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Equipment and Technology

Designing a Computer-Based Simulator for Interventional Cardiology Training

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Interventional cardiology training traditionally involves one-on-one experience following a master-apprentice model, much as other procedural disciplines. Development of a realistic computer-based training system that includes hand-eye coordination, catheter and guide wire choices, three-dimensional anatomic representations, and an integrated learning system is desirable, in order to permit learning to occur safely, without putting patients at risk. Here we present the first report of a PC-based simulator that incorporates synthetic fluoroscopy, real-time three-dimensional interactive anatomic display, and selective right- and left-sided coronary catheterization and angiography using actual catheters. Significant learning components also are integrated into the simulator. *Cathet. Cardiovasc. Intervent. 51:522–527, 2000.* © 2000 Wiley-Liss, Inc.

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INTRODUCTION

The growth of minimally invasive therapies has spawned parallel interest in the potential for computer-based simulation for training. Over the past 7 yr, several computer-based medical simulators have been designed to teach these new techniques. Most of these efforts have focused on laparoscopic surgery, in which rigid tools are inserted into the patient's abdomen and visual feedback is provided by an endoscopic camera that produces a high-definition color image. These simulators are predominantly skills trainers, emphasizing the two-dimensional hand-eye coordination practice that is useful for laparoscopic surgery [1–7].

Interventional cardiology shares characteristics with other minimally invasive therapies that make it suitable for simulator-based learning: it requires complex understanding of three-dimensional anatomy from two-dimensional displays and fine hand-eye coordination. As with surgery, complications from improperly performed cardiac catheterization can have catastrophic results. Jollis et al. [8] and Ellis et al. [9] showed that procedural success is related to the volume of procedures a cardiologist performs, yet over 86% of catheterization laboratories undertake fewer than 50 procedures per year [10]. Traditional angiographic teaching uses a master-apprentice model with intense one-on-one contact between the teacher and the student, an inherently inefficient method of teaching and one that can result in uneven exposure of trainees to difficult procedures and their complications. Current interventional cardiology training methods require practice on animals, on mechanical models that use real medical devices and X-ray equipment, or on patients. These approaches have disadvantages, including ethical problems of animal-based training, radiation exposure for the trainees, and the use of expensive devices in mechanical models. Most important, patients are put at risk during the least experienced time of a physician's career.

This article describes the development of an interventional cardiology training system conducted at Mitsubishi Electric Research Lab, in collaboration with CIMIT and the Massachusetts General Hospital. An overview of the technical simulator is presented as well as a brief description of the learning system built upon the simulation core.

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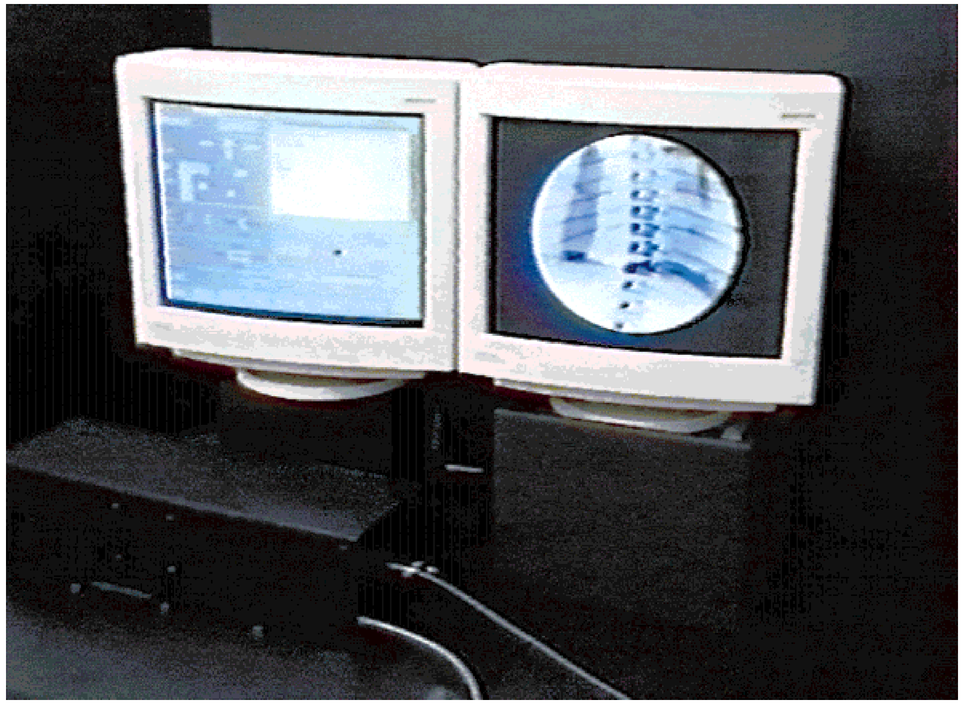

Fig. 1. The prototype design for the ICTS simulator. The left monitor displays physiological values, such as ECG and pressures, fluoroscopy controls, and learning system controls, including "Undo," "Record," and "Pause." The right monitor displays the actual procedure in real time, including catheter movement, cardiac motion, and contrast injection. The haptics interface device is in the foreground, with one channel for catheters and one for the contrast syringe.

INTERVENTIONAL CARDIOLOGY TRAINING SYSTEM

Interventional cardiology simulation presents unique challenges. First, visual feedback is not provided by visible light but by fluoroscopy, which must be simulated in real time while allowing for changes in points of view as the fluoroscope moves around the patient. Second, the catheters, guide wires, and stents are flexible devices and therefore must be modeled as deformable objects, which is not the case for rigid laparoscopic tools. Among the few articles published in this area, Blezek and associates [11] have described a nonendoscopic system for anesthesiology training, and van Walsum and colleagues [12] have presented a method to create X-ray images from computed tomography scans and simulated injection of contrast. Van Walsum's approach, however, is based on volume-rendering methods and is therefore limited in its ability to permit real-time changes in the vascular anatomy or point of view. Real-time interactivity is a critical issue when considering the design of a simulator for interventional cardiology, where it is desirable for the simulation experience to be intuitive and "transparent" to the student in terms of a useful clinical learning experience.

When a physician uses the interventional cardiology training system (ICTS), actual catheters and guide wires are manipulated as they enter the haptics interface device that tracks their motion through a series of electromechanical sensors. Insertion and withdrawal or torquing of the catheter produce corresponding motions of the simulated catheter on the computer screen. At present, right- and left-sided selective coronary angiography can be simulated, but future refinements will permit actual training for device insertion using the system.

The system (Fig. 1) provides visual feedback similar to what the cardiologist sees on the monitor. It simulates the physics and physiology of the human cardiovascular system and is interfaced with a haptic device that gives the user a natural way to interact with the simulation. A graphic user interface is coupled to an instructional system, providing a framework for learning from the simulation. (Fig. 2).

As part of the ongoing development of the system, the ICTS now runs on a four-processor PC instead of the four-processor Onyx 2 Silicon Graphics workstation on which it was developed.

Geometric Modeling

Geometric modeling provides information about the thoracic anatomy and the attenuation coefficients that are used to generate the fluoroscopic images (Fig. 3). Geometric and topological characteristics of the vascular system were created in collaboration with a cardiologist to ensure accuracy. The anatomic models used in the ICTS can be divided into three classes. These classes are (a) polygonal representations of the static anatomy based on segmented data from the Visible Human Project; (b) animated polygonal models (i.e., the heart and lungs) created in Maya, an animation and modeling package; and (c) animated NURBS surfaces (correlated to the

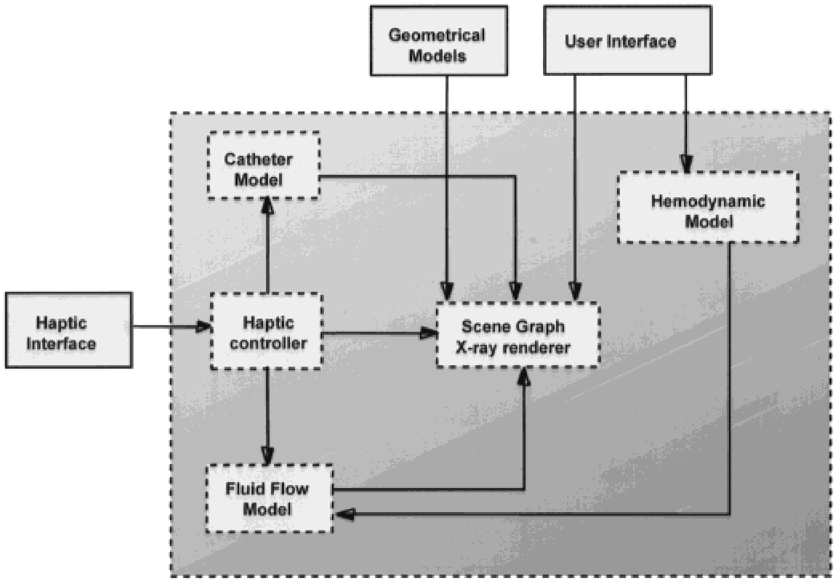

Fig. 2. Components of a real-time simulator. The user interacts with the haptics interface device containing catheters and guide wires linked to force-feedback mechanisms. A haptic controller integrates the catheter model, blood flow models, and synthetic fluoroscopy renderer. Hemodynamic models affect fluid flow and subsequent fluoroscopic appearance. Geometric models of anatomy and devices used during procedures provide tissue-tool interactions. The user interface relays information about the physiologic state of the patient (hemodynamic model) and the progress of the procedure through the fluoroscopic display.

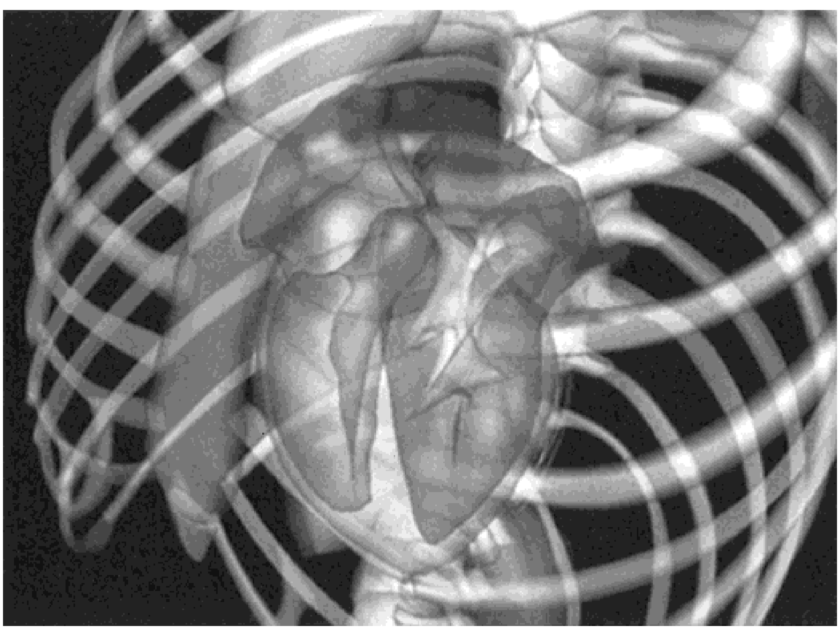

Fig. 3. Left anterior oblique cranial visible light rendering of cardiothoracic structures from the ICTS, with the lungs removed for clarity. This view emphasizes that the anatomic model contained within the simulation is based on three-dimensional data and therefore can be viewed from any angle, even unconventional viewpoints, during simulated procedures. Note the presence of individual cardiac chambers within the data set.

cardiac motion), which represent the coronary arteries. Once the models are complete, an X-ray attenuation value is associated with each anatomic model. To create the beating heart, the cardiovascular model is key-framed while a deformation is applied to the polygonal and non-uniform rational B-splines (NURBS) surfaces. The result is a cyclic regular heartbeat exhibiting the characteristics of a real heart—twist, elongation, and contraction. In addition, it is possible to control the heart rate and to vary the respiratory rate from the user interface. Finally, the three geometric models are processed by a converter and integrated into the other simulator subsystems, such as physical models, haptics, and physiology.

Physical Modeling

Although geometric modeling is important to permitting deformation of the organ, realistic simulation also must introduce physical and functional forms of behavior into virtual organs. The ICTS includes a simple hemodynamic model and algorithms representing fluid flow and contrast agent diffusion.

Hemodynamics. The ICTS hemodynamics component provides simulated patient physiology, particularly information related to coronary blood flow. Two categories of hemodynamic parameters are computed: steady-state and transient characteristics. The steady-state hemodynamic characteristics describe parameters whose values do not change during any given cardiac cycle, for instance, heart rate, vascular compliance, and vessel resistance. Transient characteristics of the circulation and heart action have values that change in a continuous way during the cardiac cycle. Those that can be generated are ECG lead I, right and left ventricular volumes, aortic root pressure, and intraventricular pressure. At present, the hemodynamic model does not provide full control feedback. Instead, an instructor can change such parameters as heart rate or blood pressure at any time.

Fluid flow. To simulate the coronary angiogram, one must construct a mathematical model of the contrast agent moving through the blood-filled coronary artery and integrate that model with both the simulated fluoroscopy and the contrast syringe in the haptic interface device.

The fluid-flow model computes the pressure and movement of blood at every point within the coronary arteries, the intravascular contrast density, and the intravascular pressure at the catheter tip. To compute blood flow in real time, the system assumes one-dimensional flow, since the coronary radius is small. The current model does not take into account any turbulent motion and is not, at present, well suited for simulations of intra-aortic blood flow.

Blood flow is computed according to the pressure gradient between the entry and exit points of the vascular system, that is, the aortic pressure and the myocardial pressure. Owing to the topology and geometry of the coronary arteries—small diameters and treelike bifurcations—it is possible to compute the flow by using an analogy with a resistive network and applying techniques from electrical engineering. The resistance of each blood vessel is a function of its length and radius as defined in Poiseuille's law, $R = 8L\mu/\pi r^4$, but the simulator permits resistance to be modified "on the fly" to simulate a stenosis. The hemodynamic module provides the driving pressures—aortic and myocardial. The aortic pressure varies from 80 mm Hg to 120 mm Hg during a cardiac cycle, whereas the myocardial pressure is almost constant, about 5 mm Hg. As a result, the ICTS renders real-time pulsatile one-dimensional flow in the simulated coronary arteries.

When the coronary angiogram is simulated, mixing between blood and contrast is computed according to a diffusion and advection model. Arterial opacity takes into account the amount and velocity of contrast injected combined with fluid flow and the volume of contrast already in the vessel. The calculated intravascular contrast density then is used to compute the visual properties of the vessel in the synthetic fluoroscopic image (Fig. 4).

Catheters. Catheters and guide wires are represented as a multibody system, that is, a set of rigid links connected by joints. Three different forces can be applied to the multibody object: contact forces, injection forces for the catheter, and force applied by the user at the proximal end of the instrument.

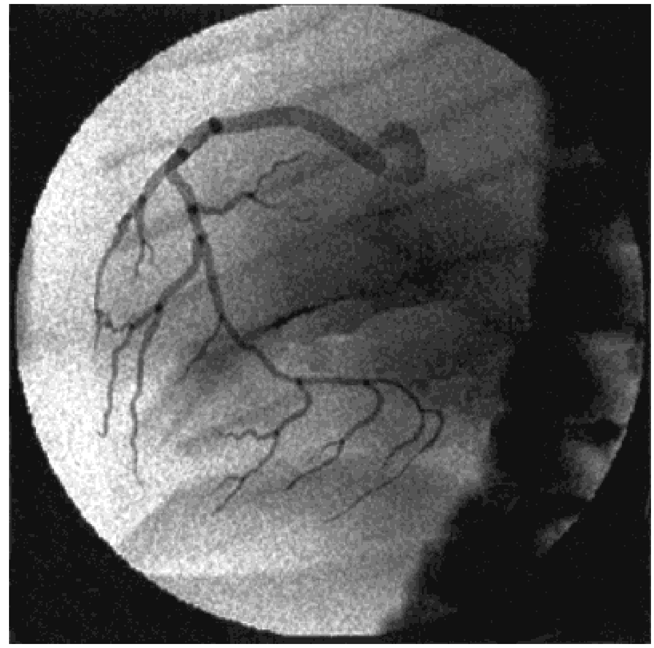

Fig. 4. Simulated left anterior oblique projection "freeze-frame image" of selective right coronary angiogram from the ICTS. Because it is based on a three-dimensional model, this image can be rotated about any axis in real time to show anatomic relationships, location of stenoses, bifurcation points, and instrument/device positions.

Contact forces are the result of interaction with vessel walls. Collision along the entire length of the catheter is calculated, and contact forces are determined according to the stiffness, damping, and friction of the vessel wall.

Contrast injection is calculated as an injection force that is applied to the tip link of the catheter. The injection force is computed from the flow rate of the injected contrast, the cross-sectional area of the catheter, and the mass density of the fluid.

To apply motion at the proximal end of the catheter, tool positions are sent from the haptic device and used to compute the derivatives of motion, which then drive the base link of the tool multibody system.

Finally, when all the forces are evaluated at each link, a numerical integration is used to determine the velocity and position of the links at the following time step. At the same time, the resulting force and moment applied on the base link are sent back to the haptic device to provide force feedback (Fig. 2). The calculations then begin again as a feedback loop: read the position and orientation of the catheter from the haptics device, evaluate the external and internal forces, and compute the next position and orientation of the multibody system.

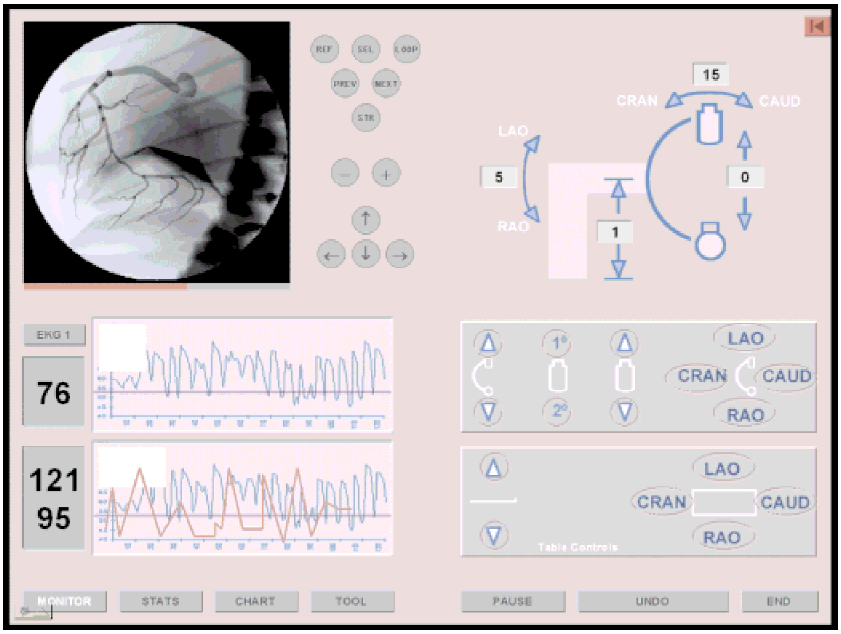

Fig. 5. A representative screen from the ICTS user interface showing the fluoroscopic controls and hemodynamic monitoring parameters. This information is a component of the learning system integrated within the ICTS. Among other screens, some show the patient's history, allow choice of catheters and guide wires, or permit recording of procedures performed by students for later review by an instructor or examiner.

Haptics

Commercially available haptic devices are not acceptable for endovascular simulations. The ICTS haptic interface (Fig. 1) consists of a tracking device that measures catheter translation and rotation and independently controlled servomotors that produce force and torque resistance. Motion measurements are sent to the simulator and combined with other data from the physical model to compute the proximal catheter force and torque. In addition to catheter motion measurement, the interface device senses contrast injection and pressing of a momentary contact foot switch that permits the fluoroscope to be turned on and off during simulation.

The haptics controller runs on a dedicated workstation, connected to the main simulation computer by an Ethernet link using a high-speed communication protocol.

Rendering

During cardiac catheterization, the fluoroscope translates and rotates around the patient. For this reason, it is not suitable to use real fluoroscopic images or visual feedback methods based on preprocessing of volumetric data combined with volume rendering. The ICTS uses a polygonal model associated with specific X-ray attenuation coefficients. This permits real-time realistic fluoroscopic image computation and rendering on OpenGL accelerated hardware. For instance, the anatomy shown in Fig. 4 can be rendered at a frequency of about 30 Hz.

Realistic fluoroscopic representation needs to account for anatomic (heart, lung, coronary arteries) as well as instrument (catheter or guide wire) motions. Thus, visual feedback is synchronized with the hemodynamic, fluid flow, user interface, and catheter modules. As an example, the instantaneous calculation of the appropriate heart shape to be rendered is a function of the cardiac cycle (defined by the hemodynamic modules) and heart rate (specified in the user interface).

Integration of Components

Once the different components described here have been created, the major remaining challenge is system integration in a way that will permit real-time user interactions. Since each component of the simulator needs to run at a specific frequency and exchange data with several other components, the integration task is complex.

User Interface and Learning System

The simulator embeds the integrated, closed-loop system of modeling, rendering, and haptics into a larger context of "virtual rounds." (See Shaffer et al. [13] for more details.) Virtual rounds replicates traditional learning methods, such as patient interview, physical findings, and laboratory evaluation, but also augments reality by adding features made possible through the computer medium of the simulation (Fig. 5). There are several examples of augmented reality.

Undo. One of the fundamental and most powerful augmentations in the system is the ability to roll time forward and backward. This makes it possible to "skip ahead" in a previously simulated procedure to focus on the most interesting and complex parts. More important, the ability to move backward through simulated time means that trainees can easily learn from their mistakes. The capability to "undo" an action makes it possible to experiment freely and safely in the simulator, learning through trial and error.

Pause. With the simulator, it is possible to pause the X-ray rendering process, preserving a "freeze-frame" fluoroscopic image. Because the underlying anatomic data set is three dimensional and based on correct physical models, the viewing angle of the fluoroscope can be changed, making it possible to view the same "frozen" anatomic image from many perspectives, unlike real fluoroscopy. With this feature, trainees can quickly determine optimum viewing angles and understand why multiple images are essential to understanding the characteristics of coronary pathologic characteristics.

Learning curriculum. The ICTS contains a set of virtual patients on whom trainees can choose to perform procedures. With this curriculum of standard cases, every interventional cardiologist could carry out a number of procedures on both typical and atypical cases.

Edit anatomy. In addition to providing a set of standardized patients, the ICTS makes it possible to change each patient's anatomy and physiology. This can be done before the intervention or during the procedure, to introduce complications at the same time that a trainee is performing a simulated procedure, making it possible to create simulated crisis situations.

FUTURE DEVELOPMENTS

The ICTS represents the first attempt at computer-based interventional cardiology simulation with an integrated learning curriculum. Further refinements will include improved system stability; more advanced physical models, including procedural simulations for new devices; and creation of multi-axial haptic interactivity. Clearly, we see the simulator as a work in progress. The ICTS also needs to be validated as an effective learning system through rigorous testing at an academic center. At present, the ICTS core is being prepared for its first multicenter training trials in Europe, where initial data will be obtained concerning its effectiveness in terms of learning new procedures.

The importance of integrating an educational framework within computer-based medical simulations cannot be overemphasized: this union changes the perspective from which one views procedural simulators [14]. Successful validated simulators that can impart clinically useful knowledge could shift the educational model such that patients are no longer put at greatest risk during the early phase of a physician's learning curve. This is analogous to learning to fly commercial airliners: once flight simulation was validated, one did not learn to fly a 747 while it was full of passengers.

The same principles we describe for coronary interventions also apply to simulation of instrument and device interactions within other vascular systems. CIMIT's ongoing research efforts extend this work and also focus on basic tissue modeling and haptics research fundamental to the creation of the next generation of endovascular simulators.

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