of these parameters is the wall shear stress (WSS) that the flowing blood is exerting onto the arterial wall. Wall shear is an important determinant of dissection. Other parameters include dynamic pressures (dynP) and recirculation patterns; the latter may facilitate the adhesion of material onto the artery wall and promote the creation of atherosclerotic lesions, as in the bulb of the carotid bifurcation, for example.

Hemodynamics may play an important role in type B aortic dissections (TB-AD). A recent flow study of a chronic TB-AD demonstrated a direct dependence of systolic and diastolic pressures in the true and false lumen on TB-AD morphology, emphasizing the need for a better understanding of hemodynamic forces in TB-AD.[8, 9] Towards this goal, we employed CFD simulations to investigate the feasibility of quantifying changes in hemodynamic parameters before and after thoracic endovascular aortic repair (TEVAR) treatment of type B aortic dissections.[10, 11]

Fluoro Computed Tomography

The ability to rapidly spin a radiation source and detector around the patient permits acquisition of a wide-field computerized tomographic image. Imaging companies have developed new combined angiography/CT suites, which use flat-panel detector (FD) technology for improved resolution angiography that is also able to produce improved cone-beam volume CT images (Figure 3). The system permits 3D rotational digital subtraction angiography (DSA) or cone-beam volume CT interchangeably with the same FD C-arm (Figure 4) so that patients do not have to be transferred to a separate unit in order to obtain both imaging modalities. Real-time feedback of endovascular procedures is possible for both DSA and CT.

When comparing fluoro CT to a 16-slice multidetector CT scanner, Irie et al. found that fluoro CT was able to scan a wider area in a shorter period of time while delivering superior quality coronal and sagittal reconstruction images.[12] Fluoro CT allows a contrast resolution of 10 HU as well as a slice thickness and in-plane resolution of <1 mm.[13]

One of the concerns with this cone-beam technology is the amount of radiation exposure to the surgeon/interventionalist and patient. It was found that the total radiation dose is 236 mGy for FD-based fluoro CT, while the dose for 3D DSA using the same system is about 50 mGy.[12] Other authors revealed that the dose of radiation for a conventional head CT was similar to that of fluoro CT, namely 60 mGy.[14]

Figure 5. A 3D angiogram (white) has been fused on top of a previously acquired CT scan (brown), demonstrating how accurate image fusion can be.

Fluoro CT can be used to import and overlay previously acquired 64-slice images (Figure 5). This registration process allows interventionalists to intervene in real time using a previously acquired high-resolution image. For the first time, interventionalists will have the ability to rapidly acquire a CT image while performing a procedure and to evaluate the adequacy of an intervention. This CT capability is likely to dramatically affect how many procedures are performed, allowing point-of-service adjustment of an operative plan (Figures 6a, 6b, 7). One of the areas where fluoro CT has the potential to garner the most advantages is as a navigational tool. As devices become more refined and are able to challenge more complex anatomy, fluoro CT will be able to assist in obtaining the indispensable 3D imaging necessary to situate and guide the instrument to its target. This can be a particularly attractive feature when one starts discussing potential applications for flexible robotics.

Importing and Fusing Images: Registration of Axial Imaging with Angiography

The fusion of axial imaging and angiography in the interventional suite will soon enable endovascular navigation in

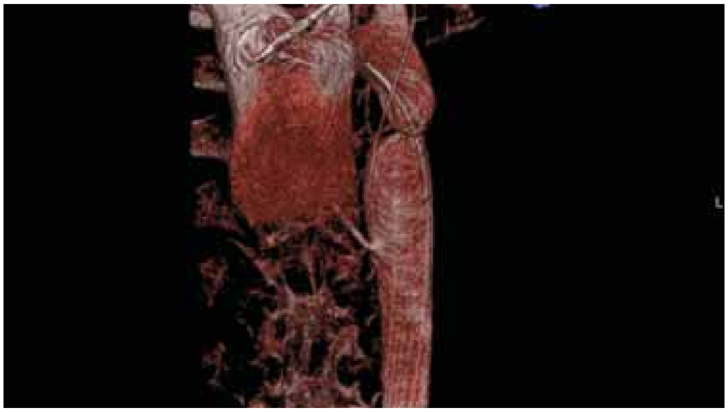


Figure 6A. Fluoro CT scan of an aortic coarctation with a stent graft being positioned within the stenosis.

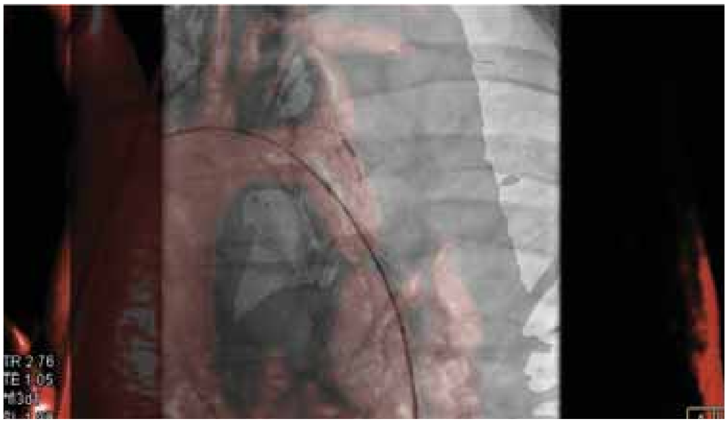


Figure 6B. The fluoro CT image of the aorta has been projected back onto the image intensifier and is being used as a 3D road map for accurate device deployment.

3D-like perspective. Co-registration of multimodality imaging in the angiographic suite overcomes some of the weakness of each separate modality and accentuates the strengths of both. Angiography provides 2D luminal contour detail but does not provide extraluminal tissue information. Combination technology that aligns 2D angiography with 3D images allows for better visualization of vessel tortuosity and the relationship of the lumen to surrounding structures. Since the vessels are 3D structures, visualizing them in 3D during procedures is more intuitive (Figures 6, 7).

Specialized software now allows for co-registration of the angiographic images with the reconstructed axial images. Initially, most applications for fused multimodality imaging were used for cardiac or intracranial interventions.[15-17] In the future, multimodality imaging and processing will likely evolve to become standard tools of vascular specialists. Multimodality image fusion can be achieved in different ways. One option for co-registration of fluoroscopy and axial imaging is real-time MRI or CT in the interventional suite. However, this currently requires specialized endovascular equipment and poses safety concerns for the treating clinicians.

Once the CT or MRI images are co-registered with the angiographic images, a real-time working overlay or roadmapping can be projected for the treating clinician. New software to perform the co-registration with CT and MR is now becoming commercially available, but the quality of the fusion images remains unclear.

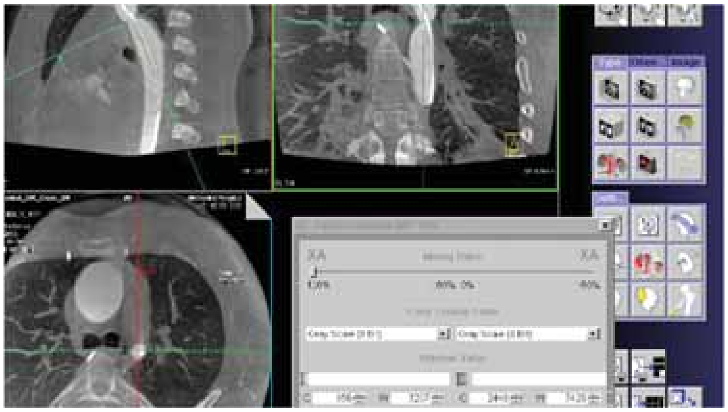


Figure 7. Workstation image of the 3D reconstructed aorta. Center line tracking through the coarctation permits very accurate measurement of the degree of stenosis. The images can be manipulated in multiple different planes and rendered in the format shown in Figure 6A. This patient also has a dilated ascending aorta.

One unsolved problem is the vessel deformity caused by stiff intraluminal wires, catheters, and devices. The deformity of the vessel causes a mismatch between the preoperative imaging and the live angiogram. However, as this exciting technique evolves, more precise and integrated images will become available.

Simulation and Patient-Specific Simulation in Aortic Disease

One real challenge in the evolution of a true simulation experience for aortic endografts has been the disconnect that has existed between simulation companies and the device manufacturers. The device companies have long been uncertain about the real value in simulation and consequently have been reluctant to invest in development of simulation modules. The simulation companies, with fewer cash reserves, have not had the resources or desire to go it alone in the development of these aortic environments. Both have long felt that hospitals should appreciate the potential role of simulation in credentialing and re-credentialing. But, to date, no matrices exist by which hospitals can utilize these expensive simulators to credential, refuse credentialing, or remove credentialing for physicians based on their performance in aortic simulation or in any other endovascular models.

Consequently, it is only recently that aortic endograft simulation models have evolved. Medtronic first developed a thoracic simulation environment in partnership with Medical Simulation Corporation for deployment of their Talent™ endograft. Interestingly, they also developed a dissection module that would have been of immense value but was unavailable for U.S. physicians since this was an off-label indication for their device.

W. L. Gore has partnered with Simbionix to develop an Excluder® (abdominal aortic aneurysm endograft) simulation platform. One potential advantage of the Simbionix platform is the ease of performing patient-specific simulation. CT scans in DICOM format can be loaded into the simulator to provide what is better termed "patient-like" simulation. Why the distinction? Basically, these simulation scenarios are created from a contrast-enhanced CT scan whereas interventionalists deploy devices using angiography. Not only do we deploy using real-time angiography, but the device itself deforms the anatomy and these device-tissue interactions are not yet modeled in simulation scenarios. Consequently, most simulation companies are not quite ready to claim the true fidelity of "patient-specific" scenarios. This claim may need an FDAapproved clinical trial to demonstrate true fidelity before that claim can be made. Nevertheless, we strongly believe that the capability of continuously modifying the scenarios is absolutely a prerequisite to provide value in simulation. Real value is in simulating tomorrow's case today, provided one is not seduced into performing the procedure because of ease of use in a simulation environment.

Putting It All Together: Illustrative Case

The patient was a 75-year-old male, 4 years post treatment of an abdominal aortic aneurysm with an aortic endograft. Follow-up CT scan showed the presence of an endoleak, thought to be type 2, confirmed by duplex scanning. During the next 2 years there was a progressive increase in aneurysm size. Retrograde embolization of feeding lumbar arteries was performed via the ascending lumbar. The aneurysm continued to increase to 7.3 cm. We decided to proceed with direct sac puncture.

The patient was placed prone on the hybrid table. Noncontrast fluoro CT scan was performed using a Siemens Artis zeego®. The previously performed contrast-enhanced CT scan was imported into the workstation and, using image fusion software, fused with the noncontrast fluoro CT. The procedure was planned on a workstation — where we selected the target endoleak blush on the CT scan, the appropriate skin access location, and placed target markers on both electronically. Length to target was 14 cm. A virtual needle guide was then created and transmitted to the live fluoro image. A 15-cm Chiba needle was advanced along the virtual needle guide directly into the target immediately anterior to the left limb of the device, and a sacogram was performed. This demonstrated a large vessel draining from the sac and several small lumbar arteries. A 4-Fr sheath was advanced into the sac, and selective catheterization of feeding and draining vessels was achieved using standard techniques. Direct embolization was successfully performed. Duplex scanning 24 hours later showed that, for the first time in 4 years, there was no endoleak.

This patient scenario demonstrates the effective use of image fusion software to minimize contrast utilization, real-time case planning in a 3D hybrid environment, and the use of a virtual needle guide to facilitate safe and accurate access to the intra sac leak location.

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