Chapter 2
Principles of Stereotaxy

Introduction

There are few parts of the body, which may not be approached by means of a surgical operation. An exception to this rule is the deep parts of the brain. The reasons are easy to understand. The head is a rigid cavity and about 90% by volume of its contents is cerebral tissue. This tissue tolerates retraction and displacement badly. Moreover, access to, for example, the basal ganglia involves an unavoidable and unacceptable risk of damage to eloquent areas lying superficial to or adjacent to these ganglia. Thus, conventional open surgical techniques are an essentially inappropriate method to use for operations in the depths of the brain, irrespective of the sophistication of modern microsurgical techniques. These problems have been appreciated for a long time. A solution, at least in principle, has also been around for a long time, in fact since before the First World War.

The famous British neurosurgeon and neurophysiologist, Victor Horsley, wished to gain access to deep cerebellar structures in animal experiments. He sought the help of an Oxford mathematician and physician, Robert Clarke and together they published an account of the first stereotactic instrument in 1908 [1]. However, neither this instrument, nor any modification of it was ever used in clinical work, though one was designed but abandoned for lack of interest. Approximately 40 years were to pass before two Americans, Spiegel and Wycis in 1947 published the results of their operations with a “stereoencephalatome”, as they called it; designed for use for pain and psychiatric disorders [2].

The term stereotaxy derives from two Greek roots “stereos” meaning solid and “takse” meaning arrangement. However, in the past there has been an at times passionate debate, as to whether the correct adjective from stereotaxy should be stereotaxic or stereotactic. The former is etymologically correct. However, the latter was felt to be somehow more in keeping with a surgical procedure, in that “tactic is derived from touch. But! It is derived from the *Latin* word for touch, so that etymologically speaking stereotactic is a chimera. Nonetheless, in 1973 the international body responsible for furthering the interests of those involved in this

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form of surgery changed its previously rather cumbersome name to "World Society for Stereotactic and Functional Neurosurgery". Thus, this is the form, which will be used throughout this book.

Principles

While knowing what the word stereotaxy means may indicate the area of interest, it does not tell us any more about the principles of the method. The aim of the technique is to relate the location of deep and inaccessible intracerebral structures to a three-dimensional Cartesian axis system. The first step in this process is to enclose the head in such a system. This is done by fixing a rigid metal frame to the head. The borders of the frame then constitute the Cartesian axes, while the cranium serves as a platform to support the frame and the cerebrum is enclosed both physically and conceptually within a microcosm, where every point can be precisely defined in space. The zero for the three axes lies above and behind the right ear. Thus the "X" axis increases from right to left, the "Y" axis from back to front and the "Z" axis from above downwards. The way in which a point within the frame is defined in terms of the three Cartesian axes is depicted in Fig. 2.1.

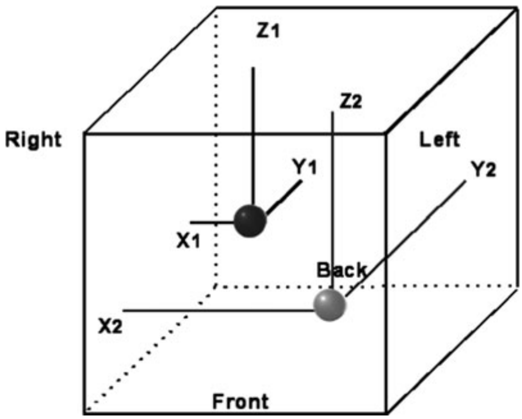

Fig. 2.1 Stereotactic technique relates the position of targets within the body to a system of appropriately designed markers or "fiducials". The system employed for GKNS uses a Cartesian axis system as illustrated in this figure. The system consists of a notional rectangular hexahedron (or cuboid with some definitions). Any point can be connected to the sides of the cube by a line meeting that side at a right angle. If a line is dropped from the top back and right side the length of the lines are characteristic for that particular location which is thus defined by these lengths, or in other words by three numbers. As shown the two locations in the illustration each have sets of lines with different lengths characterising the two locations with two sets of three numbers. It is to be remembered that stereotaxy is performed in relation to the axis system and markers. Any structure within a stereotactically defined space can be characterised in the way shown. Thus if a frame, substituting for the notional box is fitted to the skull, any intracranial location can be defined in relation to that frame

Thus, it is possible to define any intracranial target in respect of the frame. However, to be of any use the frame must itself be a platform for a device, which will hold an instrument or electrode, to be introduced into the brain, to reach the target. The small diameter of the instruments used and the mechanical stability with which they are held and introduced, by means of a rigid holder and guide, and the extreme accuracy of the localization implicit in the method are the basis of the exceptionally atraumatic nature of stereotactic procedures.

The Leksell System

A great variety of different stereotactic systems have been designed over the last 40 years. Each system has its protagonists and its special fields of application. For a description of the essential technical principles of stereotactic surgery reference will be made only to the Leksell system, because it is the system used in GKNS. These principles are on the whole independent of the system used, though the ways in which technical problems are solved differ from system to system. As indicated in Chap.1, while the Leksell stereotactic system was not the first, it was the first to be constructed with a view to ease of application and frequent use [3]. The sides of the cuboid frame constitute the axes of the instrument. An arc is mounted on the instrument in an adjustable holder, which is regulated in respect of the desired values in the three axes. The arc may be rotated backwards and forwards, with respect to the frame. The instrument holder is mounted on the arc and may be moved transversely across the whole circumference of the arc. When the axis values for the target point have been determined, the centre of the arc will always coincide with this target point. This arrangement allows a needle to be pointed at its target from an almost infinite number of directions. Thus, it is simple to design an optimal trajectory for the instrument to be introduced into the depths of the brain, avoiding especially sensitive structures, for example eloquent brain or important blood vessels. An important point of the design is that, for a given target setting, the point of the instrument introduced to the centre of the arc does not move. It does not move irrespective of how the direction of the shaft of the instrument is varied, by moving the arc backwards and forwards or by moving the needle holder transversely across the arc. This effect is quite uncanny and is illustrated in Fig. 2.2.

Target Identification

The features of a stereotactic system, which have been outlined so far, describe how a point in space, a so-called target point may be defined in terms of the reference axis system, built into the stereotactic frame that is fixed to the head. If the target is "visible", for example a space occupying lesion, then a general knowledge of cerebral anatomy together with adequate imaging techniques will suffice. However,

Fig. 2.2 This is an illustration of the Leksell stereotactic frame with the arc attached for use in open surgery. A needle is fixed to the ark and is moved across its circumference in 5° movements. The picture is taken repeatedly and as can be seen, while the direction of approach of the needle varies, there is an uncanny stability of its tip located at a stereotactically defined point. The Gamma Knife is built on the same principle with a single needle on an arc being replaced by multiple fine radiation beams mounted on a 3 dimensional array

in the early days, stereotactic technique was almost exclusively used for the treatment of functional disorders. The targets in this situation are "invisible", consisting of discrete nuclei or tracts within larger anatomical entities, such as the thalamus or the basal ganglia. To locate such targets, a map of the region is required or rather a collection of maps in an atlas. An atlas of the internal cerebral anatomy of a variety of laboratory animals had already been produced by Horsley and Clarke, in the first decade of this century [1]. The production of a human stereotactic atlas in 1962 was one of the major contributions of the pioneers Spiegel and Wycis, mentioned above [4].

While an atlas will show where a given nucleus or tract should be it will not show its precise location in an individual patient. It is necessary to have some visible structure with a constant relationship to intracerebral structures. In Horsley and Clarke's experimental work, skull landmarks were used. They had no choice in this, because contrast materials, which could outline soft tissues on X-ray, were not available, at the time they performed their studies. They were aware of the limitations of this method of localization and checked the location of the lesions they made at post-mortem. Their physiological studies included only those animals where the lesion was correctly placed. This sort of inaccuracy would clearly be inappropriate for operations performed in human patients, so some other means of localization was necessary. To accomplish this, an internal cerebral reference system had to be defined. Air ventriculography had been first described by Harvey Cushing's pupil, Walter Dandy, in 1918 [5]. This technique was thus well established at the time when Spiegel and Wycis performed the first stereotactic operations, in humans. They outlined the third ventricle and used a line drawn between the posterior border of the Foramen of Monro and the anterior border of the pineal body, as a reference. They could then relate the anatomical structures, as depicted in their atlas, to this line.

Moreover, they used the technique to demonstrate just how great the variability of the relationship between intracerebral structures and skull landmarks really is. Subsequently, Tailairach in France used a line joining the anterior and posterior commissures, visualized on an air ventriculogram of the third ventricle, as a reference in his atlas. This reference line is more constant than that based on the Foramen of Monro and the Pineal Body. This is because the borders of the former can be difficult to see and the latter varies a lot, in terms of size and ease of definition. Since that time the intercommissural line has been a standard reference in functional stereotactic surgery. The adequate definition of the posterior commissure required a somewhat refined air ventriculography technique. The subsequent introduction of iodinated positive contrast substances, in particular the discovery of water-soluble contrast media greatly improved the quality of the anatomical definition of the boundaries of the third ventricle. This technique is still used in many centres during treatment, because it is still unusual to find a CT scanner in the operating room. Moreover, repeated ventriculograms can be used not only to identify a target location but also to check that the instruments are placed correctly at the target. Thus, with adequate X-ray definition and using the intercommissural line and an appropriate stereotactic atlas, the location of "invisible" targets became reliable enough for systematic clinical use. The "invisible" targets had been made "visible".

Newer Localization Methods

The treatment of pain, Parkinsonism and psychiatric disturbance, which required the localization of invisible targets, remained the dominating indication for stereotactic neurosurgery for approximately 20 years. However, stereotactic technique could also enable completely accurate placement of instruments into deep-sitting space occupying lesions, where this is appropriate. And it is clearly desirable to obtain a biopsy from those deep-sitting lesions that are tumours and puncture those that are cysts, haematomas or abscesses. Prior to the stereotactic era, these procedures were performed free hand, with a considerable margin of error. It is interesting, in this context, that Leksell's first stereotactic operation on a patient, using his own instrument, was to instil radioactive isotopes into a craniopharyngioma cyst. The problem in the early days, with using stereotaxy in the investigation and treatment of space-occupying lesions was that the X-rays available were inadequate for localization in many cases. Angiography could help with those lesions, which show pathological vessels, but often distortion or displacement of blood vessels is all that can be seen and this is too imprecise. Even so, with the advent of radiosurgery, the angiogram became the examination of choice in the treatment of arteriovenous malformations. The various techniques for displaying the CSF spaces were really only adequate for the stereotactic localization of lesions which distort these spaces. Thus, identification of smaller lesions, deep in the cerebral parenchyma was difficult. However, the development of computer assisted tomography (CT) and more recently magnetic resonance imaging (MRI) has greatly facilitated stereotactic procedures. These techniques render space-occupying lesions truly visible and thus simple to localize. The stereotactic CT or MRI is performed with an adapter [6], to fit and fix the patient's frame to the table of the imaging machine. Then an indicator box is affixed to the frame to enable definition of the stereotactic space. This is described in detail in more Chap. 8. However, the principles of this system are illustrated in Fig. 2.3.

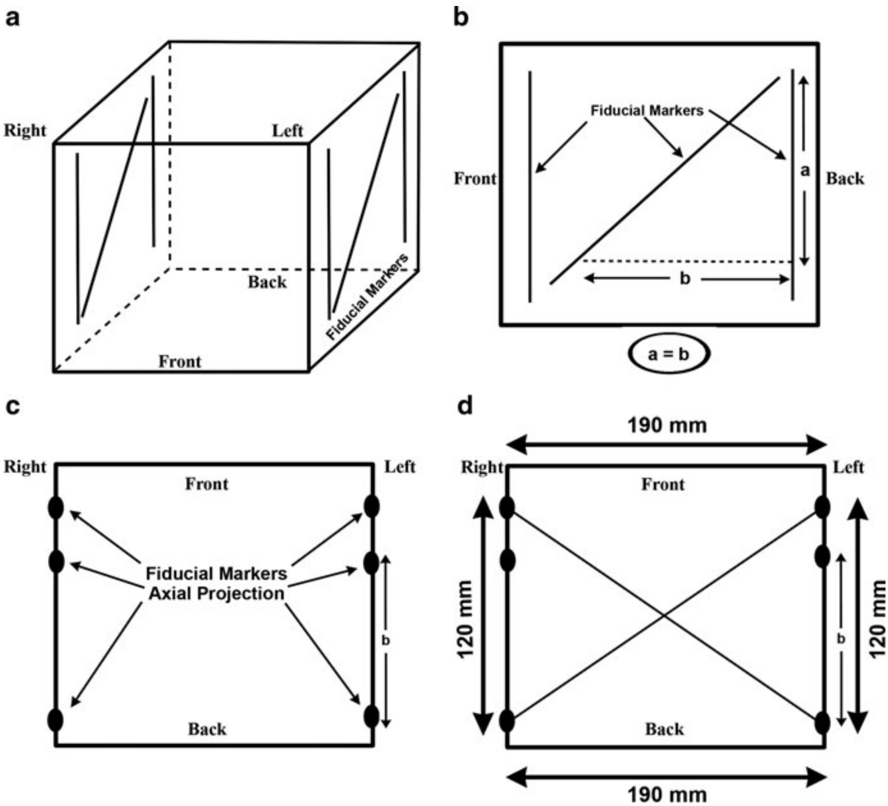

Fig. 2.3 (**a**) Shows the basic principle of the stereotaxic system which includes a plastic box with fiducial markers in the walls. The vertical markers at the front and back are at fixed positions in the stereotactic space and define positions in the XY (axial) plane. The oblique marker permits estimation of the position in the "Z" direction. (**b**) Shows how the distance from the posterior vertical fiducial to the oblique fiducial is the same as the distance from the top of the fiducial to the level of the slice. This is because the oblique fiducial forms part of an isosceles right angled triangle. (**c**) shows how this arrangement appears in axial slice on a computerised image, be it CT or more commonly MRI. (**d**) Shows the distances between the vertical fiducial markers from back to front (120 mm) and side to side (190 mm). These distances MUST be checked at every MR examination to ensure geometric accuracy. It is permissible for the measurement to deviate 1 mm from the true distance because of the size of the pixels. However, the two opposite measurements must not differ by more than 1 mm. The presence of such a difference indicates that the MR machine must be shimmed

Modern Indications for Stereotaxy

Stereotactic technique, following the advent of CT imaging has a large number of indications, most of which have been mentioned. There has however been a tendency for its use to be restricted to a relatively small number of enthusiasts. It is not, even today, used routinely by all neurosurgeons. This is partly because, in the majority of centres, it has been used for functional work, which requires a specialised neurophysiological knowledge that is not a part of all general neurosurgical training programs. Furthermore, the basis of the technique is not technical surgical virtuosity but rather the avoidance of the need for such virtuosity. The Karolinska Hospital Neurosurgery Department, under Leksell's aegis taught that stereotaxy was not to be considered an alternative to other forms of treatment but to be used in addition. This teaching has spread. Moreover, the spread of radiosurgery has encouraged the concomitant spread of intracranial stereotaxy as well. Another result is that stereotactic technique is today no longer limited to the cranium. There are a variety of instruments, both linear accelerators and particle accelerators which can be adapted or specifically designed to deliver focussed radiation using stereotactic methods to any place in the body. This does not of course apply to the Gamma Knife which is and always will be mainly used on intracranial illnesses. It is true, that the latest model, "Perfexion" has the capability to treat lesions in the neck but this method is still in its infancy. Moreover, it would be inappropriate to make machines for use outside the head with the extreme sub-millimetre accuracy of the Gamma Knife. The body movements due to heart beat and respiration prevent the application of focussed radiation with the same accuracy as applies intracranially. These matters are mentioned as they represent a modern trend which has grown up in the last 15 years and which clearly is here to stay. Focussed radiation has many advantages. However, extracranial radiosurgery lies outside the scope of this book so no further mention will be made. Moreover, this is a book exclusively about GKNS. Thus, other methods of delivering stereotactically guided focused radiation such as linear accelerators or particle accelerators are considered outside the range of this text and will not be described or discussed. This is not a comment on the value of alternative techniques. There are plenty of texts which describe their value and use in detail. They simply lie outside the context of this particular book.

Conclusion

Thus after a slow start in the 1950s, stereotaxy is now a commonly used technique both in neurosurgery and radiation oncology. In view of the relative frequency of appropriate extracranial disease this is a trend which is likely to expand. However, it is emphasised that the current book is concerned with Gamma Knife Neurosurgery and discussion of other techniques, except in very special situations is considered outside the range of the topic.

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