Computer-Assisted Volumetric Stereotactic Neurosurgery: Present Methodology and Future Directions

PATRICK J. KELLY, M.D., F.A.C.S.
PROFESSOR AND CHAIRMAN, DEPARTMENT OF NEUROLOGICAL SURGERY
NEW YORK UNIVERSITY MEDICAL CENTER
NEW YORK, NEW YORK

Classic craniotomy for biopsy or resection of intra-axial brain tumors usually employed large skin flaps and craniotomy openings. These were necessary so that surgeons could be certain that a subcortical tumor could be localized and that the extent of the lesion lay somewhere beneath and within the limits of the craniotomy. Localization methods for classic resection methods were qualitative and imprecise.

With the advent of computed tomography (CT scanning) and MRI (magnetic resonance imaging), surgeons began rethinking their surgical approaches to common intracranial tumors. These computer-based imaging modalities provide precise information on the anatomical localization and extent of intracranial tumors. However, accurate transfer of this three-dimensional information to the actual surgical field was imprecise with conventional surgical techniques which depended on a surgeon's hand-eye coordination, knowledge of anatomy, and osseous and brain surface anatomy for lesion localization.

In addition, CT and MRI provide a three-dimensionally precise database which could be transported to a stereotactically defined surgical field. The incorporation of imaging-based stereotaxis into tumor neurosurgery not only improved the accuracy with which CT and MRI information could be used in surgical planning but also made minimally invasive techniques possible.

Point-in-space stereotactic biopsies performed through a burr hole or a $\frac{1}{8}$-inch twist drill hole were certainly less invasive than a classic craniotomy to perform a biopsy of a subcortical lesion. In addition, stereotaxis could be used to center relatively small bone flaps over superficial lesions and to find deep lesions. Stereotactic methods for intracranial navigation over and above the large exposure line of sight methods used for lesion localization in classic neurosurgery resulted in a transition to more minimally invasive procedures for intracranial tumors. In addition, CT- and MRI-derived information can also be used to indicate the extent of a subcortical lesion in stereotactic space. These tumor boundaries can now be accessed directly through minimally invasive surgical methods which employ stereotactically directed retractors or endoscopes.

Since 1981, our group has been working on and ultimately developed such a system for imaging-based intracranial navigation for the minimally invasive resection of intracranial tumors.[1] The system is stereotactic and computer-based. It has not, until the present time, received widespread acceptance within the neurosurgical community because of the high cost of the computer systems and software development necessary for the high level image processing required.

Impressive developments in computer hardware and software over the past 20 years have provided powerful computer systems at progressively lower cost so that computers capable of sophisticated image processing can now be acquired by any surgeon and most hospitals. Information technology allows the management of huge data sets which can be manipulated for efficient use by the surgeon in the operating room. Procedures which were cumbersome and complex when employing manual methods have become efficient, convenient, and cost-effective when computer assistance has been instituted. The following will describe state-of-the-art procedures and future trends made possible by information technology.

VOLUMETRIC STEREOTACTIC PROCEDURES

Volumetric stereotaxis is a method for gathering, storing, and reformatting imaging-derived three-dimensional volumetric information defining an intracranial lesion with respect to the surgical field. With this technique, a surgeon can plan and simulate the surgical procedure beforehand, in order to reach deep-seated or centrally located brain tumors by employing the safest and least invasive route possible.

Most importantly, this computer-generated information is displayed to the surgeon intraoperatively on computer monitors in the operating room and into a "heads-up display unit" (similar to that used in jet fighter aircraft) mounted on the operating microscope. These images provide a CT- and MRI-defined map of the surgical field area scaled to the actual size and location. This map guides the surgeon in finding and defining the boundaries of brain tumors for more complete and safer removal of these lesions. The computer-generated images are indexed (registered) to the surgical field by means of a robotics-controlled stereotactic frame which positions the patient's tumor within a defined targeting area.

METHODS FOR MINIMALLY INVASIVE STEREOTACTIC TUMOR RESECTION

Database Acquisition

A CT- and MRI-compatible stereotactic headframe, applied under local anesthesia, is attached to the patient's skull by means of four flanged carbon fiber pins inserted through drill holes made in the outer table of the skull. A detachable micrometer registration system allows removal of the headholder following data acquisition and accurate replacement for surgery. A preoperative database comprising stereotactic CT, MRI, and Digital Angiography (DA) is acquired.

CT, MRI, and DA data are transferred by data link from the imaging host computers to the operating room computer system (Compass™, Admiral Series, Compass International Inc., Rochester, Minn.). The surgeon traces around the contours of the tumor detected on serial CT slices and MR images. These slices are suspended within a three-dimensional computer image matrix which corresponds directly to the coordinate system of the stereotactic frame. An interpolation program creates intermediate slices between the digitized slices and then fills in these with cubic voxels, thus creating a volume in abstract stereotactic space.

SURGICAL PLANNING

Slices through the CT-, MRI-defined lesional volume scaled to the proper image size can also be displayed in the correct location within the stereoscopic angiogram or upon a map of the brain sulci and fissures derived from the stereoscopic angiogram. A surgical viewline, defined in arc and collar stereotactic arc-quadrant settings, is then selected on the display screen. In general, the viewline defines the surgical approach from the surface of the brain to the tumor in a direction parallel to major white matter fibers and which spares important brain tissue and vascular structures.

This volume can be sliced perpendicular to the intended surgical viewline in order to present to the surgeon the appearance of the lesion as it will be encountered at surgery. All of this data can be displayed within a shaded graphics rendition of the patient's skull which has been extracted from the stereotactic CT scan. Such displays are used in surgical simulations: planning the stereotactic trajectory to an intracranial lesion in order to approach and extract a tumor in the safest possible manner.

SURGICAL PROCEDURES

These procedures employ the following: a Compass™ stereotactic frame, a heads-up video display terminal (similar to those found on jet fighter aircraft) which is attached to the operating microscope, a carbon dioxide laser system and various custom microsurgical instruments which have been designed specifically for these procedures. The Compass™ stereotactic frame is basically a cartesian robotics system in which the patient's head fixed in the stereotactic headholder is moved in X, Y, and Z space by a stepper motor-controlled three-dimensional slide system in order to position the intracranial target volume in the isocenter of a fixed arc-quadrant. Surgical trajectories are expressed in terms of settings on the arc-quadrant: Collar and Arc angles (the former from the horizontal plane, the latter from the vertical).

Computer-generated images of the imaging-defined tumor volume sliced perpendicular to the surgical approach trajectory are projected into a heads-up display unit mounted on the operating microscope. These images are scaled to the exact size of the surgical field viewed through the operating microscope and are superimposed upon it. Thus, during these procedures, the surgeon views not only the surgical field itself but also a computer-generated rendition of what that surgical field should look like based on the CT, MRI, and DA databases.

The carbon dioxide surgical laser is useful in vaporizing tissue from a deep cavity into which there is limited access. This is very appropriate in the stereotactic approach to and resection of deep-seated neoplasms which are removed through stereotactically directed 140-cm-long retractors which are 2 cm in diameter. This is the minimum diameter for which a surgeon can still have stereoscopic vision when viewing the surgical field with a Zeiss operating microscope. Stereoscopic vision is especially important in intra-axial brain surgery to deal with bleeding and for the accurate manipulation of surgical instruments at the 140-mm distance.

Computer-assisted stereotactic resections can be performed in superficial and deep-seated lesions. In superficial lesions a circular trephine is turned on a stereotactically placed cranial pilot hole centered over the lesion. The trephine must be slightly larger than the largest cross-sectional diameter of the CT- and MRI-defined tumor slice. The trephine defect having a known configuration and size serves as a reference structure for indexing of the scaled image within the heads-up display of the operating microscope. The computer-generated image of the trephine with respect to the CT-, MRI-defined tumor volume is superimposed over the actual trephine in the surgical field viewed through the operating microscope.

Thus the computer-generated tumor slice images serve as a template which guides the dissection around subcortical lesions and facilitates identification of the plane between the lesion and the surrounding brain parenchyma.

Deep-seated lesions are resected by means of a stereotactically directed cylindrical retractor which is inserted through a dilated cortical and subcortical white matter incision as illustrated in Figure 1.

The incision is made utilizing the carbon dioxide laser and dilated by means of the retractor-dilator system. The configuration of the deep end of the retractor is represented in the computer-generated slice images so that this may be superimposed over the actual surgical field by means of the heads-up display unit on the operating microscope. In practice, a plane is developed between tumor and surrounding brain tissue before the lesion is vaporized with a high-power defocused carbon dioxide laser. Lesions which are much larger than the retractor can be removed by multiple image translations on the display screen which result in the calculation of new stereotactic coordinates. These, once executed on the stereotactic slide system, position a new part of the tumor under the stereotactic retractor. A plane can then be developed between tumor and brain for some distance beyond the retractor by using the computer-generated slice images depicting the CT-, MRI-defined limits and the image of the retractor as a guide. Once the lesion has been isolated from surrounding brain tissue, it can be removed piecemeal with biopsy forceps, defocused carbon dioxide laser, or suction.

In contrast to standard intra-axial tumor resection techniques in which an internal decompression is done before trying to dissect the edges free from surrounding brain, in stereotactic resection the tumor edges are separated from brain tissue before the central mass of the tumor is entered. If the tumor is too large for complete isolation from surrounding brain tissue (usually encountered in the resection of large deep tumors through a stereotactically directed cylindrical retractor), the superficial aspects of the lesion are dissected free of surrounding brain and then removed layer by layer progressing from the most superficial to the deepest. The purpose of the volumetric stereotactic technique is to facilitate identification of a plane between tumor and surrounding brain tissue. However, the tumor must remain intact for as long as possible; otherwise, the brain around it can fill into the cavity produced by internal decompression.

RESULTS

One thousand eleven hundred sixty-five (1165) patients underwent computer-assisted volumetric stereotactic resection procedures performed at the Mayo Clinic and New York University Medical Center in the 10-year period between August 1984 and December 1994 (Mayo 8/1984 to 7/1993; NYU 9/1993 to 12/1994). Overall surgical morbidity was 6.5%; mortality less than 1%. Postoperative imaging studies confirmed complete resection of the target volume in over 90% of the cases. Postoperative and follow-up results have been published in a series of publications.[2-4] In addition, the average global charges (physician-related plus hospital-related) for tumor resec-

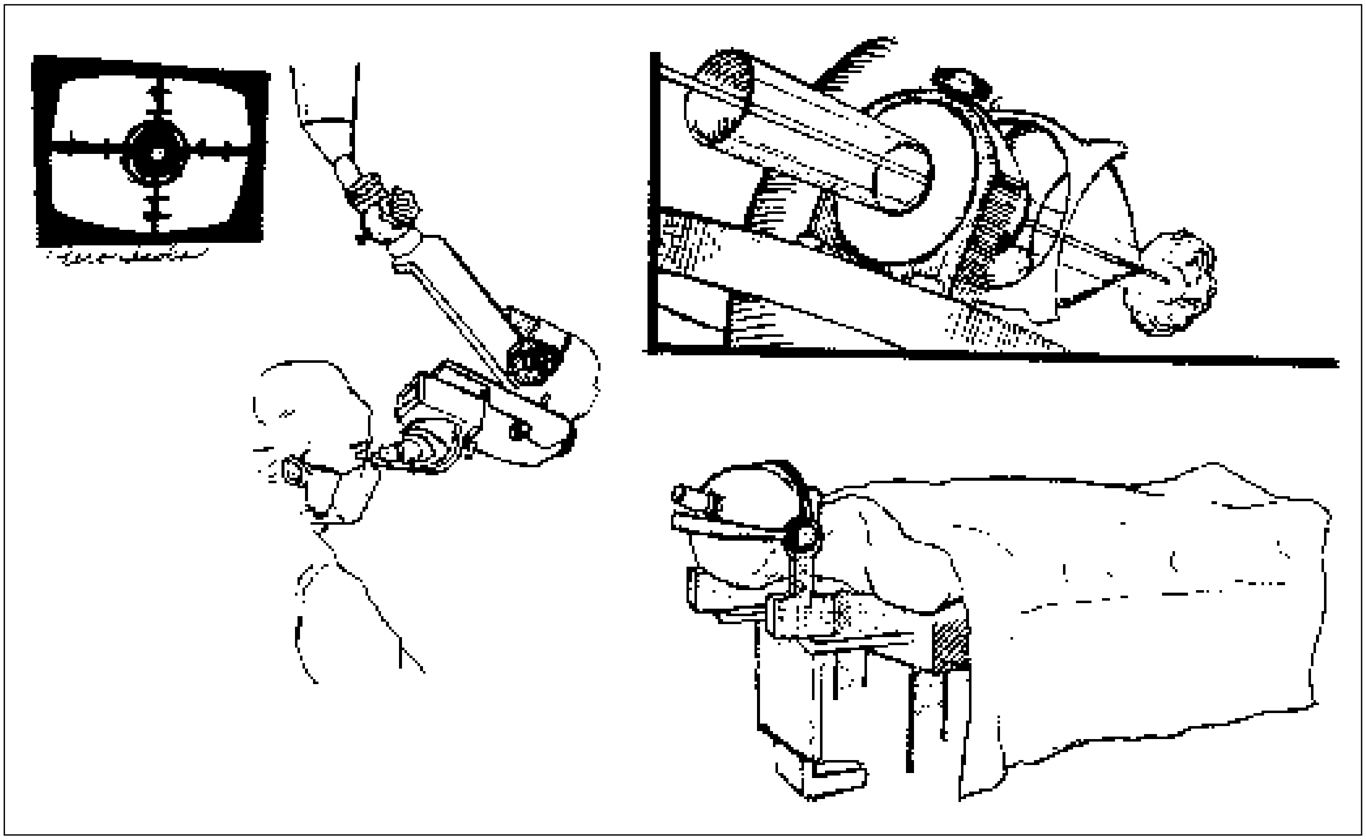

Figure 1. Method for minimally invasive stereotactic resection of deep-seated tumors. The surgeon works through a stereotactically directed 2-cm diameter cylindrical retractor. The surgical field is visualized through an operating microscope. The computer display monitor shows the position of the CT- and MRI-defined limits of the lesion with respect to the edges of the retractor. (Adapted from Kelly PJ. Volumetric stereotactic surgical resection of intra-axial brain mass lesions. Mayo Clin Proc 1988;63:1186; with permission.)

tion by volumetric minimally invasive stereotaxis were 67% of the charges for patients undergoing classic craniotomy for similar lesions.

DISCUSSION

Intracranial mass lesions (tumors) are volumes in space. This is easily apparent on review of contiguous CT and MRI slice images of the lesion. However, translation of this three-dimensional information at surgery from the imaging studies (CT and MRI) to three-dimensional surgical operating space within the patient's head is difficult and imprecise. A surgeon may have difficulty in knowing at surgery where tumor ends and normal brain begins–in spite of the fact that this information is usually clear on the imaging studies. Indeed, there may even be difficulty in finding some subcortical tumors.

This problem is more extreme in minimally invasive surgical procedures, where surgeons can no longer rely on visualized intracranial landmarks to guide small access ports or endoscopes to the edges of the lesion. However, computer-assisted volumetric stereotaxis provides the surgeon real-time feedback of the location of the surgical exposure or endoscope in the three-dimensionally defined surgical field.

Without volumetric stereotaxis three things are possible: (1) A surgeon can get lost attempting to find the tumor. Brain tissue is damaged unnecessarily. This can result in neurologic deficit and prolonged and expensive rehabilitation efforts. (2) A surgeon cannot tell where tumor ends and normal brain tissue begins. Thus there is some risk that the surgeon can resect normal brain tissue along with the tumor. In important brain areas, this will also result in neurologic deficit. (3) A surgeon performs a subtotal removal of the lesion. Much tumor remains behind, will recur sooner and require another operation later on.

Volumetric stereotaxis provides the following major advantages to the surgeon in the management of intra-axial brain lesions: (1) It allows the surgeon to find the lesion. (2) It imparts a concept of the three-dimensional shape of the lesion which is to be removed. (3) It allows preoperative surgical simulation and surgical approach or trajectory planning with respect to the configuration of the lesion and normal brain and vascular anatomy which must be preserved. Thus the safest and most effective surgical approach may be selected. (4) It indicates by means of a scaled real-time display, interactive software, and stereotactic instrument where tumor ends and normal brain begins.

Volumetric stereotaxis has major advantages for the patient: (1) The smallest possible skin incision, craniotomy, and brain incision. This minimizes injury to normal brain tissue. (2) Since the surgeon knows exactly where tumor ends and normal brain begins, a more complete tumor removal can be accomplished with much less risk to surrounding brain tissue. (3) The postoperative neurologic results are better than those associated with conventional (nonstereotactic, nonvolumetric) surgical techniques.

Finally, minimally invasive volumetric stereotactic surgery provides advantages to third-party payers: patients get out of the hospital faster, do better neurologically, and return back to work earlier. In a practical sense, volumetric stereotaxis will save third-party payers money due to the following reasons: (1) Volumetric procedures are less invasive than conventional intracranial neurosurgical procedures. Postoperative results are better, and patients get out of the intensive care unit and out of the hospital faster. Less money is spent on ICU charges and postoperative hospital days. (2) Volumetric stereotactic procedures require less time in the operating room (two to three hours less in some cases) than conventional neurosurgical procedures for brain tumors. This is because the procedures are simulated on a computer system beforehand and can proceed efficiently as planned. This saves money on operating room charges. (3) "Inoperable" tumors (inoperable by conventional surgical techniques) can be resected with volumetric stereotactic resection procedures. Frequently, these are deep-seated, relatively benign tumors in children and young adults. Many of these tumors can be cured with volumetric stereotaxis. This saves money wasted on useless radiation and chemotherapy which will not be effective for these lesions and saves money spent on rehabilitation and terminal care as the tumor progressively disables and kills the patient. (4) Neurologic results are better with minimally invasive stereotactically guided methods; fewer patients require rehabilitation programs and, instead, return to work sooner.

FUTURE DIRECTIONS FOR MINIMALLY INVASIVE COMPUTER-ASSISTED VOLUMETRIC STEREOTACTIC SURGERY

Our own work and experience has demonstrated the utility of computer reconstructions of stereotactically acquired CT and MRI data. These allow not only the representation of a tumor volume in stereotactic space but also the relationships of normal vascular and neuroanatomical structures to that volume. From our experience in which we have seen the tremendous potential of computer-assisted surgery, we have embarked on several developmental projects which are outlined below.

First, it is clear that computers can be used to monitor and display to the surgeon the position of surgical instruments within a stereotactically defined work envelope. This will make possible a trend toward more minimally invasive and endoscopic surgery, not only in subarachnoid and intraventricular spaces, but also for intra-axial target volumes.

Surgical Computer Systems

The computer is able to accumulate, reformat, and display a huge database with respect to the coordinate system of the surgical field. About 10 years ago, powerful computer systems capable of such image processing were prohibitively expensive.

Over the past few years, the computer industry has given us even more powerful machines at progressively lower cost. Powerful microprocessor-based workstations provide tremendous capacity at a cost low enough for any neurosurgeon to acquire.

These computers will render stereotaxis irresistible to most neurosurgeons. Because of computers, all surgical procedures may become, in a larger sense, stereotactically based: three-dimensionally controlled procedures in a preoperatively defined work envelope.

Frameless Stereotaxis

Computers make possible instrumentation for the on-line registration of the surgical instrument position within the surgical work envelope. This is possible through several technologies–all of which could be employed for transmitting the position of a surgical instrument to an operating room computer system.

We have tried multiple-jointed digitizers. They are less cumbersome than a stereotactic frame for retrieving surgical work-space coordinates. However, they are more cumbersome than most of our surgical instruments.

Alternatively, we have used magnetic field digitizers to cross-register points from the imaging database to the surgical field. Sensors on this device are connected to a wire no different than bipolar forceps. With tuning of the magnetic field and computer-generated distortion corrections, we have reliable and reasonable accuracy with this instrument as a pointing device. We are presently incorporating a suction device and a heads-up display to this unit in order to increase its utility in the operating room.

However, other technologies now being explored will permit us to know conveniently the precise position of a surgical instrument within an imaging-defined surgical field. These include radio frequency and optical digitizing systems which will be accurate and convenient to use.

Image–Surgical Field Registration

But how do we register the imaging (CT, MRI, and other three-dimensional bases) to the field? With a stereotactic frame, this registration is straightforward. The patient's head is fixed and we have reference fiducials in precise locations in real-world space and on the imaging studies. How are we going to relate imaging data to the surgical coordinate system in a frameless system?

We could place markers on the scalp. But the scalp moves! We could drill the reference fiducial markers into the skull prior to imaging. But if we are to go to all of that trouble, we may as well place a stereotactic frame. Nonetheless, there are other methods.

We could use the geometry of the patient's head as its own reference system. Computer reconstructions of CT and MRI provide excellent surface detail which we could match to the patient's head in real-world space.

The patient's head could be digitized in three-dimensional space by scanners–similar to those used in industry for putting three-dimensional data into a computer system. Special laser scanners could be used in the OR to establish not only the location of the patient's head in real-world operating room space; but also define the *configuration* of the head in space. Computer software would then match the surfaces of the patient's head on the operating table with the surface of the patient's head extracted from CT and MRI imaging. Routines for transformation, rotation, and scaling would fit one volume into another like a hand fitting into a glove or a head into a hat. Operating room workspace coordinates could then be assigned to imaging coordinates.

Holographic Imaging

One problem with computer displays in surgery is that we as surgeons are interested in a three-dimensional object. Contemporary computers have only two-dimensional display screens. We can display shaded graphics images and stereoscopic pairs. It is not the same as seeing things in three dimensions as is the case with a true projection hologram.

The usual hologram requires days to prepare; hence these are impractical for the usual surgical planning situation. However, a new process allows the production of a projection hologram from CT and MRI slice data within about 20 minutes. Units with this capability will, in the not-too-distant future, become available to any hospital radiology department. Then on a viewbox in the operating room, a surgeon could have not only copies of the CT and MRI images, the angiogram, but also, on a diffraction grating "view box," a projection hologram containing the computer-fused CT, MRI, and angiographic data for his or her patient.

Ultimately, the ideal solution would be real-time holography. Computer-generated holograms have been around since the late 1970s. Limited computer power has restricted their resolution in the past. However, MIT is working on a new technique for generating real-time holograms on a holographic terminal. This process requires an expensive supercomputer at this time. Nonetheless, if computer power and capacity continue to climb and cost continues to decrease, real-time holographic terminals may become available for use in the operating room. I predict that at some time in the future we will have a reformatted real-time projection hologram displayed to us in the OR–a three-dimensional imaging-defined map of our surgical field which can show us the position of our surgical instruments in that display.

Robotics and Dexterity Enhancement

Robotics technologies have some application to future minimally invasive neurosurgical procedures. With continued ultraminiaturization of electronics, robots can get even smaller and more delicate. Custom devices can be designed to hold surgical instruments and retractors and even to provide extra microdexterity to a surgeon.

When working through an endoscope in a minimally invasive procedure, surgeons will need immense dexterity. An excellent microsurgeon working at a short distance operates with an accuracy of about plus or minus 40 microns. This accuracy is reduced considerably when working at the long distances required by minimally invasive techniques. However, there is now a robotic device under development by the Jet Propulsion Laboratory (Pasadena, Calif.) and Microdexterity Systems (Memphis, Tenn.) which will provide surgical accuracy on the order of 4 microns. These devices controlled at a surgical workstation could manipulate instruments with extreme precision through endoscopes.

Telerobotics applications have already been tested in experimental surgery. A surgeon working at a virtual console could actually do a minimally invasive surgical procedure at another distant location. Here the surgeon would view the surgical field not directly but through a transmitted video image. The military is actively pursuing a program of telepresence surgery so that surgeons at a base camp could actually perform surgery in a robotically equipped surgical suite near the front lines.

CONCLUSIONS

Many technologies will impact the future of minimally invasive tumor neurosurgery. These technologies will include electronics, robotics, lasers, and other technologies adapted from industry and the military. They will have the most impact in stereotactic neurosurgery–a three-dimensionally and mathematically precise surgical discipline which can best exploit techniques (such as endoscopy) borrowed from other fields. Most importantly, surgical computer systems coupled to surgical instrumentation will make significant future advances possible.

Use and incorporation of these technologies into neurosurgical procedures will depend on having access to the know-how necessary to bring about these applications. Few neurosurgeons will have the time or technical knowledge to be truly effective in this area. Therefore, engineers and computer scientists must become part of or maintain a close affiliation with academic neurosurgical departments. They will provide the tools for the future of surgery. Surgeons will provide the guidance necessary by telling them what we need and what is useful.

In conclusion, the following three factors, now at work, will result in more universal neurosurgical use of computer-assisted minimally invasive surgical systems: (1) Computers are getting cheaper and more powerful. (2) Neurosurgeons are becoming more interested in minimally invasive techniques. (3) There is now considerable pressure for more cost-effective procedures with lower risk. Computer-assisted volumetric minimally invasive procedures provide the means for achieving maximal tumor reduction with the best possible postoperative outcomes and shortest hospital stay in comparison to classic neurosurgical techniques. STI

ACKNOWLEDGEMENT

Universal Medical Press expresses its appreciation to Piero B. Isola for his illustration.

REFERENCES

1. Kelly PJ, Alker GJ Jr. A stereotactic approach to deep seated CNS neoplasms using the carbon dioxide laser. Surg Neurol 1981;15:331-4.
2. Kelly PJ, Kall B, Goerss S, et al. Computer-assisted stereotaxic resection of intra-axial brain neoplasms. J Neurosurg 1986;64: 427-39.
3. Kelly PJ. Volumetric stereotactic surgical resection of intra-axial brain mass lesions. Mayo Clin Proc 1988;63:1186-98.
4. Kelly PJ. Tumor Stereotaxis. Philadelphia: WB Saunders; 1991. 400 p.