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13. ABSTRACT ***(Maximum 200 Words)***

The purpose of this research is to develop minimally invasive procedural simulation technologies that are broadly applicable to the improvement of medical training. The implementation of this technology will enable the Department of Defense (DoD) to provide improved medical support to the wounded soldier through enhanced medical training with improved diagnosis, rehearsal, and treatment planning. This project leverages the involvement of ongoing DoD and civilian work in virtual reality and will improve military readiness through shortened recovery times. It will also lead to the production of commercially viable products with educational and training benefits for U.S. hospitals and medical schools. The specific application chosen for this research was the simulation of flexible ureteroscopy.

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I. Introduction

The purpose of this research is to develop minimally invasive procedural simulation technologies that are broadly applicable to the improvement of medical training. The implementation of this technology will enable the Department of Defense (DoD) to provide improved medical support to the wounded soldier through enhanced medical training with improved diagnosis, rehearsal, and treatment planning. This project leverages the involvement of ongoing DoD and civilian work in virtual reality and will improve military readiness through shortened recovery times. It will also lead to the production of commercially viable products with educational and training benefits for U.S. hospitals and medical schools. The specific application chosen for this research was the simulation of flexible ureteroscopy.

II. Body

Overview of Ureteroscopy

A task analysis of ureteroscopy was performed. A flow diagram of this task analysis is in Appendix A. Briefly, however, ureteroscopy is the placement of an endoscope into the ureter and up to the kidney. Access to the ureter is obtained by inserting a rigid cystoscope through the urethra and into the bladder. A guidewire is then navigated through the ureterovesical junction. A balloon catheter is used to dilate the distal portion of the ureter where it inserts in the bladder. Occasionally the proximal portion of the ureter must also be dilated. Illustrations of the pertinent anatomy are shown in Figure 1 of Appendix B.

The ureteroscope is navigated through the ureter using both the endoscopic and fluoroscopic views. Both views are essential to this procedure. Contrast is used to ascertain the location and size of the ureteral lumen. The scope may be advanced up to the kidney. Tools may be placed through the working channel to perform a variety of procedures.

Overview of Technical Accomplishments

The overall technical product of this work is an initial version of a ureteroscopy training simulator. The simulator consists of hardware, software, and data elements.

The COTS hardware consists of a 550MHz Pentium III computer with 128M RAM equipped with an OpenGL accelerated graphics card (a WinTel computer with a GeForce display card). The custom hardware consists of an interface device that simulates male urological anatomy along with a modified Storz^{TM} ureteroscope. We modified to enable detection of motion of the thumb lever to detect articulation of the scope tip. We experimented with an instrumented working channel with force feedback on the working channel tool that we previously implemented in a bronchoscope, but we did not complete development of a sufficiently small version to fit within the confines of the ureteroscope.

COTS software consists of the Microsoft Windows NT 4.0 Operating System software, Blue Water Systems real time kernel, and various drivers for OpenGL and hardware interface boards. Custom software includes the integrated simulation system with modules for hardware interface, physiological and anatomical modeling, lighting, kinematics and dynamics, fluid flow and particle dynamics. Custom developed models (data) include those of the bladder, the ureter, the calyces of the kidney, surface textures, and models for interaction of fluids with lighting and particles.

The integrated system achieves a minimum real-time frame rate of 20 frames per second. The system was evaluated during development and on completion by engineers, physicians, and training specialists to gauge suitability for training use and to determine whether solutions to stability, anatomical modeling and interaction modeling problems were satisfactory.

Images of the prototype simulator developed under this contract are shown in Figures 1-3 in Appendix C. Additional detail of our accomplishments and positive and negative findings under each technical task in the approved statement of work are provided in the sections below.

Techniques for the simulation of physiological events

We developed models of anatomical motion caused by scope-anatomy interaction, as well as interaction with other nearby anatomy. In particular, the renal artery causes very visible motion which is useful as a landmark during navigation of the ureter. We implemented a system that utilizes moving line segments outside the visible model to simulate such phenomena. We couple motion of these external lines with a number of parameterized variables for distance and coupling compliance to provide easily adjustable and realistic coupling to the anatomical model.

We implemented a real-time fluoro display that models fluid flow and diffusion. In order to obtain real-time response, we chose to model fluid flow at the surface of the anatomical model thus yielding a two dimensional (surface) representation of the three-dimensional (volume) phenomenon. The model is linked with the actual polygons of the inner surface of the ureter and the calyces of the kidney. The method works well with moving anatomy and thus enables realistic synchronization of endoscopic and fluoro views.

The resultant reduction of dimensionality greatly speeds the fluoro view computations. Our initial examination of the implications of rendering a surface vs. a volume suggested that the opacity of the resultant image would be higher at the edges than the center of the lumen, whereas the actual view would be more opaque near the center. In evaluations with urologists, we found that the differences between our technique and actual fluoro were minimal and were not judged to be unrealistic.

We plan in the future to extend the model to accurately reflect interactions encountered in complications such as dissection of the lining of the ureter.

Creation of realistic endoscopic lighting simulation

The endoscopic view through a ureteroscope is made complex by a number of phenomena. Saline solution and urine have different refractive indices and different coloration. Lighting projected from the scope tip reflects off the bladder and ureter walls and produces specular reflections whose shapes point in the direction of curvature. Kidney stones have a characteristic surface roughness, and when fragmented for removal, can produce a cloud of small particles, all of which swirl around in the field of view with the fluid flow from the endoscope. Representing these elements realistically could easily require a supercomputer for adequate real time rendering. Our target platform was a 550MHz PIII processor and a hardware accelerated OpenGL graphics card. Our processing budget for setting up the graphics pipeline and rendering is 30 ms (milliseconds), based on a total 67 ms overall frame time. We therefore experimented with a number of effects that provide a realistic visual simulation while still being able to meet the rendering budget.

To simulate the specular reflection pointing towards the center of the lumen of the ureter, we use environment maps which we move in realtime in concert with a reduced dimensionality model of the scope and ureter. We modified methods previously developed for representation of mucus on endoscope lenses to produce effects that look realistically like urine and saline mixing. While the visual effect is judged to be good, real time control of the image requires a complex fluid flow model which we only were able to partially implement. Our final design involved a simplified flow model with a steady stream out the end of the scope that moves in a toroidal pattern – an elongated smoke-ring. The visual effects produced by this technique produce slight where the flow interacts with the anatomy. We have redesigned the system to incorporate a flow pattern that is warped by a set of control points that are in turn controlled by a low-order particle system but were not able to complete implementation due to resource constraints. We will plan to complete implementation in the future.

Real-time collision processing

The complexity of the anatomy of the urinary system requires a large number of polygons to represent realistically. The addition of dynamically movable particles, such as kidney stones greatly increases the complexity of the task. We have used a number of techniques to make the collision detection processing manageable. We break the anatomy into a series of viewing/collision groups that are at successively greater distances from the point of insertion. We use these groups as a coarse filter for the collision detection algorithm. Within the collision groups we use oriented bounding boxes (OBB) for objects in an object-to-object collision detection algorithm. This intermediate filter minimizes the number of potential collisions passed to the low level collision detection processing, where point to polygon collision detection processing is performed. We take advantage of the minimal motion of most areas of the anatomy, and combining this with the temporal coherence of scope movement, we have been able to achieve our target 20 ms collision detection processing in most areas of the model.

We developed an overall structure to realistically handle interactions with kidney stones. These present a number of challenges that required extension of the framework. Interaction of the scope and working-channel tools with these objects that are in the anatomy but not attached, and can tumble and move freely required a specialized collision detection model. Fragmentation of stones in real-time required a structure for model representation which is more dynamic than other parts of the anatomy. We developed stones that react with each other and the anatomy, and that can be fragmented in arbitrary ways while retaining the energy and momentum of the original stone in the resulting particles. We still have some problems with stone-model interpenetration, but the basic framework is in place and works. Stones currently do not interact with tools or the scope and we will incorporate this in the future.

Representations of the physics of the flexible endoscope

The problem of simulating the physics of the flexible endoscope is complicated by the interaction of the scope with instruments placed through the working channel of the scope. During initial navigation, we assume a navigational wire has already been placed in the ureter. The scope is then threaded over the navigational wire through the urethra into the bladder and then into the ureter. We have created a combination physics model for the scope based on a rigid body representation of the individual segments of the scope. We use penalty forces to represent forces from the anatomy on the scope and then solve a set of ordinary differential equations using a second or forth order Runge-Kutta method. We compute corrective forces on the rigid body links to enforce rigid length constraints on the scope elements, then move forward one time step. For stability and realism we limit both acceleration and velocity. At each time step, we compare the dynamic solution with a static equilibrium solution computed using the principle of virtual work.

We had stability problems with the fluoroscopic view caused by high frequency artifacts in the solution of the physics equations of motion for the ureteroscope. The real-time rendering of the scope on fluoro was adequate but the rendering of the scope view was too jittery. We used a parameterized Kalman filter process to remove unwanted high frequency components while retaining realistic responsiveness when the scope is manipulated quickly

We have constructed a number of alternative physics based models of general purpose endoscopes and evaluated them for stability across the range of input motions that are anticipated in procedures of this type. We refined the modeling system and to enable interactively changing the physical properties of the scope and navigational wire in real-time, allowing simulation of the insertion and withdrawal of working channel tools into the scope during navigation with the resultant decrease in navigational flexibility.

We devised a two level deformation and interaction model to obtain adequate speed and responsiveness. A global model is used to quickly compute macro deformation of the bladder and ureter, and to compute the forces transmitted by the scope back to the practitioner, and a micro model is used for computation and display of the localized, small deformations of the anatomy caused by the tip of the scope or tools inserted through the working channel. We are using an innovative application of dynamic B-Splines that permits adaptable inertia, elasticity, and damping parameters to be applied on a local or global basis in response to modeled physiological effects.

Integration of a computer-based geometric model of the urinary tract

We have developed a model of the urinary tract including the urethra, the bladder, the ureter, and the calyces of the kidney. We developed the model using a nurbs-based modeling tool, then used a custom tool to produce a polygonal model that has the capability of deforming with tool/anatomy interaction. We augment the resultant data structure with a number of additional indices that are implemented as threaded lists of pointers that enable traversal of the model in a non-linear fashion. These are produced with an off-line utility and enable us to quickly access neighboring polygons and vertices to speed up real-time collision detection between the scope, the wire, and the anatomy

To aid in recognition of anatomical landmarks, we created a generic framework for OpenGL billboards, which are two-dimensional elements that exist in three dimensions by automatically rotating to face the camera position. These are used to add "road signs" that, when enabled, provide labels for anatomical structures that pop up as the user explores the anatomy. These aid in learning the basic anatomy and, along with the fluoro and external views, assist the student in developing a good understanding of the relationships between scope manipulation and scope orientation in the anatomy.

Tactile/force feedback

We designed a number of testbeds for evaluation of alternative means of adapting our haptic interface devices to enable the application of a range of working channel tools with realistic sensations of touch and feel on both the scope and the working channel simultaneously. We implemented a mechanism for providing force feedback from within the body of the scope itself and evaluated the efficacy of that mechanism in comparison with application of forces at the tip of the working channel tool. Of particular concern is the ability to couple the forces displayed on the two devices with motions of the devices relative to each other. We developed and evaluated a two level haptic feedback system which combines a 1000 Hz primary feedback loop implemented in an external microprocessor with a 100 Hz global feedback loop implemented in the simulation computer. This combination was intended to allow us to realistically and accurately display complex forces such as those associated with the use of a basket while simultaneously manipulating both the scope and the basket.

In our evaluation of this two processor approach, we found that the force feedback mechanism for the wire is highly responsive. However, we have had continuing problems with getting sufficient precision in the input from device encoders. What was originally thought to be errors in the microcode of the controller that cause it to lose an order of magnitude in reported precision are actually design incompatibilities between the microcontroller and the system driver software. We have specified a new design that is under development by the manufacturer of the microcontroller, but that was not completed by the end of the project. Therefore we reverted to an earlier design using only the computer processor. This limits our haptics loop to only 100 Hz, but we feel this to be adequate. Our implementation has an alternate interface for the higher speed loop provided in the external processor should we be able to achieve that design in the future.

Instrumentation of the working channel

Instrumenting the working channel of the ureteroscope presented a number of challenges, including dealing with the size limitations. We worked to modify a design for working channel force feedback originally developed for flexible bronchoscopy to fit within the reduced size handle of the ureteroscope. We were unable to fit the required mechanism in an off the shelf ureteroscope, but may experiment in the future with a slightly larger extension on the bottom of the scope. We evaluated working channel force feedback using a bronchoscope handle and confirmed that our force model was realistic. We implemented a new version of the hardware interface layer. This creates a generic framework that permits an arbitrary range and number of hardware devices to be used, enabling the use of a range of hardware devices, including low-end devices in the future. This will make it practical to substitute both the two-processor device as well as an operational ureteroscope with working channel force feedback in the future.

Pathologic/anatomic variations

A major issue in medical simulation development is the difficulty of producing new case studies. We addressed this problem by developing a set of modeling tools that enable us to quickly model a new case from scratch or to modify an existing case. This reduced our turnaround time on production of alternative case studies significantly, and enabled a much more effective interaction between modelers and medical experts. We worked on a method for dynamically inserting pathologies into the model but have not been able to solve some low-level compatibility problems. We have developed a technique for "stitching" in a pathology or anatomical variation in a given place in the anatomy. The technique involves producing a polygonal mesh model with a set of base or edge vertices that must be merged with the underlying polygonal anatomical model. In addition to the base mesh where it will be stitched into the anatomy, the pathology model includes a set of orientation vectors. These include a normal vector which after placement should be roughly perpendicular to the average surface normal of the local anatomy along with an axial orientation vector after placement should be approximately parallel to the axis of local lumen of the anatomy, for example the ureter. We indicate an approximate area where the pathology should occur, then use a local search procedure to find the polygon that comes closest to containing each vertex. We find the point on that polygon that is nearest the stitch vertex and from that point place an additional vertex there, then warp that vertex up (or down) to the position of the stitch vertex. This has the effect, for each stitch vertex, of adding two new triangles to the mesh at that point. The technique works well, but has some residual artifacts. In particular, overall scaling of the pathology is unrealistically affected by local anatomical variations. We attempted to extend this with a technique to make the pathology exist in it's own reference frame whereby it's shape is invariant even in the presence of severe surrounding anatomical movement.

Better methods for photo-realistic texture mapping

An issue in simulating long, tubular structures is that our graphics rendering hardware requires the visual surfaces to be rendered with texture maps that are square, e.g. 128 x 128 pixels or 256 x 256 pixels. The resultant bit maps, when mapped onto a long structure, are stretched in one dimension in a way that makes it very difficult for the medical illustrators to develop a realistic rendering. We developed a method of using smaller square bitmaps and tiling them so as to effectively allow the use of rectangular, not square, textures. Evaluations of the technique indicate that it provides good results, while simultaneously minimizing the use of texture memory. Combining this with the techniques reported above for the endoscopic lighting model and the fluid flow and refraction models described above provides an overall endoscopic view that is shown to be satisfactory for ureteroscopy training. See Figures 2 and 3 in Appendix C for examples.

Prototype Simulator

Our progress of the above mentioned tasks has enabled us to construct a prototype simulator (see Figure 1 in Appendix C). This simulator was demonstrate at the American Urological Associations Annual Meeting (April 30-May 4, 2000) and the World Congress of Endourology (September 14-16, 2000). At these meetings, the prototype simulator was used by the leading experts in ureteroscopy from around the world. They unanimously agreed that the simulator was very realistic and would be a very valuable training tool. The main request was for the use of working channel tools to remove the renal calculi. While we have the underlying technology for this, our current resources do not allow us to complete this final integration at this time. Efforts are currently underway to secure funding to finish the working channel tool functionality and to produce a final product.

III. Key Research Accomplishments

- ☐ Produced task analysis of flexible ureteroscopy
- ☐ Integrated simulated fluoroscopic and endoscopic displays
- ☐ Advanced contrast fluid flow algorithms
- ☐ Developed several physics-based models of flexible endoscope

- ☐ Constructed of an computer-based geometric model of the urinary tract from CT data sets
- ☐ Developed set of modeling tools that enable efficient development of anatomic and pathologic variations
- ☐ Designed and built devices that allow for the application of force feedback on working channel tools
- ☐ Built prototype ureteroscopy simulator
- ☐ Prototype simulator praised by experts in ureteroscopy at the American Urological Associations Annual Meeting 2000 and the World Congress of Endourology 2000 meeting.

IV. Reportable Outcomes

1. Tasto JL, Verstreken K, Brown JM, Bauer JJ. PreOp™ Endoscopic Simulator: From Bronchoscopy to Ureteroscopy. *Proceedings of Medicine Meets Virtual Reality 2000*; Newport Beach, CA; January 27-30, 2000; 344-349. See appendix D.
2. Tasto JL, Bauer JJ, Verstreken K, Brown JM, Merril GL. Training Simulator for Endoscopic Procedures. *American Telemedicine Association Fifth Annual Conference and Exhibit Showcase*; Phoenix, AZ; May 21-24, 2000. See appendix E.
3. Preminger GM, Auge BK, Greenberg J, Tasto J. Virtual Reality in Endourology Training. *Proceedings of World Congress of Endourology 2000*; Sao Paulo, Brazil; September 14-16, 2000.

V. Conclusions

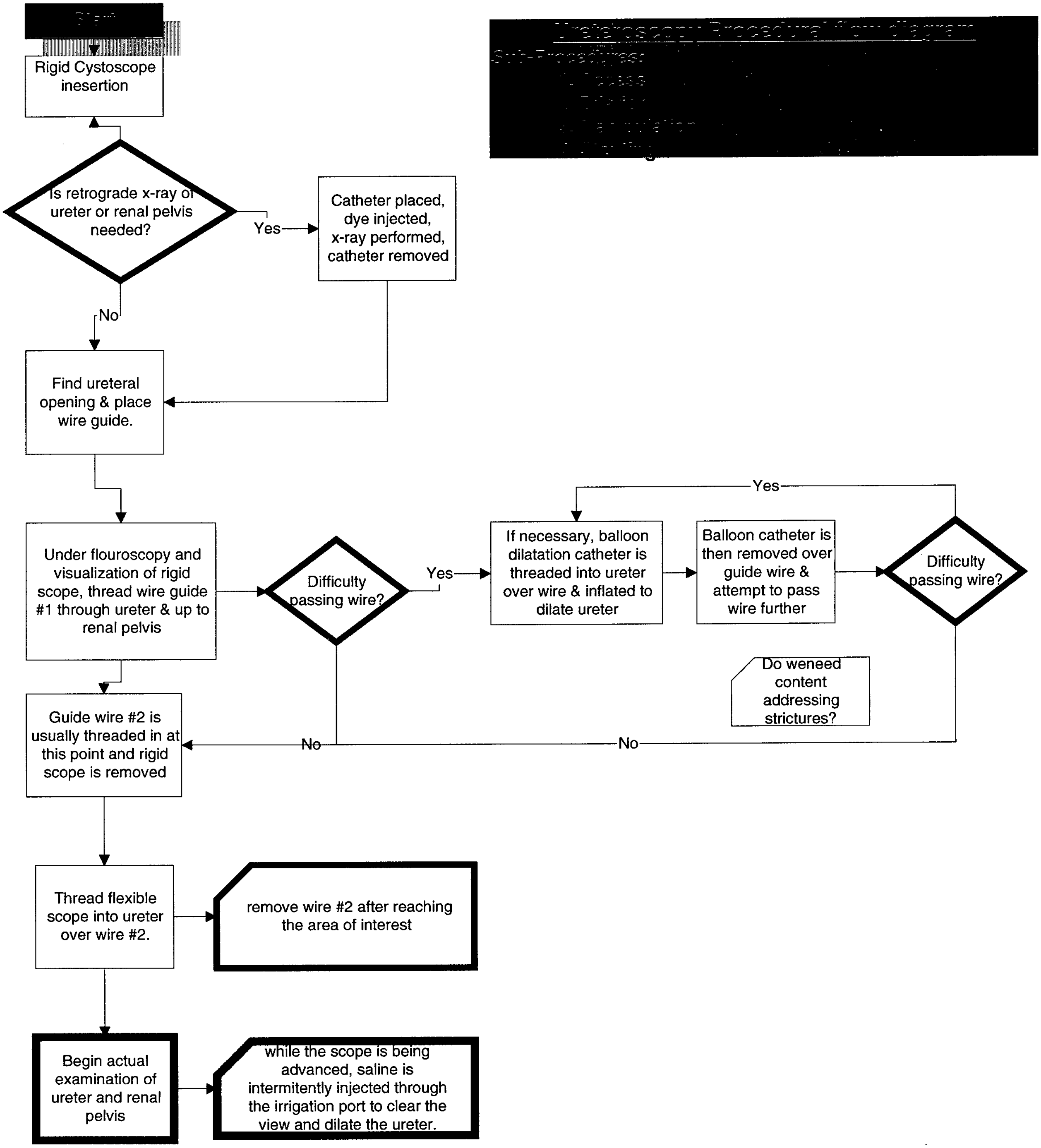
The research conducted during this contract resulted in the development of a realistic and robust prototype simulator for training in ureteroscopy. The prototype was evaluated by experts in ureteroscopy at the American Urological Associations Annual Meeting 2000 and the World Congress of Endourology 2000 meeting. These experts concluded that the simulator was very realistic and would be a very valuable training tool.

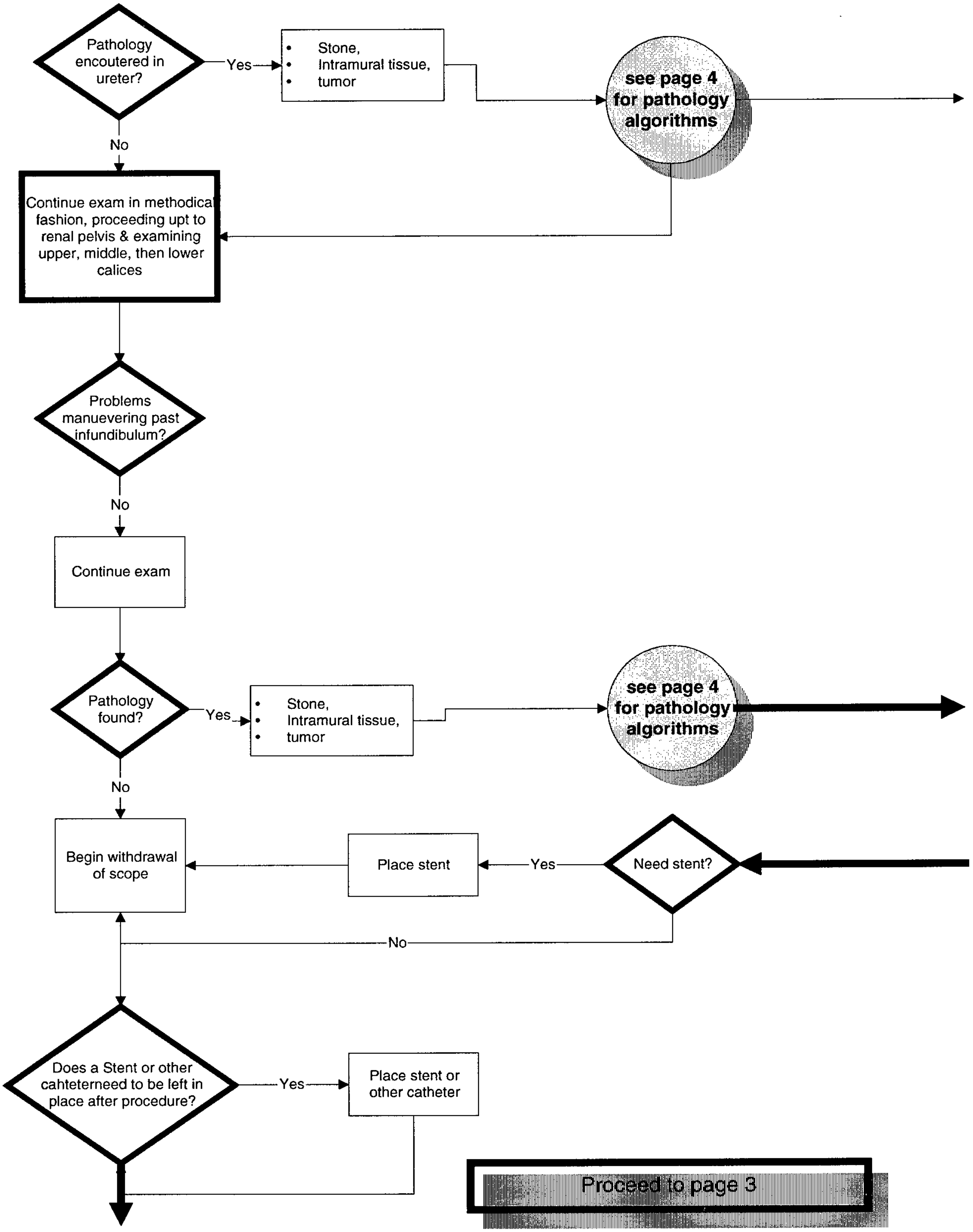
Future work in this area should concentrate on integrating the force feedback device into the working channel of the ureteroscope and developing the software to simulate a variety of working channel tools (e.g., stone baskets). The technology developed for this prototype should also be leveraged to develop other endoscopic and fluoroscopic simulators.

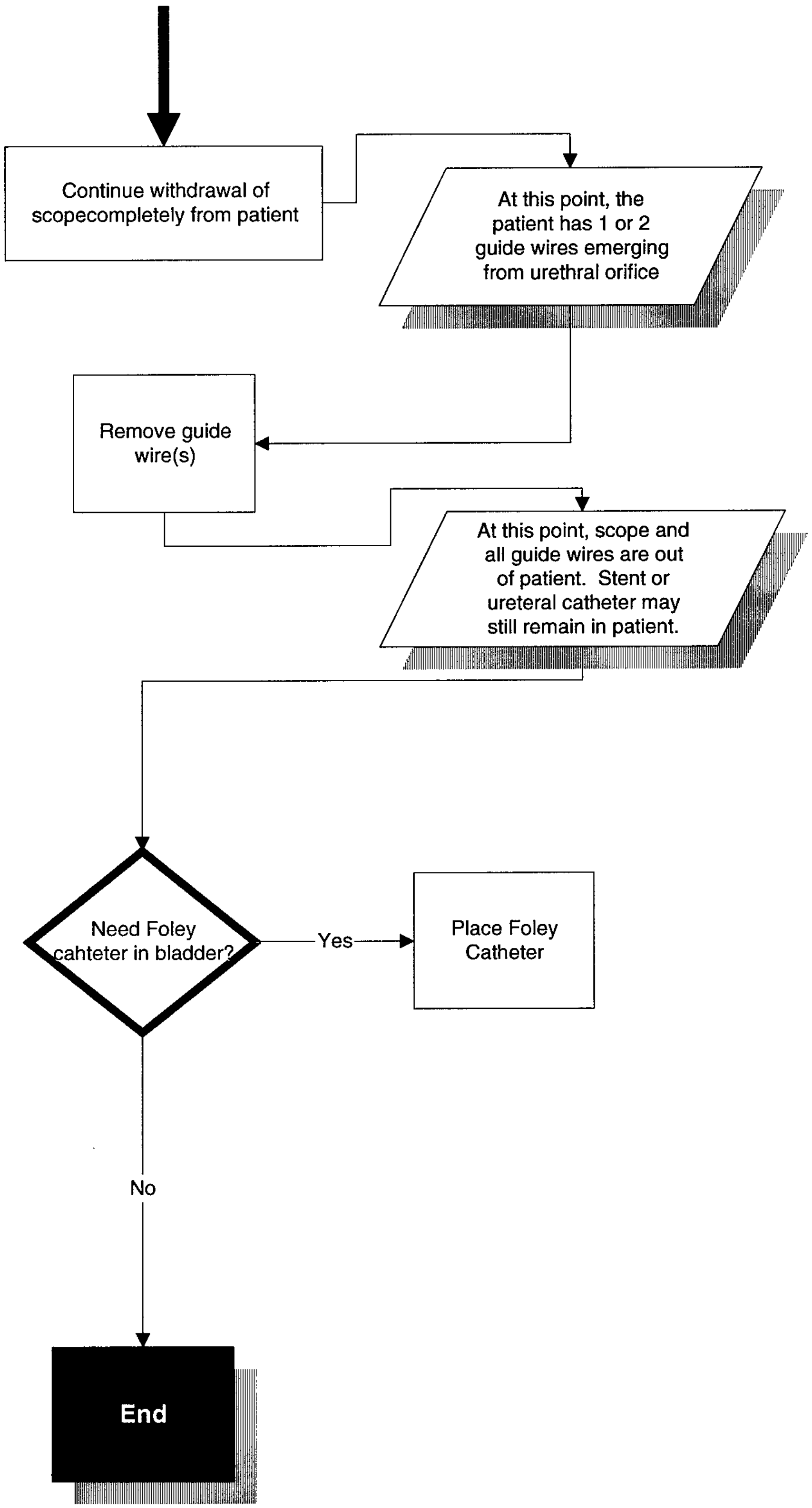
VI. References

1. Tasto JL, Verstreken K, Brown JM, Bauer JJ. PreOp™ Endoscopic Simulator: From Bronchoscopy to Ureteroscopy. *Proceedings of Medicine Meets Virtual Reality 2000*; Newport Beach, CA; January 27-30, 2000; 344-349.
2. Tasto JL, Bauer JJ, Verstreken K, Brown JM, Merril GL. Training Simulator for Endoscopic Procedures. American Telemedicine Association Fifth Annual Conference and Exhibit Showcase; Phoenix, AZ; May 21-24.
3. Preminger GM, Auge BK, Greenberg J, Tasto J. Virtual Reality in Endourology Training. Proceedings of World Congress of Endourology 2000; Sao Paulo, Brazil; September 14-16, 2000.

Appendix A: Ureteroscopy Task Analysis




Pathology encountered in ureter?
Yes
Stone,
Intramural tissue,
tumor
see page 4 for pathology algorithms
No
Continue exam in methodical fashion, proceeding upt to renal pelvis & examining upper, middle, then lower calices
Problems manuevering past infundibulum?
No
Continue exam
Pathology found?
Yes
Stone,
Intramural tissue,
tumor
see page 4 for pathology algorithms
No
Begin withdrawal of scope
Place stent
Yes
Need stent?
No
Does a Stent or other cahteterneed to be left in place after procedure?
Yes
Place stent or other catheter
Proceed to page 3


Continue withdrawal of scopecompletely from patient
At this point, the patient has 1 or 2 guide wires emerging from urethral orifice
Remove guide wire(s)
At this point, scope and all guide wires are out of patient. Stent or ureteral catheter may still remain in patient.
Need Foley cahteter in bladder?
Yes
Place Foley Catheter
No
End

[redacted]

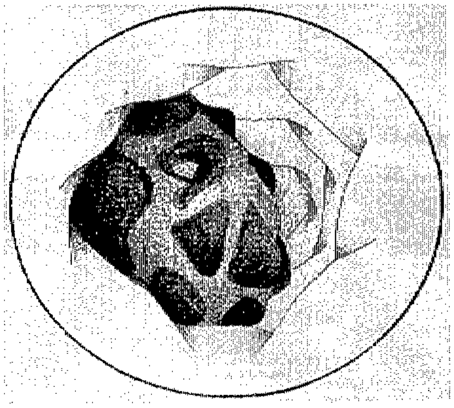


Figure 6.1. A schematic of a calcium oxalate monohydrate ureteral calculus. Access is first obtained in a retrograde fashion.

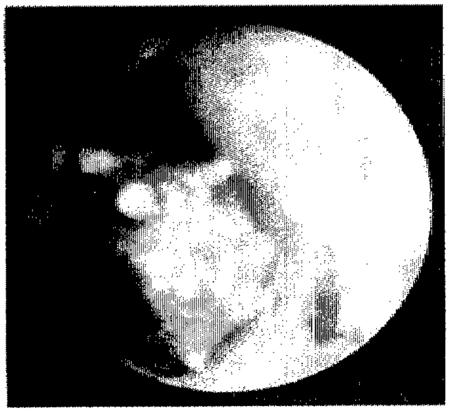


Figure 6.5. A [illegible] stone composed of [illegible]

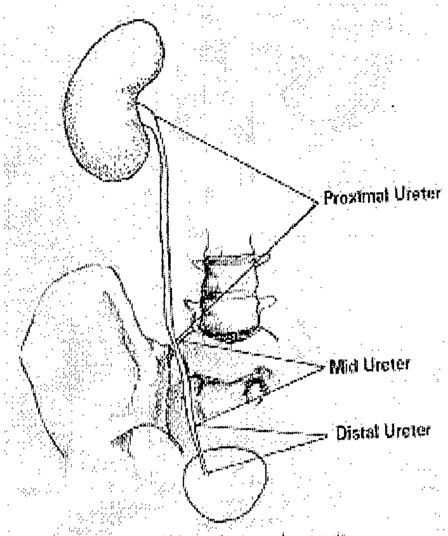
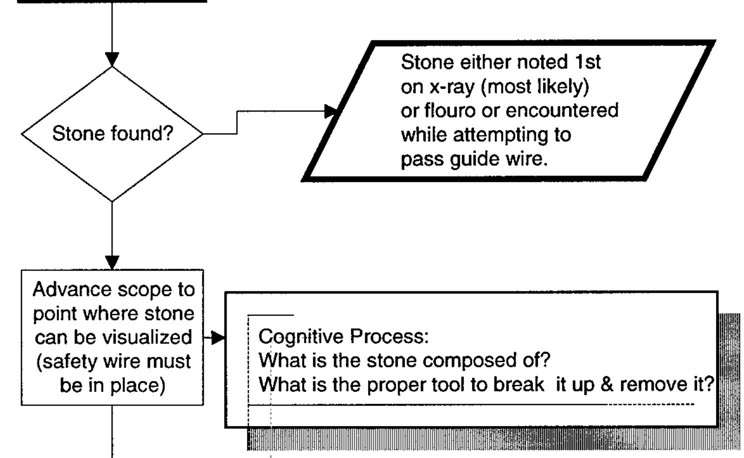
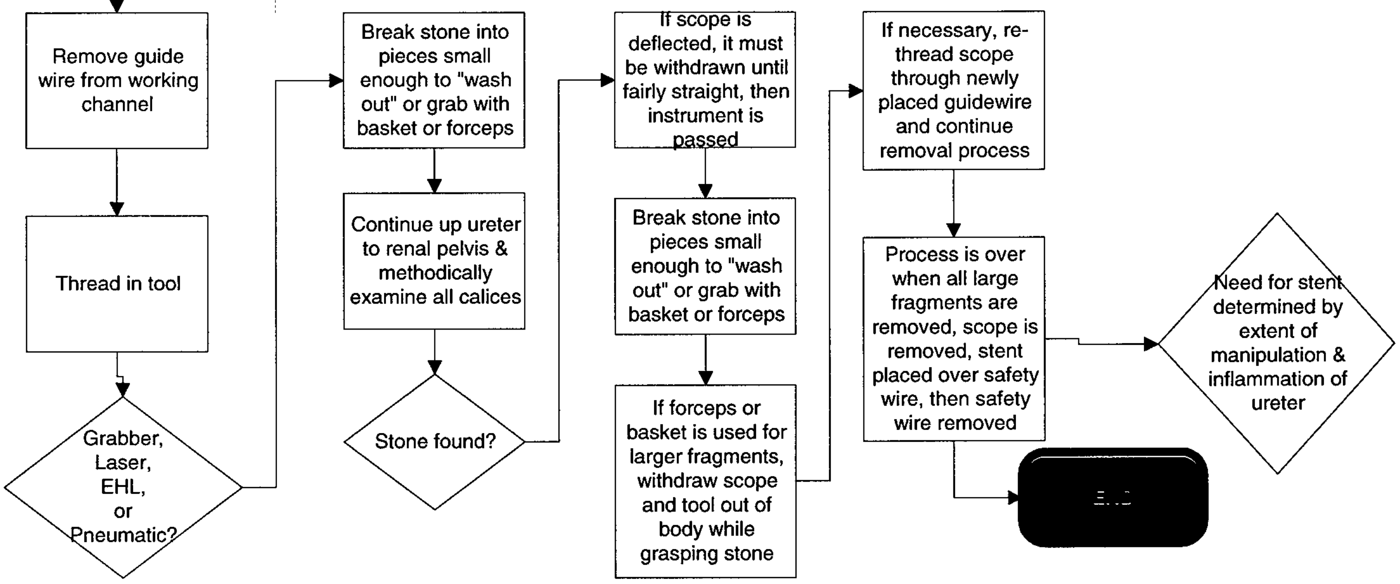


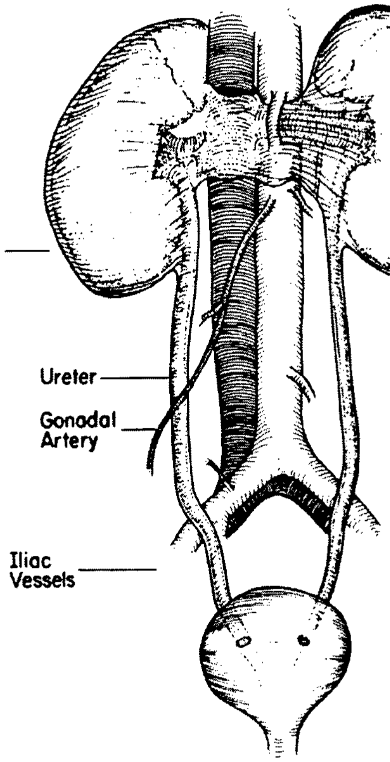
FIGURE 5-5. Ureteral segments.

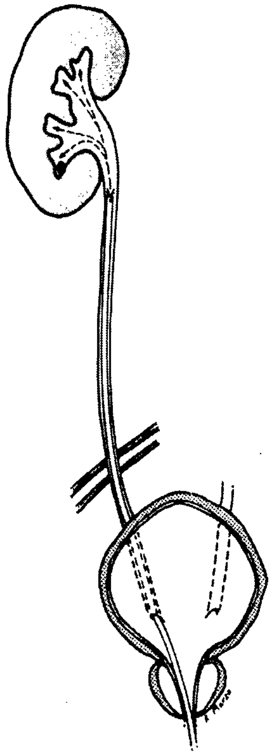
[redacted]





Appendix B: Relevant Anatomy for Ureteroscopy





Appendix C: Ureteroscopy Simulator Images

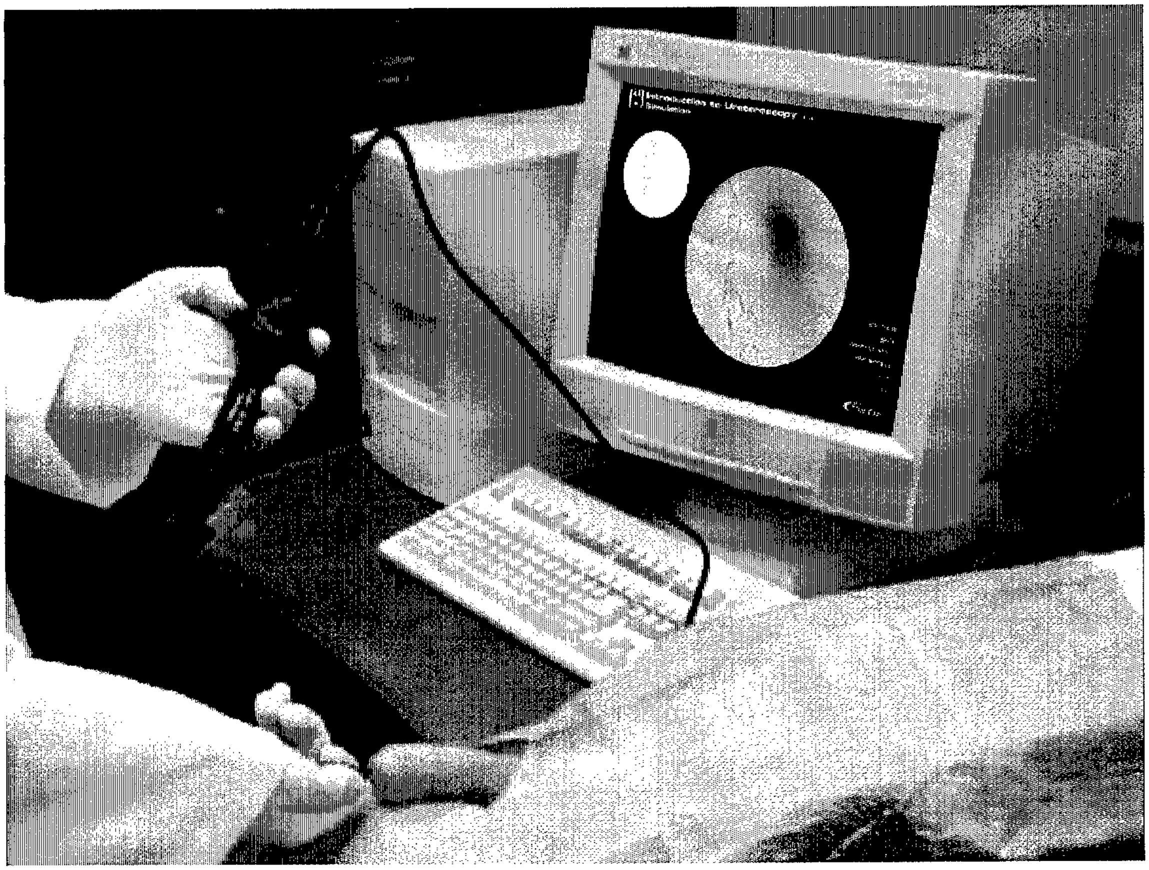


Figure 1: Ureteroscopy Simulator

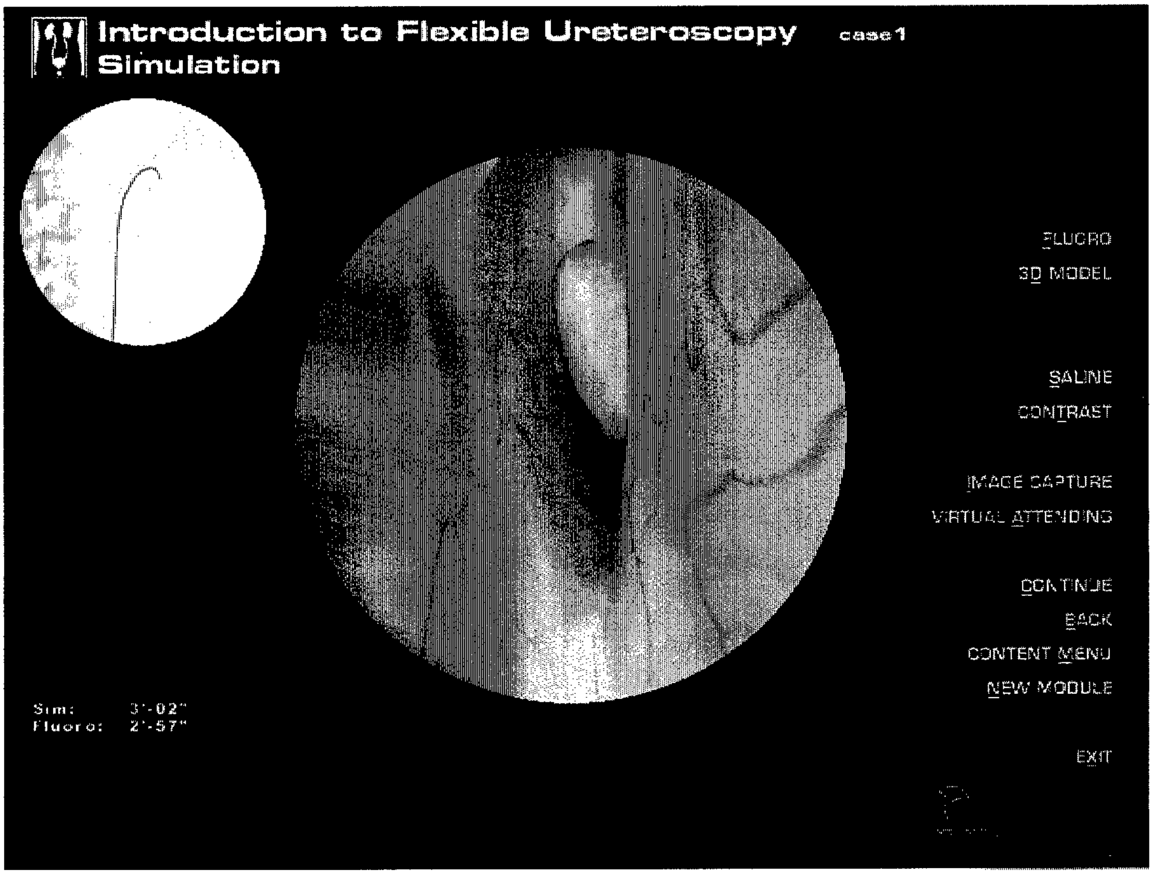


Figure 2: Simulated Ureteroscopic View with Renal Calculi

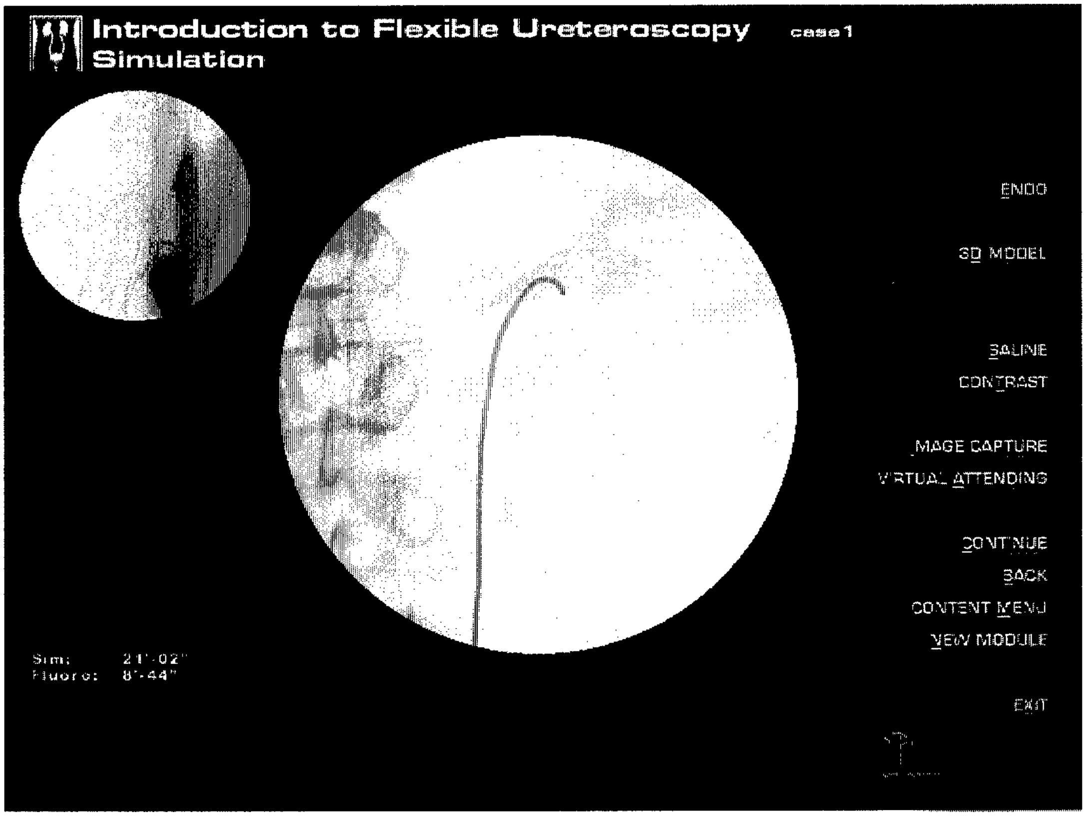


Figure 3: Simulated Fluoroscopic View of Ureteroscope

Appendix D: MMVR Paper

PREOP™ ENDOSCOPY SIMULATOR: FROM BRONCHOSCOPY TO URETEROSCOPY

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Abstract: The high cost of virtual reality simulators has posed a major obstacle to the widespread adoption of simulators for medical training. HT Medical broke through this cost barrier by developing the PreOp™ Flexible Bronchoscopy simulator, a realistic training simulation system that integrates force feedback, multimedia, and 3D graphics on a PC. We are currently extending the PreOp platform so that it can simulate other endoscopic procedures. This paper discusses our efforts to extend the platform to simulate flexible sigmoidoscopy and ureteroscopy.

1. Introduction

The high cost of virtual reality simulators has posed a major obstacle to the widespread adoption of simulators for medical training. HT Medical broke through this cost barrier by developing the PreOp™ Flexible Bronchoscopy simulator, a realistic training simulation system that integrates force feedback, multimedia, and 3D graphics on a PC.[1] This system, which became a commercially available product in the spring of 1999, consists of PC-based software, a proxy flexible bronchoscope and a robotic interface device that tracks the scope and provides force feedback to the user.

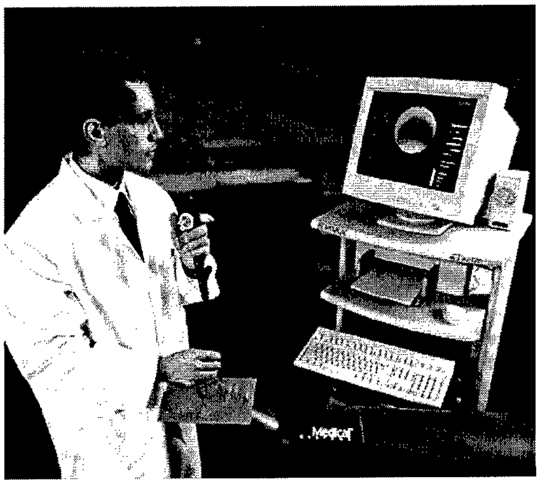

Figure 1: HT Medical's PreOp™ Flexible Bronchoscopy Simulator

We are currently extending the PreOp platform so that it can simulate other endoscopic procedures. This will allow the cost of the simulator to be shared across departments at medical schools and hospitals, accelerating the introduction of the PreOp simulator into the clinical setting. This paper discusses our efforts to extend the platform to simulate flexible sigmoidoscopy and ureteroscopy.

2. Medical Analysis

2.1 Flexible Sigmoidoscopy

The goal of flexible sigmoidoscopy is to inspect the colon for pathologic lesions using an endoscope. Often this is performed as a screening exam for colorectal cancer. There are two distinct stages of the exam. The first stage consists of advancing the sigmoidoscope from the anus to the point of maximum insertion. The point of maximum insertion depends on many factors such as the scope length, the patient's anatomy, and the level of patient discomfort. However, a 60-cm scope can usually reach the splenic flexure, which is where the transverse colon and the descending colon meet. The second stage of the procedure consists of carefully examining the mucosal walls of the colon as the scope is slowly withdrawn.

Simulating flexible sigmoidoscopy is more challenging than bronchoscopy for several reasons. Table 1 summarizes some of the pertinent differences between bronchoscopy and sigmoidoscopy. Of particular note is that the tracheobronchial tree is relatively fixed and rigid compared to the elastic and mobile colon. These differences greatly increase the computational time, which is a paramount problem given the constraints of 15-30 frames per second for real-time simulation. In addition, the sigmoidoscope is twice the diameter of the bronchoscope and has additional controls, such as left/right tip control and a two-state air/water insufflation button.

Table 1: Comparison of Significant Differences between Bronchoscopy vs. Sigmoidoscopy

Procedure Feature	Bronchoscopy	**Sigmoidoscopy**
Local Anatomy	Rigid Smooth Mucosa	Elastic Mucosal Folds
Global Anatomy	Fixed	Mobile

	Complex branching pattern	Single tube
Local Physiological Motions	Bronchial spasm Heart/aortic pulsations	Colon spasm
Global Physiological Motions	Respiratory motions	Peristalsis
Scope Length	55 cm	60 cm
Scope Diameter	6.0 mm	12.2 mm
Scope Tip Control	Up/Down	Up/Down Left/Right
Scope Buttons	Suction	Suction Air/Water insufflation

2.2 Flexible Ureteroscopy

Ureteroscopy is performed to remove kidney stones, fragment large kidney stones (lithotripsy), biopsy a tumor, or remove stents. The goal of ureteroscopy is to navigate the endoscope from the entrance of the urethra, through the bladder, into the ureter, and up to the calyces of the kidney. Access to the ureter is typically obtained by inserting a rigid cystoscope through the urethra in the penis or vagina and into the bladder. A guidewire is then navigated through the ureterovesical junction (where the ureter empties into the bladder). A balloon catheter is used to dilate the distal portion of the ureter where it inserts in the bladder. Occasionally the proximal portion of the ureter must also be dilated. The flexible ureteroscope is then advanced over the guidewire and into the ureter. The scope can be advanced up to the kidneys and procedures performed.

Ureteroscopy presents unique challenges over and above bronchoscopy and sigmoidoscopy. From a simulation standpoint, ureteroscopy can be thought of as a hybrid between bronchoscopy, sigmoidoscopy, and angioplasty. Like the tracheobronchial tree, the calyces of the kidney branch extensively, allowing for multiple paths. Like sigmoidoscopy, the ureter is a single distensible tube. Like angioplasty, ureteroscopy requires fluoroscopy, contrast injection, balloon catheters and guidewires. Thus ureteroscopy requires a system that incorporates simulation technology from bronchoscopic and sigmoidoscopic simulation, as well as from HT Medical's PreOp™ Endovascular Simulator (shown in Figure 2). We have chosen to simulate the endoscopic portion of ureteroscopy first and then add the endovascular features. Therefore, this paper will limit the discussion to endoscopic simulation.

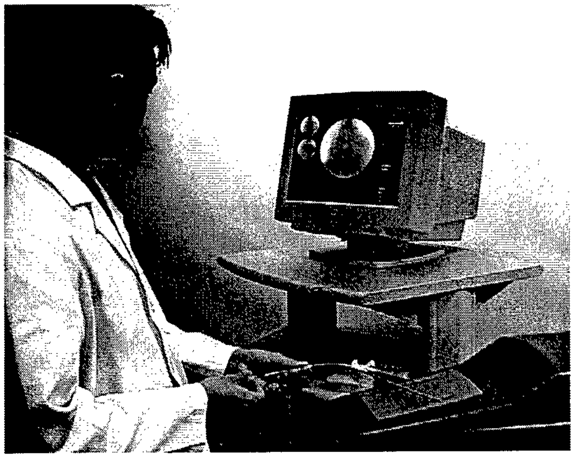

***Figure 2:** HT Medical's PreOp™ Endovascular Simulator*

3. Software Design

The tasks for the software can be broadly defined as (1) receive information from the user through the software interface and hardware interface, (2) perform the necessary computations that the user's actions require, and (3) control the resulting visual, tactile, and auditory feedback that the user receives. For example, (1) the user translates the proxy sigmoidoscope 5 cm; (2) the software then computes the consequence of this action (e.g., collision of the scope with the mucosal wall); (3) a "red-out" is displayed in the endoscopic view, the virtual patient says, "ouch," and the robotic interface device provides a resistive force that is felt by the user.

3.1 Flexible Sigmoidoscopy

From a computer-modeling standpoint, the most significant difference between bronchoscopy and sigmoidoscopy is that the tracheobronchial tree is a relatively rigid and fixed structure, while the colon is much more elastic and mobile. These differences are outlined in Table 1. Cartilaginous rings and plates support the bronchi, whereas the colon has no such rigid support. The tracheobronchial tree does not twist, rotate, and loop like the colon does.

The key element in the software design is therefore realistic modeling of the colon, the flexible sigmoidoscope, and the colon-scope interaction. This modeling can be divided into global and local modeling tasks. Global modeling defines the interaction between the entire scope and the entire colon model. Local modeling concentrates on the interactions between the scope tip and portion of the colon that is located in the immediate environment of the scope tip (which is where the scope view originates).

Examples of behaviors handled at the global level are formation of loops in the colon (e.g., alpha loops or N-loops), changes in length and diameter of the colon with suction and insufflation of air, shortening/lengthening of the colon due to compression/expansion of the haustral folds in an accordion-like fashion (i.e. "sleeving up the colon"), and "paradoxical movement" of the scope tip (scope tip retracts as scope shaft is advanced).

Examples of behaviors handled at the local level are deformation of the colon wall in response to pressure from the tip of the scope, "red-out" of the display when the scope tip pushes against the colon wall, the scope's interaction with mucosal (haustral) folds or other detailed structures such as polyps, and force feedback resulting from interaction of scope tip with the colon wall

3.2 Flexible Ureteroscopy

As mentioned above, flexible ureteroscopy requires the use of several simulation techniques. Therefore, we have chosen to divide the approach into three categories, based on the specific challenges posed by the different anatomical structures to be modeled. For the bladder, accurate modeling of wire dynamics is necessary for the navigation of the guidewire into the ureter and dilatation of the distal ureter with a balloon catheter. The ureter has properties similar to the colon and will thus be modeled using the global/local approach described above for flexible sigmoidoscopy. The kidney requires an emphasis on path finding because of the branching pattern of the calyces. Accurate collision detection is necessary to constrain the scope to the chosen path.

4. Hardware Design

Our present endoscopy simulator comprises a computer, a display monitor, and the AccuTouch™ Endoscopic Interface Device (patent pending). The interface device consists of a proxy endoscope that looks like a real endoscope and is electrically connected to the second part of the interface device, a robotic "mannequin" into which the endoscope can be inserted. Various sensors, detailed below, track the state of the system and send this information back to the host computer via a data cable. The simulation uses this state information to compute appropriate visual and tactile responses to the motions imparted by the user. These responses are transmitted to the user through visual, audio and haptic modalities, creating a powerful illusion for the user that he/she is inserting the endoscope into a real patient.

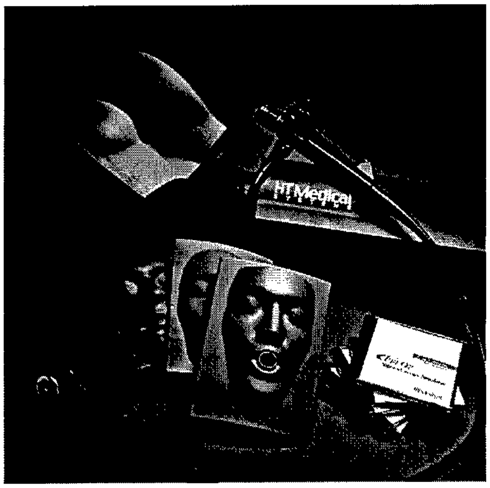

Figure 3: PreOp interface device

The endoscopy "mannequin" approximately represents the anatomical insertion site, accepts any of several proxy scopes, tracks scope insertion and rotation, and provides force feedback through the endoscope to the user's hands. Representation of the anatomical insertion site is achieved through use of a detachable local anatomic model, which is user-adjustable into horizontal, sideways, or vertical configurations.

The robotic "mannequin" has been designed to accept proxy bronchoscopes, sigmoidoscopes, colonoscopes, gastroscopes, and ureteroscopes through the appropriate anatomic models. Tracking of scope motions is achieved with sensors that monitor insertion and rotation of the scope tube, while electrical actuators provide translational and/or rotational force feedback based on the state of the endoscopy simulation.

The bronchoscope was designed to look and feel like a real scope, with the same controls, force feedback, and scope tube as the real medical tool. It accepts a proxy working channel tool, tracking both tool translation and rotation, and provides translational force feedback to the user. The scope also tracks the motion of the thumb lever, and monitors the state of the suction button and video control buttons, making that information available to the simulation. These sensor readings and actuator commands are transmitted to the host computer via a custom data cable, which looks and feels like the video/light source cable that normally is attached to the scope.

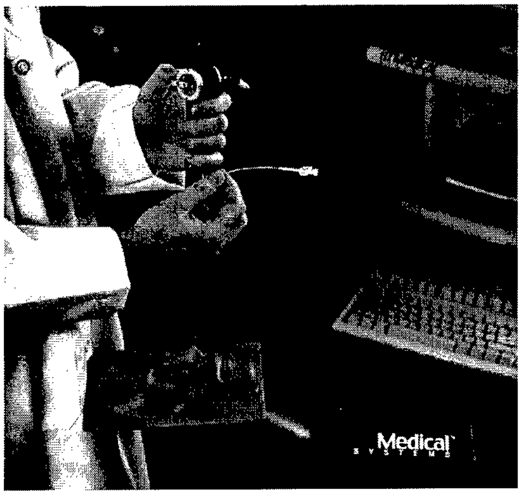

Figure 4: Manipulation of working channel tool

4.2 Flexible Sigmoidoscopy

We have developed a sigmoidoscope following similar design guidelines. As with the bronchoscope, the sigmoidoscope accepts a proxy working channel tool, tracking its translation and rotation, and providing translational force feedback to the user. The scope tracks the two knobs that control up/down and left/right motion of the scope tube tip, and has locking mechanisms as in the real scope. In addition to the suction and video control buttons, the sigmoidoscope has a two-stage button for controlling air insufflation and water instillation. These sensor readings, along with the actuator commands, are transmitted back to the host computer through the same type of data cable as with the bronchoscope.

4.2 Flexible Ureteroscopy

Currently in development, the proxy ureteroscope will incorporate many of the features described above. As in the previous cases, the scope will need to track its working channel, along with the control levers and buttons. Subtleties of the design include accommodating the smaller diameter scope tube (3.2mm, as opposed to 5.3mm for the bronchoscope and 12.2mm for the sigmoidoscope) and incorporating the use of guide wires and balloon catheters during the procedure.

5. Conclusion

The PreOp Endoscopy Simulator was designed to be modular in nature so that all endoscopic procedures could be simulated on the same software and hardware platforms. The first endoscopic procedure simulated on the PreOp platform was flexible bronchoscopy. This simulator is commercially available and has been sold both in the United States and internationally. We are currently developing modules for flexible sigmoidoscopy and flexible ureteroscopy. These additional modules will allow the cost of the system to be shared across medical specialties, thus making the system affordable and accelerating the use of simulation in the medical setting.

6. Acknowledgments

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References

[1] Bro-Nielsen M, Tasto JL, Cunningham RL, Merril GL. PreOp™ Endoscopic Simulator: A PC-based immersive training system for bronchoscopy. In: *Proceedings of Medicine Meets Virtual Reality* 7; San Francisco, CA; January 20-23, 1999; 76-82.

Appendix E: ATA Abstract

Training Simulator for Endoscopic Procedures

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Medical simulators offer the potential to improve medical training, decrease costs, and provide objective measurements of procedural competence for credentialing and certification. However, the two biggest challenges to the adoption of this technology has been the high cost and inadequate realism associated with this technology. Until recently, computer-based simulations required expensive high-end computers to maintain the real-time frame rates necessary for realistic simulation.

These challenges were overcome with the introduction of HT Medical's PreOp™ Flexible Bronchoscopy simulator, a realistic training simulation system that integrates force feedback, multimedia, and 3D graphics on a PC. This presentation will focus on the research and development efforts underway to extend this simulation system to other endoscopic procedures, such as ureteroscopy and flexible sigmoidoscopy. We describe the trade-offs and solutions that we developed to overcome the challenges of simulating the wide variety of endoscopic procedures on the same hardware and software platform.

Dr. Tasto has a unique background in medicine, engineering, and medical education. He has a Bachelor of Electrical Engineering, a Master of Science in Electrical and Computer Engineering, and Doctor of Medicine degree. Prior to joining HT Medical, Dr. Tasto was involved in innovative curriculum development for medical training. He has worked as an engineer in the field of medical imaging systems simulation. In addition, Dr. Tasto developed simulation software while employed at General Motors. He has published in the fields of medical simulation systems, medical education, emergency medicine, and electrical engineering.