I. Abstract

Computer processing of tomographic type imaging (CT, MRI, PET, ultrasound) can be used for simulation and optimization of surgical procedures. This image processing can be implemented in 3D and 2D modes and with fast computation can be used as a "real" time intraoperative display for interactive optimization of surgical procedures. This virtual "simulation" needs to be transposed into the real physical world and this has been currently accomplished by using mechanical systems attached to the patient's head for spatial reference (stereotactic systems). Further implementation is necessary to provide the neurosurgeon with an interactive tool for intraoperative localization as well as computerized guidance in the movement of surgical tools. Ultimately, robotic capabilities interfaced to artificial intelligence methodology may provide the best solution for computer controlled surgery.

II. Background

A. Problem and "Impact of Solution

The use of image processing for surgical planning and optimization of surgical procedures is especially relevant in the field of neurosurgery in order to remove intracranial lesions without damaging normal surrounding nerve structures. It also provides an accurate way of intraoperative orientation and allows the surgeon to reach accurately deep lesions. Nevertheless, further implementation is necessary to provide a way of interactive "real" time intraoperative localization in order to achieve an optimized result i.e. complete removal of a tumor without damaging normal structures. This implies the digitization and intraoperative display of surgical instruments in relationship with the target volume, and on a more sophisticated solution the computer controlled movement of surgical instruments. The main areas to use these technologies in neurosurgery are in brain lesions such as tumors, arteriovenous malformations and in obstructive vascular disease. The implementation and use of these technologies will result in more cost effective management of patients, with shorter hospitalization time, less invasive approaches, optimized treatment as well as enabling new possibilities of treatment in otherwise untreatable lesions. Patients with any brain lesion would benefit of these technologies including patients with stroke which is one of the most important causes of death in the USA. Transfer to other surgical specialties such as orthopedics, cardiovascular, plastic surgery, etc. appears as a logical step.

B. State of the art

Image-guided neurosurgery involves a three step procedure:

- a) image data acquisition
- b) surgical planning
- c) intraoperative surgical procedure. The image data acquisition usually involves CT, MRI, PET or any other image modalities acquired using a "reference" system (usually is a frame with localizers attached to the patient's head or some other kind of markers). The goal is to define a coordinate system that allows to define any image selected target in terms of x,y,z, coordinates. The next step involves the surgical planning using the image data. This planning may involve the measurement of coordinates of a single point (target) or may involve image processing in two-dimensions and three-dimensions to select the best and safest trajectory to aim a lesion. Further image processing involves the creation of files such as surgeon's eye view perspective and 3D model displays with "cutting" capabilities to display the internal structures (4). Finally, the intraoperative surgical procedure consists of an accurate
transposition of the surgical "planning" into the real, physical world. Today, the most commonly used solution involves the setting of a mechanical device that is attached to the reference frame (stereotactic arc) and allows to guide a probe into a defined x, y, z image-defined coordinate; some systems allow the transposition of a specific trajectory by means of selecting two points and calculating specific angles of the mechanical aiming device (3). This type of implementation has been applied for performance of biopsies or the placement of probes or electrodes rather than directing a section for volumetric resection of brain lesions (1, 2, 4, 5, 6). One goal has been the implementation of image-transfer in to the surgical microscope: that has been accomplished by means of a camera attached to the surgical microscope that provides a "head-up" display into one of the optics (4, 6). Further implementation involves the synchronized movement of the microscope and the image display done through computer controlled movement or servomotors. The same kind of technology has been used to move a laser micromanipulator according the image-defined margins of resection (4, 6). These initial steps in the implementation of automation in neurosurgery are insufficient as they rely on optical alignment of the microscope through retractors held by the mechanical stereotactic arcs. More precise and accurate positioning and movement of the surgical instruments is necessary as well as a better way to implement intraoperative real time localization and digitization of surgical instruments. Computer simulation and control of a robotic arm should be implemented for placement of microscope, laser micromanipulator movement, as well as placement of intracranial probes.

III. Technology Constraints and Specifications There are many areas where technology transfer may provide meaningful improvements in today's way of performing surgery with marked benefits for the patient and the surgeon. All of the following aspects focus on more accurate and safer ways to perform surgery relying on image preplanning and simulation as well as intraoperative accurate localization and manipulation of surgical instruments.

a) Image acquisition and reference system
Today's methodology of reference involves the use of a frame attached to patient's skull and localizers mounted into these frames. The main disadvantage to these methods involves pain to the patient and limits the use of the images for more than one time; there is also a tremendous limitation on the number of procedures that can be accomplished because the whole procedure needs to be performed the same day. Some ways to solve this have been ways to reposition the frame and the use of implanted markers in the bone that serve as permanent landmarks for coordinates definition. None of these solutions are excellent because there are still undesired effects on the patient, are somehow invasive and there are risks of infection. With modern computation capabilities, one could postulate the use of "internal" landmarks that could be located with different image modalities as the reference system; this could represent a step to frameless stereotaxis. An excellent model is constituted by the skull: CT or MRI data can be used for surface and volume rendering; then by automated recognition of three non-collinear landmarks such as sella or mastoid process, the "surgical space" is defined by three voxel coordinates. From now on, any point in the CT or MRI images can be defined in this space. To interface this information in the operating room we could propose the use of x-ray images that will show the selected structures used for space definition; bone edges could also eventually be found automatically on x-ray projections. This methodology may represent a promising technique for frameless stereotaxis, still involves the use of invasive x-rays intraoperatively and somehow still remains additional instrumentation to be used for intraoperative localization (sensors). An alternative would be the use of artificial intelligence methodology for "machine vision" sensing; e.g. the use of an intraoperative digitizing probe with LED emitters to be used to match the contours obtained from the processed images. Furthermore, we could postulate the implementation of fiberoptic sensor technology which involves automated real-time detection system based on a sensor network interfacing with an on-board processor that will serve as a nervous system, providing real-time information concerning the location of patient's head.

b) Intraoperative localization and digitization of surgical instruments
There are basically four technologies that can be used for advanced intraoperative "real time" digitization of a surgical probe in order to know its position in space. i. sonic digitizer: it consists on the use of emitters (usually two or three separated by a known distance) mounted in the surgical instrument (suction, bipolar, etc). These sonic emitters are captured by a ceiling
mounted microphone array and by matrix transformation it is possible to know the position of the surgical instrument in relationship to the operating room. The emitters can also be placed in the surgical microscope and in this way the surgeon could have a constant feedback of its position in relationship to the patient's lesions. Pioneering work on the use of this type of technology has been done by David Roberts at Hanover, NJ and new intents are currently being intended at St. Louis, MO by Richard Buchholz, at Cleveland Clinic by Gene Barnett. The main problem of these systems are temperature calibration and somehow currently in developing systems are cumbersome and unfriendly to use.

ii. optical system: in the author's opinion this could represent a very promising technique to use for intraoperative digitization and intraoperative localization. The system would consist of LED emitters mounted on different surgical instruments as well as the microscope. An array of 3 or 4 cameras would act as well as the position sensors. This type of solution has not been yet implemented.

iii. articulated arm: this type of technology involves the use of kinematics to calculate the position and/or orientation of the arm. It requires three degrees of freedom to get to the target and six or more if we want to obtain also the orientation. The author is currently involved in the design and development of an articulated arm to be used as adjuvant to the developed stereotactic system. It consists of a six-jointed articulated arm (six revolutes axis) of three links of 20 cm each. Six incremental encoders with interpolation hardware connect to Quadrature encoder input cards. There is a possible movement of 333 degrees at each joint. The beauty of this technology is its accuracy as well as representation of transition towards involvement of robotics into the operating room. Its main disadvantage is that it can be used with surgical instruments or probes but cannot be mounted to a microscope.

c) Intraoperative image processing

Indepently of the type of technology used to perform intraoperative localization and digitization, it involves the presence of a minicomputer workstation in the operating room for display of the "sensed" instrument into the preacquired images. This should be accomplished using cursor or trajectory display in 3D and 2D images: one proposed scenario by our group involves the display into 3D modes with "cut-away" capabilities (tip of the instrument is at the intersection of 3 planes which correspond to sagittal, coronal and axial within the 3D model), into 2D images with axial, coronal, sagittal window and into generated obliques view corresponding to surgeon's eye view perspective. This type of software implies the use of powerful workstations intraoperatively and its use somehow needs to become part of the operating room armamentarium. Very important would be the implementation of voice recognition type of commands to switch from one mode to the other.

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V. References


