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# Computer Modeling of Anatomical Structure: A Representative Example of Modeling the Inguinal Canal

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# Computer Modeling of Anatomical Structure: A Representative Example of Modeling the Inguinal Canal

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science at Virginia Commonwealth University.

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| | |
|---|---|
| 3-D | Three-dimensional |
| ANOVA | Analysis of Variance |
| CAI | Computer-Aided Instruction |
| CAD | Computer-Aided Drawing |
| CAL | Computer-Assisted Learning |
| CAM | Computer-Aided Modeling |
| CBI | Computer-Based Instruction |
| CD-ROM | Compact Disc Read Only Memory |
| CEI | Computer-Enhanced Instruction |
| CMI | Computer-Managed Instruction |
| CT | Computed Tomography |
| MB | Megabytes |
| MRI | Magnetic Resonance Interferometry |
| PET | Proton Emission Tomography |
| RAM | Random Access Memory |
| RGB | Red Green Blue |
| UFCT | Ultra Fast Computed Tomography |

# ABSTRACT

COMPUTER MODELING OF ANATOMICAL STRUCTURE: A REPRESENTATIVE EXAMPLE OF MODELING THE INGUINAL CANAL

By Jason Michael Highsmith

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science at Virginia Commonwealth University.

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As computers become an increasingly important part of medical education, a proper understanding of the techniques and applications of computer aided modeling is vital. An initial overview of medical imaging and the techniques of computer modeling is presented. Construction of three-dimensional models of anatomical structures is then discussed in great detail with specific focus on modeling structures like the inguinal canal. The inguinal canal is one region where computer modeling efforts should be directed because

it presents a special challenge. Understanding the walls, borders and layering of the inguinal canal is especially difficult but vital to accurate clinical diagnoses of hernias. Computer-based instruction based on high-quality three dimensional images promises to greatly enhance students' learning and comprehension of difficult anatomical structures and relationships.

# INTRODUCTION

The 21st century beckons the dawn of a new era integrating computer technology and medical imaging. With that, technology has revolutionized our definitions and use of three-dimensional imaging. In the 1950's photowheels were used in Viewmasters™ to view three-dimensional images stereoscopically. At that point in time the reality of today's high-powered graphics workstations was little more than science fiction. Recent technological advances over the last decade have afforded scientists and educators the opportunity to explore new applications of computers in medicine. With the advent of affordable multimedia, or the integration of text, graphics, and sound, computers have taken an even greater position in the medical curriculum.

Two areas of medicine in which computers now play a fundamental role are diagnostic imaging and computer aided instruction. Both of these areas also hold great potential for the application of three-dimensional modeling and anatomical education. Central to this approach is the understanding that anatomy, by its very nature, stands to gain a tremendous amount from computer modeling. Most conventional instructional aides are two-dimensional drawings that are difficult to translate into a three-dimensional understanding. Furthermore, an accurate understanding of anatomy is the basis for a myriad of clinical skills. From the basic physical examination and diagnosis of pathologies, to planning treatment routines and accurate surgical approaches, anatomy is a fundamental component of medical practice and thus, of medical education.

Since the initial use of plain film X-rays in 1895, by Wilhelm Conrad Röentgen, the role of diagnostic imaging in medicine has increased tremendously. Two relatively recent developments in radiological technology have afforded the data necessary for three-dimensional modeling. These modalities are computed tomography (CT) slices and magnetic resonance interferometry (MRI) data. Computerized three-dimensional modeling relies on the serial cross-sectional data that these modalities provide, as will be discussed later.

Before addressing the materials and methods of three-dimensional imaging, it is important to understand the broad applications of computer aided imaging and its implications for computer aided instruction.

## Clinical Applications

Computer modeling of anatomical structure on both the histological and gross level represents the size and shape of various structures. Histological modeling has focused primarily on cellular components, for example shape analysis of chromosomes (Bertin et al., 1993) and cell nuclei (Parazza et al., 1993). Others have examined pulmonary alveolar duct microanatomy and structure (Cookson et al., 1993). These applications have predominately made use of confocal microscopic techniques as the basis of three-dimensional viewing.

Most of the work done in computer aided three-dimensional modeling has focused on gross anatomical structures. Clinically, one of the most useful applications of computer aided imaging has been in the diagnosis and treatment of cranial carcinomas. The ability of it to accurately calculate volumes makes three-dimensional imaging especially useful to this area (Gault et al., 1988). Imaging has also proven successful in measuring volumes of the cranial vault and ventricles (Dufresne et al., 1987), and the orbit, orbital fat, and muscles (Zonneveld et al., 1991). Volume assessments are crucial not only in evaluating the metastasis of cranial carcinomas, but in calculating chemotherapy and radiation doses as well. These same images have also proven useful in guiding surgical approaches to the tumor.

Another clinical application of volumetric imaging has been measurement of cavities in artificial joint replacement procedures. The thickness of the joint space can be accurately measured to evaluate the location and extent of femoral head necrosis (Soyama et al., 1989). When these data are taken into account, the prosthesis can be placed more accurately to assure maximal contact area in the joint replacement (Wespe et al., 1989) and effectively better recovery for the patient. In some cases, computers have even been used to automate the determination of the most suitable position of the femur in a hip-joint surgery (Eba et al., 1990).

Multimodality imaging is a special diagnostic process that incorporates two or more traditional components. For example, images from a bony structure, which is ideally suited to CT data, can be overlaid on soft-tissue data such as gathered from a T1 weighted MRI. More specifically, cardiovascular data from angiograms have been successfully mapped onto CT images to better understand the impacts of hemorrhaging, ischemia and infarcts (Henri et al., 1991). Since the mid-1980s, this approach has been successful in reducing the risk of rupturing large cranial arteries by planning stereotactic approaches to target points in the brain (Peters et al., 1986 and Kall, 1987).

Surgical navigation, also known as computer-assisted surgery, has also benefited from recent advances in three-dimensional imaging. The purpose of such a technique is to topographically map the location of the surgeon's instruments in relation to critical anatomical structures surrounding the point of operation. Traditionally, this has been performed with intraoperative ultrasound, but this is not practical in areas such as the head where ultrasound cannot adequately differentiate among tissues (Zonneveld, 1994). This is where computer generated volumetric data sets are especially helpful. A pre-recorded set of CT or MRI data can be used to create registration markers, like digital flags.

When a probe is passed near or through a certain area, that area is highlighted by a moving cursor on a display (Zonneveld, 1994). Essentially, it is like navigating a city at night using the grid created by streetlamps on each city block corner. Like the streetlamps, registration markers serve as points of reference and as the basis of navigation.

Another application of image registration involves tracking the position of a rigid endoscope in endonasal sinus surgery. The surgeon is able to correlate the endoscopic view with the computerized topographic view of the paranasal sinuses (Kainz and Stammberger, 1992). This variation of a standard procedure is especially beneficial when the endoscopic image is obstructed by mucus or pus. By using an endoscopic image superimposed on a CT image, the surgeon can carefully navigate the scope and avoid damage to delicate surrounding structures (Zonneveld, 1994).

Registration-based mapping of anatomical structure is one basis for the interest in creating entire digital atlases of the human body. This also provides a bridge between the purely clinical and the purely academic applications of three-dimensional modeling. A great deal of interest has been generated in the use of three-dimensional atlases for medical education, specifically for anatomy. Some have even gone so far as to say that the instruction of anatomy stands to benefit from computer atlases more than any other biomedical discipline (Rosse, 1995).

## Academic Applications

Before progressing further, it is important to realize why anatomy instruction stands to gain so much by the use of computers. Anatomical reasoning is the basic requirement for performing a number of clinical tasks (Rosse, 1995). Such reasoning integrates both an understanding of the spatial domain, or three-dimensional geometry of the body and its parts, and the symbolic domain, or understanding of functional, developmental, pathological, and other relationships. These two domains have traditionally been difficult to integrate (Rosse, 1995). Indeed, most instructors tackle them as two separate domains: the gross anatomy lab and the lecture hall. Innovative applications of computers as instructional aids should help unify the teaching and learning of spatial and conceptual knowledge.

Some of the first uses of computers in education incorporated laser videodisc players. In a time when computer graphics were limited by technology and cost, the laser videodisc provided access to a vast library of pre-defined images and photographs. Because laser videodiscs have the capacity to store several thousand frames of high-resolution images they are ideal for this type of application. Using a computer alongside the laser videodisc simplifies navigation through the disc by providing convenient access to the images and indexing of them. The computer would then aid in selecting the images of interest which are then displayed on a television. The computer screen provides text captions and narrative as well. This was the beginning of interactive medical instruction in that it provided rapid access to a vast array of data.

In recent years, the term Computer-Based Instruction (CBI) has begun to encompass all uses of the computer in the educational process (Dowd and Bower, 1995). The most basic use of the computer in education is through Computer-Managed Instruction (CMI) where the computer is used merely for management of instructional activities. For example, class scheduling and test development/scoring are some practical uses of CMI as are the outlining of learning objectives and diagnosis of learning needs.

On a more advanced level, computers used in Computer-Aided Instruction (CAI) are the primary tool for teaching content (Dowd and Bower, 1995). CAI is the use of computers in drill-and-practice (review), tutorials, simulation, games and utility/problem solving. By its nature, it assumes one-on-one interaction with the student. This type of instruction was the basis of the early learning interfaces and its simplicity makes it by far the most popular method in use today. CAI can be accomplished on a very basic level with a minimal hardware and software investment and is usually retrocompatible with outdated equipment.

Finally, the most innovative and rapidly growing area of Computer-Based Instruction is Computer-Enhanced Instruction (CEI) (Dowd and Bower, 1995). This involves more advanced levels of interactivity than CAI which is predominately text. CEI usually incorporates simulation or interactive video and videodiscs. Not only is CEI more advanced visually, it usually has a more complex architecture. Users can usually navigate through the tutorial at their own pace, retrace their steps, or skip ahead. Furthermore, CEI has the ability to handle the complex needs of medical instruction and medical imaging. As such, CEI is the ideal target of three-dimensional models used for educational purposes.

## Research Findings

The potential benefits of computer based instruction are widespread. Unfortunately, there is a lack of hard-core scientific research in computer-based instruction due in part to the fact that many projects are still in their infancy. Indeed, most papers that have been published are either retrospective, as historical overviews, or prospective, hypothesizing on proposed implications of the technology.

Another impediment to research in this area is the reluctance among many deans and course directors to aggressively test computer-based instruction experimentally. In the ideal experimental design, one group of students would be denied access to the experimental materials in order to serve as a control. Not surprisingly, few instructors want to stand in the way of learning, and administrators are reluctant to allow such imposed diversity in the education of their future physicians.

Another reason research findings in this area have been difficult to substantiate is the problem of presenting a testable hypothesis. As such, most articles that address the issues at hand are written solely as descriptive reports. Surprisingly few studies address whether computers can effectively teach material or improve students' understanding of difficult concepts. Furthermore, many of the studies that do address these issues suffer from small sample sizes. One such paper (Chew and Smirniopoulos, 1995), found quite impressive pre- to post-test gains of 30 percentage points on average. Yet, experimentally this finding lacks relevance because only eleven subjects were evaluated and no control group was used.

However, one study (Stanford et al., 1994) not only addressed the global question of how effective computers were at teaching, but did so with testable hypotheses and clearly defined experimental and control groups. Researchers at the University of Iowa set out to answer three distinct questions. First, to what extent could a computer program be effective in teaching cardiac anatomy? Second, would there be added benefit from the addition of a computer program when combined with dissection? Third, does the effectiveness of a computer instructional program depend on the outcome measured?

The study examined students' learning of thoracic anatomy by participating in conventional lecture instruction and cadaver dissection as compared to using a computer program. The computer program consisted of anatomical diagrams, text descriptions, and labeled static and cine, or motion, Ultra Fast Computed Tomography (UFCT) images of the heart at rest and through its contraction cycle.

Subjects consisted of 175 first year medical students at the University of Iowa College of Medicine who were randomly assigned to one of four groups. The control group received no cardiac anatomy instruction while the other groups received varying levels of instruction. Students in Group 2 dissected the thorax of a human cadaver. Students in Group 3 received computer instruction alone, while students in Group 4 performed the dissection followed by the computer application.

The subjects were evaluated by a structure identification test with two subtest components. The first subtest used 10 viewbox mounted static UFCTs while the second subtest used 10 gross specimens. Results were evaluated using a two factor ANOVA. Analysis of factor one compared all four treatment levels while factor two compared scores from the two subtests.

The results revealed the expected outcome of higher scores among the experimental groups as compared to the control groups although overlapping standard deviations prevented these findings from reaching statistical significance. Among these results, scores of students receiving computer instruction combined with gross dissection were superior to those using either of the instructional methods singly.

The study did reveal three especially interesting findings. Perhaps most important is that the treatment effectiveness varied significantly with the subtest used as the outcome measure ($P < .0001$). Completing the computer program was superior to the dissection or to control procedures when the CT subtest was used. Similarly, dissection of the gross specimen was superior to use of the computer program or control when gross subtest scores were examined.

Furthermore, a statistically significant low correlation (r = .38, P < .0003) between CT and gross subtest scores suggested that these two tests were assessing markedly different qualities. Gross orientation of structures in space and the appreciation of cross-sectional relationships remain elusive components of anatomical understanding. This finding further supports the idea that due to the unique challenges of learning anatomy in three dimensions, computer based instruction holds great promise in this discipline.

Perhaps the most interesting and relevant finding of this study was revealed in comparing scores of Group 2 and Group 3 subjects. The computer program helped gross specimen subtest scores more than dissection helped the CT subtest scores. This suggests that material learned from the computer program is more transferable than that learned from cadaver dissection. In medicine, where the role of medical imaging and the understanding of cross-sectional relationships are becoming increasingly important, these added benefits of computer applications are of utmost importance.

This study does provide strong evidence for the generalizability of computer based learning and offers considerable strength to the argument that computer based learning has a special place in the educational process. Indeed, the finding that combined intervention is the most effective precludes us from saying that either computer application or gross dissection substitute for each other. Rather, as demonstrated by this study, their effects were complimentary.

## Benefits of Computer-Aided Instruction

The majority of research in this area has concluded that computer-aided education is at least as good as traditional methods. Indeed, most of the research has cited benefits of using computers which exceed those of traditional methods of instruction. Below are summarized some of the most unique findings in the assessment of CBI.

First, it is important to realize that most medical students cited as subjects in these studies have been widely exposed to computers. Thus, it is not surprising that students experience little anxiety when using computer based instruction and for the most part there is a high level of acceptance of it (Khadra et al., 1995). This study in particular, however, lacked credibility in that it stated, “Little is known regarding the acceptability of CAL [computer assisted learning = computer based learning herein] among medical students.” Even a preliminary review of literature in this area reveals that a large number of studies have reported moderate to high levels of acceptability.

Many students have come to endorse the use of computers in academics. Such studies often find that computers have a beneficial impact on students' interest and learning. Eleven radiology residents at the Armed Forces Institute of Pathology reported not only improved scores on assessment measures, but also universally expressed a preference for a computer-videodisc program over radiographs, textbooks, videotapes, and slides and audiotapes for individual study (Chew and Smirniotopoulos, 1995).

The medical education applications of computer imaging extend far beyond the first year curriculum. One author (Rosse, 1995) points to their importance in post-graduate training, stating that most clinical subspecialities call for retraining in anatomy to meet specific needs. Computer Based Instruction is also practical because it can represent a single collection of information at different levels of sophistication. Packages can easily be suited to the user, either at the patient level, the medical student level, or even the surgical resident. St. Louis University has even begun using CBI as a component of patient informed consent (Webber and Rinehart, 1992). Thus, computer based instruction is practical because of the varying levels of complexity it can address.

## Future Directions

At some of the highest levels of computer intervention, and currently at the horizon of today's applications, is the concept of surgical simulation. Many authors (Satava, 1993) have predicted that computers will become as vital to surgical education, as flight simulators are to pilot training. Furthermore, some (Satava, 1993), speculate that this position will be taken in much less time than the 40 years required for the development of practical flight simulators.

This author, however, is reluctant to commit too quickly to such a view. While technology holds great promise, one must realistically assess such claims. If one examines the area of input devices (i.e. digital pens, mice, trackpads, etc.), few technological breakthroughs have been made in the last decade. Indeed, these input devices have existed at least since the early 1980’s. Even one of the most seemingly advanced input devices of today, the wireless gyroscopic mouse, designed to be used by waving it through the air, uses technology dating from the 1960’s. The major limitation of current and future input devices is their poor tactile response which is far from simulating the delicate balance and precision of a scalpel.

Furthermore it is difficult to capture the sounds, smells, and general atmosphere of the operating room. In flight simulation, the gauges and electronic dials used by pilots can easily be replicated on a computer screen. In surgical simulation, however, it is difficult to accurately assess a trainee’s manual skills or dexterity, and many years of work will be required to solve these problems.

Regardless of present-day limitations, the benefits of CAI have been hailed by medical instructors. Such methods have gained tremendous popularity over the past several years, and have been exploited in almost all areas of medical education.

Many authors (Rosse, 1995) see the creation of 3-D electronic atlases as the next major milestone and the majority of federal funding in medical education research has been geared toward the Digital Anatomist Project at the University of Washington, a project directed by one of the most outspoken atlas proponents (Rosse, 1995). Others question the wisdom of this given the current lack of widely available funds and the lack of respect that 3-D modeling currently has in medical education.

Many proponents of 3-D atlases seem far removed from the actual learning experience of the student. Thus, several basic concerns arise. Traditionally, most of the research in computer based instruction, in order to be experimentally sound, has randomly assigned students to different "trial" groups. Thus it is difficult to assess whether students would normally be attracted to such learning methods and indeed whether such applications would be used, especially in a place where gross specimens are available. Part of the wonder of learning gross anatomy arises from handling the gross specimens, feeling their weight, texture, consistency, etc.

Secondly, even the most compact laptop computer, cannot provide the convenience and portability of a traditional printed atlas. For much the same reason, it is unlikely that the basic printed newspaper will ever be replaced. Similarly, computers and CD-ROMS have done little to decrease the popularity of the paperback novel. In the era of possible over-computerization, something like the traditional atlas will surely hold its own.

Thirdly, given that gross anatomy entails such a tremendous amount of information, it is important to realize that students have little time available to explore alternative methods of instruction. This is one possible reason why the most widely received applications have been those that provide quizzes and testing. Students are most likely to turn to an alternative instructional aide such as CBI, when it tests their understanding rather than one that attempts to build it.

Consequently, future efforts in the area of computer aided instruction and three-dimensional imaging for education should be directed toward the modeling of difficult structural concepts. For example, the pelvis, perineum, and inguinal canal are among the most difficult anatomical areas to understand because of the difficulties inherent in visualizing and comprehending them from dissection of the cadaver. Directing resources toward these challenging areas should yield far more dramatic benefits of the use of computers in medical education, which in turn should provide the results needed to encourage additional funding and research in this area. Currently the temptation is to produce elaborate images of little or no added educational value. Until three-dimensional imaging rises above the Hollywood era of pretty pictures, its dismissal as a pseudoscience will persist.

Rather than provide a broad and nebulous overview of medical education, or even computer aided instruction as a whole, this paper will focus on three distinct areas. First, the methods of creating three-dimensional images and incorporating them into computer-aided instruction will be presented. Next follows a discussion of where such efforts should be targeted. Finally, the vital role of three-dimensional imaging is illustrated in a representative example of modeling the inguinal canal.

# MATERIALS AND METHODS

The type of data used most in medical imaging as well as in computer modeling is serial cross sectional data. Use of serial data allows the structures of interest to be studied at varying depths of the specimen, thus adding the third dimension to the otherwise flat, two-dimensional images.

## Data

Sources of data for gross anatomical modeling vary immensely. Data can be gathered from surgical and pathological specimens, gross cadavers, and autopsies as well as from clinical evaluation of living specimens through photographs, MRIs, CTs, plain film x-rays, angiograms, PET scans, mammograms, ultrasounds, and the multi-modality imaging referred to earlier. However, computerized three-dimensional modeling relies predominately on serial cross-sectional data. These data can be gathered through MRIs, CTs, and cryo-section of gross specimens.

For this study, data from the Visible Human Project (Ackerman, 1991) were used. The Visible Human dataset consists of radiological and color data taken from a 39-year old convicted murderer who donated his body to science. The cadaver was prepared and imaged at the University of Colorado in 1991 under a contract with the National Library of Medicine. The radiological data were created using commercial MRI and CT. The CT data consisted of two parts. The first set was data from the fresh cadaver. The fresh set provides better soft tissue contrast and is thus suited to specific applications. The cadaver was then embedded in gelatin and frozen for the second set of CT data. Finally, the cadaver was sliced from head to toe at one millimeter intervals. Each of these layers was photographed and scanned into a computer as a color RGB photograph. The entire set consisted of over 1800 24-bit images each measuring 2048 by 1216 pixels. For comparison, to display this amount of data all at once would require over 10,000 typical computer monitors. The fresh and frozen CT, MRI and gross color data comprise over 15 gigabytes of data.

A collection of data for a female cadaver was released in the fall of 1995 with color sections taken every .333 mm. This provides a greater degree of resolution in the third dimension and represents a three fold increase in the amount of available data.

As the Visible Human Project represents the first large scale publicly accessible dataset for modeling anatomical structure, all future references to data presume that the Visible Human dataset is being used.

The vast amount of data associated with modeling anatomical structure requires tremendous quantities of on-line storage. Three-dimensional modeling is very graphics intensive and places heavy demands on system resources.

## Hardware

Processor-intensive work such as involved in computer modeling is best done under a multi-tasking operating system. Simply, multi-tasking allows several processes to be run by the computer simultaneously. Until the advent of Windows 95™, Unix® was and still is the principal operating system to make use of true multi-tasking. Unix®-based workstations include the systems such as the Silicon Graphics Indigo series and SUN Sparcstations.

Machines such as these also need to be equipped with large amounts of memory and storage to handle the enormous amounts of data. The amount of random access memory (RAM) determines how much material can be dealt with at one time. For example, memory requirements increase with the number of slices of data or with the area of each slice displayed. To do effective high-resolution work, a workstation should have at least 100 MB of RAM.

The amount of storage or hard drive space determines the quantity of material which can be made accessible. For example, will data from the entire body be available or from specific regions such as the abdomen or the head and neck? Large archives of data can be maintained on inexpensive magnetic tapes, but the for the data to be truly accessible it must reside on a hard drive. Only recently has the Visible Human dataset been made available commercially on CD-

ROMs which offer the cost benefits of digital tape with the convenience of hard disk storage. However, the speed of CD-ROM drives remains the most troublesome factor preventing their widespread use. Consequently, hard drives remain the media of choice. No degree of storage ever seems adequate, but two or three gigabytes should suffice to do most projects.

Both the tremendous amount of raw data and the computational time and memory demands of processing it, require these high-end graphics workstations which are still quite expensive in spite of steadily declining costs. Unfortunately the amount of memory or RAM, which is directly related to the productivity and efficiency of anatomical model creation, is also the most prohibitive cost.

### Software

The software, or applications, used to manipulate the data are also quite expensive. Licenses for many programs run in the tens of thousands of dollars. As holds true with the quantity of memory, the quality of software is directly related to productivity and efficiency in model creation. Some applications, which are attractive by their low licensing fee, often end up costing tremendous amount of time and frustration. Working with a small amount of memory or an inadequate application is akin to writing a dissertation with a note pad application. Similarly, it is like trying to work with a 5,000 cell spreadsheet with 1,000 5 cell documents. In both cases, the task can be done, but only at the expense of severe frustration and time.

Currently, applications exist on two levels: those that allow creation of images from existing data and those that allow creation of original images from no existing data. The latter are essentially Computer Aided Drawing (CAD) and Computer Aided Modeling (CAM) applications.

These applications essentially create images from a concept and are ideally suited to engineering applications where the final image can easily be reduced to its individual parts. For example, an elaborate model of a turbine can be dissected to reveal specific components (i.e. fifty blades of 18 gauge stainless steel each at an angle of 18.32° and 11.125 mm from the point of rotation of a 2.3 kilogram cylinder)

Irregularities and the general variability of gross structure make it difficult material to convey using CAD or CAM. For example, it is quite difficult to accurately reduce a complex object like a pelvis to a bowl with an ellipsoid hole in the center into which two triangular shaped ischial tuberosities protrude.

The application used in this study is called IsoView and was written by a student in the MD/PhD program here at MCV, John Stewart. Isoview uses existing data and was specifically tailored to use the data from the Visible Human Project. Ideally the application should be a hybrid of the two combining the benefits of each. These advantages will become apparent later.

Computerized modeling has taken essentially two distinct approaches, one using Volumetric Modeling techniques and the other using Surface Modeling. The first several steps are performed independent of the desired technique.

To better understand the steps involved in computer modeling of anatomical structure, it is important to look at a field of biology where visualization techniques are perhaps some of the most advanced. This is the field of histology where conventional imaging techniques provide the basis for understanding the more complex steps and methods of computerized modeling.

## Specimen preparation

The initial steps involved in histological preparation are nearly identical to the techniques used in three-dimensional image creation. First the specimen is fixed by immersion or perfusion. Perfusion is the method of choice as the fixing agent is administered at the cellular level. Structures that are preserved by immersion often are fixed on their exterior surface, but not in their interior. Consequently, this introduces another realm of artifact which must be accounted for. The agents of chemical fixation vary from precipitating or coagulating fixatives to cross-linking fixatives like formaldehyde or gluteraldehyde. Osmium tetroxide is used extensively for electron microscopy as its density properties make it ideal for enhancing image contrast.

As in conventional imaging, fixation artifacts present problems for reconstruction of serial images. Shrinkage and folding of the specimen create problems in aligning the serial images, a problem discussed later. While artifacts in preparation are important to avoid, they can often be overcome with computerized image enhancement, as will be discussed later.

Typically, histological sections are infiltrated with intermediate solvents like alcohol to displace water, and then infiltrated with a solvent like xylene for light microscopy or propylene oxide for electron microscopy. The infiltrated tissues are then embedded in a paraffin or epoxy/plastic resin medium for sectioning. Sectioning can be performed with simple tools like rotary or sliding microtomes, but more advanced methods are preferred. Vibratomes are especially useful since their sawing action does not squash the specimen and thus helps prevent artifact. It also eliminates the need for embedding of the specimen. Cryostats are used for a similar reason. They also eliminate the tissue embedding step, but introduce their own artifact arising from the freezing procedure. Finally, ultramicrotomes are especially useful, if not vital, to electron microscopy because they provide extremely thin slices.

Sectioning is perhaps the most important step in regards to three-dimensional modeling. The interval of section provides the degree of resolution of the model. That is how many slices there are per millimeter or micrometer, determines how much detail of a given structure will be revealed.

For example, when modeling a dendritic spine using serial electron microscopic images, the interval of sectioning is very important. If too large a sectioning interval is used, the entire dendritic spine may only be evident in one section. Consequently, any three-dimensional view will reveal no more detail about the spine's structure as the image is essentially still a two-dimensional entity.

Once adequate sections of the specimen have been made they are stained to enhance contrast and visualization of certain structures. In light microscopy this is done with basophillic and acidophillic stains. Basophillic stains like hematoxylin bind to acidic structures like rough endoplasmic reticulum and nucleic acids, while acidophillic stains bind to neutral or basic structures like mitochondria, collagen or secretory granules. In electron microscopy, lead citrate and uranyl acetate are heavy metal stains which introduce contrast and "color" the image.

## Visualization

Visualization of the stained structure is performed by certain microscopic techniques. Techniques compatible with three-dimensional imaging include conventional light and dark field microscopy, phase contrast microscopy, fluorescent microscopy, or transmission electron microscopy. All of these techniques produce the flat two-dimensional image necessary for computer modeling.

Other techniques that create their own three-dimensional appearance are incompatible with computer modeling in its current stage. For example, Nomarski, or differential interference contrast microscopy, uses specialized optics to provide relief and the perception of a third dimension. Much like the Viewmaster used in early three-dimensional imaging, this technique relies on slightly disparate or unique images reaching each eye. In animals this stereoscopic input of the visual field is the principal cue to depth perception.

Scanning electron microscopy, which uses shadowing to produce a three-dimensional appearance, is also incompatible with computer modeling. In scanning electron microscopy the specimen is coated with a thin metal foil, typically of gold or palladium. The image created by the electron microscope is essentially a picture of the specimen. The shadowed appearance of electron micrographs is provided by the light and dark patterns created by the "light-source" of the electron beam. This simulates the shadowing resulting from visible light and is also a major cue to depth perception in animals.

Laser or confocal microscopy uses reflected laser beams to create a miniature topograpy of the specimen. Similar to creating holograms, this technique combines two slightly different images in the same field, each projecting to one eye. As with Nomarski optics, the disparity, or slight differences between images, convey the illusion of three-dimensional space and depth perception.

Where the creation of cross-sectional images is essentially the goal and extent of most histological visualization, it is merely the beginning of computerized three-dimensional imaging. It should be noted, however, that the techniques involved in creating three-dimensional models described below can be applied to any serial sectional data, whether for the study of histological or gross structures.

## Gross Structures

Gross structural data can be gathered by either cryo-section of post-mortem studies and pathological evaluations or clinical measures like CTs and MRIs. Since each imaging modality is specifically suited to different types of structure, the first step in gathering the data is to choose the modality most suited to the structure of interest.

CT scans are effective in visualizing structures with vastly different radio-opacities such as bone versus fat and muscle. MRI techniques provide accurate visualization of fine detail as they provide better soft-tissue contrasts. Use of T1 weighted MRIs further enhances the contrast of soft-tissue structures. This allows a greater number of finite structures to be differentiated from the surrounding tissue. Lastly, recent availability of the Visible Human Project data has increased the use of cryo-sections of gross specimens. (Figure 1)

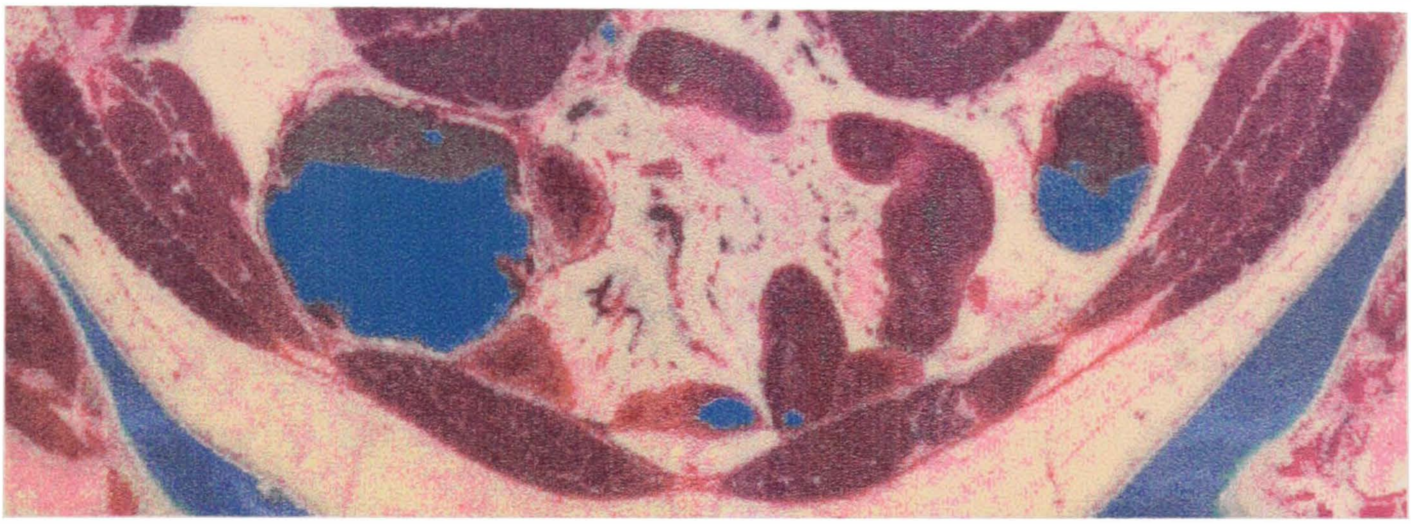

**Figure 1.** Raw color data of cryo-section of abdominal wall from cadaver of the Visible Human Project.

Use of photographic data from cryosections provides the benefit of delineating structures based on color and/or applying the color data to the final three-dimensional model to create a more realistic image. Isoview is one of the few applications to provide this feature. Most other applications simply apply a predefined color to the tissue in question (i.e. muscle is red, bone is white).

## Data Processing

CT and MRI data often require additional processing steps before the data can be used. When the data are gathered, different techniques are often used within the same modality. For example, viewing an ankle by CT would require a different film size and setting than viewing an abdomen by CT. Structures, like an esophagus, which span broad regions of the body will often use several different film sizes. Consequently the image sizes often vary. Likewise, when a series of images is taken at different levels, they often become misaligned. To both align and properly size the images, a technique called registration is used.

## Registration

Registration aligns the images along a central axis and also rescales them to create a cohesive and continuous dataset. Furthermore, registration assures that data from different modalities are properly aligned and match one another, thereby allowing structures like bone to be extracted from the CT and painted with color from the cryosection data.

## File Management

Once the data have been registered, it is important to make sure that identification of images is sequential and indicative of the proper intervals. Most data sets are labeled progressively from the first slice of data to the last with successive images numbered consecutively. As a convention, the Visible Human Data Set labels each image as a number that is the distance from the top of the head in millimeters. Thus, file 500 would be half of a meter from the top of the head, or approximately at the level of the xyphoid process. This number also synchronizes the images from different modalities so that file 500.mri would be at the same level as 500.cry. In the case of the Visible Human Data, *.raw is used for the cryosection data, *.tl for MRI data, and *.fre and *fro for fresh and frozen CT data respectively.

## Cropping

Cropping of the images on several levels is the next step. First the images are often cropped to select only the pixels belonging to the body. Next the images are cropped to include only the areas of interest. The enormous size of the images usually precludes handling full data sets all at once, necessitating cropping to conserve both RAM and hard drive storage. Once the images files are cropped initially, they are usually cropped again on loading them into the computer. This time, however, the cropping is only figurative. Instead of actually removing the areas outside of the cropping marks, the computer simply ignores and does not read them. By cropping images the second time, they load much quicker and are easier to work with.

## Volume and Surface Modeling

Creation of three-dimensional models proceeds using the data (color or signal intensity) represented by each pixel. Two approaches to three-dimensional modeling are currently in use, Volume Modeling and Surface Modeling. Volume Modeling makes use of the actual pixels which have been assigned specific values, while Surface

Modeling makes use of the contours, or borders between those pixels and the surrounding tissue.

Volume Modeling converts each pixel in the two-dimensional image into a volume element or voxel, which is essentially a pixel with depth. These voxels, or three-dimensional pixels, are then assigned an intensity value representing their associated grey-scale value. As all known applications of Volume Modeling make use exclusively of CT data, these intensity values are based on the original density values. The voxels are then assigned a partial transparency allowing some objects to be viewed independently of others. The voxels that are "turned on" by a lower partial transparency are the elements which compose the object of interest. By the process of voxel summation these "on" voxels are joined together as building blocks to resemble the object.

Volume Modeling is effective for modeling bone, air cavities, and solid mass objects. This explains why most applications of Volumetric Imaging have been useful in assessing bone structure, sinuses, and tumor expanse.

As Surface Modeling is the technique with more promise for medical education, and also the faster growing field, the remainder of this paper will discuss the techniques and applications specific to it. It is also the field to which the most research has been geared and newer applications being tailored.

Surface Modeling, unlike Volume Modeling, does not make use of the entire dataset. Rather, it creates hollow three-dimensional surfaces based on the outlines of various structures. Consequently it relies on the anatomical borders of structures, borders defined through a process called Segmentation.

## Segmentation

Segmentation is by far the most difficult task in three-dimensional modeling, but it is also the area of active research with the promise to simplify the step and make it more productive. Image segmentation is the technique by which the borders of structures of interest are delineated within the data. Segmentation allows one to associate structures both within a given slice and between slices in order to provide continuity to the structure. Essentially it allows a structure at one level to be associated with or connected to the same structure at a different level, even if it has changed in orientation. While to humans this task seems diminutive, the computer has no way of distinguishing whether neighboring structures belong to one another or not. The techniques of segmentation vary widely and with varying applications of each.

Typically CT and MRI data have been invaluable in segmenting certain structures because in their images structures like bone or muscle span a relatively narrow density window. The bone window can easily be established as a range of density values and segmentation of bone is accomplished simply by selecting this range. For example, in modeling the lower extremity, segmentation allows one to associate the different parts of the femur. While the compact bone of the femoral head differs in appearance from the cancellous mid-shaft, their organic densities, as revealed by CT or MRI, are the same. One major limitation of using color data lies in its ambiguity. In gross cross-sections, cancellous bone with its interspersed red marrow actually gives the entire bone a red appearance. Compact bone however, does give the uniform color we typically associate with bone. Consequently, it is difficult to associate these different components both within a given slice and between slices at different levels with color data alone. In fact the color of bone in the color data closely resembles the color of fascia, fat and tendon. Thus, CT and MRI data which are based on radioopacity and density respectively are invaluable in segmentation.

For example, in visualizing the abdominal musculature, segmentation proves especially challenging given the tendinous fascias between fibrous myofilaments. On gross examination, these two components of muscle look drastically different as they do on CT or MRI exam because of their different chemical compositions and consequently different densities. All current imaging modalities will artificially separate these two components into distinct entities.

The primary challenge in automating the image segmentation process lies in training the computer to recognize two entities as being part of the same item without having to artificially link them. Indeed, most, if not all three-dimensional modeling has bypassed the step of segmentation entirely by manual intervention in an effort to overcome this problem. Several studies (Rosse, 1995) actually use photographic or radiographic images placed over digitizer pads to physically trace the structures of interest. While tedious and laborious, especially for data sets spanning several hundred images, this step may indeed prove to be the most effective for difficult structures.

Regardless of its current limitations, a great deal of work has been done into the area of image segmentation. Training the computer to recognize certain structures as being composed of distinct components is a form of artificial intelligence. Both now and in the immediate future, this is an area where human intervention of some type is still required.

The Isoview program addresses the problem of segmentation with a novel approach. It uses an algorithm which allows structures of different colors to be segmented as a single object (Stewart et al., submitted). The software allows the user to interactively select the component colors of the item of interest in the gross data. Essentially, the user paints the area of interest to create a color range which represents the structures of interest. This painting technique is referred to as Masking. (Figure 2)

**Figure 2.** Masking exemplified. *Arrowhead* - Note the light grey/green pixels representing the area where the Mask was chosen.

## Masking

Masking requires a perfect balance between selecting too few colors (i.e. only a few muscle fibers within a muscle) and too many colors (selecting such a broad range of red that blood vessels are included). As such, Masking must be very selective to avoid "contaminating" the Mask with the wrong color. For example, if in selecting muscle, a dark purple pixel representing clotted blood in a venule was chosen, the Mask would be too broad, and the model would include structures or tissues other than muscle.

The specific colors of interest are translated into a grey-scale equivalent. This new image resembles a CT image, but is very different. The major difference is that while the grey-scale level in a CT image reflects density values, the grey-scale from a gross image reflects color wavelength values. (Figure 3)

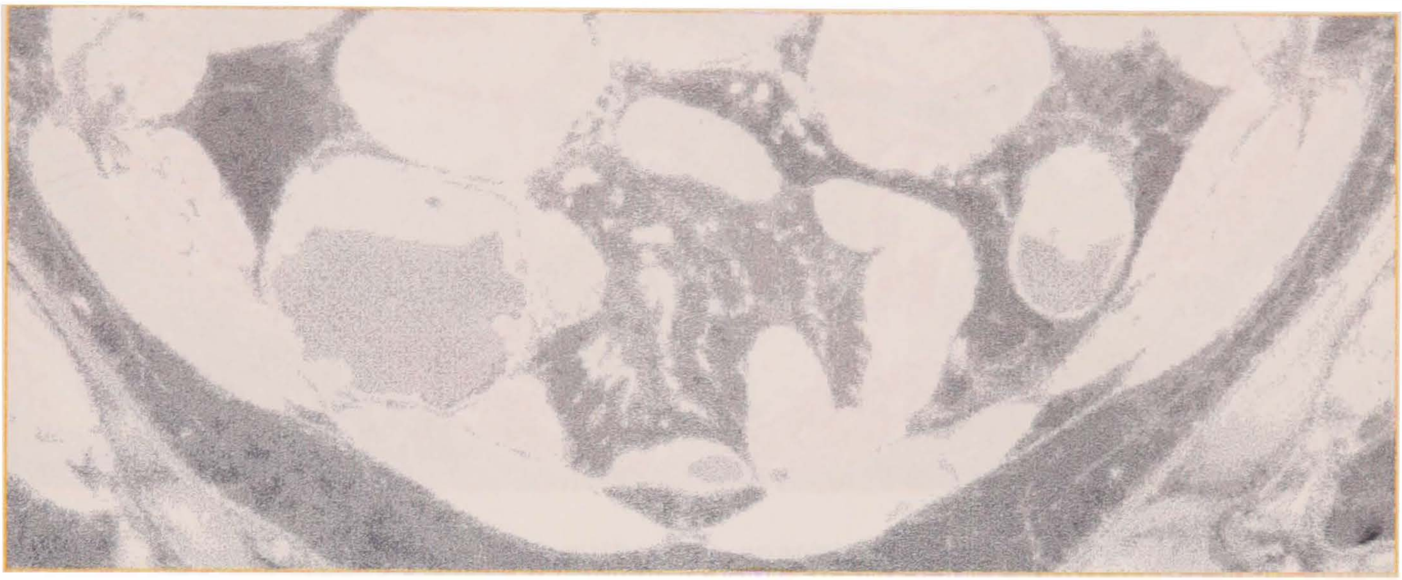

**Figure 3.** Grey-scale image based on color data. Light values represent colors close to the Mask, or color of interest.

Colors which are close to the selected mask colors have a higher (white) value while those far from the selected colors have a low (black) grey-scale value. However, after the data are manipulated, the original colors can be reapplied to it.

## Contour Delineation

A threshold is then established from the Mask by defining a range of grey-scale which encompasses the original colors of interest. This range is further refined using an interactive technique called Contour Delineation. Here the computer outlines the structure of interest by selecting all grey-scale values above the given threshold. (Figure 4)

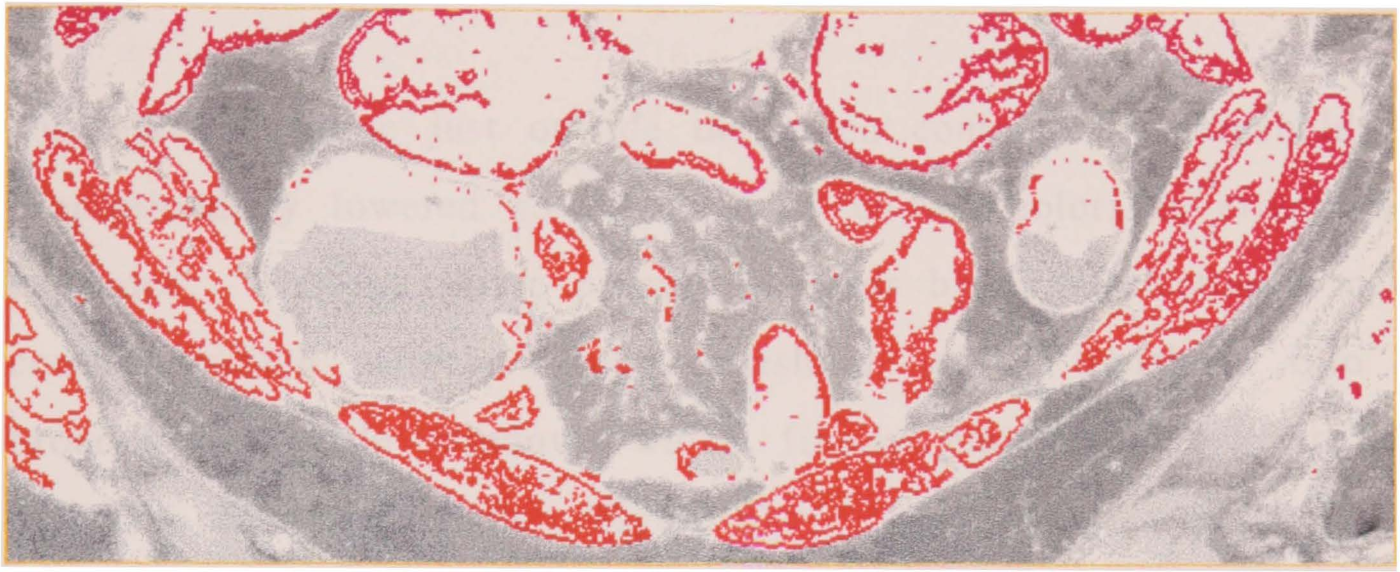

**Figure 4.** Grey-scale image with red contours surrounding values above the given threshold.

These contour lines surround the colors of interest that were initially selected by the Mask. When the contours are displayed with the original color data, this range is clearly defined. (Figure 5)

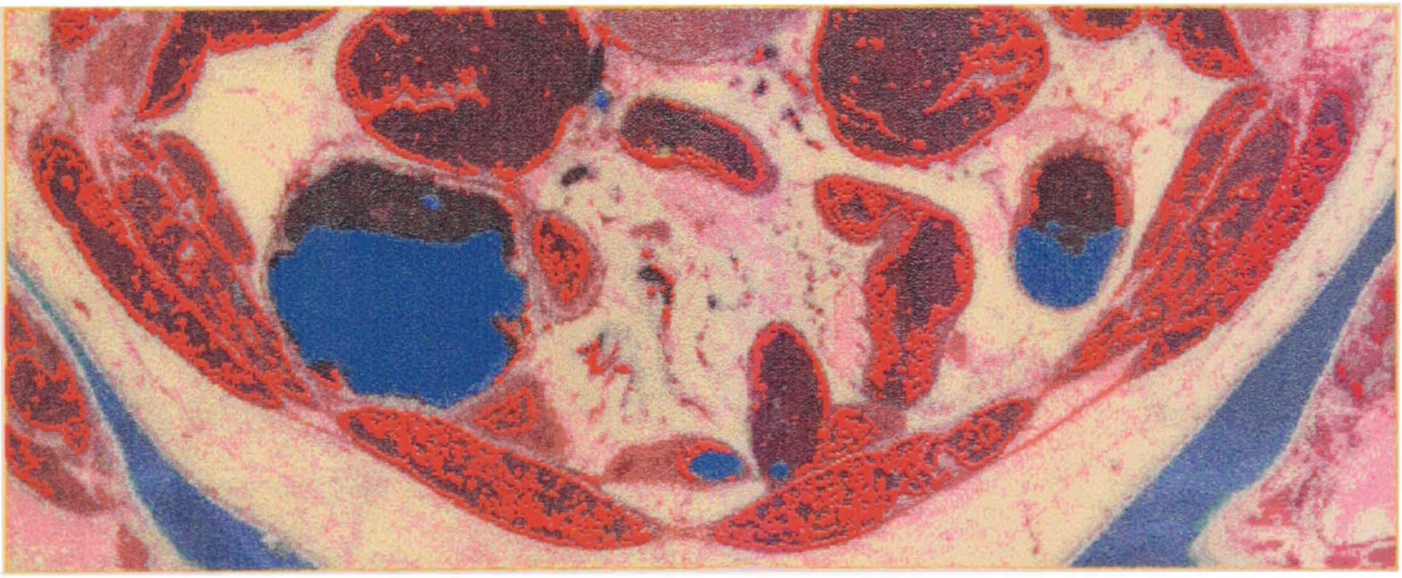

**Figure 5.** Red lines represent contours of pixels whose color value is above the Mask threshold. Note the original Mask can still be seen.

By selecting tissue just outside the given contour, the threshold is proportionately lowered so the span of chosen colors is effectively expanded. The interactive process proceeds by first selecting a new contour, which reflects a new threshold, which translates into a broader grey-scale window, which finally encompasses a greater range of color wavelength. (Figure 6)

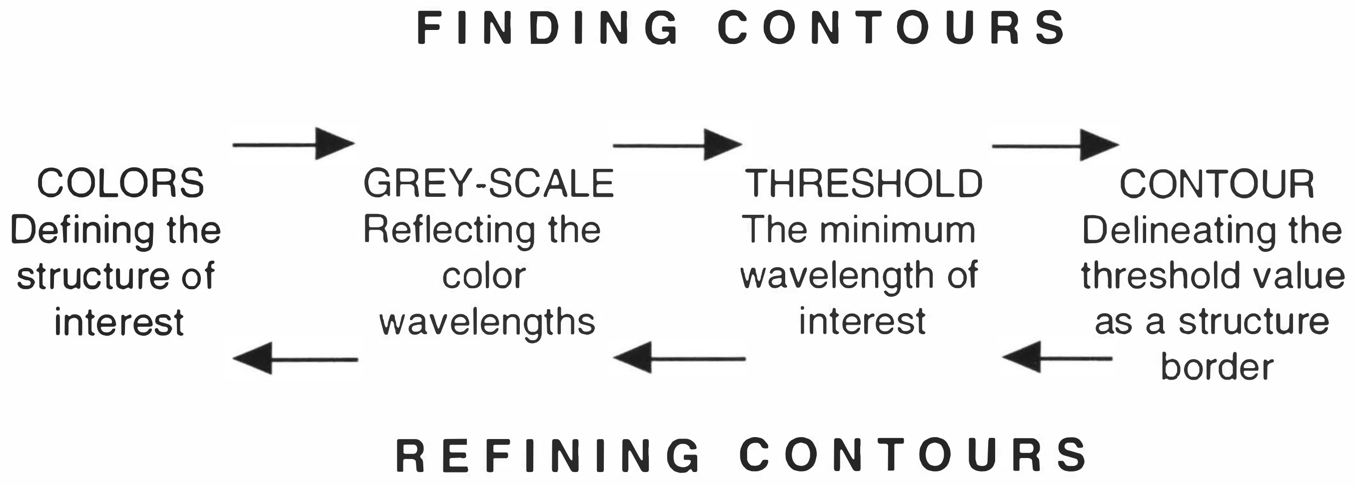

**FIGURE 6.** The process of Finding Contours and Refining Contours.

Once the contours have been found on one image that information is translated in all of the loaded files. The computer simply applies the same Mask and Threshold values to all of the remaining images. Thus, we have the tissue of interest clearly defined on each image in the data set.

In theory, the process to this point flows as smoothly as just described. However, as alluded to previously, the processes of computer segmentation are far from perfect, especially in areas such as the pelvis and perineum where fat, fascia, and tendon blend insensibly. Consequently, many researchers prefer to manually segment the tissues of interest. By doing so, they have visually selected the tissue of interest by color or CT/MRI grayscale and in doing so, have subconsciously selected the threshold value. On the basis of this threshold they have manually drawn the contours onto a graphics tablet which records the contour as a data file.

## Polygon Application

Regardless of how the contours are selected, the remaining steps are the same. Simplistically these steps involve sandwiching together all of the contours from each image in order. While logistically simple, this is where the real benefits of a computer become apparent. The computer takes the contour of each image and reduces it to several small lines and vertices. That is a curved surface is now represented as several, often hundreds, of short lines often only two or three pixels long. Once the computer has reduced the contours to straight lines and vertices, the three-dimensional surface can be constructed (Figure 7).

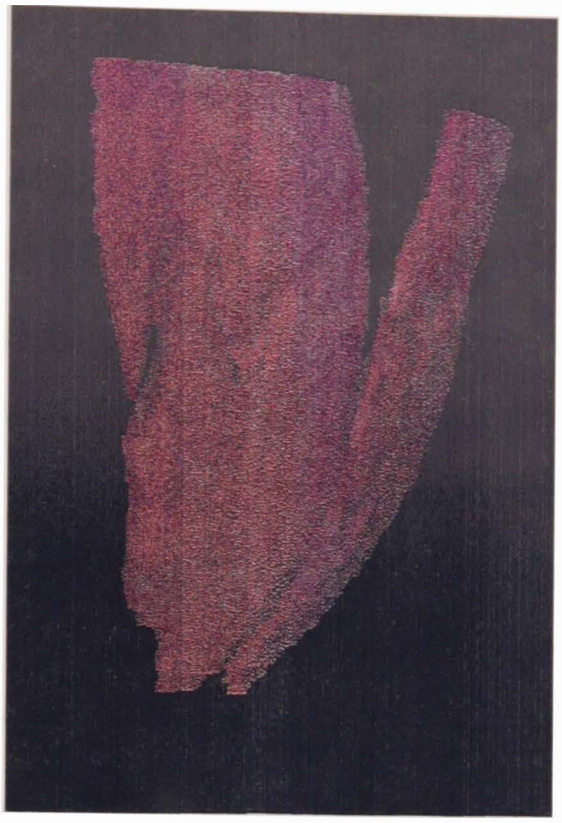

**Figure 7.** Three-dimensional model of isolated bilateral rectus abdominis muscle viewed anterolaterally.

Like the area of segmentation, the area of surface creation is an active area of research in computer imaging. Several different algorithms, or program components, have been developed which use different techniques to produce a three-dimensional surface. The variations and advantages of these algorithms are worthy of an entire thesis alone. However, a general overview of these algorithms will suffice for this discussion.

For the most part all of the algorithms work the same way, that is by joining the vertices from nearby two-dimensional images. Through a technique called Polygon Application, the lines connecting vertices of neighboring contours create three-dimensionally oriented polygons. These polygons can be triangles, squares, rhomboids, pentagons, hexagons, etc. or a combination thereof.

Isoview and many other applications use a standard algorithm called Marching Cubes (Lorensen and Cline, 1987). In Isoview, this algorithm is combined with a technique called Border Case Comparison, developed at the Medical College of Virginia (Stewart and Broaddus, submitted 1996). While its name may be misleading the Marching Cubes algorithm creates surfaces using triangles as the polygon. Triangles are the polygon of preference as they allow smoother, more accurate surfaces to be made. They do however take up more space, as several triangles are required to create a surface that could effectively be made by one hexagon for example. When all of the adjacent contours have been incorporated we have an enormous group of polygons forming a wire-frame skeletogram. The spaces within each polygon are then filled in and painted. Isoview paints this surface with the color of the nearest pixel in the color data image.

## Smoothing

Once the general surface has been created, the lines joining two adjacent contours often produce a banding pattern at the interval of initial section. These bands, or “surface steps”, are an artifact of the image creation. Since the images were acquired at a certain interval (e.g. every millimeter), all of the vertices occur at this interval. On close inspection this reveals somewhat of an accordion pattern.

Smoothing algorithms help remove this banding pattern. Isoview uses surface and normal smoothing to enhance the three-dimensional image. A third algorithm is used to smooth the variations in color by smudging them to diffuse abberants.

It is important to remember at this point that the three-dimensional surface created is essentially that, a surface. It represents merely a shell around the cavity or mass of interest. This shell surface lends itself well to being "dissected" as the different layers can simply be peeled away. These surfaces can also be given different levels of transparency to create see-through structures.

Visualization of three-dimensional structures is still perhaps the biggest obstacle in integration with computer-based instruction. The surface of one structure alone usually entails tens of thousands of triangles. When two or more surfaces are viewed, the number of triangles can easily exceed 100,000. To make the visualization of these surfaces interactive requires a tremendous amount of computing power.

## Surface Compression

Yet another area of research involves compression techniques which seek to simplify a surface without sacrificing the quality of the model. One technique which increases the speed of display instructs the computer simply to ignore the triangles which are out of sight by the viewer. Other techniques, such as triangle decimation which Isoview uses, reduce the number of triangles composing the surface.

For example, a large flat surface such as the ileum of the pelvis can be represented by a hundred triangles instead of the ten or so thousand that originally modeled it.

### Model Enhancement

Once models are created, they need to be adequately enhanced, labeled, and modified before they are included in a computer-based instruction package. Enhancing involves clearly delineating the individual components of the model. Similar to the initial segmentation, enhancement of the model allows delineation of distinct anatomical subdivisions. These distinct structures usually blend together in the gross specimen and need to be manually split apart by dissection. Likewise in the computer model, the current limitations in segmentation necessitate manual separation of particular structures. Herein lies the major benefit of three-dimensional modeling in computer based instruction. Structures like the inguinal canal which have traditionally been very difficult to visualize even in a carefully dissected prosection can now be clarified in a computer recreation.

High-power computer aided design (CAD) packages are required to effectively enhance a model. Since a typical model is composed of hundreds of thousands of data points, programs like I3DM™, which was used in the present preliminary investigation, are tedious and inefficient for most uses. High-level CAD programs allow quick rendering of three-dimensional structures so modifications can be made interactively. When an object's characteristics are changed, the image on screen immediately reflects those changes.

Programs like Silicon Graphics' Alias/Wavefront are examples of such CAD programs. This package is particularly well-suited to working with anatomical models as it allows free-form CAD. Applications such as these have been used extensively in Hollywood for theatrical special effects, but surprisingly, they meet the same needs of biological and anatomical artists as well. Free-form CAD simply means that the objects being created are not standard geometrical objects like cubes, cylinders, and cones, but rather curved surfaces resembling organs, bones, etc. These same free-form design tools allow existing models to be manipulated and modified more easily than conventional CAD tools.

## Representative Model of Inguinal Canal

In the present attempt to model the inguinal canal, the abdominal wall musculature was first divided into its individual components: the transversalis fascia, transversus abdominis muscle, internal abdominal oblique muscle, external abdominal oblique muscle, anterior and posterior rectus sheath, linea alba, and rectus abdominis muscle. Other structures which must be included to enhance clinical understanding of this area include specializations of the musculature. For example, the superficial inguinal ring, which is an opening in the external abdominal oblique aponeurosis, is especially important as the target of direct inguinal hernias. Other specializations of the external oblique aponeurosis include the inguinal ligament, forming part of the floor of the inguinal canal, the reflected inguinal ligament, which is an upward extension of the inguinal ligament, the lacunar ligament and the pectineal ligament.

Model enhancement not only provides clearer delineation of anatomical structures, but also conveys certain anatomical principles more easily. For example, the formation of the conjoined tendon, or falx inguinalis, can be demonstrated by fibers from the transversus abdominis muscle joining those from the internal oblique muscle. Similarly, the transition between the split and unsplit portions of the aponeurosis of the internal abdominal oblique aponeurosis at the arcuate line can be demonstrated. Enhancement also allows one to visualize the continuity between musculature, fascia and coverings of the spermatic cord. For example, the internal abdominal oblique muscle which gives rise to the cremaster muscle and middle spermatic fascia of the spermatic cord, can be demonstrated and isolated in a particular model. Other structures like the superficial ring with its medial and lateral crura formed by the external abdominal oblique aponeurosis and the deep inguinal ring formed by an opening in the transversalis fascia can be highlighted. Finally structures like the peritoneal folds, which are especially difficult to isolate in the gross specimen, can be exaggerated through model enhancement. Specific folds which can be demonstrated include the median umbilical fold overlying the obliterated urachus, the medial umbilical fold overlying the obliterated umbilical artery, and the lateral umbilical fold overlying the inferior epigastric vessels.

In addition to structure separation through model segmentation, structure augmentation or clarification, and structure amplification, model enhancement also may include applying a biological symmetry to a model to recreate the other half. Since most model creation is done on one half of the body, biological symmetry allows us to create a mirror image of the model to represent to other side. This of course, is not effective in areas like the digestive system which are not bilaterally symmetrical.

Model enhancement also entails adding structures which are not well shown in the gross data, such as small blood vessels and nerves. These structures are usually hidden within sections of the specimen or are too small to be resolved by the imaging modality. The resolution of typical CT scans, 512 x 512 pixels, is too low to decipher fine detail. The course of various nerves and vessels should be mapped out in regard to landmark anatomical structures. In model enhancement, this route can be traced directly on the computer screen through a drawing tablet, mouse, or other input device. Once the route has been established by a series of points, a circle element can be extruded or traced along that line to create the nerve, artery, vein, or entire neurovascular bundle.

The inferior epigastric artery is one structure in particular which should be added to models of the inguinal canal because of its important clinical significance in this area. The inferior epigastric artery is a landmark in distinguishing direct and indirect hernias. The sac of an indirect inguinal hernia arises lateral to the inferior epigastric artery, while a direct hernia arises medial to the artery. This rather simple, but important, anatomical concept can easily be demonstrated and tested.

Nerves, which may not be prominent in the model can also be added. An example is the ilioinguinal nerve which courses through the inguinal canal. A clear demonstration of this nerve, with its femoral and anterior scrotal branches demonstrated, can help students better understand the innervation of this region.

Other important structures which do not model well and will have to be added include lymph nodes and lymph vessels. It is critical that the student understand the lymphatic drainage of this important area.

### Structure Labeling

Labeling of the anatomical structures is the key benefit to the student. Static or dynamic text labels that identify certain structures can be used. Static labels remain in the same position on the screen no matter what angle the structure is being viewed from. Dynamic labels on the other hand are three-dimensional objects themselves which follow the object to which they are connected. A dynamic label, for example, will read backwards when the object is viewed from its posterior side. While static labels provide a cleaner appearance, dynamic labels help to add depth to the structure and improve visual orientation.

Modification of a model allows simulation of various pathologies. With the inguinal canal example, modification could include simulating a hernia. Here a section of bowel would be bulged or herniated through a section of abdominal wall musculature. This can be done by manipulating the tissues around the "hernia" on the computer to give the appearance of bowel protruding through them. Some high-end graphics packages allow a model of bowel to be dragged through the wall to create the hernia. Warping of the abdominal surface can be done automatically as the bowel literally pushes through the herniation.

## Hernia Simulation and Embryology

With relatively few simple steps, a number of hernias can be simulated. These hernias can then be viewed individually or simulated interactively. A student for example can use a mouse to select a certain area of abdominal wall, and bowel will herniate through that region triggering a discussion of that particular type of hernia. On the other hand, the student can be shown a hernia in late stages, or one developing, and be asked to diagnose which type it is. Either of these examples can be tied in with the causes of direct and acquired indirect hernias caused by decreased collagen production and loss of elastic tissue associated with aging.

Perhaps the most powerful application of model modification is in the simulation of the embryological development of anatomical structure. Essentially, models of structures at different stages of embryology can be created and linked together sequentially. This would help students understand embryological events such as descent of the testes in the fetus as well as pathologies within that sequence, such as a patent processus vaginalis predisposing to an indirect inguinal hernia.

Models from the high-end graphics workstation are then compressed and exported to other computer platforms as either still-frame images or as a manipulable model. Since most models are too complex to interactively view on a personal computer, the former method is preferred. By capturing a number of carefully selected views, the model's characteristics can be accurately conveyed and incorporated into a computer-based instruction package.

# RESULTS

Both cryosection and CT data were chosen to model the inguinal canal. Initial structures were successfully modeled using the color data from the cryosections. The transversus abdominis muscle, internal abdominal oblique muscle, external abdominal oblique muscle, and rectus abdominis muscle were all successfully modeled as was the bony pelvis with anterior superior iliac spine, anterior inferior iliac spine, and pubic tubercle.

However, the cryosections alone were not well suited to deciphering and discriminating between the fascias and tendons which comprise the inguinal canal. The color of fat, bone, fascia, and tendon were so close that it was difficult to isolate the specific tissues. Given the varying densities of these structures, the next attempt employed the CT data. While MRI data would be the modality of choice, given its ability to illustrate soft-tissue contrasts, the MRI data for the Visible Human Project was only collected every five or ten millimeters, a resolution too low to produce accurate models. While creation of a pelvis and basic abdominal musculature proved feasible, modeling more difficult structures such as the delicate layering of the inguinal canal, proved unsuccessful. Despite the high resolution of the cryosection and the CT data and the associated values (color or density) of each, the fascias of the inguinal canal proved too difficult to accurately model with the given software. (Figure 8)

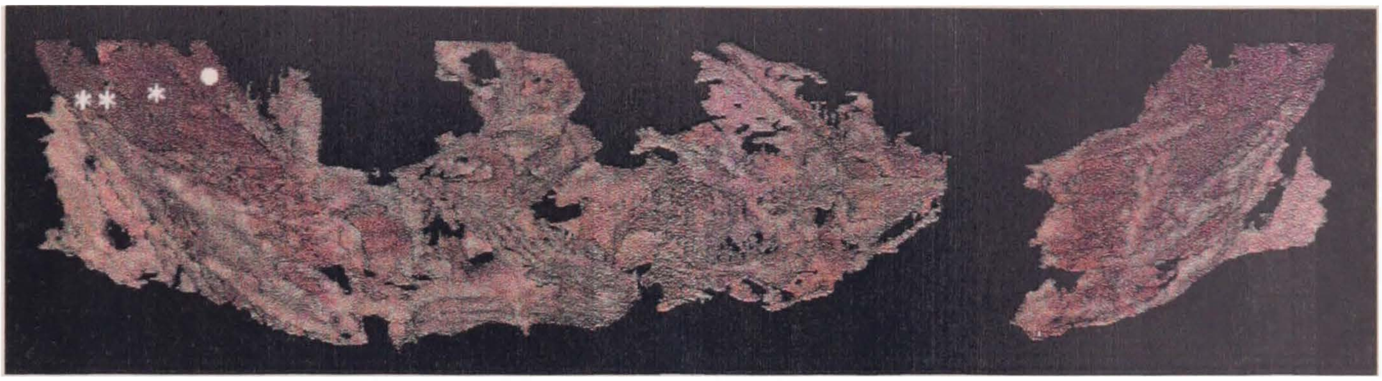

**Figure 8.** Three-dimensional model of bilateral abdominal wall musculature with fascias viewed anterosuperiorally. ** - External oblique muscle, * - Internal oblique muscle, • - Transversus abdominis muscle.

Structures like the spermatic cord were especially difficult to model given their oblique course through the body. While on cross section, the spermatic cord appeared rather distinct, the three-dimensional model was indiscriminate. Despite the reasonable modeling of its course through the pelvis and perineum, the details of the spermatic cord were too obscured. (Figure 9)

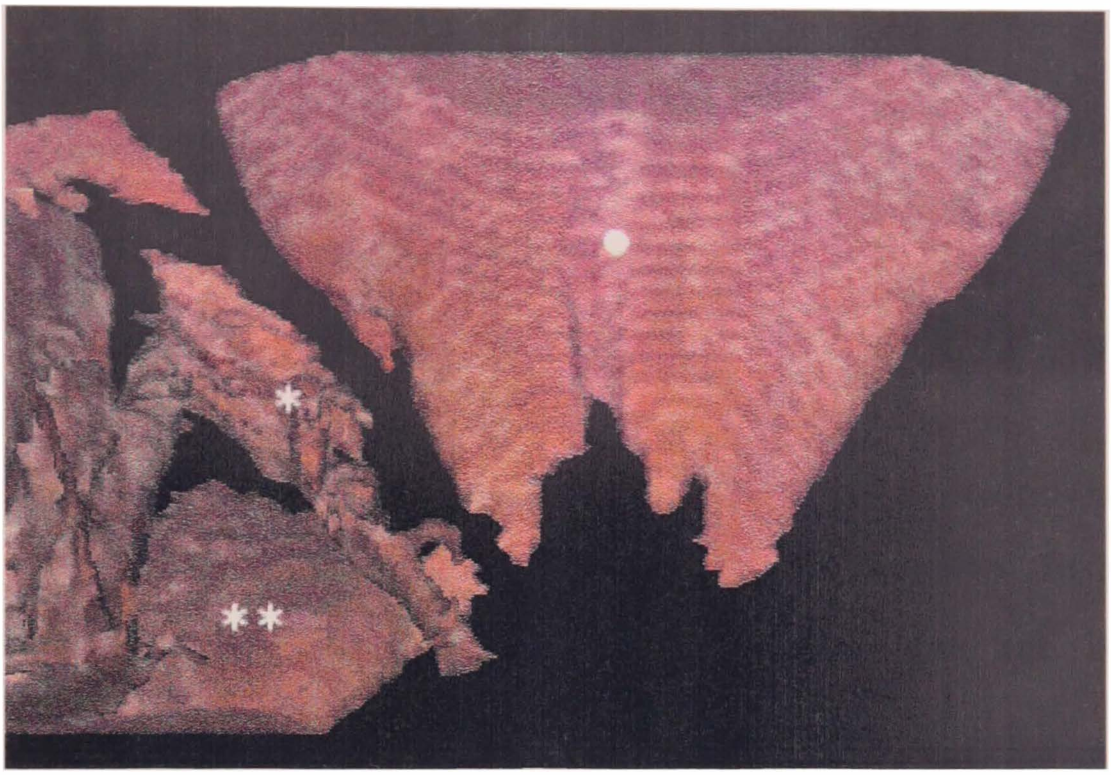

**Figure 9.** Three-dimensional model of bilateral rectus abdominis muscle (•), iliacus muscle (**), and cremaster muscle/spermatic cord (*), viewed anteroinferiorally.

# DISCUSSION

The most important factor in creating a computer-based instruction package is that it needs to be tailored to fit a need. Simply, the package must present material in a unique and beneficial way. In order to be useful, the package must make a difficult concept more comprehensible. If it is to be effective it must present information that cannot be obtained any other way and should at least complement if not replace some traditional learning methods.

Terminology and determining which anatomical subdivisions belong to which structures is one area where many students struggle. The specializations of the external oblique aponeurosis are such structures. A model can effectively demonstrate that while the aponeurosis has many specializations, they are all still components of the one single layer.

The layering of the spermatic cord coverings is another elusive concept. Since the spermatic cord is oblique in its course through the abdomen, a model would clarify how it traverses and collects one layer of aponeurosis at a time. By sequentially making the layers of a model visible, the illusion of traveling down the cord can be simulated. This would also convey the continuity between spermatic cord coverings, abdominal muscles and pelvic fascias.

Students also often misjudge anatomical landmarks. An area where three-dimensional modeling would be especially useful is in the understanding of topical anatomy and its clinical relevancy. In considering the inguinal canal, students often misjudge the exact location of the inguinal ligament, mistakenly identifying it as the area of the inguinal crease. The inguinal crease, however, is a highly variable landmark where Scarpa's fascia of the abdomen adheres to the fascia lata of the thigh. For obese individuals in particular, the inguinal crease is displaced several inches below the inguinal ligament.

Additionally, three-dimensional modeling can help students visualize concepts and relationships, rather than simply memorizing them. For example, Hesselbach's Triangle is often studied by simply memorizing its borders as the inferior epigastric vessels superolaterally, the lateral borders of the rectus, and the inguinal ligament inferolaterally. With a model, students can toggle a triangular overlay which clearly demonstrates the borders and also visually demonstrate how the triangle is a target of direct inguinal hernias. Furthermore, they can understand concepts such as why the medial border of the rectus sheath is the most suitable structure for hernia repair. Similarly, students can visualize why a hernia is named as either direct or indirect rather than simply memorizing its associations.

By focusing on alternative learning tools such as computer models, students can gain a better understanding of difficult anatomical relationships, have a higher retention of those concepts, and effectively become better clinicians.

# BIBLIOGRAPHY

# BIBLIOGRAPHY

Ackerman M.J. The Visible Human Project. The Journal of Biocommunication 18(2): 14, (1991).

Bertin E., Parazza F., Chjassery J.M. Segmentation and measurement based on 3D Voronoi Diagram: application to confocal microscopy. Computerized Medical Imaging and Graphics 17: 175-182, (1993).

Chew F.S. and Smirniotopoulos J.G. Teaching skeletal radiology with use of computer-assisted instruction with interactive videodisc. Joural of Bone and Joint Surgery 77(7): 1080-1086, (1995).

Cookson M.J., Davies C.J., Entwistle A., Whimster W.F. The microanatomy of the alveolar duct of the human lung imaged by confocal microscopy and visualized with computer-based 3D reconstruction. Computerized Medical Imaging and Graphics 17: 201-210, (1993).

Dowd S.B. and Bower R. Computer-based instruction. Radiological Technology 66(4): 247-252, (1995).

Dufresne C.R., McCarthy J.G., Cutting C.B., Epstein F.J., Hoffman W.Y. Volumetric quantification of intracranial and ventricular volume following cranial vault remodeling: a preliminary report. Plastic and Reconstructive Surgery 79: 24-32, (1987).

Eba T., Yasuda T., Yokoi S., Toriwaki J. Automatic decision for the most suitable femur position in a hip-joint surgical planning system. Transactions of the Institute of Electronics Information and Communications Engineers D-II: J73D-II, (1990).

Gault D., Brunelle F., Renier D., Marchac D. The calculation of intracranial volume using CT scans. Childrens' Nervous System 4: 271-273, (1988).

Henri C.J., Pike G.B., Collins D.L., Peters T.M. Three-dimensional display of cortical anatomy and vasculature: magnetic resonance angiography versus multimodality integration. Journal of Digital Imaging 4: 21-27, (1991).

Kall B.A. The impact of computer and imaging technology on stereotactic surgery. Applied Neurophysiology 50: 9-22, (1987).

Kainz J., Stammberger H. Danger areas of the posterior rhinobasis. Acta Otolaryngology (Stockholm) 112: 852-861, (1992).

Khadra M.H., Guinea A.I., Hill D.A. The acceptance of computer assisted learning by medical students. Australia and New Zealand Journal of Surgery 65(8): 610-612, (1995).

Lorensen W.E. and Cline H.E. Marching Cubes: A high resolution 3D surface construction algorithm. Computer Graphics 21: 163-169, (1987).

Parazza F., Humbert C., Usson Y. Method for 3D volumetric analysis of intranuclear fluorescence distribution in confocal microscopy. Computerized Medical Imaging and Graphics 17: 189-200, (1993).

Peters T.M., Clark J.A., Olivier A., et al. Integrated stereotaxic imaging with CT, MR imaging, and digital subtraction angiography. Radiology 161: 821-826, (1986).

Rosse C. The potential of computerized representations of anatomy in the training of health care providers. Academic Medicine 70(6): 499-505, (1995).

Satava R.M. Virtual reality surgical simulator: the first steps. Surgical Endoscopy 7(3): 203-205, (1993).

Soyama Y., Yasuda T., Yokoi S., Toriwaki J., Fujioka M. A hip joint surgical planning system using 3-D images. Japanese Journal of Medical Engineering 27: 70-78, (1989).

Stanford W., Erkonen W.E., Cassell M.D., Moran B.D., Easley G., Carris R.L., Albanese M.A. Evaluation of a computer-based program for teaching cardiac anatomy. Investigative Radiology 29(2): 248-252, (1994).

Stewart J.E. and Broaddus W.C. Coherently-oriented manifold surfaces from medical images. Proceedings of Visualization in Biomedical Computer ‘96, Submitted, (1996).

Stewart J.E., Broaddus W.C., Johnson J.H. Rebuilding the Visible Man. Submitted to the National Library of Medicine, (1996).

Webber W.B. and Rinehart G.C. Computer-based multimedia in plastic surgery education. Proceedings of the Annual Symposium on Computer Applications in Medical Care 1992: 829-830, (1992).

Wespe R., Wallin A., Klaue K., Ganz R., Schneider E. Three-dimensional quantification of established femoral head necrosis. Proceedings CAR '89. Berlin Germany: Springer-Verlag: 362-368, (1989).

Zonneveld F.W., Koornneef, L. Wittebol-Post D. Quantitative volumetric assessment of orbital soft tissue. Proceedings CAR '91. Berlin, Germany: Springer-Verlag: 181-186, (1991).

Zonneveld, F.W. A decade of clinical three-dimensional imaging: a review. Investigative Radiology 29(7): 716-725, (1994).

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