A Vascular Catheterization Simulator for Training and Treatment Planning

James H. Anderson and Raghu Raghavan

We have developed a working prototype of an augmented reality based vascular catheterization simulator. The simulator is called daVinci, and provides the interventional radiologist with a "hands-on," user friendly, image based environment to augment training, enhance pretreatment planning and design interventional products and devices. daVinci is based on computational modeling of human anatomical images and provides the user with capabilities for realtime simulated navigation of catheters in both 2-D and 3-D modeled vessels. In addition, multiplaner CT, MRI and anatomical data sets are incorporated into the simulator to enhance the understanding of anatomical relationships associated with vascular catheterization procedures. The current prototype is designed for peripheral vascular applications. Additional systems are currently being considered for both interventional neuroradiology and cardiology.

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SIMULATOR TECHNOLOGY is beginning to be applied in medicine and first generation simulators have or are already being developed for many procedures or applications including bronchoscopy,¹ flexible ureteroscopy,² endoscopy,³ laparoscopic abdominal surgery,⁴ angioplasty.⁵ Recent advances in graphics computing power, haptics technology and the availability of accurate anatomical models have enabled the development of high fidelity, virtual reality-based simulators in procedural medicine.^{6,7} Virtual reality-based simulation technology provides an environment in which to test medical devices and new therapies, train and credential physicians, and plan interventional procedures using patient-specific data. Image guided procedures such as vascular catheterization, angioplasty, stent placement and endoscopy are especially suited for simulation because they already place the physician at-a-distance from the operative site manipulating surgical instruments and viewing the procedures on video monitors. Applications for

Interventional Radiology include the use of a catheterization simulator for (1) physician training and possible certification, (2) patient specific pretreatment planning, and (3) evaluation of new intravascular devices and procedures. Three separate interventional cardiovascular specialties, i.e., peripheral vascular radiology, neuroradiology, and cardiology could benefit from the development of a realistic vascular catheterization simulator. Computer driven simulator systems have had a significant impact in the industrial and military sector for training and for evaluating approaches to situation specific problem solving. Because Radiology is such an image oriented medical discipline, it is not surprising that the visual oriented world of virtual reality should have applications in training simulators and pretreatment planning.

SYSTEM DESCRIPTION

Our prototype system provides hands-on, real-time 2-D and simultaneous 3-D navigation of catheters through simulated blood vessels registered with anatomical and fluoroscopic image data sets.⁸⁻¹⁴ The simulator incorporates computational modeling of human vascular data sets as well as radiographs and gross anatomical images from the National Library of Medicine's Visible Human Project. Initial development components include realtime catheter navigation and tracking coupled with a hand activated electro-mechanical catheter device and 3-D geometric and topological representation of the catheter position with respect to surrounding radiographic and anatomical structures. A mathematical model of vascular anatomy and the physical properties of catheters/guidewires is the foundation for the computer simulation. An important function of the simulator is the opportunity to view the catheter and vessels in 3-D and to relate catheter tip position with multiplaner CT, MRI or gross anatomical color images of the body in the region of the catheter tip.

The simulator is designed to duplicate as closely as possible, the environment and functionality of the catheterization laboratory. A wide variety of catheter and guidewire shapes are available to the user thorough a pull down library menu. A unique feature of the system is the opportunity to custom

From the Department of Radiology, Johns Hopkins School of Medicine, Baltimore, MD; and the Center for Information Enhanced Medicine (CieMed), National University of Singapore, Singapore.

Address reprint requests to James H. Anderson, PhD, Radiology Research Laboratory, Johns Hopkins School of Medicine, 330 Traylor Bldg., 720 Rutland Ave., Baltimore, MD 21205.

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design and test catheters and guidewires. This feature provides the opportunity to test catheters of different designs for their operation in vessels of various selected geometric configurations. Eventually, this feature will be expanded to include the design of intravascular devices.

During the catheterization procedure, the user has control over various parameters of the fluoroscopic image presentation such as collimation, zoom features, image contrast control and patient table movement in the X, Y and rotational axis. The catheter can be navigated forward and backward and rotated. The movement of the catheter can be seen in real time on the fluoroscopic image with the vasculature being transparent or with the vessels outlined (Fig 1). The responses of the catheter and guide wire have been modeled to reflect the physical properties of the devices chosen and the volume rendered 3-D morphology of the vessels. Because the physical properties of the catheters are modeled, the shape of the catheter tip is influenced by the geometry of the vessels and passage of the guide wire. Simulated contrast medium injections and road mapping capabilities are also provided and can be viewed on the primary fluoroscopic

image or viewed next to the primary fluoroscopic image as a split screen presentation. In addition to providing stereo and 3-D views of the catheterization process, daVinci can relate catheter tip position with multiplanar images of the body in the region of the catheter tip. These images can be view in the axial, coronal, sagittal or all three views and can be represented as either CT, MRI or gross anatomical color images. The 3-D views and the multiplaner images are valuable in teaching complex techniques such as those used in Transjugular Intrahepatic Portocaval Shunts (TIPS) procedures.

The catheter navigation simulation employs a finite element representation of the catheter, with six-degree-of-freedom beam elements. This allows incorporation of changing material properties along the catheter length. The vessel wall is represented by a potential field in a region enclosing the wall which determines the interaction energy between the catheter and the vessel wall. The material properties of the catheter which are used in the simulation are the Young's modulus and the Poisson's ratio (or equivalently, the shear modulus) of the catheter. Geometrical information about the catheter's outer and inner diameters is also re-

Fig 1. Simulator view of catheter passed from the femoral artery entry site to the mid abdominal aorta.

quired. These physical and geometrical catheter characteristics enter into coefficients in the expression for the catheter's elastic energy. Friction between the catheter and the vessel wall is ignored in the current model; however it could easily be included by allowing for a coefficient of friction (which could depend on wall geometry and/or catheter head location, and may conceivably also depend on insertion rate) in the model.

For the finite element representation, an accurate depiction of the catheter head shape is also required. Currently, we use a fine piece-wise linear decomposition, though this can be easily changed to use higher order elements. The vessel wall is currently modeled as rigid; accordingly a steeply rising potential field is chosen which disallows large excursions of the catheter beyond the vessel wall. The vessel diameter provides a rough indication of the move step size used in the computation; in addition, the region of definition of the potential field is taken to be an annular region of outer diameter approximately equal to a few times the vessel diameter. This allows for larger move steps inside thicker vessels.

Interventional Radiology procedures are based on hand-eye coordination and the catheter interface device to the simulator must provide high performance capabilities. This device will be housed in a mannequin positioned on a table with the catheter/guide wire entering the groin which is the most preferred vascular access in humans. Monitors of the realtime fluoroscopic image, stored digital "road map images," as well as 3-D volume vascular images and images of anatomical displays will be suspended from the ceiling. The catheter and wire tracking system tracks the rotation and translation each of the catheter and the guidewire. Rotational resolutions scales accurately with the catheter and wire circumference to accurately maintain the rotational state for the varying diameter sizes. The mechanism to track the catheter is capable of update rates of several kilohertz, to accommodate

force-feedback designs with tightly coupled control systems to the force actuators.

DISCUSSION

We anticipate that the use of medical and surgical simulators will have an impact in reducing the cost of health care. Recent studies have equated the relationship between levels of training and complications in cardiovascular procedures and clearly demonstrate the potential value of vascular catheter simulators in training physicians.¹⁵ Our vision for the future acceptance of medical simulators in training, patient specific pretreatment planning and medical device design and evaluation is based on our belief that in the very near future, we will experience increased:

- Availability of low cost high speed/memory PC systems
- Availability of easy access non-invasive vascular imaging
- Mandated health care cost reduction strategies
- Application and acceptance of Virtual Reality based technology
- FDA acceptance of some form of simulator testing of products

Further image enhancements for the simulator could include the incorporation of ultrasound images and video presentations of the lining of the blood vessels obtained from fiber optic views through small endoscopes placed within blood vessels. In addition, the system should include simulated injections of radiopaque dye to fill the vessels and outline their shape and distribution. Modeling of vascular hemodynamics could be used to simulate normal as well as abnormal blood flow patterns seen in areas of vessel narrowing and malformations. In order to provide training capabilities in therapeutic procedures, it would be necessary to simulate the use of balloon angioplasty catheters and the deployment of intravascular devices such as blood vessel occluding devices, stents and filters.

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