Original Research

An Integrated Visualization System for Surgical Planning and Guidance Using Image Fusion and an Open MR

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A surgical guidance and visualization system is presented, which uniquely integrates capabilities for data analysis and on-line interventional guidance into the setting of interventional MRI. Various pre-operative scans (T1- and T2-weighted MRI, MR angiography, and functional MRI (fMRI)) are fused and automatically aligned with the operating field of the interventional MR system. Both pre-surgical and intra-operative data may be segmented to generate three-dimensional surface models of key anatomical and functional structures. Models are combined in a three-dimensional scene along with reformatted slices that are driven by a tracked surgical device. Thus, pre-operative data augments interventional imaging to expedite tissue characterization and precise localization and targeting. As the surgery progresses, and anatomical changes subsequently reduce the relevance of pre-operative data, interventional data is refreshed for software navigation in true real time. The system has been applied in 45 neurosurgical cases and found to have beneficial utility for planning and guidance. J. Magn. Reson. Imaging 2001; 13:967–975. © 2001 Wiley-Liss, Inc.

Index terms: neurosurgical planning; image guided surgery; image fusion; 3D visualization; interventional MRI

IMAGE-GUIDED SURGERY SYSTEMS strive to enhance the surgeon's capability to utilize medical imagery to decrease the invasiveness of surgical procedures and increase their accuracy and safety. These systems can be categorized into performing one or more of the following functions: data analysis (2,3,4), surgical planning (2,3,4), surgical guidance (5,6,7,8,9,10), and surgical guidance with intra-operative updates (11,12,13,14). The systems focused on surgical guidance tend to present the surgeon with data that was gathered prior to surgery, track surgical instruments within the operating field, and render the tracked devices along with the data. For more difficult surgeries, it is beneficial to present the surgeon with not just one diagnostic scan, but with an array of information derived from fusing data sets with information on morphology, cortical function, and metabolic activity. These varied data sets are acquired in different coordinate systems and need to be aligned, or registered, to a common framework for surgical planning before that framework is in turn registered to the patient for surgical guidance. The latter registration allows the surgeon to establish a correspondence between the patient lying on the operating table and the images rendered on a nearby computer screen.

The major shortcoming of image guided surgery systems is that the use of pre-surgically acquired data does not account for intra-operative changes in brain morphology. The systems with intra-operative updates have been introduced to fill that void, but they have fallen short of achieving perfect interactivity and full information disclosure to the surgeon. In particular, the benefits of interventional MRI could be amplified by focusing on five issues: image quality, imaging time, multi-modal fusion, faster localization, and three-dimensional visualization. The need for better image quality arises because some anatomical structures are difficult to distinguish on interventional MR images, but are clearer on conventional, diagnostic MRI that benefits from a higher magnetic field and longer imaging times. Our goal is to provide both in surgery. Imaging time is a critical constraint because in order for surgical guidance to be interactive, images must be acquired quickly enough to be utilized without disrupting or slowing down the procedure. Multi-modal fusion is desirable considering that functional and metabolic data that is acquired pre-operatively could deliver increased benefit if integrated with intra-operative, anatomical information. Faster localization is needed because interventional MR provides the capability of planning approach trajectories by maneuvering a

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Table 1
Population for Craniotomies by Histopathology

Pathology	Age range	No. females	No. males
Astrocytoma I–II	4–63	8	6
Astrocytoma III anaplastic	35–67	0	2
AVM	37	0	1
Ganglioglioma	26	1	0
Glioblastoma	29–67	4	6
Metastasis	13–31	2	0
Oligodendroglioma	27–49	4	1
Other	6–67	6	3

tracked surgical instrument and collecting images at the rate of 6–20 seconds per image, but an ideally interactive system needs an update rate of 0.1 seconds per image. Lastly, three-dimensional visualization would free the surgeon from needing to mentally map the two-dimensional interventional images seen on a computer screen to the three-dimensional operating field.

Any attempt to improve interventional MRI by using the combination of several currently available data analysis and surgical planning systems can be cumbersome and time-consuming, making it impractical for clinical applications. Therefore, the aim of this study was to integrate all facets of image guided medicine (data analysis, surgical planning, surgical guidance, and intra-operative updates) into a single environment. Our system is the first to augment the functionality of an open MR scanner (15,16) with various pre-operative data sets featuring information on morphology (MR, CT, MR angiography), cortical function (fMRI), and metabolic activity (PET, SPECT), as well as to offer the same level of analysis previously reserved for pre-operative data to interventional data. The 3D Slicer is the software package we developed to address the five aforementioned issues. Image quality, visualization time, and localization are improved by performing real-time re-slicing of both pre-operative and intra-operative data sets, and displaying them for simultaneous review. Multi-modal information is aligned using automatic registration for visualizing in the same scene. Three-dimensional visualization is accomplished with a computer graphics display that offers the flexibility to see the situation from viewpoints not physically possible, in order to facilitate the understanding of complex situations and to aid in avoiding damage to healthy tissue.

MATERIALS AND METHODS

Patient Population

Over a one-year period, the system was applied to 45 patients (25 female, 20 male), ages 4 to 67. All patients received craniotomies with the exception of one biopsy. Table 1 aggregates the population for craniotomies by histopathology.

Pre-procedural Imaging

MRI examination was performed in a 1.5-Tesla clinical scanner (Signa Horizon; GE Medical Systems, Milwaukee, WI). The standard protocol in our hospital includes acquiring a T1-weighted, spoiled gradient echo (SPGR) volume (124 1.5mm sagittal slices, TR=35msec, TE=5msec, Flip angle=45, FOV=24cm, matrix=256×192, NEX=1), a T2-weighted fast spin echo (FSE) volume (124 axial slices, TR=600msec, TE=19msec, FOV=22cm, matrix=256×192, NEX=1), and a phase-contrast MR angiogram (60 axial slices, TR=32msec, Flip angle=20, FOV=24cm, matrix=256×128, NEX=1). Patients whose pathology was located within the vicinity of eloquent cortex additionally received an fMRI exam (HORIZON EPI-BOLD sequence, 21 contiguous 7mm coronal slices, TE=50msec, TR=3sec, FOV=24cm, matrix=64×64, 6 alternating 30-second epochs of stimulus and control tasks).

Augmented Interventional MR System

All procedures were performed in an open-configuration MRI system (Signa SP; GE Medical Systems, Milwaukee, WI). The location of the imaging plane was specified with an optical tracking system (Flashpoint; Image Guided Technologies, Boulder, CO), referred to hereafter as the *locator*. The spatial relationship of the locator relative to the scanner was reported as both a position and an orientation with an update rate of 10 Hz.

We added a visualization workstation (Ultra 30; Sun Microsystems, Mountain View, CA) with a TCP/IP network connection to the SP imaging workstation. Whenever the locator's position or orientation changed, or a new image was acquired, a server process we created on the SP imaging workstation sent the new data to our 3D Slicer software resident on the visualization workstation. The visualization workstation contained two Sun Creator three-dimensional graphics accelerator cards. One drove the 20-inch display placed in the control area of the surgical suite, and the other output the three-dimensional view to color LCD panels inside the scanner gantry.

Key Features of the 3D Slicer That Enable This Application

Open Source Design

The 3D Slicer is an application package we developed which comprises the Visualization Toolkit (VTK) (17) for processing, OpenGL (18) for graphics acceleration, and Tcl/Tk (19) for the user interface. The architecture of the 3D Slicer is crafted around a modular paradigm that optimizes extendability. Adding a new module (for interfacing with a robot, for example) consists of adding only one new Tcl file containing the user-interface code and optionally adding new VTK objects for processing. The mechanisms for controlling that module's behavior with respect to the data already exist within the framework. The 3D Slicer is a freely available, open source tool for clinicians and scientists (20).

Multi-Volume Reformatting

Volume data is commonly visualized through multiplane reformatting (MPR). We made novel extensions to MPR to allow the three slices to:

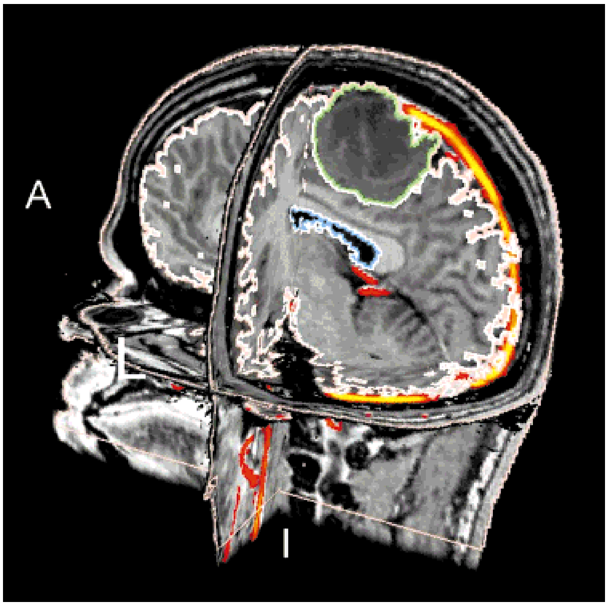

Figure 1. Multiple layers are displayed on each slice, allowing the fusion of data from different times or modalities. MR phase contrast angiography information (red and yellow) is overlaid on grayscale SPGR data. Also, the boundaries created through segmentation are displayed: the tumor is outlined in green, the skin in pink, the brain in white, and the ventricles in blue. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

- be orthogonal or independently oblique,
- orient orthogonal slices relative to either the scanner (mm space) or the data (voxel space),
- follow either the user's pointing device in the operating room,
- slice through multiple volumes simultaneously: each slice is the composite of a background layer, a foreground layer, and a label layer.

Typically, functional information is presented in color on the foreground layer, which is overlaid with an adjustable opacity on a gray background layer. Additionally, the output of the segmentation process is funneled into the label layer to draw a boundary around key structures, such as the tumor and vessels, as illustrated in Figure 1.

Segmentation

Volumetric data can be semi-automatically segmented using the 3D Slicer's suite of editing tools. Effects such as thresholding, morphological operations (erosion, dilation), island removal (erasing small groupings of similar pixels), measuring the size of islands, cropping, and free-hand drawing of polygons, lines, or points can be applied to the data. Each effect can be administered on either a three-dimensional or slice-by-slice basis. One strength of our system is that effects can be visualized by overlaying the edited volume translucently on the original volume and exploring both in the three-dimensional view, as shown in Figure 2.

Three-Dimensional Surface Models

Surface models of key anatomical structures (usually tumor, vessels, ventricles, skin, brain, and functional regions when applicable) are generated from the segmentations using Marching Cubes (21) and decimation (22). Surface models are visualized in the three-dimensional view along with the reformatted slices. Our surgeons prefer to view a portion of the skin as a landmark, so we allow for the slice planes to selectively clip away the skin model to reveal other unclipped models beneath, such as a tumor or critical structures like blood vessels, as well as the respective image planes. Each model is colored differently (and consistently between cases), and rendered with adjustable opacity as presented in Figure 3. As an alternative to generating mod-

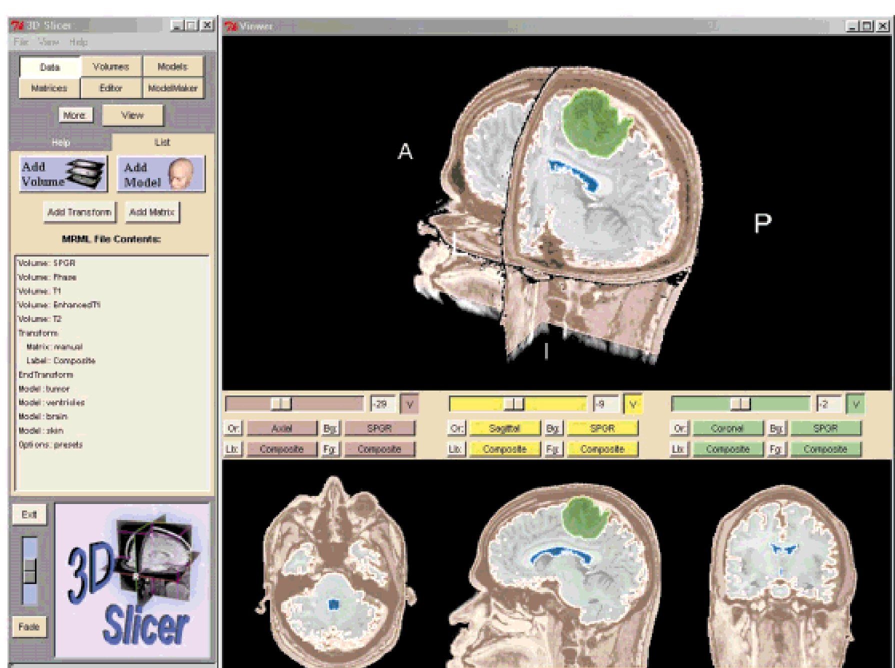

Figure 2. The output of a segmentation is displayed with variable opacity over the original grayscale SPGR images. The three slices on the bottom of the screen correspond to those shown above in the three-dimensional view. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

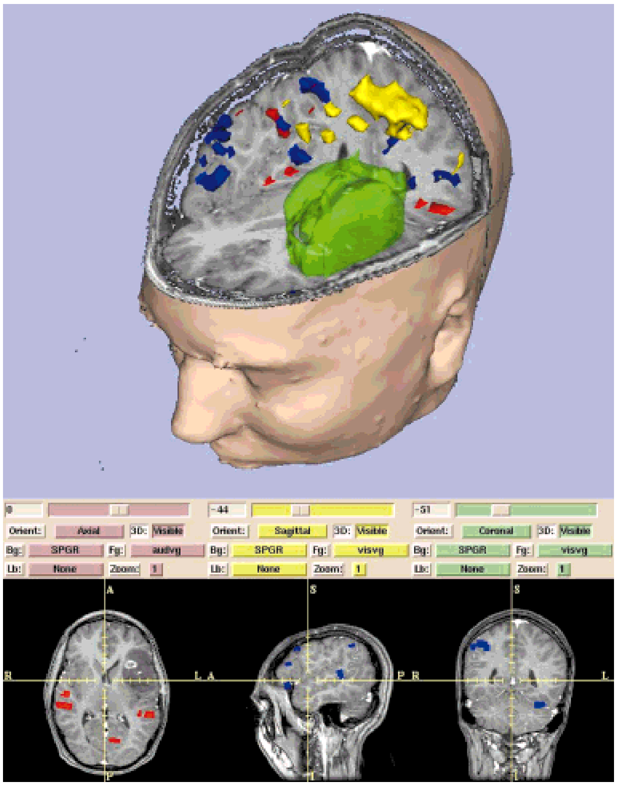

Figure 3. Surface models of key anatomical structures can be visualized in the three-dimensional view along with the reformatted slices. Shown here are models of skin, tumor (green), motor cortex (yellow), auditory verb generation (red), and visual verb generation (blue). [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

els with the 3D Slicer, the system also possesses the capability to import models created externally by experimental programs.

Multi-Modal Registration

The various volumes being segmented and reformatted in the 3D Slicer are acquired in different coordinate systems and need to be registered to a common framework in order to correctly view all components in a single, unified scene. The 3D Slicer supports manual rigid registration as well as automatic registration by maximization of mutual information (MI) (23,24). This method is of general utility, and other implementations of it have performed well in an NIH-sponsored test (25). MI is more robust than conventional correlation techniques that use a mean squared error. For example, when registering T1-weighted MRI to T2-weighted MRI, tissue that appears hypointense in one image can be hyperintense in the other, and therefore correlation is an incorrect metric for multi-contrast alignment.

Medical Reality Modeling Language (MRML)

Visualizing medical data involves combining various data sets into a single scene, and exploring the scene interactively. The usage of the 3D Slicer typically involves the creation of a scene from a variety of volume data sets, surface models derived from those volumes, and transformations obtained through three-dimensional registrations of both the volumes and models. We have found that the proper coordination of these items is easiest to obtain by the use of a hierarchical paradigm as exemplified by the modeling systems and languages of graphics and CAD/CAM. Toward this end, we created the MRML as a format for describing scenes that consist of various types of data sets collected in various geometric locations and fused using multiple registrations.

Trajectory Assistance

A key component of neurosurgical planning is plotting an approach trajectory that avoids critical structures such as blood vessels or the motor cortex. The 3D Slicer facilitates trajectory planning by automatically orienting slice planes relative to a trajectory specified by entry and target points. The plane perpendicular to the candidate trajectory may be slid along its path to visualize the structures that will be encountered en route. Additionally, the other two orthogonal planes allow views through the tissue that lines the approach. This feature can help prevent unfortunate surprises during surgery, as we detail below with an actual biopsy.

Pre-Operative Procedure in the Open MR

A volume scan (same parameters as below) is collected while the patient is being prepped in the operating room. In cases where pre-procedural anatomical or functional imaging is relevant and not obtainable intra-operatively, the new volume scan serves as an intermediate registration reference that relates the pre-operative data sets to the coordinate frame of the interventional MR scanner. The relation is expressed as a transformation matrix that is inserted into the MRML file for the case. The MR scanner is treated as the reference frame to preserve the highest accuracy for the measurements of intra-operative movements relative to earlier intra-operative data. To assure the surgeon that the volume, as rendered in the 3D Slicer, is aligned with the patient's actual position, external anatomical landmarks are touched with the locator while observing whether the real-time graphics rendering agrees.

In cases where pre-procedural imaging is not required for guidance, the new volume scan is utilized for reformatting during trajectory planning, or as a pre-operative reference for comparative evaluation of contrast diffusion or brain shift as the surgery progresses.

Intra-Operative Imaging Protocol

The radiologist involved in intra-operative imaging in our institution routinely specifies two-dimensional acquisitions to answer questions asked by the surgeon. Additionally for this study, data volumes were collected for reformatting, and updated 3–5 times throughout the duration of every craniotomy at the request of the surgeon. These volumes are 3D SPGR (12–60 2.5mm thick axial slices, TR=28.6, TE=12.8, FOV=24, matrix=256×128, NEX=1), with imaging times ranging from 0:55 to 3:55 minutes.

A summary of the complete pre- and intra-operative procedure is listed below:

1. Collect diagnostic anatomical scans (MR, CT, angiography).
2. For cases near eloquent cortex, conduct functional exams (fMRI).
3. Use the 3D Slicer to segment the scans and generate three-dimensional surface models of key structures, both anatomical and functional.
4. Automatically register all pre-operative data together using the 3D Slicer.
5. Position patient in the interventional MR, collect a volume scan, and set up the 3D Slicer.
6. Automatically register pre-operative data to intra-operative data using the 3D Slicer.
7. Use the fusion of all data to plan the optimal trajectory. Guide the initial resection by aiming the locator while viewing the 3D Slicer's display on the in-bore monitor.
8. As surgery progresses, periodically acquire intra-operative volumes for visualization within the 3D Slicer. Drive the location of reformatted slices with the tracked locator device.
9. Re-register if necessary due to patient movement.

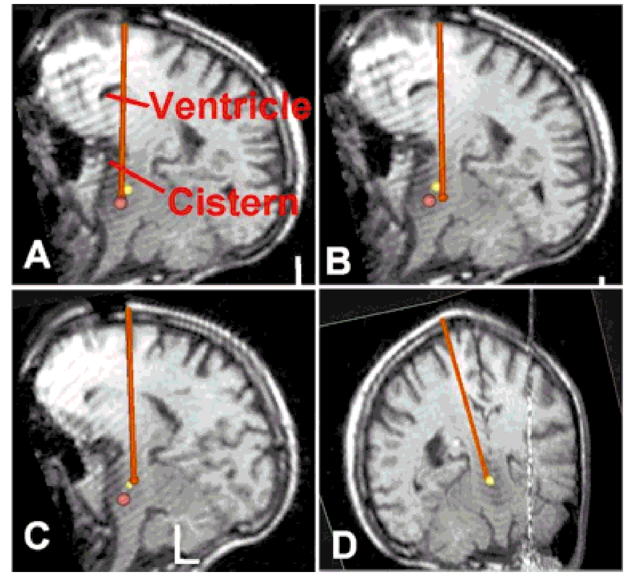

Figure 4. Altering the surgical tactic during biopsy planning. (**A**) Trajectory planning using the original access hole, but hitting the cistern. (**B**) Avoiding the cistern and ventricle, but missing the two targets (marked with red and yellow spheres). (**C**) Trajectory planning using a new hole that allows reaching the targets while missing both the cistern and ventricle. (**D**) Actual biopsy with coronal and sagittal reformatted slices. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

RESULTS

The open MR scanner, complemented by the 3D Slicer, has been applied as a navigational tool in 45 neurosurgical procedures over the course of a year.

Registration With Pre-Procedural Data

In two of the cases, pre-surgical studies were relevant regarding functional or structural data that could not be obtained intra-operatively. Registration performed between pre- and intra-operative data during craniotomy was completed within five minutes to be ready for use when needed by the surgeon. Although intra-operative brain deformation is non-rigid, rigid registration was sufficient in these cases, since the primary use of the pre-surgical data was to guide the initial approach.

Trajectory Planning

In many cases, the optimal trajectory from the skin surface to the tumor was obvious from the two-dimensional images. However, the 3D Slicer became helpful in cases where the tumor was deeply situated or dangerously near critical functional tissue or vasculature. Prior to the opening of the skull, the surgeon maneuvered the locator to point at his intended craniotomy at various angles. The pointer and its trajectory were rendered in true real time with the anatomy, a feat presently achievable only with computer reformatting. As the tracked pointer moved within the surgical field, the reformatted slice planes followed its position, sweeping through the volumes. The surgeon verified, and in one case altered, the planned approach by visualizing it on the display relative to all the surface models of critical structures.

The biopsy case depicted in Figure 4 is the prime example of the surgeon altering the approach following examination with the 3D Slicer. According to a conventional examination of MRI on a light box outside the operating room, an access hole was created near the top of the head to reach a deep tumor in the brain stem. Then the locator was held at the site of the craniotomy by a Buckwalter clamp and oriented to try various trajectories. The locator, normally a handpiece with a needle of known length protruding from its center, was used *without* the needle in order to visualize penetration in the 3D Slicer. The 3D Slicer was used to reformat images in the plane of the locator, and the biopsy targets were clearly marked using red and yellow spheres. The surgeon needed to reach the tumor while avoiding the ventricle and the peripeduncular cistern with the basilar artery. The 3D Slicer revealed that the surgeon would pierce either the ventricle or cistern (Fig. 4A). Avoiding both hazards would require missing the tumor as well (Fig. 4B).

Therefore, a new access hole was drilled in the skull. Figure 4C shows the same planning exercise being executed with the new hole. With the 3D Slicer's guidance, the tumor was reached while avoiding damage to both the ventricle and cistern. Figure 4D shows the actual biopsy with a real needle in place. Here, two slices are being reformatted in perpendicular planes so that both hazards may be seen simultaneously, since a single two-dimensional view cannot reveal all hazards.

Augmenting Intra-Operative Images With Pre-Operative Images

Of the 45 patients in this study, nine had tumors in the immediate vicinity of the motor, speech, or visual cortices. Therefore, navigation with respect to pre-surgically acquired fMRI was a helpful tool in defining the surgical goal and preventing morbidity. In the case depicted in Figure 5, the locator was maneuvered to the

Figure 5. Pre-surgical information emphasizes three-dimensional spatial relationships between critical structures, with vessels in pink and results of functional MRI in yellow. Slices are reformatted according to the position of the tracked locator, which is shown following a safe path to the cavernoma. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

cavernoma while avoiding hazards consisting of vessels and visual cortex.

Progressive Intra-Operative Imaging Updates

Once trajectory planning was complete, the 3D Slicer assisted in monitoring the progress of the resection. Since the positions of anatomical structures changed throughout the time course of the procedures, 3–5 new slabs of data were acquired for reformatting during each craniotomy.

We experimented with exploiting overlays to relate the intra-operative changes to the higher-resolution definition of tumor location. A lower-resolution T1-weighted slab acquired quickly during resection was overlaid semi-transparently on an SPGR that was scanned after craniotomy but prior to resection. Figure 6 depicts one of these cases with a fronto-temporal glioma where the SPGR was contrast-enhanced. Figure

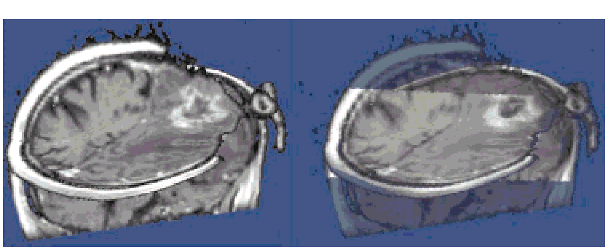

Figure 6. The image on the left is from an SPGR scan of a fronto-temporal glioma taken prior to resection. The image on the right shows data from a lower-resolution T1 scan acquired during resection, overlaid on the earlier SPGR scan for comparison.

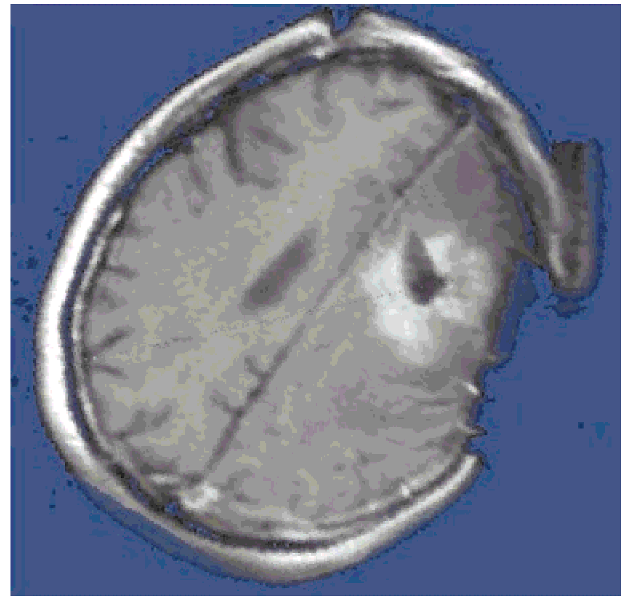

Figure 7. Surgeons are able to characterize the intra-operative shift by transparently overlaying recent images on previously acquired images.

7 displays a reformatted axial slice overlaid on a reformatted slice from the same location prior to resection. The collapse of brain tissue during the resection is indicated by the pronounced shadow.

Post-Resection Validation

The 3D Slicer offered assistance with anatomy that appeared normal to the eye but displayed abnormal signal intensities in the applied sequences (T1 or T2). In these circumstances, the 3D Slicer was used to create real-time, reformatted images through an intra-operatively acquired slab of images. Near the end of the procedures, the surgeon steered the locator around the perimeter of the cavity that was vacated through resection, and noted the boundary between the non-enhanced normal tissue and the enhanced diseased tissue after resection of the lesion. By viewing the location of the locator's tip on the display, the surgeon had a direct correlation between his visual impression of the tissue and the MR definition of the tissue, as illustrated in Figure 8. The attending neuroradiologist also examined the reformatted images for evidence of residual, diseased tissue to be removed.

In two cases we experimented with affixing the locator's handle to the ultrasonic aspirator so that the surgeon could directly correlate the aspirator's position to the information present in the dynamically reformatted images.

DISCUSSION

In this paper, we have presented an integrated software tool, called the 3D Slicer, that, when used in conjunction with an open configuration MR scanner, has the capability to beneficially address the issues of interventional image quality, imaging time, multi-modal fusion, faster localization, and three-dimensional visualiza-

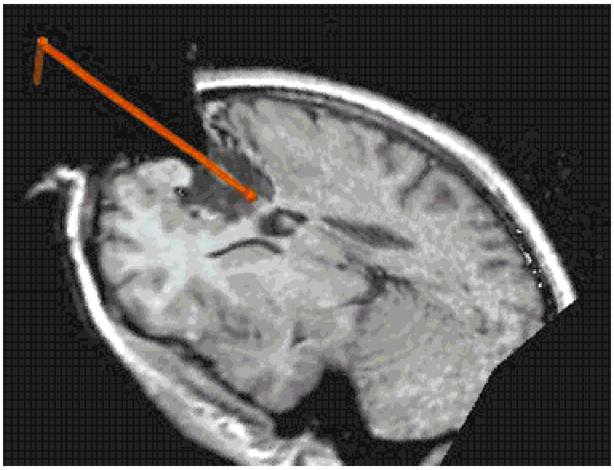

Figure 8. Virtual real-time imaging: the surgical instrument (red) is tracked, and two orthogonal planes are shown reformatted relative to the instrument tip's position and updated at 10 frames per second. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

tion. This initial feasibility phase has been an experiment to determine the utility of various features, and the results have been strictly qualitative so far. The 3D Slicer has proved to be a stable and reliable application, as highlighted by the variety of histopathology in the 45 cases. As we apply the 3D Slicer on a routine basis, a clinical evaluation of its influence on surgical decision-making and resection control is being conducted. Our neurosurgical colleagues have found the 3D Slicer helpful for blending data sets together that differ in information-type and time. First, it can merge functional information, anatomical information, and information from contrast agents into a single view. Second, it can fuse images serially distributed throughout the course of surgery. This carries two important benefits. First, surgeons are given the ability to distinguish between the diffusion of an intra-operatively administered contrast agent over a prolonged period into regions exterior to the pathology, and the shifting of the pathology itself. Second, since the warping of pre-surgical data to account for intra-operative shift has yet to reach a clinically acceptable level of accuracy, data that is not easily acquired interventionally (fMRI, MRA) needs to be mentally warped by the surgeon to account for morphological changes. The 3D Slicer's overlay capability conveniently facilitates this process.

The 3D Slicer has been shown by case study to be critically beneficial in biopsies. Biopsy localization is much better facilitated when imaging and tracking are in real time. If the needle's trajectory is only slightly incorrect, the needle's tip veers off target. To provide interactive trajectory planning, a small volume is acquired for software reformatting. Positioning is critical because negative histopathological results can indicate either that the tumor is benign, or that the needle missed the mark. The surgeon watches the 3D Slicer's display to help prevent the latter while simultaneously avoiding repeated needle repositioning. In this way, the importance of the 3D Slicer increases for the deeper tumors, since the risks associated with tissue damage rise with repeated penetrations and maneuvering. Although surgeons are accustomed to viewing two-dimensional images, a single two-dimensional view cannot reveal all hazards.

Another very important application of the 3D Slicer is in cavernoma cases, because the lesion is benign, small, and difficult to find. Before the existence of interventional imaging, such lesions could be found only through following the blood after an episode of bleeding. Even with imaging, experienced surgeons have trouble pinpointing the lesion. Invasion of the brain always carries the risk of side effects such as paresis or bleeding, complications which may be unavoidable in cases of malignant tumors that must be removed completely for survival. Cavernomas seldom occur, but they are benign, which reduces the tolerance of error. The 3D Slicer could potentially reduce the risk of damage by guiding the surgeon more directly toward small lesions.

In cases with low-grade gliomas, for which total resection is correlated with a prolonged survival time and even total cure, precise margin definition was of utmost importance. Visual differentiation of tissue in these tumors was difficult, whereas T2-weighted images gave a good estimate of the tumor extent. The display of these pre-surgical images allowed more careful control of total tumor resection.

Other JMRI articles (26) have cited "software limitations" as barriers to trajectory optimization, and have expressed the need for fusing and transferring three-dimensional models derived from different MR sequences to the operating field of the interventional MR system. The 3D Slicer satisfies that need and is freely available for researchers to use in their own interventional environments. Furthermore, due to its modular design and open source nature, the 3D Slicer is a useful platform for bootstrapping development of image-analysis algorithms. In addition, our novel file format, MRML, can be adopted for describing three-dimensional medical scenes for any application.

Besides these positive implications for impacting planning and guidance, there are limitations pertaining to the surgeon's learning curve, the applicability of pre-surgical models throughout the procedure, the efficacy of the overhead display, and registration problems due to magnetic field inhomogeneity. Although the 3D Slicer has the capability to present the surgeon with a vast array of information, we found that all available information was extremely beneficial for planning in practice, but overwhelming for on-line guidance. As a result, we presented the surgeon with one or two reformatted planes and one key surface model at a time. Surgeons are gradually becoming more accustomed to three-dimensional guidance, but require more time to fully embrace the technology. The use of three-dimensional models during surgery is limited, because intra-operative shift inaccurately renders surfaces created from pre-operative data. Creating new models on-line from intra-operative data was attempted during this study, but was found to be too time-intensive to be useful. Future progress in automatic segmentation may enable this approach. Caveats of registering intra-operative MR data stem from magnetic field inhomogeneity and patient movement. Patients are typically positioned in the magnet to optimize the surgeon's access to the area of interest, which sometimes leaves features near the extremities, such as the tip of the skull, near the boundary for homogeneity. This can present a problem for fully automatic registration algorithms that rely on the strong signal present in the skin. In particular, we found that patients who are positioned according to a worst-case scenario experience a flattening of the head in the interventional images. This usually does not present a problem for accurate tracking of the locator, since the tumor tends to be positioned near the center of the magnetic field. Proper patient positioning is presently used to avoid this situation. Patient movement has not posed a problem in our cases; complete re-registration was required in only one case, in which the patient moved during seizure. As one final present limitation, the display screen in the gantry, though useful, is not ergonomically sound, as it forced the surgeon to frequently look up from the patient in order to view the images.

Our future plans are to work toward automatic segmentation and deformable registration. As automatic and faster semi-automatic segmentation algorithms are invented, more rapid model generation will become possible. Potential applications are in surgery where models could be created from intra-operative data, and also in surgical planning, where model generation would become less labor-intensive. Since model deformation has yet to achieve a sufficiently dependable accuracy for surgeons, we often stop using pre-operative models once resection is well underway. Deformable registration being developed (27,28) holds promise in being able to warp pre-operative data to match the intra-operative changes. Existing algorithms are not yet accurate enough to be relied upon by surgeons, but when ready, such tools can be incorporated in the 3D Slicer.

In conclusion, we have presented here an integrated visualization tool that allows the incorporation of multiple data sets into a single display environment. Tools are available in this environment for data fusion, segmentation, three-dimensional model generation, and tracking of instrumented sensors. We have utilized this tool in 45 neurosurgical procedures, and have found its integrated functionality to be critical in providing the surgeon with full access to all available imaging data. The 3D Slicer achieves the objectives established in the introduction as an end-to-end solution that bundles different aspects of analysis into a single visualization framework. The system has been used in the most difficult cases where precise margin definition is of utmost importance, and where updated navigation is a valuable tool to define the surgical goal and prevent morbidity. Feedback from clinical users suggests that they most appreciate its ability to help them navigate a complicated assembly of information. The system's flexible design will allow it to expand as a highly integrated suite for analysis and visualization.

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APPENDIX

Medical Reality Modeling Language

MRML files essentially describe three aspects of data:

Disk Location: MRML files are not a copy of the data in another format. Instead, a MRML file describes where the data is stored so the data can remain in its original format and location.

Geometric Position: A MRML file describes how to position the data sets relative to each other in three-dimensional space.

Appearance: A MRML file describes how to display the data by specifying parameters for rendering and coloring.

XML Syntax

MRML is implemented as a type of XML document where new tags have been defined to handle medical data types such as volumes, models, and the coordinate transforms between them. XML (29) is the next generation of HTML for use as the document language of the World Wide Web. HTML tags data with instructions of how a browser should interpret the data. Example tags are images, links, and tables. XML extends this functionality by allowing users to define their own tags.

There are several advantages to building on the XML standard, as opposed to an original format. The World Wide Web has popularized markup languages so that the XML structure is immediately familiar to computer scientists everywhere. There are off-the-shelf XML parsers available in several programming languages. Double-clicking on any XML file in Windows opens the file in Microsoft Internet Explorer, where it can be viewed.

Design

A three-dimensional scene is represented in MRML as a tree-like graph where volumes, models, and other items are the nodes in the graph. Each node has attributes for specifying its data. We introduce the most important MRML nodes here, and more details can be found at the 3D Slicer Web site (20).

Volume

Volume nodes describe data sets that can be thought of as stacks of two-dimensional images that form a three-dimensional volume. Volume nodes describe where the images are stored on disk, how to render the data (window and level), and how to read the files. This information is extracted from the image headers (if they exist) at the time the MRML file is generated. Consequently, MRML files isolate MRML browsers from needing to understand how to read the myriad of file formats for medical data.

Model

Model nodes describe polygonal data. They indicate where the model is stored on disk, and how to render it (e.g., color, opacity). Models are assumed to have been constructed with the orientation and voxel dimensions of the original segmented volume.

Matrix

The output of a rigid-body registration is a rotation and translation expressed mathematically as a transformation matrix. These transforms can be inserted into MRML files as matrix nodes. Each matrix affects volumes and models that appear inside its transform node in the MRML file. Multiple matrices can be concatenated.

Transform

A transform is not a node with attributes, but a construct for building MRML files. A transform encapsulates the matrix nodes inside it such that they are invisible to nodes outside the transform.

Color

Color nodes define colors by describing not only the actual color value, but also their names and a list of label values. One attribute of a model node is the name of its color. When the 3D Slicer displays label maps, it colors each voxel by looking up the color associated with that label value. Thus, when label maps are displayed on reformatted slices, their colors match the corresponding surface models in the three-dimensional view.

Option

Option nodes allow browser-specific information to be stored in a MRML file. For example, the 3D Slicer uses option nodes to store the user's three-dimensional viewpoint information.

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