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Chapter 5

Cranial Base Tumor Visualization through High-Performance Computing

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Tumors of the skull base in general are considered among the more difficult head and neck pathological entities to treat surgically; some surgeons, in fact, consider lesions in this area inoperable. The most appropriate and safest surgical approach to lesions of the anterior and lateral skull base can be devised only with accurate and precise pre-operative assessment. The literature demonstrates the constant evolution of and search for more efficient less invasive, and safe surgical approaches to this region. With the development of a more exact three-dimensional, interactive anatomical "road map" for each patient's disease and anatomy, the skull base surgeon can not only achieve a more accurate pre-operative assessment leading to a less invasive and less morbid approach, but also can continue to develop and refine new approaches without fear of actual morbidity and mortality. An interdisciplinary team approach, the advent and continued development of faster high performance computers, and the development of new and innovative rendering algorithms can lead to surgical simulation. A prototype of an interactive system has been developed. The system will be iteratively modified through a stepwise evaluation of its clinical usefulness by continually reassessing the system with clinical trials. The current state of the system and the potential benefits are presented.

INTRODUCTION

Tumors of the skull base in general are considered one of the more difficult head and neck pathological entities to treat surgically; some surgeons, in fact, consider lesions in this area inoperable. Close proximity to vital structures such as cranial nerves, organs of special sensation such as the eye and inner ear, major vascular structures to the brain, and the brain itself make operating in this area extremely challenging even for the "experts". In the past, injury to nearby vital structures led to unacceptable operative morbidity, and surgical mortality was overwhelming, secondary to hemorrhage and sepsis. Within the recent past surgical treatment of lesions in this area has become a reasonable alternative for patients with these tumors (Jackson 1981).

The most appropriate and safest surgical approach to lesions of the anterior and lateral skull base can be devised only with accurate and precise pre-operative assessment. The advent of new diagnostic technologies of MRI and high resolution CT scanning have improved our understanding of the anatomy in the area. However, these tools do not reveal everything about the complex nature of the normal anatomy in this area, let alone that which has been pathologically altered or changed by prior surgery. This problem is ultimately demonstrated by the fact that occasionally a surgeon performs a major surgical procedure only to realize that the tumor cannot be resected. Most approaches to the skull base require widened exposure and peripheral control of vascular structures, leading to disfiguring and morbid results directly imposed by the surgical approach itself and not necessarily from tumor extirpation. The literature demonstrates the constant evolution of and search for more efficient, less invasive, and safe surgical approaches to this region (Jackson 1981, 1991, Fisch 1984, Janeka, 1991, Spetzler et al, 1990, Cummings et al., 1992 Schuller et al., 1992).

The preoperative evaluation of brain and skull based tumors requires multiple imaging modalities. Precise imaging of cranial base contents, as well as of the tumor itself, is vital for the accurate diagnosis and treatment of such entities. Currently, magnetic resonance, computed tomography, and angiography are used to plan various surgical trajectories, to define surgical anatomy, to analyze tumor volume or to establish tumor burden, and to characterize complex tissue types (Shtern 1992, Kelly 1992). Operatively, these images are used to provide step-wise comparisons with the surgical field, for incision planning, and tumor margin definition. Postoperatively, these modalities help determine the extent of tumor resection, the degree of response to radiation therapy or chemotherapy, and in follow-up, to compare clinical condition and tumor burden for decisions regarding future care.

With the development of new scanning techniques and rendering algorithms, three-dimensional imaging is becoming more available. Recent studies have shown the usefulness of such imaging techniques. Specifically, in the head and neck, Ferstl et al. found that, using 3D spiral CT, they could easily resolve the branches of the external carotid with resolution comparable to digital subtraction angiography and study the vessels in three dimensions. This allows for a more accurate estimation of vessel position and lumen size (Ferstl et al, 1994). We have recently demonstrated resolution of the branches of the external carotid artery with our high resolution 3D MRI protocols (Oehler et al, 1995). In a review article on applications of 3D imaging in head and neck pathology, Ray et al outlined its use in several different areas (Ray et al., 1993). In congenital and developmental abnormalities, 3D CT was thought to be invaluable in the pre-operative and postoperative assessment of craniosynostoses, "revealing subtleties of asymmetry not readily seen in two dimensions". The authors raised the possibility of the use of surgical simulation, based on these image data, which would allow the surgeon to determine pre-operatively a surgical plan and approach as well as to evaluate the sites and sizes of osteotomies and implants. The simulation would also allow the determination, preoperatively, of the likely outcome of certain surgical procedures, thereby leading to decreased intraoperative time and, therefore, lowering the risk of a poor outcome for the patient. In traumatic injury, 3D reconstruction is most helpful in evaluating maxillary, mandibular, and orbital fractures; severely comminuted fractures; and those fractures with complex rotational elements. In tumors of the head and neck, the value of 3D CT and MRI of the paranasal sinuses, orbit, and cranial base is apparent by the easy of verification of tumor boundaries, including the relationship between mass and important surrounding osseous structures such as neural foramina at the base of the skull. Ray et al. state that reconstruction of head and neck tumor resection defects benefit from such imaging capability. There continues to be a proliferation of reports of using 3D imaging techniques in the evaluation of both adults and pediatric head and neck patients (Davis et al., 1991; Tomura et al, 1993; Mösges, 1993; Grevers et al, 1991). Another area of new imaging capabilities is the use of "multimodal" images, (the matching of images obtained by different imaging modalities such as CT and MRI) creating a "fused" image which exploits the advantages of both (Chisin et al, 1993). These studies allow a synergism of imaging data that, when viewed in three dimensions, allow for a more accurate reproduction or "model" of the patient.

With the development of a more exact three-dimensional, interactive anatomical "road map" for each patient's disease and anatomy, the skull base surgeon can not only achieve a more accurate pre-operative assessment, leading to a less invasive and less morbid approach, but can also continue to develop and refine new approaches without fear of actual morbidity and mortality. This system has additional benefits in that students of this type of surgery can practice and obtain expertise in a non-threatening environment, animals need not be used for training and development of new techniques, and with this tool, the patients may even visualize and understand their disease processes more completely, leading to a new standard of informed consent. The problems that arise when such a goal is proposed may presently seem insurmountable. The large amounts of data (up to 60 megabytes per study) make visualizing and manipulating the "model" very difficult, let alone being able to interact with the data in a real-time environment. Another current lmitation is the inability to accurately model tissue properties, such as deformation, elasticity, compression, bleeding, etc. Such aspects are nontrivial but necessary if true simulation is to be achieved. There is a paucity of research in the area of tissue modeling. There are no recent studies which deliniate mathmatical equations which predict tissue mechnical characteristics or relate tissue contrast in imaging studies to biomechanical properties. Investigators need to develop new techniques and novel approaches to get this type of data. An interdisciplinary team approach to improve image acquisition methods to generate images with higher spatial resolution and better contrast between different tissue types, new and innovative rendering algorithms and their implementation on parallel systems, development of mathmatical models of tissue properties linked to image data, coupled with the enevitable development of faster high performance hardware can lead to true surgical simulation.

An interdisciplinary team has been working for the past 2.5 years to integrate current surgical practice in tumor management with new and evolving technology in image aquisition, image rendering, and hardware development. The goal of this group is to iteratively design and build a system that will provide a paradigm shift from passive witnessing of medical information to actively participating with the information. It is hypothesized that through the employment of real-time interaction (10-15 frames per second) and the use of intuitive computer interfaces, researchers will develop a system that can be instrumental in fundamentally changing the way practitioners manage medical image data.

Already in existance is a prototype of an interactive system with an intuitive interface for the purpose of generating real-time virtual simulations of medical data. The system will be iteratively modified through a stepwise evaluation of its clinical usefulness by continually reassessing the following goals:

- The system will facilitate the practitioner in the diagnosis and management of cranial base tumors.
- It will promote the use of minimally invasive therapies.
- It will promote the use of less morbid surgical techniques.
- It will facilitate the development of new surgical approaches.
- It will accelerate the learning curve from novice to expert.
- It will promote increased patient understanding of his/her disease.

METHODS

The interdisciplinary research team is composed of three separate groups that meet regularly to discuss the development of the system and provide feedback to each other for future studies and design modifications. These are the applications, the technical, and the user modeling and evaluations groups.

The Applications Group comprises physicians in Otolaryngology - Head and Neck Surgery and Neurosurgery who are members of the Cranial Base Surgical Team at The Ohio State University Medical Center. The Technical Group comprises specialists in medical imaging, computer graphics and visualization/rendering, and advanced interface design and integration. The technical group comprises individuals from the Magnetic Resonance Imaging Research Facility, the Ohio Supercomputer Center, and the Department of Computer and Information Science. The User Modeling and Evaluation Group comprises members specializing in cognitive psychology, human factors, and knowledge engineering from the Division of Medical Informatics, Department of Pathology, and Computer and Information Science.

The general duties of the Application Group are the following:

- to serve as domain experts.
- to serve as liaisons to selected experts to be studied on the system under verbal and motor (think aloud) protocols (see below) set forth by the User Modeling and Evaluation Group.
- to identify and collect data, and create selected case studies.
- to assist in the segmentation of selected structures to be used in the virtual simulation.
- to assist with tissue modelling development.
- to coordinate clinical trials of the system.

The technical group is responsible for the following:

- to develop and test the interface.
- to develop and improve the rendering software.
- to develop and refine high resolution image acquisition protocols.
- to develop and refine tissue modelling algorithms.
- to provide technical support for the clinical trials.

The tasks of the User Modeling and Evaluation Group are:

- to establish protocols for obtaining data during expert trials of the system.
- to collect and analyze both verbal and motor protocols of the selected experts during trials.
- provide formative feedback for the iterative design and implementation of the system in general and the interface in paticular.

Evaluation is occurring concurrently with system development, so that the technical group receives feedback on issues concerning the system design. A clinical pilot study designed to test the clinical efficacy of the system is underway. The study tests a group of 3 otolaryngologists and 3 neurosurgeons at The Ohio State University Medical Center. The 6 individuals are evaluating several case studies from the collection of patients with cranial base tumor for which data has been obtained. Each expert reviews each case and provides location of the tumor, involvement of adjacent structures, and proposed surgical approach. Individuals are asked to "think aloud" (van Someren, 1994) or verbalize their thoughts as they are evaluating the cases using both traditional films and the system. What the individual's attention is directed toward is recorded. Mouse positions and clicks are also recorded. These data are then transcribed, recorded, and analyzed to provide a quantitative evaluation of the system. Next, a second stage clinical study, employing the same techniques, will involve a larger number of individuals from various institutions across the country. The system is being iteratively designed throughout the rest of its development based on the results of these and other evaluations. The effects of the new technology upon the diagnostic process is quantified, using techniques from the "think aloud" method of cognitive psychology (Ericsson and Simon, 1993).

CURRENT PROGRESS

To date, the system is in its first stage of development. Fourteen patients with cranial base lesions have been scanned, using unique, high resolution scanning protocols for CT (Davis et al, 1991) and MR (Schmalbrock et al, 1990; Schmalbrock et al, 1993; Ying et al, 1995) protocols. We have set up a computerized data base that tracks pertinent pre-operative, operative, and postoperative patient information from which clinical scenarios are developed. A unique surface-matching algorithm has been developed to generate merged CT and MR data from scans performed on different machines at different times and without fiduciaries. The two datasets, one CT and the other MRI are different resolutions and different grid sizes. A marching cubes algorithm is used to create a surface of the face of each dataset. The face is used for two reasons: 1) the marching cubes algorithm seeks out an isosurface, and the signal difference across the air-skin boundary is fairly prominent for both types of scans, and 2) it is easy to visually tell when the two faces are the same size and resolution. The CT dataset is scaled, rotated, and translated until it visually matches the MRI surface data set. The matrix is determined that transforms the CT surface into the MRI surface. This same matrix is then used to resample the CT volume into a new volume. After this step, the CT and MRI datasets are registered: they have the same resolution and grid size. The merged volume data sets are precomputed into rendered simulations on high performance workstations and are available for recall, using discrete phrase voice recognition software. The clinician sits at the terminal and, using voice commands, can recall either standard CT and MR presentations of the case or rendered simulations of the three-dimensional data. Rendered simulations include high resolution reconstructed CT or MR, merged reconstructions, and specific views of the lesion and surrounding vasculature (Figure 1). Currently, the 3D data is rendered into pre-determined cine loops (Figure 2), which may then be played back by the practitioner. This particular technique allows for high quality rendered pictures, which for volume data sets are not yet available in real time. These visualizations provide unique perspectives of the tumor and surrounding anatomy, hypothetically, enabling the surgeon to better understand the relationships of the tumor to critical structures.

We now have Real time volume rendering capabilities (Yagel et al., 1995, Ebert et al., 1994) which allow the surgeon to manipulate the volume data set at almost 10-15 frames per second. The renderer achieves this speed by extracting from the volume data set only those voxels that contribute to the final image, which for most medical images are a significantly small fraction of the total number of voxels present in the data set. It then uses the hardware rendering capabilities of high-end graphic workstations, such and the Silicon Graphics CRIMSON® and ONYX®, to render these "significant" voxels. This process allows the extracted data set to be rendered at 10 to 15 frames per second, a speed that is not possible for the full data set even on modern high-end workstations. This unique capability allows high resolution visualization of the patient's anatomy similar to cadaver dissection, in which individual anatomical components (i.e., skull, brain, blood vessels, tumor) can be examined separately or together but with the unique ability to allow various components to become semi- or fully transparent (Figure 3). A cutting plane has also been implemented to allow arbitrary slicing through the data set. The rendering technique does not yet attain the quality of ray tracing rendering but accomplishes real time speed. As the algorithms and hardware develop, this level of resolution will continue to improve.

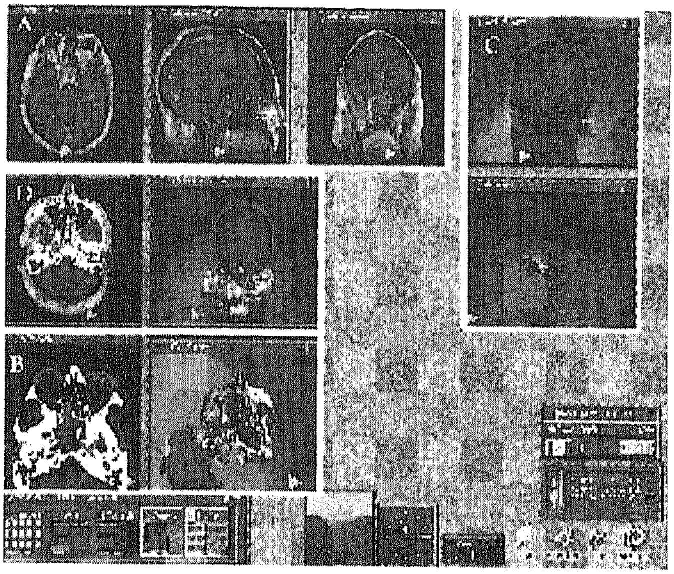


Figure 1:

High resolution MRI cine loops in cardinal planes (A), high resolution CT cine loops in axial plane and 3D (B), high resolution MRI cine loops with tumor and vasculature separated out (C), multimodal CT and MRI cine loops in axial plane and 3D (D).

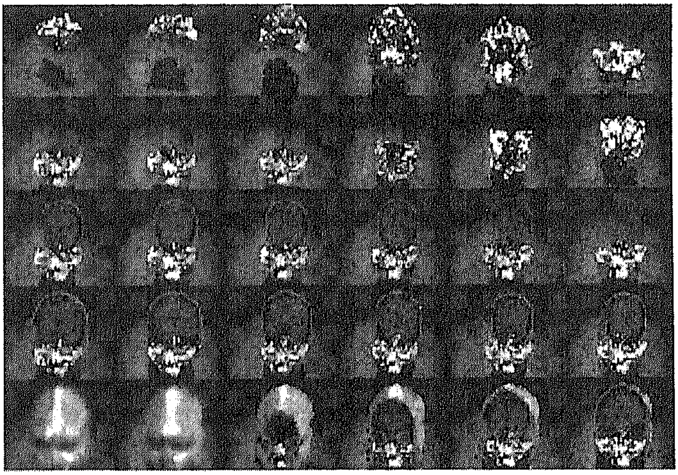
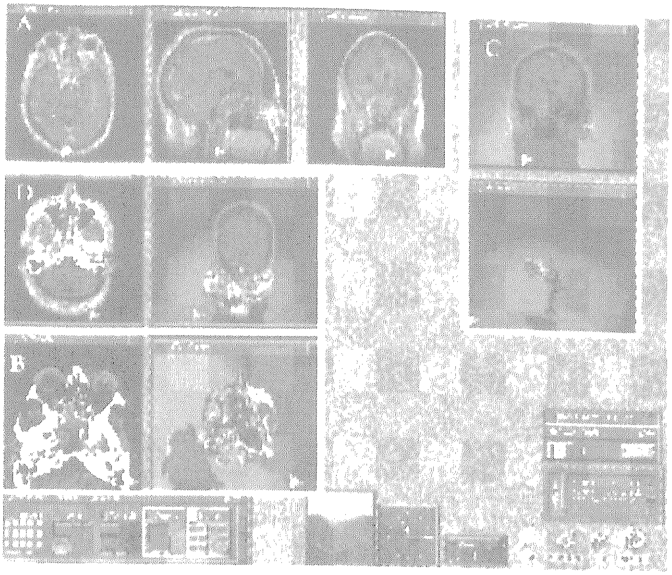


Figure 2:

Pre computed cine loop of multimodal 3D rendering.



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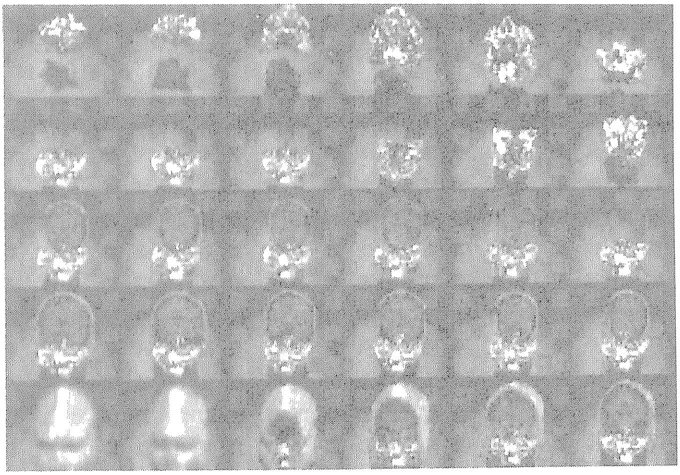

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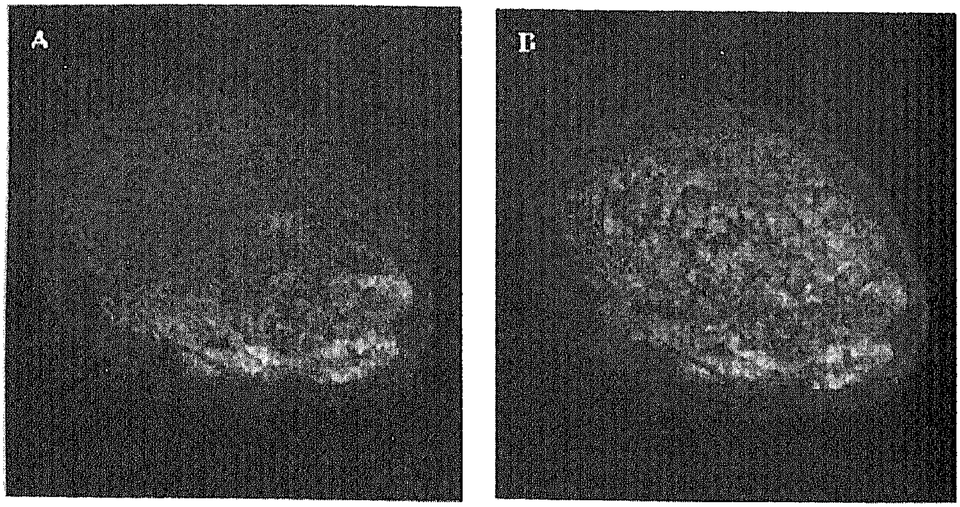
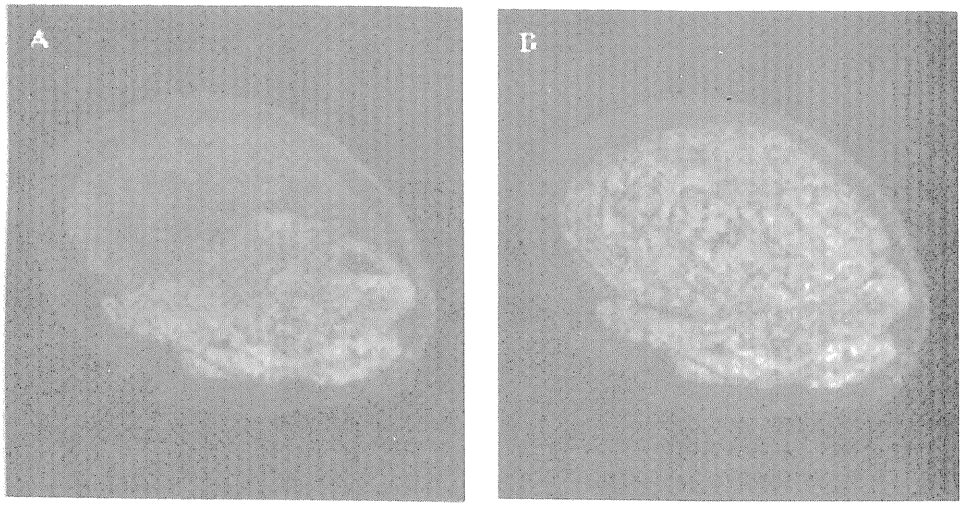


Figure 3:

Screen capture of real time renderer. Skin and brain transparant (A), skin and brain visible (B).

Unique structures for separate visualization are currently hand segmented. Existing neural network based software (Wang and Terman, 1995) is capable of automatically segmenting subsets of the data (Figure 4). To rate the quality of our segmentation algorithms, a study is under way to evaluate the differences between hand segmented and automatic segmented structures. When these algorithms are developed to a level of accepible accuracy, they will be incorporated, into the automatic phases of our system to segment constant structures such as bone, brain and vasculature.

Other unique aspects that are currently being incorporated into the system and constitute the second stage of the system (simulation) include volume morphing (Kurzion and Yagel, 1995) and haptic feedback. Morphing will facilitate merging multimodality data sets and simulate cutting and tumor resection. Haptic feedback technology will add a critical feedback channel for realistic surgical simulation and surgical training. A six



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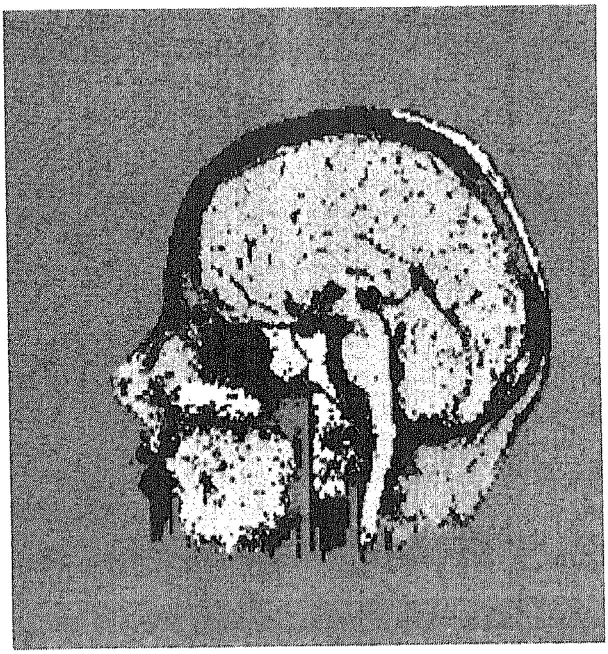


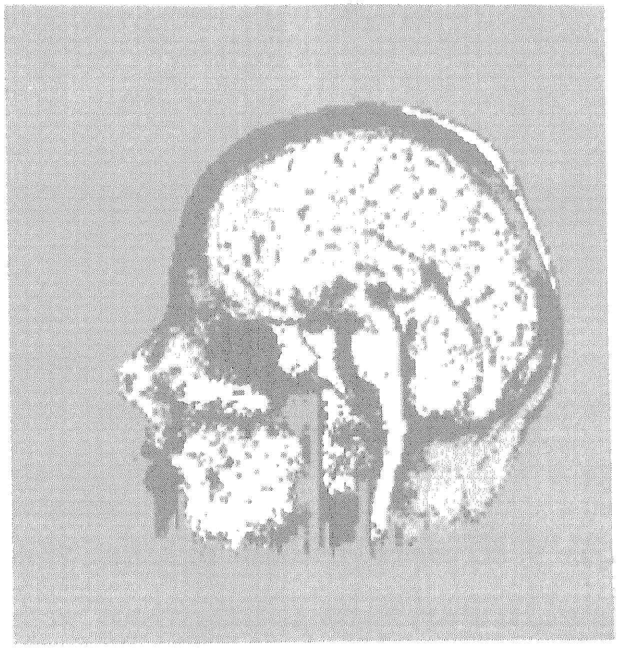
Figure 4:

MRI section which has been automatically segmented using neural net software.

degree of freedom probe (Figure 5) (Immersion Corporation), as well as traditional mouse-based techniques are incorporated as manipulation devices to allow the physician user to intuitively explore the reconstructed image data. Curmetly, the Immersion Probe ® is used to manipulate the cutting plane through the rendered data set.

DISCUSSION

Several accomplishments arise from this research. An interactive, intuitive system for visualizing and manipulating patient specific anatomical representations improves understanding of disease states existing in areas of complex anatomy. This advancement will enhance all phases of the treatment of cranial base tumors. Diagnostic and therapeutic approaches to tumor management will therefore expand and improve. In addition, by providing improved methods to comprehensively manage brain and cranial



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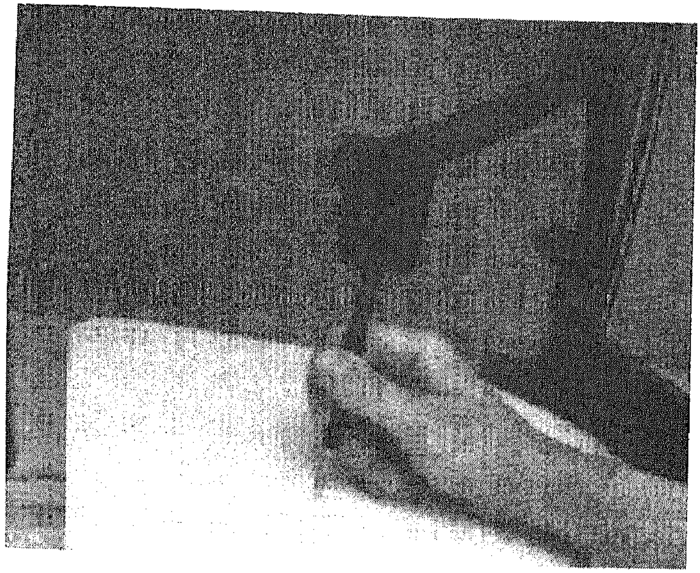

Figure 5: Six degree of freedom Immersion Probe®.

base tumors, the system can broadly increase the quality of health care delivery to patients with these disease entities.

The system drives fundamental research in the fields of computer graphics and human computer interface design. The development and implementation of real-time interaction with large volume data sets, as well as 3D volume deformation and morphing, will advance computer graphics. The field of human computer interface will advance through the integration of user defined intuitive interfaces including visual and speech and specifically new developments in haptic feedback. New protocols designed to quantitatively evaluate and provide iterative feedback in the design of the system will advance the field of human/computer interface evaluation and design.

Future implications in medical data management will be apparant in that patient image data will be stored as volumes and interactive computer technology will produce images from this data at will. These images can be produced from arbitrary angles and can contain any specific anatomical structures or combination thereof. Additionally, with the aid of high-speed rendering as described above, the physician can view the data in three dimensions and manipulate the viewing angle and display features such as cutting into the volume data set to allow more intuitive exploration of the data. In much the same way an individual can manipulate a skull in the palm of the hand. It will no longer be necessary to generate and store banks of patient images.

SUMMARY

In summary, the paper presents an interdisciplinary effort to design, build, and implement a high performance computer based system that will aid the physician treating patients with cranial base tumors. Specifically, the system uses volumetric data generated from standard CT and MR scanners using unique high resolution scanning protocols. To date, the system displays these data in various formats, including cardinal planes and three-dimensional rendered simulations. The physician uses intuitive interface devices to interact with the image data, such as control of random slicing through the data with a 6 degree of freedom probe. The system will be iteratively developed through multiple clinical trials into a fully interactive "simulator". With this more exact three-dimensional, interactive anatomical "road map" for each patient's disease and anatomy, the skull base surgeon can not only achieve a more accurate pre-operative assessment, leading to a less invasive and less morbid approach, but can also continue to develop and refine new approaches without fear of actual morbidity and mortality.

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