Digital Design of a Surgical Simulator for Interventional Magnetic Resonance Imaging*

Terry S. Yoo†
National Library of Medicine
National Institutes of Health

Penny Rheingans‡
Department of Computer Science and Electrical Engineering
University of Maryland Baltimore County

Abstract

We present the design of a simulator for a prototype interventional magnetic resonance imaging scanner. This MRI scanner is integrated with an operating theater, enabling new techniques in minimally invasive surgery. The simulator is designed with a threefold purpose: (1) to provide a rehearsal apparatus for practicing and modifying conventional procedures for use in the magnetic environment, (2) to serve as a visualization workstation for procedure planning and previewing as well as a post-operative review, and (3) to form the foundation of a laboratory workbench for the development of new surgical tools and procedures for minimally invasive surgery. The simulator incorporates preoperative data, either MRI or CT exams, as well as plans generated from a commercial surgical planning product to provide visual feedback during simulated procedures. Dynamic control of the simulation and interactive display of preoperative data in lieu of intra-operative data is handled via an opto-electronic tracking system. The resulting system is contributing insights into how best to perform visualization for this new surgical environment.

Keywords: interventional MRI, minimally invasive surgery, intraoperative imaging, surgical simulation, dynamic visualization

1 Introduction

In an effort to control the spiraling costs of health care, medicine is looking more and more toward minimally invasive surgical techniques. Such methods lead to smaller incisions, reduced chance of infection, more rapid recovery, and better quality of life for the patient. The need for image guidance during procedures through interventional radiology has led to the development of the General Electric Medical Systems Signa SP, a supercooled superconducting 0.5 Tesla MRI system designed to permit simultaneous surgery and MR imaging. This system allows surgeons and other practitioners to guide their interventions when visual access must be balanced for the need for minimal disturbance. Most neurosurgical procedures fall into this category. The Signa SP can be used to verify that tumors and other lesions are completely removed before incisions are closed, reducing the need for repeated operations.

Beyond the imaging capabilities, this type of operating room scanner creates new opportunities for flexible and demanding image guided procedures not possible through other technologies. In order to explore new methods and procedures, to develop new protocols, and to help design new instrumentation for this environment, we have designed and built a digital simulation of the Signa SP. The simulator includes visualization capabilities beyond those found in the current surgical environment.

Related work includes a variety of surgical planning systems as well as digital simulations of other procedures or clinical treatment methods. There are recently published case studies for virtual angioscopy [Gobetti 98], craniofacial surgery [Montgomery 98], virtual colonoscopy [Hong 97], and related uses of visual computing in medicine [Kikinis 96]. This case study differs from previous work, targeting a specific surgical scanner with innovative imaging capabilities.

2 Scanner Description

The Signa SP is the culmination of a vision for minimally invasive surgery from the Harvard Brigham and Women's Hospital (BWH) Department of Radiology and research efforts at the General Electric Corporate R&D Center. The first prototype was delivered to BWH in the Fall of 1993 and was operational in early 1994. Since that time, fourteen other prototypes have been manufactured and delivered worldwide to medical research hospitals to encourage the development of new protocols and procedures enabled by this system. [Schenck 95] [Jolesz 97a]

The design of the Signa SP is a departure from conventional MRI scanners. The primary difference is the creation of the induced magnetic field by two superconducting magnets rather than a single coil. The two magnets are separated by a 60 cm. gap with the imaging volume between the coils, permitting clinical access to the patient. Unlike other open magnet designs, the annular magnets are mounted upright with a circular. bore running perpendicular to the vertical gap. A practitioner and an assisting clinician can operate on a patient while imaging the relevant anatomy without the need to move the patient (See Figure 1).

2.1 Digital Tracking System

A Flashpoint™ 5000, infrared opto-electronic tracking system from Image Guided Technologies, Inc. is incorporated directly into the MRI scanner. This device locates infrared LEDs in the imaging volume. By combining the inputs from multiple LEDs mounted on a known rigid object, points, line segments, and coordinate frames can be located and monitored near the patient.

Figure 1. A side view of the GE Medical Systems Signa SP, a 0.5 Tesla, Interventional MRI at the Univ. of Mississippi Medical Center. It provides the surgeon access to the patient while simultaneously acquiring volume data during the procedure. The patient can be prone or supine on the bed, presented perpendicular to the physician. The patient can also be seated and upright in the gap. Two video screens are available for the physician. Lighting and an infrared 3D tracking system are housed in the overhead gantry.

* This work was performed at the University of Mississippi, CIS Dept. and the University of Mississippi Medical Center, Radiology Dept and was supported by a contract from the Institute of Technology Development and an Academic Equipment Grant from Sun Microsystems, Inc.

† yoo@nlm.nih.gov, National Library of Medicine, NIH, Bldg. 38A, Rm. B1N30P, 8600 Rockville Pike, Bethesda, MD 20894, USA

‡ rheingan@cs.umbc.edu, CSEE Dept., UMBC, 1000 Hilltop Circle, Baltimore, MD 21250, USA

An optical system was selected to eliminate interference from the magnetic fields produced by the scanner.

2.2 Interactive Scanplane Control

Using the tracker, the position and orientation of surgical instruments can be monitored within the imaging volume. The proximity of a biopsy needle to a lesion or tumor can be calculated and dynamic surgical computer assistance is enabled. GE incorporated instrument tracking directly into the scanner, allowing interactive control of the imaging plane. Thus, during a procedure a clinician can request an image along the track of a probe or needle and receive a view showing the trajectory of his instrument through the patient. This capability combines the superior image quality of MRI with interactive directed imaging control similar to that available in medical ultrasound scanners. Image guided biopsies and other procedures are now commonplace at facilities with a Signa SP, even in acoustically opaque regions such as the skull, which prevents the use of other technologies such as ultrasound.

2.3 Support apparatus and Design Materials

The closed nature of the surgical space around the imaging volume requires the relocation of support apparatus and personnel from their common positions during conventional procedures. Only a single assistant is available across from the surgeon during a procedure conducted in the Signa SP. Instrument handling, communication with the anesthesiologist, and many other essential activities must be revised to accommodate the confined space of the image guided operating room. Although the technology provides great advantages for the surgeon and the patient, people must retrain themselves to perform amidst new limitations.

An interventional MRI also places different concerns on equipment. The scanner is very sensitive to radiofrequency emissions. All support apparatus (e.g., pulse/oxygen monitors, anesthesia delivery equipment, lights, etc.) must be shielded in grounded Faraday cages to limit radiofrequency interference. Moreover, a strong constantly-induced magnetic field (approx. 10,000 times the magnitude of the earth's magnetic field) and fluctuating magnetic fields from gradient coils create a environment hostile to instruments made of steel, iron, or other magnetic and paramagnetic materials. Even simple instruments such as clamps and scalpels must be recrafted from titanium, composite carbon fiber-laminate plastics, ceramics, and other non-magnetic materials lest they become projectiles during surgery.

3 Simulation Design Elements

The Signa SP is a unique imaging instrument that combines a real-time interactive 3D data acquisition capability with tracked instruments for virtual and real interaction with the patient. Traditional surgical planning systems share the limitation that preoperative scans do not reflect the realtime patient situation. Interactive imaging is required to reflect the changes in the patient's anatomy as the procedure progresses. As a procedure continues, the surgical plan reflects reality with less fidelity.

A simulator is desired to help train surgeons and interventional radiologists on how to use this capability. It also will provide an environment to track a procedure and to learn to adapt a surgical plan to the real clinical situation as it unfolds. Finally, this type of environment may create the need for a new class of tracked instruments. Currently the Signa SP is mostly used intermittently to check the progress of an operation. Procedure development that includes continuous scanning may evolve simultaneously with instrument development supported by the rich visualization environment offered by interventional MRI. Instrument development in the actual scanner environment is demanding. Since many tracked instruments will be modified from existing tools, the simulator serves as a workspace where conventional instruments can be safely handled and tested.

3.1 Dynamic Visual Feedback

The simulator should at least replicate the reconstruction speed of the Signa SP, allowing interactive updates of the imaging field with the user guiding the acquisition plane with a tracked pointer. The scanner is capable of generating new images every 750 msec, with a one-frame lag. Thus, new images can be acquired every 1.5 sec. This latency can often impede navigation in the physical scanner, even with the patient present as a reference.

In his keynote address to the 1997 meeting of the Radiological Society of North America, Dr. Ferenc Jolesz described this situation and suggested that near-real-time imaging would provide a sufficient update frequency to benefit the surgery with faster and more natural visual navigation [Jolesz 97b]. In this scenario, intraoperative 3D data would be acquired in a volume scan, processed, and provided immediately to a visualization system in the operating room. While the data in the visualization would be static, it would only be seconds old. The benefits of dynamic navigation would likely outweigh the drawback of using static data. The simulator incorporates these ideas, demonstrating both dynamic visual navigation and accurate simulation of the interventional MRI environment.

In addition to the simulated 2D planar reconstructions, the simulator also has been designed to provide segmented 3D views of the patient data. These anatomical structures provide visual landmarks in a 3D rendering window. These views show the spatial relationships between anatomical structures, providing observers with a separate means of understanding the procedures being performed.

3.2 Pre-operative Data and Surgical Planning

The simulator incorporates a variety of data sources, taking advantage of all available information where possible. In the absence of real-time image data, pre-operative data can be used to simulate the scanning process. Data acquired on diagnostic instruments is often of higher fidelity and raster resolution than data available on the interventional scanner. Moreover, diagnostic imaging can be adjusted for better data acquisition since time is not usually a critical factor during a diagnostic scan.

Information from commercial surgical planning systems including segmented and extracted anatomical structures can be incorporated into the display. Preoperative data can add richness to the visualization. While the intraoperative images are limited to an MRI modality, the simulator can just as easily display volume data from X-ray CT or nuclear medicine studies. Even functional MRI and MR-angiography data that might be difficult to acquire with the Signa SP can be used in the simulator and superimposed over intraoperative images.

3.3 Tactile Feedback

The simulator must provide tactile or haptic cues to function as an instrument design workbench. New tools for clinical procedures that include infrared tracking must be designed to limit obsurcation of the tracking targets under normal use. Patient anatomy is recognized in the simulator as both an obstacle and an active object. Since the scanner has obvious applications in neurosurgery, the head has been selected as a representative anatomical object. Common operation of the simulator uses a mannequin to provide tactile feedback when practicing procedures as well as a tracked object to enhance the visualization by allowing

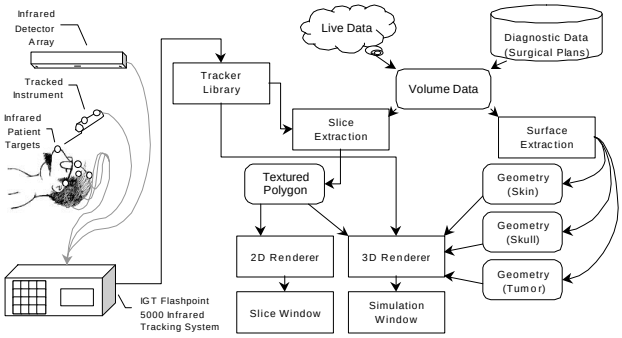


Figure 2. Data flow for the interventional MRI simulator. Live data can be acquired from the scanner. Diagnostic data can be retrieved from a variety of sources. The tracking system provides position information for slice interpolation and 3D rendering orientation.

interactive changes to the patient position. If the patient is available, infrared tracking targets can be attached temporarily to the patient, permitting realistic interactive procedure rehearsal.

4 Implementation

The simulator is implemented with many of the same elements as the original surgical MRI environment. The control windows of the original control console are faithfully replicated in the simulation. The heart of the simulator is the digital volume data resampling and display systems that interactively acquire user inputs and display them in near-real time. (See Figure 2). A Sun Ultrasparc2 with Creator 3D graphics was chosen as the target architecture. The selection was based on operating system and software tool compatibility with the existing GE console (based on a Sun Sparc 20). The Visualization Toolkit (VTK) was used as the foundation for much of the simulation [Schroeder 98]. Many of the interpolation, surface extraction, and polygon reduction elements of the simulator are VTK objects.

4.1 Basic Interventional MRI Operations

We obtained the configuration files used to generate the original user interface for the Signa SP's support workstation. Using the SDK configuration files but connecting the button and slider events directly to the digital simulation, we were able to reconstruct the same user interface as the actual instrument.

The serial output from the tracking system is polled using a separate Unix process. The dual processor Ultrasparc2 splits the I/O intensive process from the compute bound processes, reducing overall latency and improving the average framerate. The tracker software provides position information to the slice extraction software that interpolates a 2D array from the 3D volume. This procedure can be considered as the extraction of a 2D texture from a solid texture. Contrast and brightness (window and level) adjustments are provided using the graphical user interface from the scanner's workstation, and the output is presented in the same format as the Signa SP workstation console. (See Figure 3).

4.2 Extraction and Simplification of Surface Geometry

Beyond the standard operation of the MR scanner, we have incorporated reconstructed 3D surfaces to enhance the visualization of the image space. It is often difficult from the 2D slice images alone to orient yourself within the patient, even if you are a physician. A separate window is used to display anatomical structures and their relationships to the scan plane.

We used the Marching Cubes algorithm to extract the surface geometry [Lorensen 87]. This worked particularly well when applying the visualization capabilities of the simulator to X-ray CT

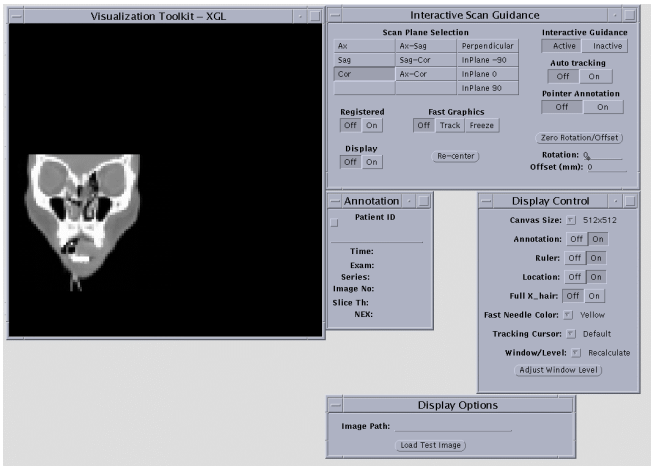
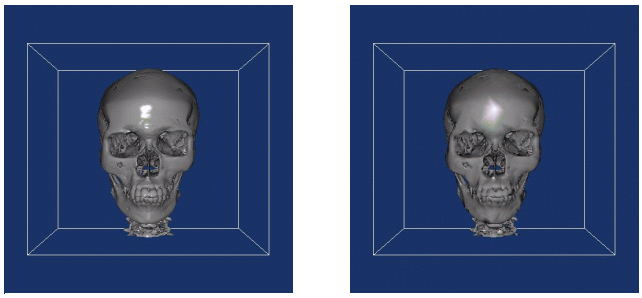


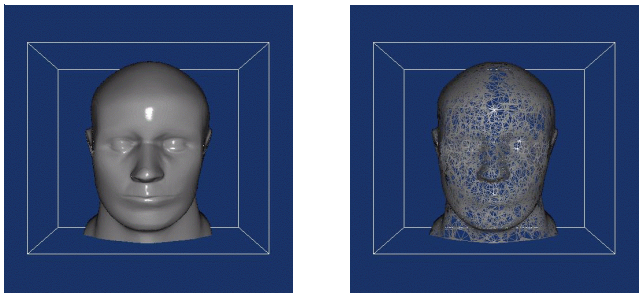
Figure 3. The Basic Simulator for the Interventional MRI Scanner console. The graphical user interface is constructed directly from the GUI configuration files. The coronal slice in the image is from a pediatric X-ray CT exam.

data. However, significant difficulties arise when isointensity surfaces are generated from MRI data. Skin surfaces proved particularly useful as navigation aids.

Mesh simplification was performed using the polygon decimation algorithm from Schroeder, Zarge, and Lorensen [Schroeder 92]. Interactive speeds for the 3D display were only obtained after the surface geometry was significantly reduced in complexity. Figure 4a shows a surface rendering of a skull, segmented and extracted from a CT exam using the Marching Cubes algorithm. Figure 4b shows the same skull with the polygonal dataset reduced by 98%. Figure 5a shows the skin surface of the same data as a shaded wireframe. Notice that the wireframe is so dense that it almost appears as a surface. Figure 5b



Left: Figure 4a. Skull surface extracted from an X-ray CT Dataset. Right: Figure 4b. Same surface with polygonal representation reduced by 95%. Specular highlights show differences, but the gross geometry is still anatomically correct.



Left: Figure 5a. Shaded wireframe representation of the skin surface extracted from a CT dataset with the Marching Cubes algorithm. The mesh is so dense that it appears as a shaded surface. Right: Figure 5b. Same surface with the polygonal representation reduced by 98%. Reductions such as these enable dynamic interactive display for the simulator using the existing hardware.

shows the skin surface after a 98% in polygons. The reduced polygonal geometry retains sufficient resolution to serve as anatomical references to aid in navigation for slice selection.

5 Discussion and Results

The digital simulation of the Signa SP was demonstrated in May 1997, shortly after the scanner was installed at the University of Mississippi Medical Center. The color plate (Plate 1) shows the user interface for the simulator, including the 3D navigation window as well as the control windows and the slice plane display. Experience with this project has led to several refinements in the simulator design and the handling of medical volume data.

5.1 Enhanced Visualization

The digital simulation provides more capabilities than the actual interventional MRI scanner. The simulator can assist in surgical planning by providing a view of diagnostic X-ray CT images, surgical plans created on other workstations, and some MRI views not available on the Signa SP. Moreover, the simulator (average framerate: 10-15 Hz) is significantly faster than the scanner (framerate: 0.75-1 Hz), allowing for more natural interaction with the data. If data is downloaded from the MR scanner during procedures and position information provided from the tracked instruments in the surgical environment, near-real-time display of patient information with diagnostic preoperative radiographic data can be provided in the operating theater.

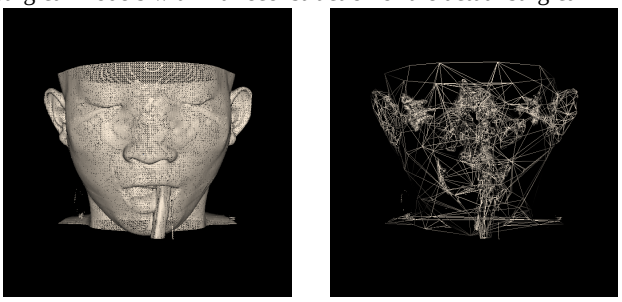
5.2 Segmentation and Mesh Simplification

Since the surfaces are used to provide spatial references, some consideration should be given to the fidelity required in their construction. If the planned procedure does not require visualization of areas such as the ear canals, sinuses, or other geometrically complex air spaces, do not include them in the final representation.

Consider the two images in Figure 6. The left image, Figure 6a shows the isosurface corresponding to the skin constructed from a pediatric X-ray CT exam. The right image, Figure 6b shows an attempt at polygon reduction. The high curvature of surfaces of the nasal passages and ear canals cause them to be preserved while the skin surface has deteriorated and is unrecognizable. The result is unacceptable since the goal of the visualization is to generate external landmarks to show spatial relationships. Elimination of internal air spaces and other irrelevant structures (irrelevant with respect to the visualization task) is an initial processing step.

5.3 Conclusions and Future Work

We have created an interactive digital simulation of a surgical environment. This simulator enables dynamic manipulation of the surgical models within a reconstruction of the actual surgical MRI.



Left: Figure 6a. Wireframe representation of the skin surface of a child from a pediatric X-ray CT exam. Right: Figure 6b. Wireframe representation of the same surface after a 95% polygon reduction. The simplification algorithm attempted to preserve areas of high curvature, sacraficing the realtively smooth skin surface for the irrelevant hidden internal air spaces. The result is unrecognizable and unusable.

The simulator exceeds the visualization capabilities of the scanner in flexibility, the richness of information presented, and update rate. Future integration of the simulator's visualization capabilities with the operating room may enhance the doctor's insights during procedures.

The current project includes simple placeholders for the rigid and confining surgical environment. A larger weight-bearing structure was planned to serve as a workbench for full sized operating table and chair apparatuses. Accurate reproduction of the surgical gap will improve the training and tool design functions of the simulator. In addition, only a few simple 3D tracked tools including a pointer and a disposable hypodermic needle, have been produced to date. Some prototype tools that demonstrate the flexibility of instrument tracking with interactive imaging would hopefully encourage imaginative thinking into new medical procedures.

One of the critical issues in advancing intraoperative visualization is in the area of data registration, both rigid and deformable. To take full advantage of the richness of the available CT, angiography, and diagnostic MRI information, the data must be accurately aligned. This area stands out as one of the biggest challenges for this research.

Acknowledgments

This work was made possible through the contributions of our research assistants Aaron Rodden, Charles Bland, and Brent Fox.

This work has been supported by the Institute for Technology Development (ITD), by GE Medical Systems (GEMS), and by Sun Microsystems, Inc. The simulator was originally developed at the University of Mississippi Medical Center, Department of Radiology. Digital design and implementation was performed under a subcontract to the University of Mississippi Department of Computer Science.

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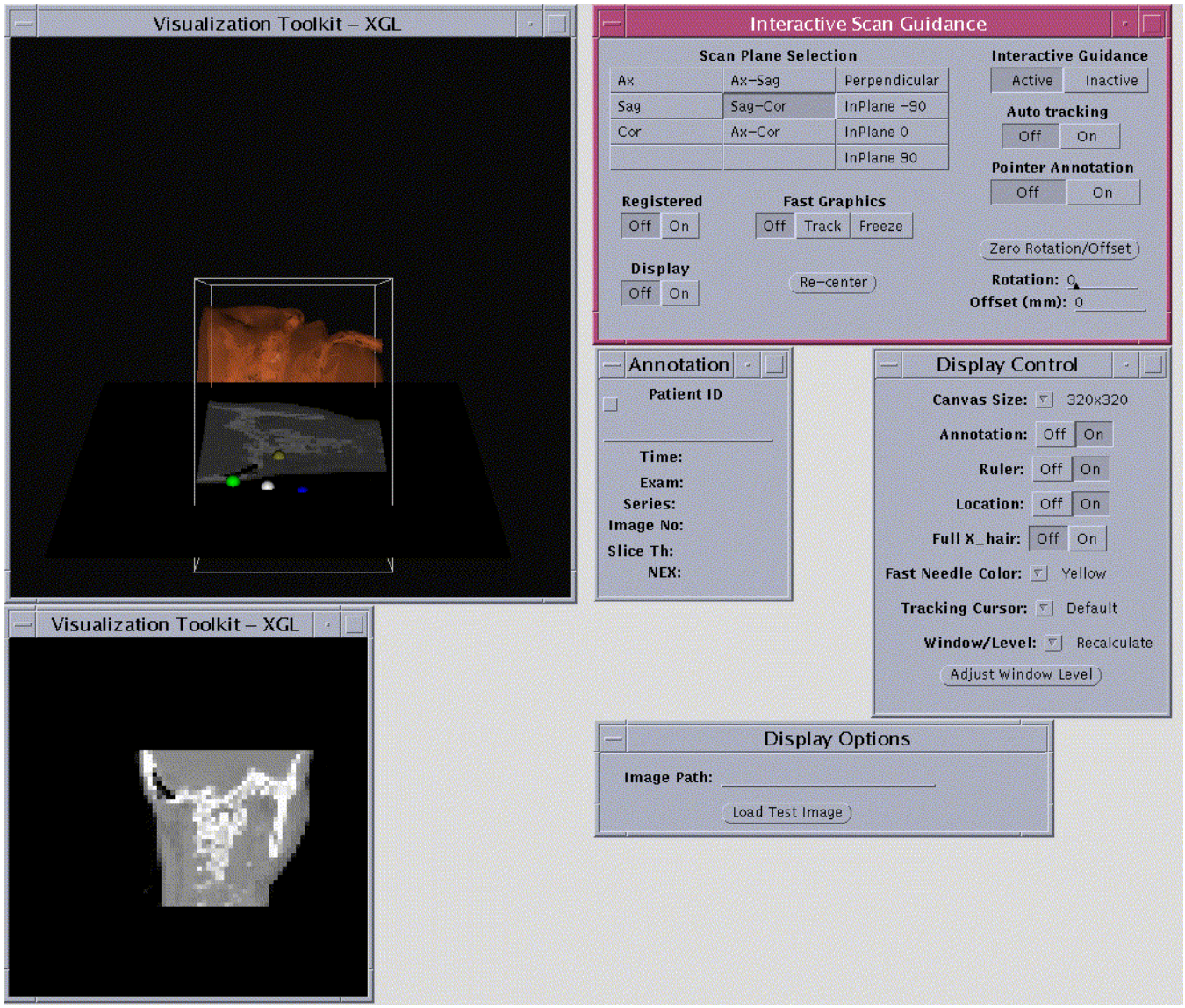

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Color Plate 1. Yoo/Rheinagns - Digital Design of a Surgical Simulator for Interventional Magnetic Resonance Imaging.

View of the simulation workstation screen including the control windows, the sliceplane window, and the 3D navigation display. The colored spheres are icons for the 3D tracked position pointer used to select the slice from the patient data. Anatomical structures such as bone and skin are shown partially transparent as navigation aids and to help visualize spatial relationships. All the control windows are faithful recreations of the windows of the GE Medical Systems Signa SP workstation console. They were generated directly from the GUI configuration files and their events redirected to control the simulator.