INTRAOPERATIVE VASCULAR IMAGING AND ROBOTICS: HOW OPERATING ROOMS WILL LOOK IN THE NEAR FUTURE

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INTRODUCTION

Describing the appearance of the operating room of the future is challenging due to the rapid developments in both imaging and robotics. As described elsewhere in this journal, both rigid (Intuitive) and flexible (Hansen) robotics promise to fundamentally alter the way we deliver therapy within body cavities and blood vessels. In this manuscript, we describe yet another application of robotics in cardiovascular therapy, namely the development of robotics angiographic imaging systems.

The vascular bed is a dynamic one and thus, not including motion, could allow for misinterpretation. Therefore, imaging must include four aspects 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) it must include a *fourth dimension,* the ability to evaluate motion.

The ideal operating room would be able to incorporate all these features into a flat panel, high-definition system that can be controlled from a common user interface. Furthermore, since post-imaging analysis is commonplace, it is imperative that all imaging be saved in the same format. The most common and exploitable format is Digital Imaging and Communications in Medicine (DICOM).

The Siemens Zeego angiographic imaging system is a completely new concept in angiographic imaging (Figure 1), replacing traditional C-arms with robotic, highly articulated C-arrns modeled around car assembly line robots. There are numerous advantages for such a system: it optimizes space efficiency in equipment-laden hybrid rooms, it allows for rapid repositioning for total body imaging, and the speed of camera movement optimizes image quality. The capability of these C-arms to rapidly acquire a fluoro CT (or DynaCT) image will revolutionize catheter and device navigation (Figure 2).

FLUORO CT

What is fluoro CT? The abilicy to rapidly spin the radiation source and detector around the patient permits acquisition of a wide-field computerized tomographic image.

Several manufacturers have developed new combined angiography/CT suites, which use flat-panel detector (FD) technology for improved resolution angiography that can also produce improved cone-beam volume CT images. The system permits 3D rotational digital subtraction angiography (DSA) or cone-beam volume CT interchangeably with the same C-arm so that patients do not have to be transferred to a separate unit to obtain both imaging modalities. Real-time feedback of endovascular procedures is possible for both DSA and CT. One of the most striking features of this technology is its simplicity, which allows for efficient and fluid endovascular procedures.

When comparing DynaCT to a 16-slice mulcidecector CT scanner (SOMATOM Sensation 16; Siemens Medical Solution, Erlangen, Germany), Irie et al. found chat DynaCT was able to scan a wider area in a shorter period of time while delivering superior quality coronal and saginal reconstruction images.[1] DynaCT allows a contrast resolution of 10 HU as well as a slice thickness and in-plane resolution of <1 mm.[2] It is also ideal if the system is able to boast better coverage, which can be a clear advantage when treating an obese patient but can also serve to decrease exposure times.

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 DynaCT, while the dose for 3 0 DSA using the same system is about 50 mGy.[1] Ocher authors revealed that the dose of radiation for a conventional head CT was similar to chat of DynaCT, namely 60 mGy.3 Another significant limitation of DynaCT relative to conventional CT is that reconstructions can be quite time-consuming, taking up towards five to 10 minutes.

One area in which DynaCT has the potential to be most useful is as a navigational tool. As devices become more refined and are able to challenge more complex anatomy, DynaCT 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.

Although not of the qualicy of images acquired using traditional 64-slice

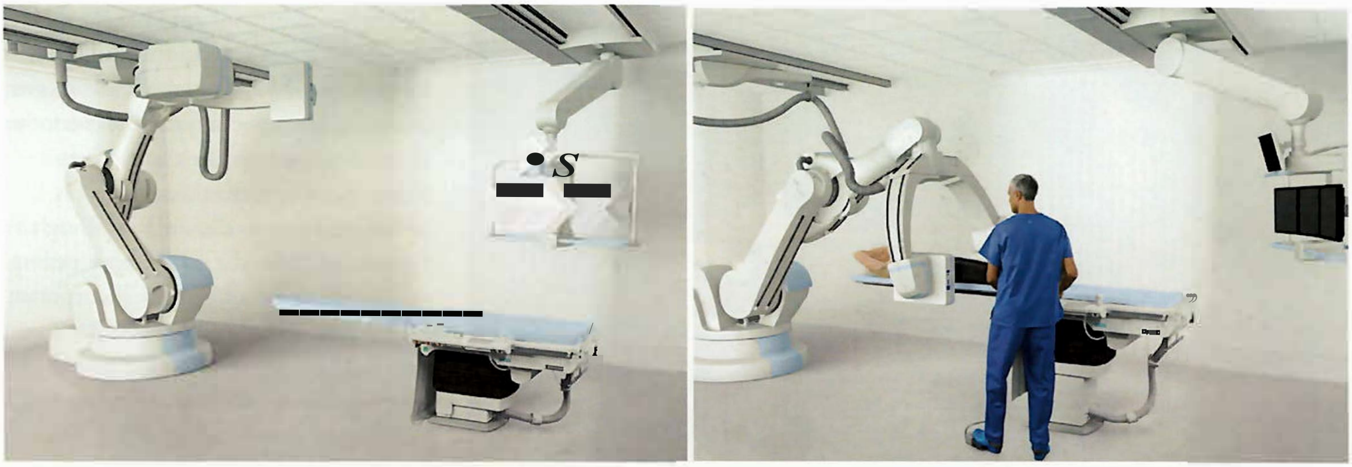

Figure 1. The Zeego Robot (Siemens) has remarkable manouverability, optimizing available space for both open surgical procedures and imaging.

CT scanners, the fluoro CT can be used to import and overlay previously acquired 64-slice images. This registration process allows imervemionalists to intervene real time using a previously acquired high-resolution image. For the first time, surgeons will have the ability to rapidly acquire a CT image during a procedure and 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.

Combining chis imaging technology with catheter robotics (Figure 3) will potentially revolutionize our ability to navigate catheters in three dimensions, remotely or semi-automatically, over predetermined "glide paths." The ability co perform real-time fluoro CT also fundamentally airers our ability to localize and biopsy lung or other intrathoracic lesions: CT-guided biopsy can immediately progress to thoracoscopic biopsy co immediate lesion resection. Many ocher combined or hybrid procedures will develop using open and endoluminal approaches (Table 1).

FLEXIBLE ROBOTICS

Hansen Medical is the global leader in flexible robotics and the developer of robotic technology for accurate three-dimensional control of catheter movement. This technology is currently being used for cardiac ablation therapy in the treatment of aberrant cardiac rhythms, the only application for which it is FDA approved. More recently, surgeons have used the Hansen robot to assist in the placement of endovascular grafts for exclusion of an abdominal aortic aneurysm. Although these endografts are placed roucinely without such advanced technology, surgeons are often presented with complex anatomy. This recent success speaks not only for its feasibility but also its safety.

The advantage of a catheter that can be guided with a high degree of safety and precision opens the door for a multitude of applications in vascular surgery. Currently, diagnostic and intervemional catheters are limited by their ability co simply rotate around one axis. Surgeons are often required to use a mulcirude of catheters co get to the site of the intended intervention, and they muse depend on a variety of preformed catheters co fit the existing anatomy. As vascular anatomy is not uniform, catheters are often less than adequate and therefore present a veritable challenge. This can potentially place a patient at risk, particularly in the arterial tree with degenerative atherosclerotic disease. A catheter that allows controlled movement in multiple planes would enable the surgeon to proceed through the arterial anatomy with greater precision, confidence, and safety.[4] As endograft and stent technology improves, so must our ability co deploy these devices. It is our opinion that flexible robotics will allow us to do just that. Robot-assisted surgery enables the surgeon to make fine, precise, and consistent movements. This ultimately increases procedural speed and reliability.

Table 1. Procedures to be performed in Zeego Hybrid Room

- Off-pump **LIMA** to LAD bypass with coronary angioplasty and stenting
- Thoracoscopic mini-Maze procedure with immediate EP monitoring and/or adjunctive ablations
- Hybrid aortic debranching and endograft placement
- Abdominal aortic endografts

SURGICAL ROBOTICS

In 1995, Intuitive Surgical, Inc. created the computer enhanced robotic system known coday as the *da Vinci*® Surgical System. The goal of this device was co

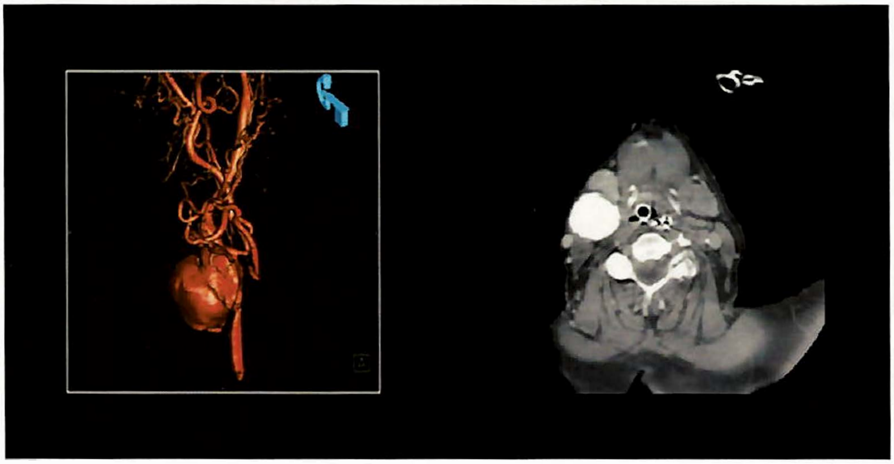

Figure 2. This is a CT scan acquired using the Zeego system. It demonstrates the placement of an aortic endograft within an aortic aneurysm.

Figure 3. Hansen Medical's catheter robotics, Sensei™ Robotic Catheter System.

create familiar hand movements from open surgery while performing operations via a minimally invasive approach. This could effectively remove the diffteculcies chat many surgeons experience using the laparoscopic technique. The advent of robotics in vascular surgery could suddenly make a technically challenging procedure practicable. This rationale is further supported by the development of Intuitive Surgical's *EndoWrist*, a form of telemanipulacion that facilitates eye-hand coordination similar to the human brain and provides dual-channel (three-dimensional) vision necessary for the more dexterous maneuvers required to create vascular anascomoses.[5] In 1999, Mohr and colleagues were already successful in performing five coronary artery bypasses and four mitral valve repairs using the ***da Vinci*** Surgical System.[6]

Animal studies confirmed the benefits of robotics, more specifically the da ***Vinci*** Surgical System, which was shown to reduce the time required to perform an anastomosis, reduce clamp time, and reduce total operative rimes.[8-9]

Refinements to the ***da Vinci*** Surgical System include the ability to ceiling mount the unit and again incorporate endoscopic imaging with high-definition flat panel screens, which are already an integral part of rhe imaging system.

SURGICAL ROBOTICS PROGRAMS AT MOHVC

The Methodist Hospital is one of 29 is one of 29 training centers in che United States for the ***da Vinci*** Surgical System; it currently has five systems in place, more than any hospital in the state. In August 2007, Gerald Lawrie, M.D., the DeBakey Chair in Cardiac Surgery, was the first to use a surgical robot co successfully repair a micral valve using an advanced technique called the "American Correction" that he developed 15 years ago.[7] Mahesh Ramchandani, M.D., has used the Intuitive Robot for thymectomy as well as cake down of the left internal mammary artery as part of the center's off-pump CABG program.

Jean Bismuth, M.D., a vascular surgeon at MDHVC, has initiated an aortic robotics program in partnership with Intuitive Surgical, with support from the faculty of the Methodist Institute for Technology, Innovation and Education. This program is designed to evaluate feasibility, develop training programs, develop models, and launch a clinical aortic robotics program within 18 months. Dr. Bismuth is also exploring the applications of flexible robotics within the peripheral vascular system. Through a generous award from the Dyer Research Foundation, Dr. Bismuth has traveled to world-renowned robotics centers at Imperial College London and at Prague in the Czech Republic.

Eric Beyer, M.D., an internationally renowned cardiac surgeon at MDHVC, has been a leader in che development of minimally invasive atrial fibrillation surgery. Dr. Beyer is exploring the use of robotics to develop alternate approaches to performing arrhythmia surgery as well as further reducing the magnitude of the minimally invasive procedures he currently performs.

THE OPTIMAL HYBRID OPERATING ROOM

Designing the optimal operating room requires having the vision to accommodate future innovations. This means having a system with the capacity to grow and physicians who keep abreast of developments in the imaging and robotics arena.

The primary goal of a solid operating room design is to maintain a simple, intuitive, and efficient dialogue between surgeons and machines. This means having great flexibility to eliminate the performance of procedures in less ideal positions. The primary imaging equipment in the hybrid operating room is the C-arm; ideally, when a case is being done by open surgical techniques, one should be able to position the unit so chat the surgeons can stand comfortable at any position. This can be further accommodated by the ability to control the operating room table in a multitude of directions. For the surgeon, maneuverability of the C-arm and table means decreasing the likelihood of injury to the back and neck and decreasing exposure to radiation.

Another concept that remains central to all aspects of medicine is teaching. This would need to be a major consideration in developing a future operating room. Adequate high-definition video equipmem must be installed to allow remote observation of cases, and it should include screen-in-screen function so that the observer can relate what is being observed to the imaging being recorded, be it angiography, DynaCT, or IVUS.

We at the Methodist DeBakey Heart & Vascular Center are in the process of installing the country's first robotics hybrid suite: operating rooms char feacure state-of-the-art imaging and operating environments and permit surgeons to combine the best of traditional operating skills with endoluminal and endoscopic approaches.

CONCLUSION

The concept that should remain fundamental today and in the future is that all technological advances in the fields of imaging and robotics should have a common goal - mainly, to improve safety and outcomes. This should happen irrespective of the procedure: whether placing an endografc for Type B aortic dissection, performing a complex venous procedure, challenging a complex aortic arch to stent a carotid, or performing a peripheral intervention.

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