Abstract.
This paper outlines the proposal, approved by The United States Army Medical Research and Material Command, to develop and implement an ENT surgical simulator.

1. Executive Summary

1.1 Introduction

The proposed research aims to develop and evaluate a minimally invasive prototype surgical simulator to establish real-time fidelity requirements for tactile feedback and computer image synthesis. The project will enhance Graduate Medical Education programs, as well as quality of care and patient-oriented risk management. The prototype will be used to evaluate surgical training requirements. As such, the project will contribute to improved readiness of medical personnel. Upon validation of concept and requirements, applicable technology can be extended to training for battlefield trauma care. The project is an important step in the technological evolution of surgical simulation in the virtual reality training environment.

1.2 The Problem

Chronic sinusitis affects over thirty-one million Americans and outranks both arthritis and hypertension as the number one cause of chronic illness. The use of endoscopic sinus surgical procedures as a means of treating patients with chronic and recurrent sinus disease has gained widespread surgical acceptance (Stammberger 1991). The success that has been achieved with the use of the endoscope in sinus surgery has resulted in its expanded use in a variety of surgical maladies, to include: benign and malignant sino-nasal tumors, pituitary adenomas, skull base lesions, graves ophthalmopathy, optic nerve compressive disorders and in the treatment of cerebrospinal fluid leaks. However, training resident physicians to develop surgical competence in this advancing field is a complex task. Acquiring the visual, manual and psychomotor skills necessary for successful endoscopic paranasal sinus surgery requires considerable experience. In part, this is due to the inter-subject and intra-subject paranasal sinus variability. In addition, the proximity of the brain and orbits to the paranasal sinuses magnifies the complexity and potential risks of these procedures. Misadventures in operative cases have resulted in devastating consequences.

Electronic simulators, a proven and invaluable tool in the training of military and commercial pilot and crew training, promise similar value to medical training. However, there are significant technological challenges to overcome before successful medical simulation can become reality. As opposed to oblique views of geographical terrain and rigid moving objects, the medical scene consists of complex topological structures with close-up views of their intricate visual features. Furthermore, tissue exhibits complex motion that has no simple mathematical representation. It is necessary to account for the internal volumetric properties of anatomical structures to faithfully simulate them for anatomical simulation.

It is logical to select a procedure as first choice that is not exceedingly demanding on every front. Endoscopic sinus surgery, specifically dissection of the ethmoidal system, appears a good target for the following reasons: The surgeon observes his progress on a color monitor, for which a computer can substitute simulated video. Next, the anatomy is rigid to a good approximation, a significant simplification. Also, dissection with the Blakeslee forceps is localized and controlled, modest compared to other surgical manipulations such as laparoscopy. The targeted endoscopic sinus procedure, therefore, permits focus on the visual simulation necessary in training the cognitive skills of the ENT surgeon. Endoscopic computer simulation modules
offer the potential for standardized basic training and skill assessment without direct patient involvement. Repetitive exposure to common and uncommonly performed endoscopic techniques in a virtual environment will serve to enhance Graduate Medical Education programs, as well as quality of care and patient-oriented risk management.

1.3 Military Significance

Advances in minimally invasive endoscopic surgical procedures have revolutionized the physician's approach to a multitude of surgical maladies. The application of endoscopic techniques has translated into an enormous saving in hospital bed days, fewer personnel days lost to convalescence and limited duty days. In the battlefield of the future, the application of these advances will be realized in the management of the injured soldier. Presently in the arena of otolaryngology head and neck surgery, the use of endoscopic surgery for trauma has been limited to evaluation of midface trauma, optic nerve and orbital decompression. It is projected that in the not too distant future, the use of endoscopes to manage maxillofacial trauma, mandibular fractures and penetrating head and neck trauma will be expanded. By gaining experience and developing technology towards constructing surgically interactive and visually realistic patient models, the goal of enhancing the delivery of quality care to the wounded soldier will be strengthened.

Simulation training in the format of flight simulation has a proven track record within the military. The application of endoscopic surgical simulation may prove to equal or surpass the training benefit realized with flight simulation. The immediate benefit of surgical simulation training would be the acquisition of endoscopic skills at an accelerated pace, with an emphasis on increasing surgical comprehension and competence, without added risks to patients.

In addition, with the downsizing and inherent flux within the Army Medical Corps, the need to assess surgical skill and/or rapidly train deployable surgeons in appropriate battlefield endoscopic techniques would become feasible with computer-simulated surgery. The long range benefits gained from this project will assist endeavors in advanced technologies utilizing computer-assisted surgery, telerobotic, teleoperations and telepresent surgery

1.4 Project Description

PHASE I:

The goal of Phase I, which is 18 months in duration, is to undertake research and development of a simulator prototype to serve as a platform for further enhancement and evaluation. This activity includes conducting an image fidelity analysis study, development of a geometric and visual database of the human sinus anatomy, development of a system to track the surgical instruments, and development of the system software to implement sinuscope camera simulation and tissue dissection. The prototype will provide the surgeon the ability to perform sinus surgery on a virtual patient using sinuscope and surgical tools similar to those used in the operating room.

PHASE II:

In Phase II, development will continue by enhancing the simulator to include changes and enhancements suggested by surgeons in the Phase I evaluation. The video response of the system is again expected to be a major focus of this phase. Additional features such as tactile feedback and tissue deformation will be integrated into the prototype. During Phase II further analysis will evaluate the simulator's training effectiveness in operation. Phase II is planned for six months.

2. Simulator description

The prototype simulator will consist of a high speed computer system that runs the simulation on a database of a virtual patient. This system is interfaced to the tactile feedback subsystem, permitting the surgeon to use forceps and sinuscope with the virtual patient. When the sinuscope enters the mannequin the computer system generates a simulated image. To simulate the image from the correct perspective, the six degrees of freedom that define the position and orientation of the endoscope are monitored by the tactile subsystem and relayed to the simulation software. The motion of the forceps is handled similarly. The tactile feedback subsystem reflects the force that would result from contact with the patient anatomy. Also, the tools must move in the endoscope image in real time.

The virtual patient model consists of three components: a spatial or geometric model is derived from computed tomography (CT) data. The CT slices are mathematically assembled into a volumetric model
of the paranasal sinus region. The second component of the model is the visual texture which is overlaid onto the geometric model. The source of this will be from the Visible Human Project. The third component is the stiffness model which defines the response of the anatomy to palpation by the surgeon.

This project targets image synthesis, a fundamental clinical requirement common to general surgical procedures, as the primary technical challenge to address. Conventional computer graphics imaging approximates visible surfaces as multi-faceted flat surfaced polygons -- a technique which performs well with planar surfaces but may not be the most cost effective technique for adequately representing anatomical surfaces. Initially, this technique is chosen because it is well developed for the purpose of determining the visual fidelity requirements: spatial resolution, texture detail and specular reflection. The knowledge of visual fidelity requirements will guide the choice of the most cost effective technology in future refinements.

3. Computer-assisted instruction

One of the appealing aspects of the training simulator is the potential to integrate other computer-based interactive educational functionality with automated performance assessment. We intend to test the concept by developing an interactive tutorial that will enable medical students and resident staff to prepare for endoscopic surgical procedure on a virtual cadaver. Following the tutorial, the student could exercise and test his/her skill using the simulator.

4. Evaluations

4.1 Image synthesis evaluation

Recognition of the anatomy and special conditions is the critical surgical task in ENT surgery. We consider visual rendering fidelity to be the most crucial requirement of the simulator. It is also a factor that profoundly influences the cost of the simulator and will weigh heavily on the eventual acceptability of this technology into the increasingly price-sensitive medical market.

In the first six months of Phase I, we will conduct an analysis of the level of geometric complexity, textural detail and other visual cues required for effective simulation of the targeted surgery task. We will adapt videotaped endoscopy records and anatomical models to create animation that depict the visual rendering strategies under consideration. Expert ENT surgeons can then assess the anticipated effectiveness of the simulation strategies. The importance of the illumination model and attributes such as specular reflection will also be assessed. Procedural awareness in representative surgery students will be measured after viewing the animation.

4.2 Simulator evaluation

Procedure and evaluation criteria will be developed to evaluate simulator functions with respect to training efficacy. Evaluation will be on-going, that is "formative" as well as "summative." At the end of each major phase of simulator development, the prototype will be tested with three or four subjects drawn from the population of potential users to gather information about its usability (human factors data) and success in training (performance and comprehension data). Refinements and further developments would then reflect the results of formative evaluation at an early time when it is still relatively easy to change.

The evaluation will require three major activities: establishing user performance criteria; gathering information about user knowledge and performance; and analyzing the data to apply the results to revisions and further developments. Early in the project, the evaluation designer will work with the sinus surgeon to determine:

- What students must be able to do and with what level of skill
- What students need to know and what level of complexity
- Conditions under which students are expected to perform the tasks and apply the knowledge

We will use five standard techniques for gathering information on training effectiveness.

- Observation
- Performance tests
- Debriefing
- Think-aloud
- Audit trails

Data gathered by the above procedures will be analyzed and utilized to guide further revision and development. Evaluations provide both quantitative and qualitative data. In formative evaluation, the simulator is not compared against traditional training methods, and descriptive statistics are usually sufficient to guide revision. If most students make the same error, it will be obvious from frequency data.
summative evaluation, the simulator will be compared with other training methods.

4. Future Work

Additional patient models will enhance the simulator significantly. The capability to create virtual patients with battlefield trauma would be valuable in the training and development of improved casualty care. Given the degree of variability of the sinus anatomy in the general population, it is also of general importance to develop models representative of patient variability. A library of trauma and/or pathologies could allow an instructor to select and create custom models. The simulator can then be used to increase the student familiarity with a wide range of conditions and would also enable the simulator to be used for evaluation of the surgeon's recognition abilities. As a computer-based training platform, the simulator can be further enhanced by storing procedures performed by expert surgeons. These can be used for their pedagogical value and to compare the student's own performance with the expert's.

Yet another goal is to develop automated or semi-automated software tools that can quickly create patient-specific models from the patient's CT exam. This would demonstrate clinical utility, allowing the surgeon to preoperatively perform a surgical procedure. The surgeon could experiment with competing surgical approaches.

Finally, the simulator could be extended to other surgical procedures (neurosurgical, oral maxillofacial, plastic and reconstructive, ophthalmologic, otologic and dental).

5. Program Team and Team Management

The project will be managed by Madigan Army Medical Center and Loral Defense Systems - Akron. Loral will subcontract to Ohio State Supercomputer Center, Human Interface Technology Lab, Immersion Corp., Institute for Defense Analysis and Mission Research Corp.

Ohio State Supercomputer Center
Don Stredney - Visual model development
Roni Yagel, Ph.D. - Anatomy Visualization
Greg Wiet MD - Consultant - model generation

Human Interface Technology Lab
Suzanne Weghorst - Human factors
Bill Winn, Ph.D. - User performance evaluations

Immersion Corp.
Louis Rosenberg, Ph.D. - Tactile feedback subsystem development

Mission Research Corp
Bob Eisler - Consultant - Ballistic wound modeling

Institute for Defense Analysis
Bob Johnstone - Systems evaluation

University of Washington School of Medicine
Ernest Weymuller MD - Clinical consultant

Uniformed Services University of the Health Sciences
Bill Bolger MD - Clinical Consultant

References

Loral Defense Systems - Akron
Doug Sluis Ph.D. - Systems and software engineering
Dale Fawcett - Systems and software engineering

Madigan Army Medical Center
Charles V. Edmond MD - Principal Investigator
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