THE POTENTIAL USE OF MRI GUIDANCE FOR COMPUTERIZED SURGICAL PROCEDURES

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ABSTRACT

We report recent work in the development of computerized reconstruction and image processing techniques which allow planning and rehearsal of surgical procedures, and which will also be used for real-time control during therapeutical interventions. Sample applications are described, including neurosurgical and radiation therapy planning for astrocytomas; laser energy deposition via fiberoptic waveguide transmission deep within tissue for ablative surgery in the brain and other organs, hyperthermia of tumors, or laser angioplasty; and computer-guided stereotactic techniques for image-guided robotic arms or other intraoperative mechanical navigation systems. Technical requirements for acquisition and processing of 3D rendered data applicable for surgical planning are delineated, and avenues for further development suggested.

INTRODUCTION: DEFINITION OF THE FIELD

The surgeons of today as in the past rely primarily upon hand-eye coordination for performing various procedures. Because light does not penetrate deeply into tissue, the surgeon's vision is limited to the exposed surface, and this restriction essentially defines the way most surgical procedures are performed. The surgeon's vision, however, can be extended by the use of MRI, a powerful imaging technology which can penetrate beneath the surface and provide an image of the human body in three dimensions. Using computerized reconstruction and image processing techniques, images can be provided in a form in which the surgeon, using an interactive computer workstation, can navigate through the simulated organs without cutting, and can plan and rehearse surgical procedures. Three-dimensional reconstructions of imaging data can also be used for real-time control during the performance of surgical procedures or other therapeutical interventions.

Integration of recent advances in computed tomography (CT), magnetic resonance imaging (MRI), nuclear medicine imaging, and image processing technology with modern therapeutic techniques (stereotactic and microscopic surgery, radiosurgery, and radiation therapy) has dramatically affected the clinical approach to the treatment planning of tumors. It has been realized that these advances in imaging can be utilized not only for diagnosis and anatomical mapping, or localization of tumors on cross-sectional planes, but also for establishing the exact three-dimensional (3D) spatial coordinates of a surgical procedure, preoperatively.

SAMPLE APPLICATIONS

Neurosurgical Planning

Advanced imaging techniques such as CT, MRI, SPECT, and PET have had a significant impact upon the clinical diagnosis of intracranial astrocytomas, and their influence upon neurosurgery and radiation therapy planning should be at least as great. Despite the demonstrated clinical utility of these modalities, there are apparent limitations in the therapeutical use of imaging data. The manner in which the spatial information is presented has hindered its full utilization in characterizing normal anatomy as well as pathological changes and their distribution. Current therapeutical approaches to intracranial tumors, such as stereotactic serial biopsy, stereotactic surgery or radiosurgery, microsurgery, and laser surgery all require a more complete delineation not only of the 3D extent of the tumor with its boundaries, but also of the relationship of the components of the complex mass (tumor, edema, necrosis, etc.) to each other and to surrounding and intervening structures such as vasculature, white matter tracts, cortical and subcortical gray matter structures, etc. Neurosurgical treatment planning should include not only 3D display of intracranial anatomy but also the exact definition of coordinates and quantification of volumes of interest, and should apply various tools which allow the interactive manipulation of the data within an arbitrary reference plane or view. These tools allow interactive control of neurosurgical procedures, and are also useful for simulation and neuroanatomical or neurosurgical training. The first computerized systems for neurosurgical planning and assistance during the actual performance of surgical procedures have already been achieved and more complex systems are under development which provide access to information previously unavailable from cross-sectional imaging data.

Laser Interventions

Laser surgery is currently used routinely in situations where the effect on tissues can be controlled by visual observation. Its use is limited when the fiberoptic waveguide transmitting the laser energy is deep within tissue and the laser-induced changes are therefore invisible. To overcome this obvious restriction, we suggested the marriage of two advanced medical technologies: lasers and MRI (1). MRI offers several advantages; it is not only able to visualize noninvasively the target organ for laser surgical procedures deep within the tissues, but it can also demonstrate laser-induced heating and tissue changes which are secondary to the increased temperature. Simultaneous MR imaging of the effects of the laser as the energy is deposited has the potential not only for monitoring but also controlling laser interventional procedures. While exact 3D temperature monitoring is unlikely, near-real-time MR imaging of T1 and diffusion has the potential to provide safe control of thermal energy deposition. This technique may be applicable for ablative laser surgery in the brain and other organs, hyperthermia of tumors, or laser angioplasty. Using experimental techniques, the concept has been tested successfully in several organs, and the results have already been applied to clinical situations. This method offers the possibility to develop well-controlled laser surgery and other interventions within the MRI system, and by doing so to increase the accuracy while minimizing the invasiveness of these procedures.

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Robotic Applications

Computer-guided stereotactic techniques may be improved further by the use of image-guided robotic arms or other intraoperative mechanical navigation systems. These instruments can be utilized for the positioning of biopsy needles and laser fibers. Similar principles can be used to direct focused waves or particles, such as ultrasound, microwaves, or ionizing radiation.

TECHNICAL REQUIREMENTS

Several steps are required to obtain 3D rendered data applicable for surgical planning (2,3):

1) Image Acquisition.

Cross-sectional MRI images are acquired in a two-dimensional (2D) format (slices) within a defined plane in the reference frame of the imaging system. To be appropriate for either surface or volume renderings to be used for surgical planning these images should fulfill the following requirements:

a) Spatial Extent. The series of cross-sectional planes should include the entire volume of interest (usually the target plus a reasonably wide margin). This requires the prescription of a sufficient number of slices without gap (or interleaved) which may increase imaging time required, although new fast imaging techniques make this less significant.

b) Spatial Resolution. Resolution within the imaging plane is defined by the size of the digital matrix in which the images are displayed and its smallest element (the pixel), while slice thickness defines the resolution perpendicular to the plane of the image. These two measures describe the smallest volume element of the image acquisition (the voxel). In the ideal case, images for 3D surface or volume rendering are acquired with isotropic voxels; i.e., the in-plane and slice resolution are identical. 3D reconstructions from anisotropic voxels are suboptimal.

c) Tissue Contrast Resolution. Optimization of tissue contrast is especially important in MRI in which the differentiation of various components depends upon the selection of appropriate pulse sequences. Contrast between normal tissue elements (e.g., gray and white matter) and the components of a mass lesion (tumor vs. edema); as well as depiction of the vascular anatomy by use of intravenous contrast agents or MR angiography techniques are all essential for obtaining suitable information for surgical planning.

2) Reformatting.

Because cross-sectional images are acquired in only a single plane, visualization in other planes requires either additional acquisitions or the reformatting of the original data. Using multiple, arbitrary 2D planes intersecting at varying angles, there is better appreciation of the 3D extent of tumors and adjacent anatomic structures. The use of flexible and powerful reformatting tools allows the surgeon some degree of interactive manipulation.

3) Extraction of Volumes.

Using these techniques, it is also possible to quantitate the volumes of each of the tissue components defined by the segmentation (1), automatically reconstruct the various components in 3D, and reveal their distinct spatial relationships. The information obtained with this method (e.g., the relationship of tumor to vasculature or to the lateral ventricles) is not otherwise accessible.

4) Segmentation and Surface Rendering.

Segmentation, or the separation of anatomical entities from the original whole data sets, makes it possible to represent the configuration and distribution of various tissues, and to reveal the anatomical relationship of different structures. Using the segmented 2D maps, reconstruction of the surfaces of each defined tissue element is possible (2).

5) Definition of the Reference Frame, and Image Fusion.

Image definition is primarily a function of the reference frame of the given imaging system. For complex image integration it is necessary to display simultanously images obtained within the same system but with different fields of view (e.g., spin echo MRI and MR angiogram), or images acquired with different modalities (e.g., CT, MRI, and/or PET). For stereotactic procedures, images obtained within the reference frame of the imaging system must be transposed to the reference frame of the stereotactic apparatus, unless the procedure is actually performed within the imaging system itself. A method for integrating preoperative imaging information into the operating microscope field in the correct perspective has also been developed.

6) Interactive Data Manipulation and Simulation.

Using appropriate surgical or stereotactic reference frames and various tools for data manipulation (e.g., connectivity or editing in 2D or 3D), the processed image information can be used for simulating various surgical procedures and to attempt various surgical approaches and trajectories preoperatively. These simulations can not only optimize surgical planning for resection, but the data can be utilized during the surgical procedure (if the reference frame is transposed to the stereotactic frame or via intraoperative imaging).

Target definition for stereotactic procedures simply requires the interactive identification of the target point, therefore 2D planes are usually sufficient if they can be reformatted in arbitrary planes. For the selection of needle trajectories, the use of 3D reconstructions of anatomic and pathologic structures is necessary. Ideally, stereotactic procedures and computerized neurosurgical planning systems should be based upon interactive 2D and 3D reformatting tools integrated within a single work station.

AVENUES FOR FURTHER DEVELOPMENT

Interactive speed requires enormous computing power: the 3D convolution of a 256^3 data set is about 400 Megainstructions. Our image processing procedure, for example, requires about 8 convolutions. In addition to refining, accelerating, and further automating the software for image acquisition, reconstruction, and integration with other frames of reference, other possible applications for advanced image processing should be explored. For example, there is the intriguing possibility of using medical imaging data to create full-color holographic stereograms, making it possible to present 3D reconstructions in a portable form without the need for a computer workstation. Flat holograms permit the freezing of short 3D "movie" sequences within a readily transportable piece of glass and can be viewed any place. Alcove holograms, semi-cylindrical holograms that project a computer generated image viewable from 180° around, permit the simulated manipulation of objects in a 3D space. Such a display method could have unique potential for surgical training and could even be used within the operating suite with no hazard of contamination. Further work will also be beneficial in developing more advanced "artificial intelligence" techniques for directing and monitoring imaging procedures based upon pre-defined goals, and for integrated imaging control of interventional procedures such as biopsies, laser surgery, radiation therapy, etc.

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