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Functional Stereotactic Neurosurgery With Magnetic Resonance Imaging Guidance

Ronald F. Young

University of California, Irvine

The development of stereotactic surgery has been dependent upon concomitant advances in brain imaging techniques. Human stereotactic surgery effectively began in 1950 with the advent of contrast ventriculography. The anatomy of the third ventricle outlined by ventriculography was used as a reference to determine the location of structures, within essentially normal brains, whose functions could be surgically altered to favorably affect the course of certain neurological diseases. Such functional neurosurgery has been employed most effectively in the treatment of movement disorders such as Parkinson's disease and for surgery of intractable pain. Unfortunately, ventriculography does not allow direct visualization of the target in the brain to be treated, thus providing inaccuracies in target localization. Functional stereotactic guidance, by computerized tomographic scan data, provides a near direct view of the brain, but lack of resolution and radiation exposure limit its usefulness. Magnetic resonance imaging guidance for stereotactic surgery offers the possibility of improved target visualization and avoids radiation exposure. This report describes the author's preliminary experience using the Leksell stereotactic system and magnetic resonance imaging guidance for the performance of functional stereotactic neurosurgery.

Stereotactic neurosurgery employs an external reference system in order to safely and accurately reach deep targets within the brain without direct visualization of the targets. The reference system is composed of a stereotactic "frame" applied to the patient's head and an imaging technique which mathematically relates the frame to brain structures. Functional neurosurgery refers to surgical procedures undertaken to alter brain function in order to favorably affect diseases of the nervous system.

The earliest attempts at human stereotactic surgery appear to have been carried out in Russia by Zernov in 1890 (Kandel and Schavinsky, 1972). Later, Altuchov and Rossolimo also reported human stereotactic operations using individually designed guidance apparatuses. Clarke and Horsely (1906) described one of the earliest stereotactic systems, for use in animals, which

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Requests for reprints should be sent to Ronald F. Young, M.D., Division of Neurological Surgery, California College of Medicine, 101 City Drive South, University of California, Irvine, California 92668.

consisted of a mechanical device fixed to the animal's head via bars placed in the external auditory canals. The device incorporated a cartesian coordinate system into a metallic frame, to allow manipulation of an attached probe in three dimensions. Brain targets were identified by reference to the line connecting the auditory canals (interaural line) and the sagittal suture of the skull, which were used to mark the midline (Horsley and Clarke, 1908). Animal brains were then fixed and sectioned in three planes, perpendicular or parallel to the interaural line and sagittal suture, in order to determine the distance of various structures right or left of the midline (x coordinate); anterior or posterior to the interaural line (y coordinate); or superior or inferior to the interaural plane (z coordinate). Thus, any point in the brain could be located by this three dimensional reference system, if the x, y, and z coordinates were known. Horsley and Clarke (1908) suggested the term "stereotaxis" to describe their technique. Olivier, Bertrand, and Picard (1983) credit Aubrey Mussen with the design of the first human stereotactic appartus in 1918. Picard, Olivier, and Bertrand (1983) believe that the early apparatuses used in Russia were not true stereotactic systems, since they were used primarily to locate external skull landmarks.

Unfortunately, the relationship between external skull landmarks (such as the ear canals) and the human brain were too variable to allow targets to be precisely reached stereotactically (Riechert, 1975). Spiegel, Wycis, Marks, and Lee (1947) described air or a positive contrast ventriculography to outline the anatomy of the third ventricle and suggested the anterior commissure (AC) and posterior commissure (PC) as reference points for intracerebral targets (Spiegel, 1982; Spiegel and Wycis, 1952). Stereotactic atlases of the human brain were then prepared in which the brains were sectioned in three planes, perpendicular or parallel to the line connecting AC and PC (Andrew and Watkins, 1969; Schaltenbrand and Wahren, 1977). Thus, x, y, and z coordinates could be identified for any intracerebral target in reference to the AC-PC line.

Human functional neurosurgery began subsequent to the work of Spiegel and Wycis (1952) and Spiegel, Wycis, Marks, and Lee (1947) and was primarily directed towards the treatment of two diseases of the nervous system: (1) movement disorders and (2) intractable pain.

Lesions were made in the globus pallidus and the thalamus for treatment of Parkinson's disease and other movement disorders such as dystonia, musculorum deformans, post traumatic spasticity, spasmodic torticollis, etc. (Walker, 1982). Additionally, lesions were described in the brain stem and the thalamus for treatment of chronic intractable pain (Young and Modesti, 1985). Unfortunately, due to the variability in anatomical relationships and to size variations in the human brain, the use of the AC-PC reference system as delineated by ventriculography, did not eliminate misplaced lesions. Such misplaced lesions could lead to failure to alleviate the disease process as well as to unintended injury to other structures—sometimes with important functional consequences to the patient. For instance, lesions intended for the thalamic nucleus ventralis lateralis to treat the tremor of Parkinson's disease, if placed too far laterally, may injure the internal capsule, with resultant hemiparesis. A further drawback of stereotactic neurosurgery using ventriculography to define reference points in the brain concerns the risk of ventriculography itself. For instance, the contrast material used for ventriculography may cause complications, such as seizures, and puncture of the ventricle itself may cause intraventricular or intracerebral hemorrhage or ventriculitis.

The advent of CT scanning in the mid 1970's gave new impetus to stereotactic surgery and a variety of stereotactic frames were designed for use with CT guidance (Brown, Roberts, and Osborn, 1980; Carol, 1985; Leksell and Jernberg, 1980; Perry, Rosenbaum, Lunsford, Swink, and Zorub, 1980; Slater, Rhodes, and Glenn, 1984). CT guided stereotactic systems avoided the need for ventriculography, increasing the safety of such procedures. Additionally, pathological lesions could be visualized directly on CT scans employed for CT guided stereotactic surgery. Thus, CT guided stereotactic systems were particularly useful for diagnosis and treatment of intracranial lesions such as tumors, abscesses, hematomas, etc. which were well delineated by CT (Apuzzo and Sabshin, 1983; Heilbrun, Roberts, Apuzzo, Wells, and Sabshin, 1983; Levin, 1985; Matsumoto, Shichijo, Masuda, and Miyake, 1985). The CT stereotactic systems are less useful for functional stereotactic surgery since CT scanning has limited resolving power, which makes small structures, such as the AC, PC, and the thalamus difficult to identify exactly. A number of reports have described CT guided stereotactic approaches to functional neurosurgery and the author has employed a CT guided stereotactic approach to placement of stimulating electrodes in the periaqueductal grey (PAG) region of the midbrain and sensory thalamus for treatment of chronic pain (Gildenberg, Kaufman, and Murthy, 1982; Laitinen, 1985; Young, Kroenig, Fulton, Feldman, and Chambi, 1985). Hadley, Shetter, and Amos (1985) have reported that there is good, although not perfect, correlation between targets selected by CT as compared to ventriculographic guidance. The CT technique avoids completely the risks of ventriculography, since the third ventricle as well as AC and PC may be seen directly on the CT scan.

The improved ability of magnetic resonance (MR) imaging systems to demonstrate small targets within the brain, the lack of radiation exposure, the ease in delineating the AC and PC on sagittal images, and the ability to clearly identify structures such as the internal capsule and the thalamus have all pointed to considerable interest in MR guided stereotactic systems (Birg, Mundinger, Mohadjer, Weigel, and Feurmaier, 1985; Montagno and Nashold, 1985; Olivier, Bertrand, and Picard, 1983; Olivier, Peters, and Bertrand,1985). This paper describes the author's preliminary experience with an MRI guided stereotactic system for functional neurosurgery.

MR Stereotactic System

The author has employed the Leksell system for MR guided functional stereotactic neurosurgery (Leksell, Leksell, and Schwebel, 1985; Lunsford, Martinez, and Latchaw, 1986). This system is versatile and can, with minor modifications, be used for stereotactic surgery using x-ray guidance by ventriculography, CT guidance or MR guidance. The system consists of an aluminum frame (wt 1.8 kg) which is fixed to the patient's skull via small drill openings made under local anesthesia (see Figure 1). For MR guidance the steel drill bits are removed; after, locating holes are drilled, and replaced by glass fiber locating pins, in order to prevent interaction of the steel pins with the magnetic field of the scanner. The frame contains graduated scales for setting *y* and *z* coordinates. An arc system attached to the frame allows *x* coordinate settings and provides a nearly unlimited range of trajectories for reaching a preselected target. When *x*, *y*, and *z* coordinates are set on the frame, the intended target is the center of a sphere, with the radius of 19 cm. from the arc system and thus may be reached through any desired trajectory.

In order to determine *x*, *y*, and *z* target coordinates, a system of plastic coordinate indicator plates are attached to the frame with the "N" shaped openings filled with diluted copper sulfate-water solution (see Figure 2). The patient's head, with frame attached, is connected to a plastic MR adapter via

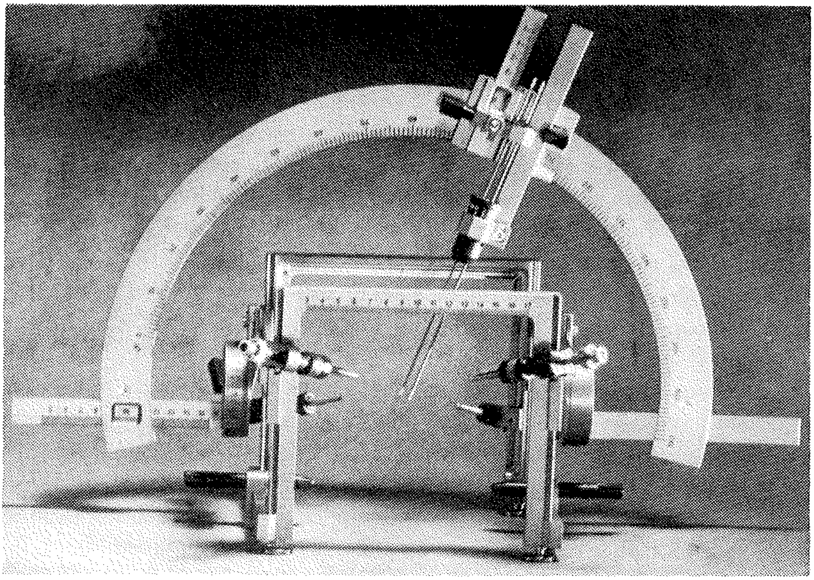

Figure 1: The Leksell stereotactic system. The frame may be used with conventional x-ray, CT or magnetic resonance imaging for target location.

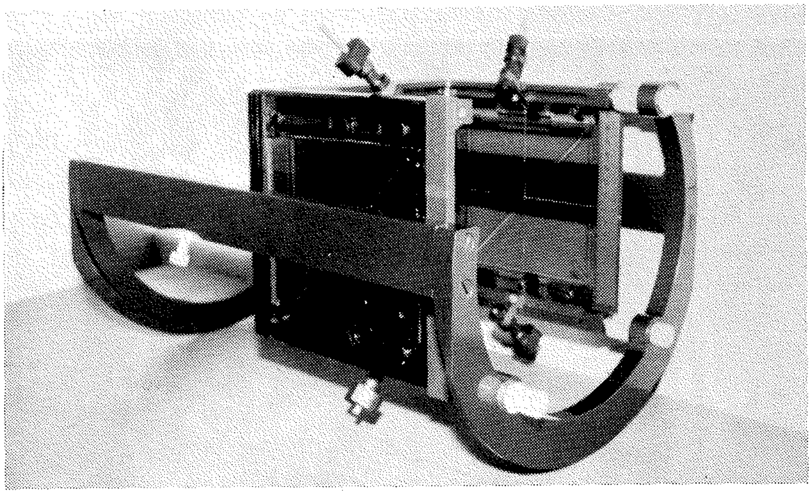

Figure 2: The Leksell stereotactic system modified for use with MR guidance. The frame is attached by plastic feet to the MR compatible base which aligns the frame in the MR Gantry. The "N" shaped coordinate plates are visible. The steel drill pins used to make locating openings in the patient's skull (see Figure 1) have been replaced with glass fiber pins.

plastic feet and advanced into the scanner coil. The adapter serves to correctly align the stereotactic frame in the scanner so that scans may be obtained perpendicular or parallel to the axis of the frame. Scans are then obtained in coronal, sagittal and axial planes (see Figures 3 and 4). The fluid filled tubes are seen as fiducial markers on the completed scans, which allow the exact relationship between the intended target in the brain and the center of the stereotactic frame to be calculated.

Such calculations may be made on hard copies of the scans, using a previously made coordinate scale. This technique allows alterations in targets to be made during surgery, with new x, y, and z coordinates easily obtained using the coordinate scale. Alternatively, the x, y and z coordinates may be obtained directly from the cathode ray tube on which the scanned data is displayed.

After target coordinates are determined, the patient is taken to the surgical suite where the arc system is attached to the stereotactic frame and x, y and z coordinates, previously determined, are transferred to frame settings. A burr hole or other suitable opening in the skull is then performed and the arc rotated to allow the probe holder to be immediately over the skull opening. The probe is then introduced through the probe holder and will reach the intended target 19 cm. from the surface of the probe holder. Functional stereotactic procedures normally involve placement of a destructive lesion by introduction of a radiofrequency heating probe or placement of electrodes for chronic electrical stimulation for treatment of chronic pain. These procedures

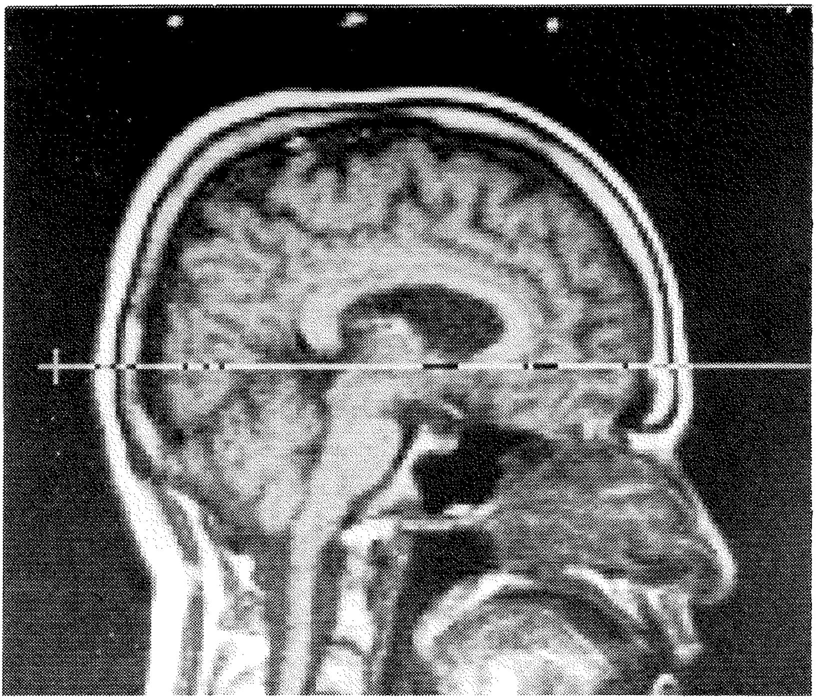

Figure 3: Mid-sagittal MR scan with patient in stereotactic frame. The horizontal line marks the plane of the anterior and posterior commissures and locates the position of the axial image seen in MRI.

are normally carried out under local anesthesia which allows for intraoperative electrical recording and stimulation as an electrode is introduced. Correlations may then be made between sensory or motor activities and either recording or electrical stimulation. Such physiological techniques supplement the anatomical localization provided by the MR guided stereotactic technique and aid in fine localization of lesioning or stimulation electrodes.

Discussion

Leksell, Leksell, and Schwebel (1985) described the MR stereotactic system used by the author of this report, but did not describe its use for functional neurosurgery. Lunsford, Martinez, and Latchaw (1986) described use of the Leksell MR system and felt it offered significant advantages over the CT guided technique. These advantages included improved morphological detail, reduced artifact, and ability to augment tissue differentiation by changing the MR

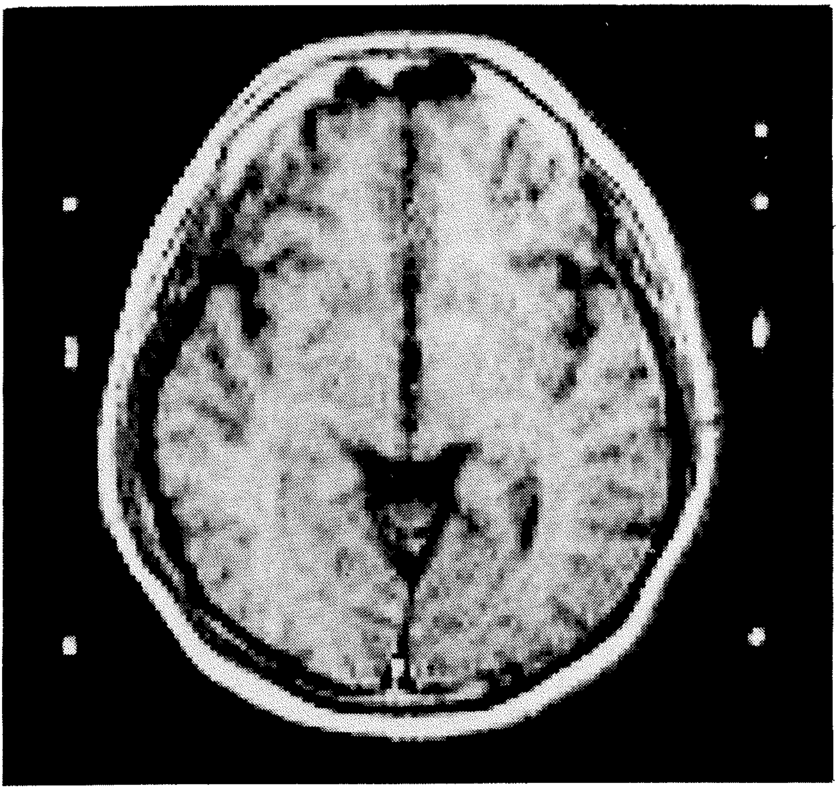

Figure 4: Axial MR scan with patient in sterotactic frame. The plane of the section is shown in Figure 3. The fiducial markings seen on either side of the scan allow correlation of the location of the MR image and the position of the stereotactic frame. The fiducial markings from the liquid filled coordinate plates are visible at the sides of the figure. These markings allow correlation between the patient's brain anatomy and the position of the stereotactic frame.

imaging techniques. Of course, MR techniques avoid the damaging effects of ionizing radiation employed in plain x-ray or CT guided stereotactic systems. Lunsford et al. (1986) indicated that scanning time was longer with MR determination of targets than with CT, and that intraoperative MR scanning was not possible at this time. The author's limited experience, so far, supports these advantages and disadvantages of MR over CT guided stereotactic surgery.

The overall advantage of both CT and MR when compared to conventional contrast ventriculography to determine stereotactic targets has been commented upon by several authors (Asakura, Uetsuhara, Kanemaru, and

Hirahara, 1985; Heilbrun, Brown, and McDonald, 1985; Turnbull, Graeb, and DaSilva, 1985). Major disadvantages of the ventriculographic method include distortion of ventricular size by contrast injection leading to incorrect target localization and the toxic effects of ventriculography itself, including headaches, nausea, vomiting, mental confusion, seizures, meningitis and meningismus as well as intraventricular hemorrhage (Diechmann, Schmidt, and Prager, 1966; Thulin, Essen, and Zeuchner, 1972). Additionally, both CT and especially MR guidance allow at least some definition of intrinsic brain structures such as the location of the internal capsule, and the size and position of the thalamus, for example. This additional data should increase the accuracy of stereotactic procedures and improve their safety. Even MR guided functional stereotactic surgery will not eliminate the need for functional corroboration that the desired target has been reached. Intraoperative stimulation and recording will continue to provide the physiological precision required for functional neurosurgery (Albe-Fessard, Arfel, Guiot, Hardy, Hertzog, and Aleonard, 1961; Ohye, 1982).

The Leksell stereotactic system offers at least one advantage over other stereotactic systems. The Leksell device can be used interchangeably for stereotactic procedures guided by standard x-ray ventriculography or by CT or MR guidance. Thus, if desired, comparisons can be easily made of the target localization accuracy by comparing the methods in an individual patient. Alternatively, the device can be used, for instance, with CT guidance for treatment of intracranial mass lesions, since such lesions are often excellently shown on CT images, and with MR guidance. Experience with functional stereotactic procedures is limited and it remains unclear at this time to what extent MR guided functional stereotactic procedures will replace those guided by conventional x-rays or CT scanning (Kelly, Kall, Goerss, and Earnest, 1985).

Conclusion

Experience with MR guided functional neurosurgery is limited at this time. The technique offers advantages over traditional guidance approaches such as ventriculography or CT scanning. MR avoids the need to inject a contrast agent into the ventricular system and also avoids radiation exposure. In addition, it provides greater image resolution to allow more accurate target identification than either ventriculography or CT scanning. Intraoperative confirmation that the intended target has been attained is not presently possible with MR scanning and provides one disadvantage of the method. Intraoperative physiological monitoring can offset this drawback, however. MR guidance offers an exciting new approach for functional stereotactic surgery but only greater experience with the technique will determine the degree to which it will replace other methods.

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