QUALITY ASSURANCE OF STEREOTACTIC TREATMENT PLANNING

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INTRODUCTION

Stereotactic radiosurgery techniques have been developed and used for many years to treat a variety of small intracranial abnormalities (Colombo et al, 1985; Engenhart et al, 1990; Laksell et al, 1971; Phillips, 1993; Simonowa et al, 1995). Sources of irradiation for this technique include X-rays, gamma rays and charged particles. All radiosurgery techniques intend to deliver a high focused radiation distribution to the target volume and to minimise the dose to surrounding normal tissues.

The stereotactic procedure has been described in details elsewhere (Philips, 1993; Novotny et al, 1996) and it can be in principal divided into three main parts: stereotactic localisation of lesion, treatment planning and application of computed dose. In this communication an attention will be paid to treatment planning procedure, analyses of errors connected with it and quality assurance procedures to minimise these errors. The quality assurance procedures will be illustrated by examples performed in our institute for treatment planning system (TPS) GAMMA PLAN, used for Gamma Knife and Leksell system, but most procedures are common for all other TPS used with different stereotactic instruments. A focus is paid only to physical contributions to inaccuracies involved in the treatment planning, subjective aspects introduced by physician (like volume delineation, dose decision, optimisation of plan, etc.) are not included in the discussion.

STEREOTACTIC TREATMENT PLANNING

Treatment planning for stereotactic radiosurgery or stereotactic radiotherapy is a fundamentally 3-D task, and requires accurate determination of the target volume and its spatial relationship to nearby critical structures in the brain. The main planning effort focuses on defining a set of beams (shots) and computing the volumetric distribution. The dosimetric results must be synthesised with anatomical information to allow a clinical evaluation of the treatment plan. This synthesis assumes multiple forms allowing both qualitative evaluations, such as isodose surface displays, and quantitative evaluation, such as integral dose-volume histograms. Criteria for selection of absorbed dose levels for individual cases are based on three major factors: a) histology of a surgical target, b) target volume and c) by proximity of critical structures close to the target. The dose is usually prescribed to periphery of the target, but sometime, and particularly for functional disorder treatments, the maximum dose is used. Very often the maximum dose is limited by the tolerance dose to critical structures, for example to brain stem.

The stereotactic treatment planning has, as it is obvious from the definition, two main aspects: the first one reflects *geometrical accuracy* which must be achieved during the whole procedure; the second one takes into account a *dosimetric accuracy* of dose distribution and absorbed dose calculations. The success of stereotactic treatment planning and treatment depends on both aspects.

TARGET LOCALISATION

Vascular lesions, such as arteriovenous malformations, are usually localised in stereotactic space by cerebral angiography. Tumour targets are typically localised in stereotactic space with CT or MR scans. The superiority of MR over CT for diagnostic neuroanatomical imaging and treatment planning is well established (Guo et al, 1995; Philips et al, 1991). Often it is only appropriate imaging modality for many brain tumours. CT images are supposed to be distortion free and analog angiography is superior to digital one as regards distortion as well. The spatial accuracy of MRI for stereotactic localisation is, however, questionable due to magnetic resonance distortion effects which can be up to 4-7 mm (Walton et al, 1995; Walton et al, 1995; Walton et al, 1996). These effects are mainly caused by inhomogeneity of the constant magnetic field induced by the imaged object and nonlinearities

in the gradient fields. Distortions in MR imaging depend mainly on the MR scanner and the stereotactic system used for localisation (Walton et al, 1996). Therefore it is absolutely necessary to check the whole system (stereotactic frame + scanner + TPS) with a suitable phantom system for possible distortions, i.e. to apply quality control of imaging process. Many stereotactic TPS use image fusion to avoid problems connected with MR distortions. Image fusion is a technique that combine information from separate studies into a single coherent study. Popular image fusion techniques are based on fiducial markers (Schat et al, 1987) or surface matching between volumes identified on each modality (Kessler et al, 1991). Again, if these techniques are used it is necessary to check their accuracy. CT, MR or angiographic images are transferred to the TPS computer either on line or with the help of a scanner (off line). Both procedures have to be checked for an accuracy.

After installation of a new magnetic resonance scanner in our hospital it was necessary to test whether MRI provides a consistent and accurate method for stereotactic localisation. A short study comparing stereotactic target coordinates of chosen anatomical structures in 10 patients submitted to both CT and MRI investigations was performed for this reason. Testing of image fusion between CT and MR images for our system, which is using fiducial markers technique, showed that both images could be fussed within the precision given by the image definition error; i.e. on average within ± 0.5 mm. However, finally we decided to perform a detailed phantom study which could provide us with more circumstantial information about an estimation of potential errors in stereotactic target localisation caused by geometric distortions in MRI. A cubical perspex phantom which could be secured to the base of Leksell stereotactic frame was constructed. The insert to this phantom consisting of array of 81 solid perspex rods (2 mm in diameter) and spaced 15 mm apart could be positioned in the cubical phantom in three different positions (horizontally left-right, horizontally anterior-posterior or vertically oriented rods) to assess the accuracy of sagittal, coronal and axial images. The water filled phantom with the insert was fixed to the stereotactic frame including also four cranial fixation posts and screws and stereotactically investigated within the head coil of a Siemens 1T MAGNETOM Expert system using T1-, T2- and proton density-weighted spin echo images as well as the three dimensional T1-weighted gradient echo. MRI of the phantom was performed for each sequence in both axial and coronal planes with the slab of slices situated piecemeal in different position of the phantom volume. The images were transferred into the treatment planning system and the stereotactic coordinates of the rods were determined. The deviations between stereotactic coordinates based on MRI and real geometrical position given by the construction of the phantom insert were evaluated for each study. The deviations were investigated as a function of: a) MRI investigation sequence, b) image investigation orientation, c) spatial position of measured points in the investigated volume. There were observed no dependencies of deviations on the investigation sequences, image orientation and spatial position of measured points. Maximal and average deviations of stereotactic coordinates X, Y, Z caused by image distortion observed for our system are given in the following Table 1.

	T1-weighted deviations [mm]		T2-weighted deviations [mm]		Proton density deviations [mm]		Three dim. deviations [mm]	
AXIAL	**X**	**Y**	**X**	**Y**	**X**	**Y**	**X**	**Y**
Maximal	1,2	0,9	1,5	0,8	1,5	0,9	1,3	1,5
Average	0,4	0,3	0,5	0,3	0,5	0,3	0,5	0,4
CORONAL	**X**	**Z**	**X**	**Z**	**X**	**Z**	**X**	**Z**
Maximal	1,1	1,8	1,0	1,4	1,0	1,5	1,7	1,3
Average	0,3	0,5	0,3	0,4	0,3	0,5	0,6	0,4

Table 2 gives possible geometrical errors connected with distortions (if they are not corrected for). Two values are recorded: maximum values reported in literature (in brackets) and average values observed for the system used in our department.

Image definition is the second step after transfer of images into TPS. The image definition procedure uses fiducial markers on images and software to define a stereotactic space in which treatment planning and treatment has to be performed. Some TPS, like GAMMA PLAN, have self-control software showing if the distortion in any coordinate on a image under definition exceed permissible level or an average and maximum values are displayed at the end of image definition; these values being typically around 0.5 mm and 1.0 mm, respectively. Possible displacement of the fiducial position might result in a miscalculation

of the whole image, when it is transformed into stereotactic space, and therefore the localisation accuracy throughout image could be affected. The extent of the miscalibration is dependent upon the algorithms used for scaling images (Walton et al, 1995; Walton et al, 1995; Walton et al, 1996).

VOLUME ESTIMATION

Since the applied dose depends on the treated volume it is necessary to establish it carefully. Practically all TPS used for stereotactic treatments are capable to calculate tumour volume which was delineated either automatically or manually on a series of images. The accuracy of volume estimation depends on number of slices used for estimation (slice step) and algorithm employed for evaluation. Typical errors are within 5-10 % of a real volume, as one can see from Tab. 2, which were established as a part of quality control procedure performed for our system with a special water phantom containing different shaped volumes (spherical, cylindrical, irregular). Errors caused by outlining person might be of the same order or larger depending on a type of lesion and are not taken into account in this discussion. Since the dose volume response curves established for a few lesions (AVM, AOVM, meningioma, etc.) are not very steep, the obtained precision in the volume evaluation is quite sufficient, because it represents only a few percent in the dose applied, which could not be radiobiologically significant.

SKULL DATA

To apply corrections for attenuation of radiation beams passing through different thickness of intracranial volume data for skull have to be introduced into TPS. This is done for some systems either by automatic outlining of skull periphery on all CT or MR images or by introducing data measured with the help of a special helmet fixed to the stereotactic frame (for example for Leksell system). The data are collected by manual measurement of distances from the helmet to skull and then transferred to TPS. A correct transfer of data has to be routinely checked for possible errors. The GAMA PLAN TPS for example interpolate between measured data some more points and displays 3-D outline of the skull for a routine quality control check. Any wrong measured or interpolated data can be detected on 3-D display as a „horns" or „holes" in the skull outline. Testing this procedure for Leksell system shown that only errors larger than 2 cm can be detected, but these errors can cause changes in absorbed dose evaluation of about 1-2 % depending on the position of erroneous reading in respect to a treated lesion, number of shots and collimator used. Skull measurements have to be performed with a maximum care and transferred data to TPS have to be checked for misprinting errors to minimise error in absorbed dose calculation. On the other hand, a daily skull measurements with adapted helmet tool are used in our department as a one of routine quality control procedures during fractionated stereotactic radiotherapy.

DOSIMETRIC DATA

For dose calculations in stereotactic TPSs, the characteristics of the individual photon beams are described by their radial and axial dosimetric properties. Since most of the used beams have a circular cross section, they are radially symmetrical. As a result the absorbed dose profiles determined perpendicularly to the beam axis are sufficient to describe the beams. Extremely narrow tolerances used in the manufacturing of individual collimators and other parts affecting the radiation field in Gamma Knife permit all beam channels to be considered identical. The characteristic of a single beam can be therefore used for all other beams of the same size for the purpose of dose calculation. For linac stereotactic based systems the data must be measured individually for each collimator and beam.

Beam profiles are measured with the help of films (either classical or chromic), semiconductor detectors, diamond detector or very small ionisation chambers. All methods have certain limitations and precision. It can be concluded that dose profiles for gamma beams in Gamma Knife are measured with the geometrical precision within $\pm$ 0.2 mm and dosimetric precision of 1-2 % (Philips, 1993) and more or less the same values could be reached for linac photon beams.

Beam profiles for Gamma Knife and their position are checked in our department twice a year, with the help of a special testing tool provided by Electa, for geometrical precision as well as for dose distribution. So far, no changes in the shape and geometry position of beams have been observed.

Because of narrow beam conditions in the Gamma Knife, the attenuation of a single beam is assumed not to change with beam size as it does in broad beam conditions. For the

same reason the attenuation is exponential at depth deeper than the dose maximum, if measured along the beam axis. In the treatment planning programme, one attenuation coefficient is used at depths greater than 10 mm to describe the axial dose characteristics of all beams. Experiments have confirmed that the attenuation coefficient used in Gamma Knife dosimetry does not significantly differ from the attenuation coefficient determined in an 18 mm and 4 mm beam. Therefore, calculation error caused by this approximation is less than 0.3 %. For X-ray beam of linear accelerator, where larger beam collimators are very often used, the attenuation coefficients can change with the size of collimators and therefore detail measurements have to be performed for individual beams.

OUTPUT FACTORS

Absolute value of absorbed dose for Gamma Knife is measured only for the largest collimator (18 mm) to avoid problems with establishment of electron equilibrium conditions. For smaller collimators an output factor (i.e. ratio of absorbed dose measured for particular collimator to dose measured for 18 mm collimator) have to be established. This is very difficult procedure due to limitation of beam size and detectors available. Originally output factors for Gamma Knife have been established with the help of small semiconductor detector and established values were introduced into TPS. A new measurements (Kreiner, 1996) which employed different type of detectors (TLD, ionisation chamber, film, semiconductors) have shown discrepancies between used output factors and measured ones up to 7 % for the smallest collimator. Since the output factors are used for absorbed dose calculations these errors immediately influence the precision of absorbed dose calculation. Next experimental work will be necessary to check values of these factors.

Similar problems are connected with the linac based stereotactic systems, where usually high energy photons (about 6 MV) are employed for treatment and basic dosimetric problems are even more difficult.

Table 2: Sources of errors and accuracies in stereotactic treatment planning .
All accuracy values expressed in % are on the level of one standard deviation; values in brackets give maximum reported or found values.

Source of error	Geometrical accuracy	Dosimetric accuracy
MR image distortions	0.5 (7) mm	
CT image distortions	0.05 mm	
Angiography image distortions (analog)	0.1 (5) mm	
Scanner transfer	0.1 (1) mm	
Image fusion	0.5 (2) mm	
Skull measurements	0.5 mm	
Image definition	0.5 (1.5) mm	
Tumour volume evaluation	5 % - 10 %	1-3 %
Isodose chart (profile)	0.2 mm	1-2 %
Output factors		3 %
Dose rate		1.5 %
Algorithm		0.5 %

DOSE RATE DETERMINATION

Absolute dose rate is measured for Gamma Knife with a small calibrated ionisation chamber in a special spherical plastic phantom designed for this purpose using dosimetric protocols valid for absorbed dose determination in therapeutic beams (for example IAEA protocol (IAEA, 1987). An accuracy of absorbed dose evaluation is of the same order as for Co-60 therapeutic photon beams, i.e. about 1.5 % on the level of one standard deviation. The same phantom is used in our department for routine quality control check every month. Measured dose is always compared with the calculated dose by TPS to check consistency of

calculated and measured doses. An average deviation between measured and TPS calculated dose for the last four years was found to be less than 0. 6 %.

DISCUSSION

Table 2 gives an overview of error sources and their magnitudes which can influence precision of stereotactic treatment planning. It is difficult to express a total uncertainty of the geometrical or dosimetrical contributions due to many reasons. Some contributions could be add, but unfortunately some of them not. For example we cannot add volume determination, which is expressed as a percentage deviation from the real volume with other contributions expressed in absolute deviations (i.e. in mm). It is necessary for any individual used procedure to calculate possible deviations. There might be a difference in uncertainty between on-line image transfer compared to transfer off-line , i.e. from an image scanner or a large difference in geometric accuracy between planning on CT or/and MRI images. Table 2 can serve only as a guide for an estimation of potential sources of errors and their magnitudes.

It is necessary to take into account that estimation of target volume or volumes of critical organs depends mainly on the slice thickness and algorithm used for reconstruction and calculation of volume. One has to keep in mind the possible volume estimation error when deciding the absorbed dose for a tumour with dose distribution partially covering critical organs (for example brain stem). Small change in the volume, caused by the evaluation error, can cause complication of the treatment.

Quality assurance of each step in the treatment planning procedure is absolutely necessary before starting stereotactic treatments for estimation of magnitude of possible errors and then periodical checks are required to prove consistency with original values. It is practice in our department to run simple tests for all mentioned sources of errors every month in order to minimise error of stereotactic treatment planning.

CONCLUSION

The treatment of brain lesions with conformal stereotactic therapy poses severe demands on the ability to accurately define the target volume, accurately calculate dose distribution and absorbed dose, etc. The localisation precision offered by stereotactic technology has a standard deviation approximately less than 1 mm for Gamma Knife and approximately 1.3 mm for linac based systems when considering all aspects of the process, and may exceed the diagnostic precision. The latter is limited by both the actual image quality and the ability of the physician to discriminate the abnormal tissues from the image. A good knowledge of performance of the stereotactic system under use is a basic requirement for performing a good stereotactic therapy. The stereotactic treatment planning system is a core unit in the whole stereotactic process. Therefore, a good knowledge of accuracies of individual processes (inputs into TPS) and drawbacks of the system are very important for producing a reliable and precise treatment plans which can be executed with high precision. A regular quality control procedures are necessary to check primarily necessary accuracies of individual procedures and secondly to control consistency of the system during its use.

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