Integration of stereotactic techniques into radiotherapy practice: a review

Euan Thomson, PhD

ABSTRACT
Use of stereotactic frames to improve the accuracy of radiotherapy treatments has found wide acceptance in recent years. Early treatments were true neurosurgical procedures, relying on frame systems to accurately place radiation sources at predetermined locations within brain tumors. More recently, stereotactic technology has been used to improve the accuracy of radiotherapy treatments delivered by externally produced radiation beams. This paper reviews the development of stereotactically guided radiation treatments in its various forms and concludes that within the next ten years, almost all radiotherapy departments are likely to be using some form of stereotactic technique.

Keywords: Stereotactic, radiotherapy.

Over recent years, the use of stereotactic equipment to improve the accuracy of localized intracranial radiotherapy has grown rapidly in its application. Use of techniques originally developed for neurosurgery, in radiotherapy departments, has now become a specialty in its own right. This paper briefly reviews the development of stereotactic radiotherapy, through the initial use of stereotactic frames, to implantation of radionuclide sources and the current, sophisticated linear accelerator based radiotherapy techniques.

Stereotactic frames Use of the word stereotactic, seems to stem from the original term 'stereotaxis', used by Horsley and Clark. Analyzing its components, 'Stereo' originates from the Greek word 'stereos' meaning solid. However, in this case, use probably stems from the popular scientific application of the word to indicate the creation of a solid, three-dimensional effect such as in stereoscopic or stereophonic. 'Taxis' is another Greek word, this time meaning order or arrangement. The word Stereotaxis, therefore implies a three dimensional arrangement in space. The term 'stereotactic frame' is used to describe a device that uses a 3-dimensional coordinate system to accurately describe the location of a point in a patient's head. Modern systems are used in conjunction with different image modalities to precisely identify a target site and in neurological procedures to guide a variety of probes to the selected location. The first 'stereotactic' frame is usually attributed to Horsley and Clark working at University College, London. The device that they developed, shown in Fig. 1, was used for psychosurgical studies of animals. Guidance of electrodes was achieved using standardized relationships between external and internal anatomy. The first truly workable frame for human subjects is generally accepted to have been that developed by Spiegel and Wycis shown in Fig. 2. Despite many subsequent transitional developments, it was not until the advent of computerized tomography (CT) that stereotactic frames became the highly precise neurological tools that are in common use today. The detailed and geometrically precise information available in CT images meant that for the first time, neurosurgeons could accurately locate small operational targets. Carefully engineered frame systems such as the Brown-Roberts-Wells system (Radionics Inc MA, USA), shown in Fig. 3, were soon to follow.

Stereotactically guided brain implants The first application of stereotactic equipment to radiotherapy was the guided injection of liquid radionuclides into brain tumors. This was rapidly followed by similar procedures designed to implant solid radionuclides, the first work being recorded by Talairach. Another pioneer of stereotactic implantation of solid radionuclides was Mundinger. Mundinger used many different radionuclides including gold-198, cobalt-
Fig. 1  The Horsley and Clark Stereotactic Apparatus (Reproduced from Thomson, 1990)

Fig. 2  The Spiegel and Wycis Stereotactic Frame (Reproduced from Thomson, 1990)

Fig. 3  The Brown-Roberts-Wells stereotactic frame (courtesy of Radionics Inc) (Reproduced from Thomson, 1990)

Fig. 4  The Photon Radiosurgery System (courtesy of the Photoclectron Corporation)
60, phosphorus-32, tantalum-182 and iridium-192. More modern techniques\textsuperscript{13,14} have centered on iodine-125 and iridium-192. It has been shown,\textsuperscript{18,19} however, that the choice of radionuclide does not significantly affect the absorbed dose distribution across the target volume. Dosimetry in close proximity to the sources is determined primarily by geometric considerations, rather than by photon energy. In terms of radiation protection, however, radionuclides emitting photons of lower energy have an obvious advantage. As with all stereotactic procedures, the development of brain implant techniques underwent significant progression with the development of advanced imaging methods, particularly CT\textsuperscript{17,18,20-22} Until this time, very little information about the size and shape of the target volume was available and implants were planned predominantly using conventional radiography. With the integration of CT into the planning process, complex patterns of precisely arranged radiation sources became more common, in line with similar treatments at other body sites.

Despite the continuing technical advances and the early promise and enthusiasm for clinical studies involving brain implants, there are few centers currently using them as a treatment modality. This is almost certainly a result of the invasiveness of the technique, compared to alternative radiotherapy treatment modalities. In addition, brain implants require complex neurosurgical and radiotherapy planning. Conventional radiotherapy implant procedures, at other body sites, rely on placement of an even distribution of radiation sources throughout the target volume. With stereotactically guided brain implants, the neurosurgical trajectory is often limited and this can severely restrict the options for locating radiation sources. Current research work is centered mainly on the use of advanced computer graphic techniques to aid the accurate placement of sources and to assist with planning of neurosurgical trajectories. These modern computer systems permit a more interactive approach to radiation source placement, allowing the neurosurgeon to work closely with the Physicist and Radiation Oncologist to plan the best trajectory and source arrangement. It is possible that as more complex computer systems find a wider acceptance that a resurgence of interest in brain implant procedures may result.

One other recent technological advance has been made by the Photoelectron Corporation (Boston, MA, USA). This group has developed a miniature x-ray source designed to be surgically implanted using a stereotactic guidance system (Fig. 4). The implant tube on the device is 10 cm long and 3 mm in diameter. The system is driven by a 12V DC supply and x-rays of up to 60kVp are produced isotropically around the tip of the probe.\textsuperscript{23} The unit is currently undergoing investigation at a number of sites worldwide as part of a coordinated clinical trial.

**Stereotactic external beam radiotherapy** In 1951, the term ‘Radiosurgery’ was introduced by the Swedish neurosurgeon Lars\textsuperscript{24} to describe a technique where high doses of radiation, from externally produced radiation beams, were delivered to small intracranial targets. This represented the first application of stereotactic frames to external beam radiotherapy. The new technique was called radiosurgery because it was intended as an alternative to surgical removal of a volume of tissue, the objective was to produce localized tissue destruction. The work program initiated at this time culminated in the later development of the ‘Gamma Knife’ treatment unit (Elekta Instruments Inc Sweden), incorporating 201 cobalt-60 sources.\textsuperscript{33,35} The photon beams from the sources are collimated such that they converge on a single point within the unit. A stereotactic frame is used to localize an intracranial target volume and subsequently to align the target, within the Gamma Knife, at the point of beam convergence. In this way highly accurate radiotherapy can be delivered to a small volume of tissue. Figure 5 is an illustration of the Gamma Knife unit (courtesy of Elekta Instruments). The acknowledged limitations of the unit include its inability to treat larger targets, those in excess of approximately 2 cm diameter, without use of multiple treatment positions.

Linear accelerator techniques producing similar radiation dose patterns to those of the Gamma Knife followed in the 1980's and rapidly became established as a viable alternative.\textsuperscript{33,35} Small circular fields are produced using the medical linear accelerators found in most radiotherapy departments. Treatment units are modified for stereotactic treatments by fitting special collimators to produce small circular radiation beams, usually 1-4 cm in diameter. Stereotactic frames are used to locate the position of small intracranial target volumes. The patient is then aligned in the treatment room, using lasers or mechanical alignment tools, such that the radiation beam is aimed directly at the target. The beam is then rotated around the patient from a variety of trajectories to build up a focussed and concentrated radiation dose pattern. Careful quality assurance techniques have been developed to achieve a high degree of alignment accuracy. A recent development in linear accelerator techniques is the use of relocatable stereotactic frames, such as the Gill-Thomas-Cosman system.\textsuperscript{36-38} This frame uses a dental impression as a removable location method, to replace the more conventional screw-pin attachment to the scalp. Relocatable frame systems have led to a dramatic broadening of clinical applications.\textsuperscript{37} The primary advantage of a relocatable stereotactic frame system is that it allows a fractionated approach to radiotherapy treatments. This has resulted in two
Fig. 5  The Gamma Knife Unit (courtesy of Elekta Instruments)

Fig. 6  The Gill Thomas Cosman relocatable stereotactic frame (courtesy of Radionics Inc.)

Fig. 7  3-D Treatment Planning for external beam stereotactic radiotherapy (the XKnife system shown courtesy of Radionics Software Applications)
distinct forms of treatment becoming recognized. The term 'Stereotactic Radiosurgery' is now generally applied to single fraction treatments using a stereotactic frame. 'Stereotactic Radiotherapy' has become the more usual term applied to fractioned treatments. The relocatable frame is shown in Fig. 6. Quality Assurance is particularly important when using the device and recommended procedures include measurements made with a specially constructed 'depth helmet' and x-ray radiographs. In addition to the radiobiological advantages of the fractioned treatments made possible by the relocatable stereotactic frame system, the user also achieves a greater degree of flexibility during the treatment planning process. Image acquisition, image processing, treatment planning and treatment in a single day can place great pressures on any clinical and scientific team. A relocatable frame system permits removal of the stereotactic system between each step of the treatment planning process and progress can be made at a more practical pace. The acknowledged disadvantage of relocatable frame systems is the inevitable small loss in positional accuracy, thought to be in the order of 1-1.5 mm. Careful quality assurance, as described, is essential. The modern stereotactic radiotherapy planning approach is characterized by the use of enhanced computer graphics (Fig. 7). Such dedicated systems solve the problems of integration of imaging modalities by forming a close link between the computer planning software and the stereotactic equipment. One particular problem in combining image information is the inherent geometric distortion found in MR and digital angiography images. It is important to distinguish between the diagnostic quality of any image used in treatment planning and its value to the stereotactic planning process. Certain images may provide important diagnostic information, digital angiography being a good example, but be less appropriate for stereotactic radiotherapy planning as a result of their poor geometric linearity. Optimum image quality is achieved where a target volume is visible within the image and the spatial linearity is good enough to enable its position within the stereotactic frame system to be precisely calculated. Some of these treatment planning problems can be overcome using computer techniques. Those relating to use of MR, for example, have been studied and advanced computer techniques have been developed to remove the distortion inherent in MR images. Problems with distortions of angiographic images can be minimized with careful quality assurance.

New developments in treatment strategies center primarily on field shaping techniques. Traditionally, circular radiation beams have been rotated around intracranial targets to build up a concentrated radiation dose pattern. Recently, centers such as the Royal Marsden Hospital in London, have been investigating the use of static conformal fields to improve dosimetry. These conformal fields are shaped to conform to the projected shape of the target in the orientation of the treatment beam. It is likely that these techniques will further improve the absorbed dose distributions for larger, irregularly shaped target volumes.

Conclusions In the past 20 years, neurosurgical equipment has found increasing application and acceptance in the radiotherapy environment. The variety of radiation treatments that rely on stereotactic techniques is continually increasing. Early developments saw radiation sources implanted by neurosurgeons in surgical procedures; radiotherapy taking place within neurosurgical operating theatres. More recently the converse process has taken place and neurosurgical equipment has found its way into radiotherapy treatment rooms. Use of stereotactic principles to guide externally produced radiation beams toward small intracranial targets is now accepted practice. In some cases, the distinction between stereotactically guided radiotherapy and conventional external beam radiotherapy is rapidly diminishing. Use of fractioned treatments and static conformal fields are reducing the differences between the standard radiotherapeutic approach and the highly specialized techniques that initiated the research program. Stereotactic systems are now under development to improve the treatment accuracy of radiotherapy at other body sites eg head and neck and pelvis. It is likely that if progress continues at the same pace, the majority of radiotherapy departments will be carrying out some form of stereotactically guided treatment within the next few years.

Acknowledgments I would like to thank all those who contributed illustrations for this review. In particular, Radionics Inc Radionics Software Applications Inc and the Photoelectron Corporation. In addition I would like to thank Ann Curley of the Radiotherapy Physics Unit at the Norfolk and Norwich Health Care NHS Trust for her help in preparation of the document.

References

Integration of stereotactic ... Thomson


35. Thomson ES, Afshar F, Plowman PN. Pediatric