ICTS, an Interventional Cardiology Training System

Stephane Cotin [(1)], Steven L. Dawson [(1)], Dwight Meglan [(2)],
David W. Shaffer [(1)], Margaret A. Ferrell [(4)],
Ryan S. Bardsley [(3)], Frederick M. Morgan [(3)], Tad Nagano [(3)], Jacob Nikom [(3)],
Paul Sherman [(3)], Michael T. Walterman [(3)], Jeffrey Wendlandt [(3)]

[(1)] *CIMIT, the Center for Innovative Minimally Invasive Therapy (www.cimit.org)*
[(2)] *Virtual Presence, Inc., Boston, MA*
[(3)] *Medical Application Group, Mitsubishi Electric, Cambridge, MA*
[(4)] *Division of Cardiology, Massachusetts General Hospital, Boston, MA*

Abstract: In this article, we present an Interventional Cardiology Training System developed by the Medical Application Group at Mitsubishi Electric in collaboration with the Center for Innovative Minimally Invasive Therapy. The core of the ICTS is a computer simulation of interventional cardiology catheterization. This simulation integrates clinical expertise, research in learning, and technical innovations to create a realistic simulated environment. The goal of this training system is to augment the training of new cardiology fellows as well as to introduce cardiologists to new devices and procedures.

To achieve this goal, both the technical components and the educational content of the ICTS bring new and unique features: a simulated fluoroscope, a physics model of a catheter, a haptic interface, a fluid flow simulation combined with a hemodynamic model and a learning system integrated in a user interface. The simulator is currently able to generate – in real-time – high quality x-ray images from a 3D anatomical model of the thorax, including a beating heart and animated lungs. The heart and lung motion is controlled by the hemodynamic model, which also computes blood pressure and EKG. The blood flow is then calculated according to the blood pressure and blood vessel characteristics. Any vascular tool, such as a catheter, guide wire or angioplasty balloon can be represented and accurately deformed by the flexible tool physics model. The haptics device controls the tool and provides appropriate feedback when contact with a vessel wall is detected. When the catheter is in place, a contrast agent can be injected into the coronary arteries; blood and contrast mixing is computed and a visual representation of the angiogram is displayed by the x-ray renderer.

By bringing key advances in the area of medical simulation – with the real-time x-ray renderer for instance – and by integrating in a single system both high quality simulation and learning tools, the ICTS opens new perspectives for computer based training systems.

1 Introduction

The growing development of minimally invasive surgical procedures, where instruments are introduced into the patient's body through small incisions, has led to the emergence of a new field in computer science: surgery simulation. Although minimally invasive surgery presents several advantages compared to traditional surgery, such as a quick recovery of the patient, the techniques are usually more complex and require new training methods. Computer based simulators have been developed over the past seven years with one common goal: provide a new way to teach these new techniques. However, most of the work has focused on laparoscopic surgery in which long rigid tools are inserted into the patient's abdomen of the patient and visual feedback is provided by an endoscopic camera that produces a high definition color image. The simulation process mainly emphasizes the eye-hand coordination problem occurring in this type of surgery, which explains why most simulators are skill trainers [2], [3], [4], [5], [8], [9]. However, there are other types of minimally invasive interventions that are technically challenging and may take advantage of computer simulation. In our approach, we chose to focus on interventional cardiology as a method of endovascular surgery. Interventional procedures use catheters or other devices inserted through blood vessels to diagnose and treat vascular disease. The most common interventional technique is called *angioplasty*: a balloon catheter is inserted into an artery, then the balloon is inflated and the plaque causing a blockage is compressed against the wall, opening the artery. Other techniques to open the artery include atherectomy and the use of stents – tiny, metal lattices that are compressed tightly over a deflated balloon. Current training methods require practicing either on animals and cadavers or on mechanical models that use real medical devices and x-ray equipment. In the latter environment, a phantom of the vasculature, made of glass or plastic, simulates the major blood vessels. These approaches have disadvantages, including ethical problems for animal-based training, exposure to x-rays, and use of expensive devices in mechanical models.

This article describes the development of an Interventional Cardiology Training System conducted at Mitsubishi Electric Research Lab, in collaboration with CIMIT[1] and the Massachusetts General Hospital. The following sections give a technical overview of the simulator as well as a description of the training system built on the simulation core. The last section will be about the current improvements of the system, in terms of technical enhancements as well as cost effectiveness.

2 Interventional Cardiology Training System

Simulation of endovascular surgery presents unique challenges that are not present in laparoscopy simulation. First, visual feedback is not provided by visible light but by fluoroscopy. This means x-ray images need to be simulated in real-time while allowing for geometric changes. Second, catheters, guide wires, and stents are flexible devices and consequently must be modeled as deformable objects, which is not the case for rigid laparoscopic tools. Among the few articles published in this area, Blezek *et al.* [10] have described a non-endoscopic training system used for anesthesiology training. Regarding the simulation of x-ray images, Van Walsum *et al.* [6] have presented a method that creates x-ray images from CT scans and also simulates contrast agent injection. However this approach is based on volume rendering and consequently is limited in its ability to change the viewpoint or the vascular geometry in real-time, which is an important feature of the fluoroscope when used for interventional cardiology.

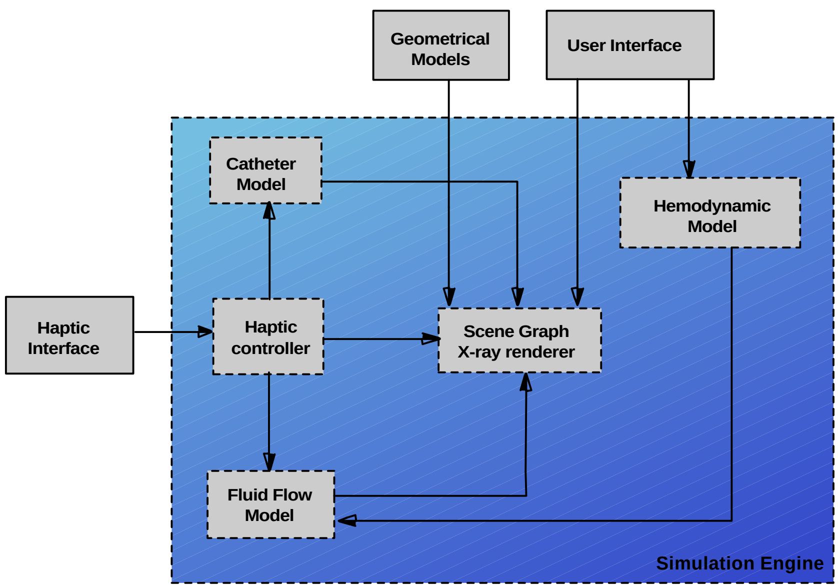


Figure 1 - Relations between the different components of the simulation engine.

The ICTS system not only provides a visual feedback similar to what a physician sees on the fluoroscope monitor, but also reproduces the major elements of the environment in which a resident learns how to perform a procedure. The ICTS simulates the physics and physiology of the human cardiovascular system, but is also interfaced to a haptic device that gives the user a natural way to interact with the simulation. It also includes a graphical user interface, coupled to an instructional system that provides a framework for learning from the simulation. Sections (2.1), (2.2), (2.3), and (2.4) describe what will be called the *simulation engine* (see fig. 1). Section (2.6) presents the user interface and instructional system. The combination of both the simulation engine and the instructional system defines the Interventional Cardiology Training System.

[1] Center for Innovative Minimally Invasive Therapy, www.cimit.org

2.1 Geometrical Modeling

Geometric modeling is used to provide information about the thoracic anatomy and the attenuation coefficients which will be used to generate the x-ray images. The anatomical models used in the ICTS can be divided in three classes: polygonal representations of the static anatomy based on segmented data from the *Visible Human Project*; animated polygonal models, i.e. the heart and lungs, created in *Maya*®, an animation and modeling package; and animated NURBS surfaces (correlated to the cardiac motion) to model the arteries. The geometrical and topological characteristics of the vascular system have been created in collaboration with a cardiologist to ensure the accuracy of the representation. Finally, an x-ray attenuation value is associated with each anatomical model. To create a beating heart, the heart model and arteries have been keyframed while a deformation was applied to the polygonal and NURBS surfaces. The result is a cyclic regular heartbeat, exhibiting all the characteristics of a real heart – twist, elongation, contraction. Moreover, it is possible to control the heart rate from the user interface. Control of lung movement has also been created. Finally, the various geometric models are processed by a converter to produce data files optimized for the subsystems of the simulator.

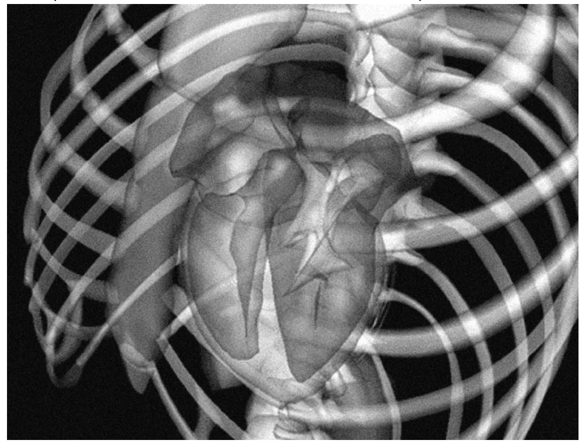


Figure 2 - Visible light rendering of the thorax..

2.2 Physical Modeling

Although geometrical modeling is a key element in the development of a realistic simulation, it is essential to introduce physical and functional behaviors into virtual organs. In the ICTS, physical modeling is not limited to the computation of a deformation of an organ or surgical device, but also comprises a simple hemodynamic model as well as a fluid flow / contrast agent diffusion algorithm.

2.2.1 Hemodynamics

The hemodynamics component provides simulated patient physiology. In particular, it provides information related to coronary blood flow. Two categories of hemodynamic parameters are computed: steady state and transient characteristics. The steady state hemodynamic characteristics of the patient describe parameters whose values are assumed to 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, i.e. aortic root pressure, ECG values, and ventricular volumes.

Steady state values are computed based on descriptions and mathematical models available from different sources, including a standard physiological textbook [12] and a model referenced in [11]. These steady state values provide “bounding boxes”, i.e. control parameters, that shape the transient components. Although these values do in reality change over time, for the purposes of the ICTS assuming their being fixed was deemed an acceptable approximation for the calculation accuracy needed. The transient components are fixed mathematical forms that approximate the appearance of real-life clinical signals. However, the transient effects have no basis in mathematical modeling of the physiology other than being shaped by the steady state parameters and exhibiting correct behaviors for a normal healthy patient. Currently, the hemodynamic model does not provide a full control feedback. Rather, control is provided by an “instructor” who can, for instance, change a parameter – like the heart rate – at any time.

The heart rate is set from the user interface and the following outputs are generated: ECG signal represented at lead I [12], right and left ventricular volumes, aortic root pressure, and intra-myocardial pressure.

2.2.2 Fluid Flow

Injection of a contrast agent into the aorta during fluoroscopic imaging gives an angiogram, which is the only way arteries can be seen during the procedure. Simulation of an angiogram involves the calculation of the spreading of contrast agent through the vessel as well as simulating the effect of the contrast on the resulting fluoroscopy. The latter aspect is described in section (2.4). For simulation of the contrast spreading, which is a 3D process, we propose a simplified one-dimensional approach.

The fluid flow model computes the pressure and flow of blood at every point within the aorta and coronary arteries, intravascular contrast density, and intravascular pressure at the catheter tip. To compute blood flow in real-time, we assume a one-dimensional flow since the radius of the coronaries is very small. Consequently, the current model does not take into account any turbulent motion and is not, at present, well suited to simulate blood flow in the aorta.

The flow of blood is computed according to the pressure gradient between the entry point and the exit point of the vascular system, i.e. the aortic pressure and the myocardial pressure. Due to its topology and geometry – small diameter and tree-like structure – the coronary network can be represented as a graph. Consequently 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 the Poisseuille's law [12] but the resistance can be modified "on the fly" to simulate a stenosis. The driving pressures – aortic and myocardial – are provided by the hemodynamic module. The aortic pressure varies from 80 mmHg to 120 mmHg during a cardiac cycle while the myocardial pressure is almost a constant value, about 5 mmHg. As a result, we obtain a real-time pulsatile one-dimensional flow in the coronary arteries.

When contrast is injected into the coronary arteries, 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. Then the calculated intravascular contrast density is used to compute the visual properties of the vessels in the synthetic x-ray (see fig. 3).

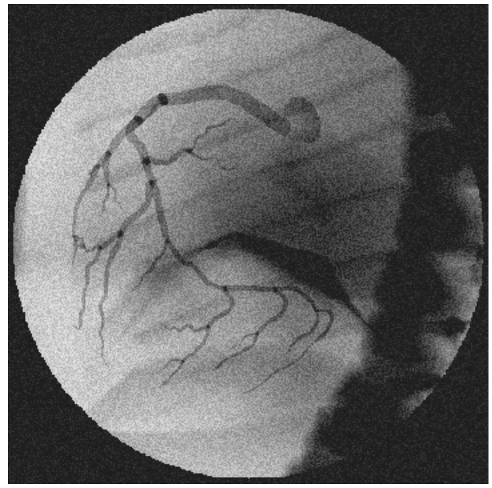


Figure 3 – Simulated Right Coronary Angiogram from the ICTS. The dark crescent represents the position of the right hemidiaphragm during respiration.

2.2.3 Catheter

The catheter model simulates a flexible instrument, such as a catheter or guide wire, as it interacts and deforms within the aorta and coronary arteries. A medical device in the ICTS is represented as a multibody system, i.e. a set of rigid links connected by joints. The multibody object can only be controlled by applying motion to the joints or forces and moments to the links and joints. Three different forces can be applied to the multibody object: contact forces, injection forces and force applied by the user at the proximal end of the instrument.

Contact forces are the result of the interaction of the tool with vessel walls. Collision along the entire length of the tool is calculated and contact forces are determined according to the stiffness, damping, and friction of the vessel wall. For efficient collision detection, the vascular system created in (2.1) is pre-processed to generate a set of segments approximating the vessels where segment length is a function of the curvature of the vessel. Then, a set of *contact points* are defined along the tool and the position of each contact point relative to every segment is computed. If a contact point moves outside the vessel, it generates a contact force at that point. The contact force is directed toward the inside of the frustrum and is a function of the contact penetration depth and velocity. There are material properties associated with each segment (stiffness and damping) that are used to calculate the force. Tangential forces can also occur due to surface friction. These are directed in a direction opposite to the velocity component that is perpendicular to the contact direction. There is both a static and kinetic coefficient of friction with the switch between them defined by a threshold velocity.

The effect of contrast injection through a catheter tip is calculated as an injection force that is applied to the tip link of the tool. This injection force is calculated from the flow rate of the injected contrast, the area of the catheter, and the mass density of the fluid.

To apply motion at the proximal end of the catheter, we read tool positions sent by the haptic device and use these to compute the derivatives of motion which are then used to 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 compute the velocity and position of the links at the following time step. Also, the resulting force and moment applied on the base link are sent back to the haptic device in order to provide force feedback (see fig. 1). Then a new loop process can restart: read position and orientation of the tool from the haptics device, evaluate external and internal forces, and compute next position and orientation of the multibody system.

2.3 Haptics

The haptic interface device used in the ICTS is a custom-designed passive force feedback system for catheter-like instruments (see fig. 5). Commercially available haptic devices are not acceptable for endovascular procedure simulations. Our haptic interface consists of a tracking device to measure catheter translation and rotation and independently controlled servomotors which produce force and torque resistance. Motion measurements are sent to the simulation and combined with other data from the physical model to compute the proximal catheter force and torque. In addition to the catheter motion measurement, the interface device senses the pressing of a momentary contact foot switch to replicate the on/off action of the fluoroscope as well as the motion of the syringe's plunger during injection of contrast.

High level functions of the tool controller have been developed as well. The controller runs on a dedicated workstation, connected to the main simulation computer by an Ethernet link using a high-speed communication protocol.

2.4 Rendering

In interventional cardiology, visual feedback through fluoroscopically controlled contrast injection is the major source of information for the cardiologist. Fluoroscopes are used in different ways depending on the procedure: in interventional cardiology, the fluoroscope translates and rotates around the patient. For this reason, approaches based on pre-processing of volumetric data combined with volume rendering, or the use of real fluoroscopic images are not suitable. The method used in the ICTS is based on 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. (2) can be rendered at a frequency of about 30 Hz.

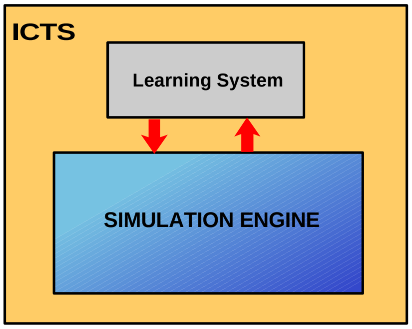
Realistic fluoroscopic representations need to account for anatomic (heart, lung, coronary arteries) as well as instrument (catheter) motion. Thus, the scene generation is synchronized with the hemodynamic, fluid flow, user interface and catheter modules. As an example, the choice of the appropriate heart shape to be rendered is a function of the cardiac cycle (defined by the hemodynamics) and the heart rate (specified in the user interface).

2.5 Integration: creating the simulation engine

A major difficulty in the creation of a simulator, besides the development of the different modules described above, is the integration of these modules in a real-time framework. Since each component of the simulator needs to run at a specific frequency and exchange data with several other components, the integration task is usually challenging. To achieve this goal, we use a component-based programming tool for system development combined with a real-time control framework. With the integrated system, a higher order approach to procedural simulation is enabled, namely the transition from the simulation as a *training* system to the simulation as a means for *learning*. It is our firm conviction that successful medical simulation must permit more than mere technical repetition. It must impart knowledge which can be transferred from the simulation to direct patient care.

2.6 User Interface and Learning System

We embedded the simulation engine, i.e. the integrated, closed-loop system of modeling, rendering and haptics, in a larger context of "virtual rounds" (see [7] for more details). Currently, in cardiac catheterization labs, trainees learn by examining a case history, deciding on a treatment protocol, performing procedures on actual patients, etc. The concept of virtual rounds is to replicate these steps "virtually", through the simulation. To implement the idea of virtual rounds, technical functionality of the simulation engine are used to support the clinical and pedagogical aspects of the training system. The user interface is the enabling portal to the different areas of the training system. A more complete discussion of the learning system can be found in [7], but a few examples of the system features that can be accessed from the user interface are described below.



Undo: one of the most fundamental and powerful augmentations in the simulation engine 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 of the procedure. More importantly, the ability to move backward through time in a simulation means that trainees can easily learn from their mistakes. The ability to “undo” an action makes it possible to experiment freely and safely in the simulation system, learning through trial and error.

Pause: with the simulator, it is possible to pause the x-ray rendering process by depressing a foot pedal. Thus, the contrast agent can be stopped in place while the viewing angle of the fluoroscope is changed, making it possible to view the same image of the anatomy from multiple perspectives. In this way, it is possible for trainees to quickly determine optimum viewing angles, and to understand why multiple images are essential to understanding the characteristics of coronary pathology.

Virtual Curriculum: a set of virtual patients is defined so as to form a curriculum of standard cases for trainees. In this way, every trained interventional cardiologist would have a chance to perform a number of procedures on both typical and atypical cases, using standard and specialized devices.

Edit Anatomy: In addition to providing a set of standardized patients, the ICTS makes it possible to change patient’s anatomy and physiology. This can be done prior to the intervention, or it can be done during the procedure to introduce complications “on the fly” while a trainee is performing a simulated procedure, making it possible to create simulated crisis situations.

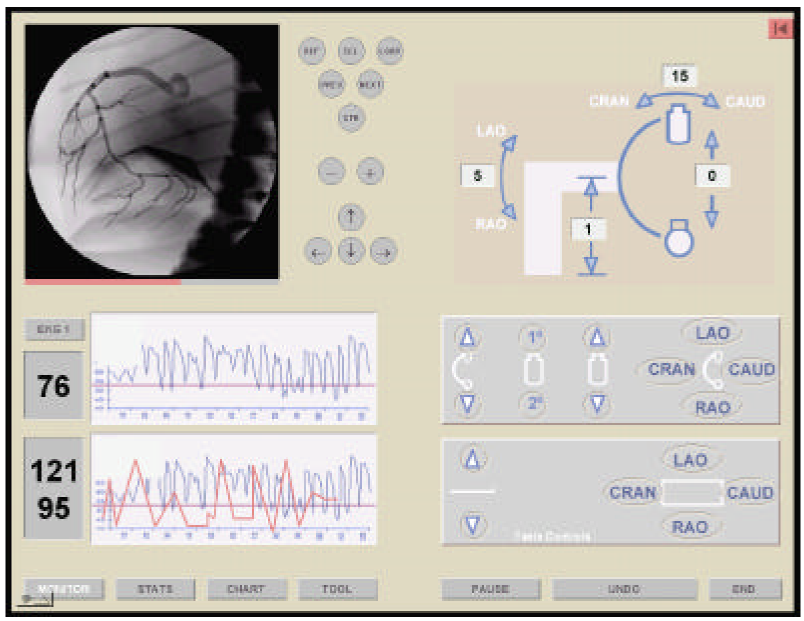


Figure 4 – A screen from the ICTS user interface. On this view, the fluoroscope controls and hemodynamic parameters are shown.

3 Conclusion and Perspectives

The Interventional Cardiology Training System described in this article, and the simulation engine framework upon which it was designed, are clearly works in progress. The system needs to integrate recently developed enhancements to improve its stability and it needs to be validated in clinical and educational use. Nevertheless, by bringing significant advances in the area of endovascular surgery simulation and by integrating in a single system both high quality simulation and learning tools, the ICTS outlines a new approach to training through medical simulation.

As part of the ongoing development of the system, the ICTS now runs on a 4-processor PC instead of the 4-processor Onyx 2 workstation on which it was initially developed. Several improvements are also being made in terms of physical modeling: more stable tool models, and 3D pulsatile flow in the aorta. It is important to note that this article describes a specific example of endovascular surgery applied to coronary artery intervention. The same principles apply for simulating tool interactions with other vascular anatomy. Our ongoing research effort address possible extensions of our work, as well as focusing on basic research fundamental to the creation of simulators which are clinically useful to physicians.

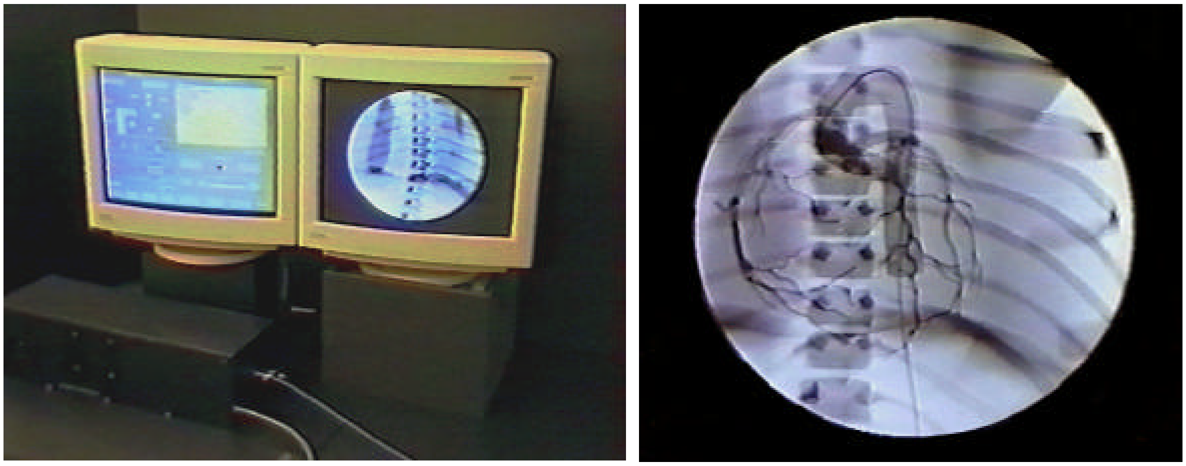


Figure 5 – (Left) A picture of the ICTS prototype with the haptic device in the foreground. (Right) a screenshot of the simulated fluoroscope showing the catheter and contrast moving into the aorta and coronary arteries.

Acknowledgements

The authors are very grateful to Karen Weissbach for editorial assistance during preparation of this article.

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