REVIEV PAPER

PHYSICAL ASPECTS OF TREATMENT PLANNING IN LINAC-BASED RADIOSURGERY OF INTRACRANIAL LESIONS

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SUMMARY

A review of physical aspects of treatment planning in stereotactic radiosurgery is presented.
A target localization procedure, a dose calculation algorithm in a linac-based stereotactic radiosurgery and multi-isocentre planning for large lesions are described and discussed.

INTRODUCTION

Stereotactic radiosurgery is treatment of small intracranial structures or lesions using external beams of radiation. The aim of this technique is to deliver, usually in a single fraction, a high dose of radiation to a stereotactically localized lesion, while minimally irradiating the adjacent normal brain tissue.

The concept of stereotaxis is to use a well-defined, 3-dimensional coordinate system to locate accurately in space any desired region of the brain. A solid, mechanical construction of a 3-dimensional reference frame that surrounds the head can be fixed firmly to the bones of the skull, thereby establishing any point within the skull as a set of three numbers defined by the reference frame.

Several intracranial diseases such as vascular malformations, functional disorders, benign or malignant primary tumours, can be treated using radiosurgery.

Three types of radiation beams are currently used in radiosurgery:

- beams of gamma radiation from specially designed units using multi-mini cobalt sources (so-called gamma-knifes);
- heavy charged particle beams from cyclotrons or synchrocyclotrons;
- X-rays from isocentric linear electron accelerators.

The relatively high cost of cyclotrons and gamma-knife units, as well as difficulties in stereotactic target localization were the reasons why for a long time radiosurgery was available in only few specialized neurosurgical centres in the world.

Excellent clinical results of stereotactic radiosurgery and considerable advances in new imaging techniques such as computerized tomography (CT), magnetic resonance imaging (MRI) or digital subtraction angiography (DSA) have stimulated the development of new radiosurgical techniques based on isocentric linear accelerators.

The earliest reports on clinical linac-based radiosurgery were published in the mid 80's by Betti (Betti and Derechinsky, 1984), Hartmann (Hartmann et al., 1985), Colombo (Colombo et al., 1985), Chierego (Chierego et al., 1988), Lutz (Lutz et al., 1988).

The modifications which are needed to adopt modern linear accelerators to radiosurgery are relatively simple and consist of a set of special cylindrical collimators of diameters in the range of 5 to 30 mm with a reduced penumbra giving a steep fall of a dose at the edge of the target volume, a remotely cotrolled motorized couch or a rotation chair for treatment , and a bracket or a floor stand for mounting the stereotactic frame.

The stereotactic frame "locks" the patient's head into the same position with respect to the fixed coordinate system on the imaging and treatment machines.

If the central point of the tumour is located at the isocentre of the accelerator, treatment is performed using a beam from a number of non-coplanar arcs by combining gantry rotation with a finite number of couch (chair) positions.

Several clinical linac-based radiosurgical techniques have been developed up to now, such as the single plane rotation described by Houdek (Houdek et al., 1985) ; the multiple non-coplanar converging arcs technique, discussed by Betti (Betti et al., 1984), Hartmann (Hartmann et al., 1985), Colombo (Colombo et al., 1985); the dynamic rotation technique developed by Podgorsak (Podgorsak et al., 1988) and the conical rotation technique used by McGinley (McGinley et al., 1990).

Pike (Pike et al., 1990) gave a very useful and comprehensive overview of different linear accelerator methods applicable to radiosurgery, showing that the dose distribution obtained with multiple-arc therapy may be similar to that obtained with the gamma knife.

In fact the spherical sector which may be covered by a multiple-arc technique can be larger than that for the gamma knife Wu (Wu et al., 1990). Another advantage of using a linear accelerator beams is the ability to use fields of a larger area than those provided by the collimators of the gamma knife.

Modifications to multiple-arc radiosurgery have been introduced, enabling non-spherical dose distributions to be obtained (Colombo et al., 1990; Lefkopoulos et al., 1993).

The physical aspects of linac-based stereotactic radiosurgery related to stereotactic frames, dosimetry of narrow photon beams and depth-dose characteristics of megavoltage photons with examples of dosimetric measurements for 15 MV X-ray beam from Mevatron, performed by the present author in the German Cancer Research Centre at Heidelberg, have been described in detail elsewhere
(Wysocka, 1996).

The purpose of this paper is to review the physical aspects of treatment planning in stereotactic radiosurgery. Special attention will be paid to the determination of treatment volume, to the dose calculation algorithm in linac-based stereotactic radiosurgery, to the effect of number and location of arcs, and to multi- isocentre planning for large lesions. The latter problem will be illustrated with an example of treatment planning performed by the author at Tenon Hospital (Paris) using Artemis-3D (Dosigray; Institute Gustave Roussy-Villejuif), the treatment planning system modified by Lefkopoulos (Lefkopoulos et al., 1993).

RADIOSURGERY TREATMENT PLANNING

In radiosurgery, as mentioned above, a high target dose is achieved by directing the radiation beam toward the target from a large number of noncoplanar directions. Simulation of radiosurgical dose distributions is therefore a 3-dimensional problem and cannot be handled with 2-dimensional techniques frequently used in radiotherapy treatment-planning.

Radiosurgical treatment planning is based on stereotactic 3-dimensional data obtained from CT, MRI, or DSA and presented in the coordinate system defined by stereotactic frames. In contrast to conventional radiotherapy, the treatment planning procedures in stereotactic radiosurgery are always performed in reference to the stereotactic head frame and its coordinate system.

Once the target volume is defined, dose planning is performed in three steps:

- definition of the field configuration through determination of the treatment parameters: the number of isocenters, the size of the collimator for each isocentre, the range and the number of arcs, the couch position;
- estimation of the needed dose; and
- assessment of the resulting dose distribution.

These steps are repeated until a satisfactory dose distribution has been found. Then a planning protocol with the resulting parameters of linac setting is printed.

Until early 90s , institutions which offered radiosurgery also developed their own 3-dimensional radiosurgical treatment planning systems. The recent rapid proliferation of linac-based radiosurgery has stimulated development of commercially avaiable radiosurgical treatment planning systems.

TARGET LOCALIZATION

The first step in treatment planning is to define the target object. This requires fitting a stereotactic reference frame to the patient's head.

The target localization in stereotactic space is usually performed by cerebral angiography, MRI and CT for vascular lesions such as arteriovenous malformations (AVM) and with CT, PET, or MRI for tumours.

The advantage of MR over CT for diagnostic neuroanatomical imaging and treatment planning is well established (Philips et al., 1991). On the other hand, the spatial accuracy of MRI for stereotactic localization cannot be strictly determined due to magnetic resonance distortion effects (Walton et al., 1995) . This distortions depend mainly on the MR scanner and the stereotactic system used for localisation. Many stereotactic treatment planning procedure combine the image information acquired with CT, MRI and DSA techniques in order to avoid problems caused by this distortion.

Techniques for registering 3-dimensional MRI, CT and PET data with digital subtraction angiograms have been developed by Henri (Henri et al., 1989). It was demonstrated by Bova (Bova and Friedman, 1991) that biplane angiography alone might be less than satisfactory. At the same time Herbert (Herbert and Froder, 1990) have developed digital tumour fluoroscopy (DTF), analogous to digital subtraction angiography.

Target images acquired with CT, MRI and DSA techniques are transferred to the treatment planning system, on-line or using a scanner.

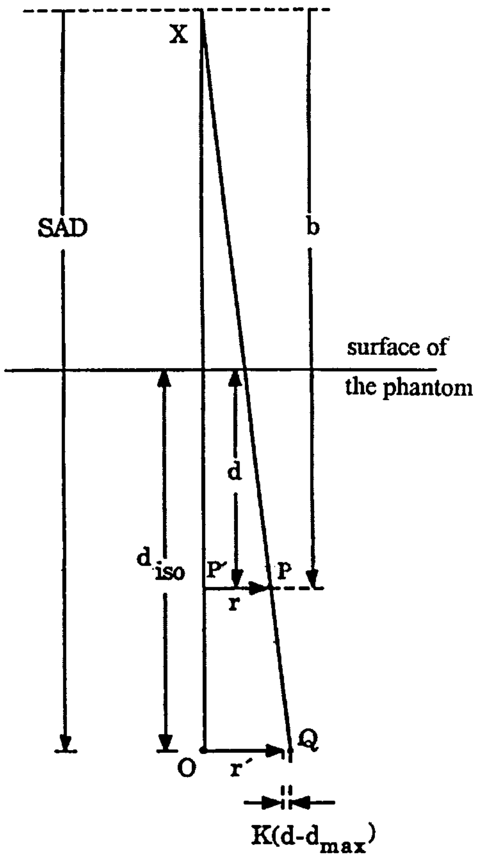

Fig. 1. Conceptual diagramme showing dose calculation for a single beam as part of stereotactic multiple-arc therapy. The dose is calculated at point P. The x-ray source is at X and the isocentre is at O. All other quantities are defined in the text (Luxton et al., 1991).

DOSE CALCULATION ALGORITHM IN LINAC-BASED STEREOTACTIC RADIOSURGERY

Several authors (e.g. Kubsad et al., 1990; Rogers et al., 1995) used the EGS4 Monte Carlo code to compute the beam profile for a linear accelerator provided with a circular (stereotactic) collimator. They made a full-scale simulation of particle transport through all the machine components: primary collimation, flattening filter, secondary collimation, moving jaws and stereotactic collimator.

The same profiles were also independently calculated in the convolution approach (a method of computing dose distributions based on a knowledge of the elemental dose distribution from radiation interactions at a point) and proved to be in agreement with full calculations and with the experimental measurements.

For complex 3- dimensional dose calculations a compromise must always be found between the accuracy of calculations and the time needed for computation. Therefore, some simplifications are useful; for instance tissue inhomogeneities of the brain and sloped skin surfaces are ignored.

Dose distributions in multiple-arc linac-based stereotactic radiosurgery are constructed as the superposition of the doses from each arc. Each arc is represented as a sum of fixed, stationary , very narrow beams. Luxton (Luxton et al., 1991) provided the formalism needed for each of these elemental beams with the following provisions:

- for each collimator the output factor OF(*S*) is defined, where *S* is the field size projected to the isocentre, as dose per monitor unit at depth d_{max} in water at a distance of SAD +d_{max} from the x-ray production target with the primary collimator set to a 5 x 5 cm opening field. SAD is the source-to-isocentre distance.

- the beam monitor is calibrated so that the dose per monitor unit (MU) to water at depth d_{max} is 1.00 cGy for a 10 x 10 cm field at distance of 1 m + d_{max} from the source.
- the tissue-maximum ratio at depth d and field size S is designated as TMR(S, d).

Then the quantity D(d, S, r, d_{iso}), being the single-beam dose per monitor unit to a point P, at a depth d from the surface and distance r from the central axis of the beam is given by the formula:

$$D(d,S,r,,d_{iso})=TMR(S,d)OF(S)R(r')(SAD+ d_{max})^2 / b^2 \quad (1.1)$$

where:

- d_{iso} is the depth of the isocentre O,
- SAD is the source-to-isocentre distance,
- b = (SAD- d_{iso} + d) is the distance from the x-ray source to the plane perpendicular to the beam axis and containing the point at which the dose is calculated;

value r' (see fig.1.) is given by

$$r' = r\,SAD / b-K(d- d_{iso}) \quad (1.2)$$

where K is a small constant which accounts for beam scattering;

-$R(r')$ is the off-axis ratio at distance r' from the central ray at a depth of d_{max} in the plane of the isocentre; this ratio may be found by measurement of the beam profile.

When several arcs of radiation are combined, the 3-dimensional dose distributions show a very important feature:the volume of highly irradiated non-target tissue increases rapidly as the diameter of the collimator increases (Winston and Lutz, 1988).

Multiple-arc techniques use a number of arcs (between one and eleven), theirs angle range changing from 100° to 360°. A detailed comparison of the dose fall-offs outside the target volume for different techniques was carried out by Podgorsak (Podgorsak et al., 1989). There is no great variation of dose fall-off close to the target volume (isodoses: 90% to 50%) if more than four arcs are applied. However the observed increasing isotropy of the dose distributions with increasing number of arcs is an advantage.

MULTI-ISOCENTER PLANNING FOR LARGE LESIONS

Multiple convergent arcs with equal arcs weight provide almost spherical isodose surfaces for dose levels above 50% of the dose maximum. The targets to be treated are often volumes of irregular shape.

In order to generate dose distributions with optimal fitting to the shape of the target volume several approaches have been proposed for Convergent Beam Irradiation (CBI):

- use of adjusted collimator openings (Leavitt, 1991; Schlegel, 1990),
- use of different weights to each of the multiple arcs (Colombo et al.,1989),
- superposition of multiple-arc irradiation for multiple isocentres.

The latter approach is used in the Department of Radiation Oncology at Tenon Hospital (Paris).

Radiosurgery at Tenon Hospital is performed with 15 MV photons produced with a linear electron accelerator (Saturn-43/GE-CGR, Buc France). Narrow beams are formed with a system of additional collimators giving fields with diameters from 6 to 20 mm at the isocentre. The patient is held in a movable Betti seat (Betti et al., 1984) in a comfortable position to adjust the centre of the target volume at the isocentre of the linear accelerator. The stereotactic frame keeping patient's head in a fixed position constitutes the patient's head reference coordinate system.

Each point, defined by sterotactic frame coordinates can be referred to the "anatomical" coordinates (see: Fig. 2; Anterior=A, Posterior=P, Right=R, Left=L, Superior=S, Inferior=I), and the irradiated part of the brain is usually presented in the coronal plane (defined by SI and RL directions) and the sagittal plane (defined by SI and AP directions). The maximum angular apertures in the sagittal and coronal planes are presented in Fig.2.

Lefkopoulos (Lefkopoulos et al., 1993; Lefkopoulos et al., 1994) invented the so-called "Associated Targets Methodology" (ATM) and, along the main idea of this methodology, they have developed a software for a treatment planning system. ARTEMIS-3D (Dosigray, France) was the basic code used and modified. In this method, the therapeutic dose (minimum target dose) is prescribed at the periphery of the lesion treated - irrespective of its size, topography and other specific stereotactic constraints-as a unique entity.

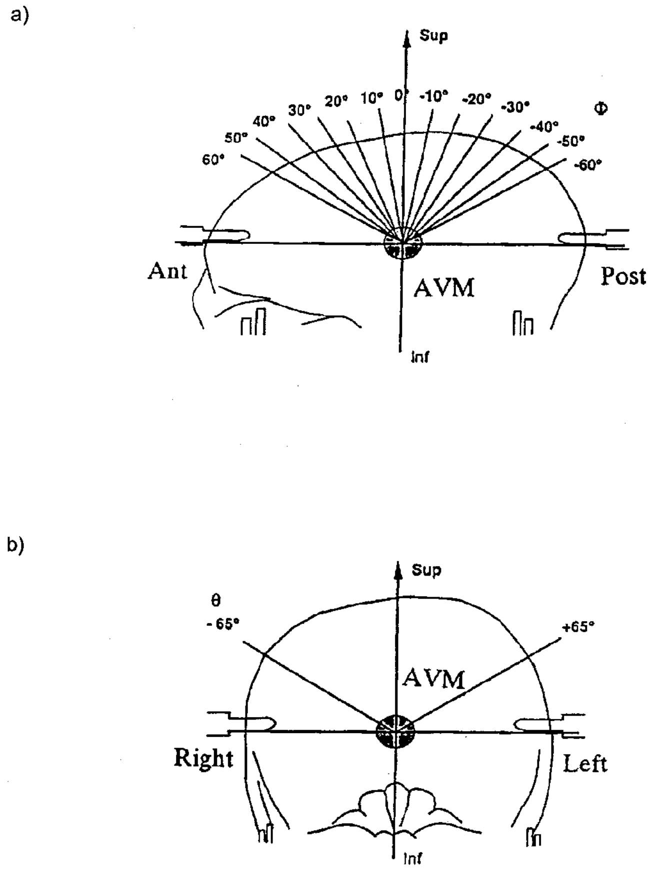

Fig. 2. The maximum angular apertures in the planes: (a) sagittal (120^0) and (b) coronal (130^0); quoted from (Lefkopoulos et al. 1990)

The successive steps of this methodology are as follows:

- evaluating the lesion's complexity, e.g.its anatomical and technical constraints,
- partitioning of the target volume into some sub-volumes, so that each of them has its own isocentre, collimator, irradiation space and isocentre dose weight,
- combining all of these sub-volumes in order to yield a cumulated dose distribution normalized to the dose maximum;
- checking that the reference cumulated isodose contains with sufficient precision the lesion contour and corresponds to the cumulated isodose range of 60% to 70%;
- final evaluation of the treatment plan taking into account the dose inside the lesion and outside the lesion to the healthy tissues, especially to the neighbouring critical structures.

An example of final dose distributions for the irradiation with four isocentres in (a) sagittal and (b) coronal planes is given in Fig. 3. It represents the evaluation of treatment planning as performed by the author exploiting the modified Artemis–3D code.

The results of the ATM method in complex lesion treatment are encouraging. As quoted by Lefkopoulos (Lefkopoulos, 1993), out of 44 cases of arteriovenous malformations which were controlled in two years, 33 cases were obliterated completely (e.g. the post-treatment angiographic study showed a complete absence of AV shunting, absence of abnormal vessels in the nidus region, and normal circulation time).

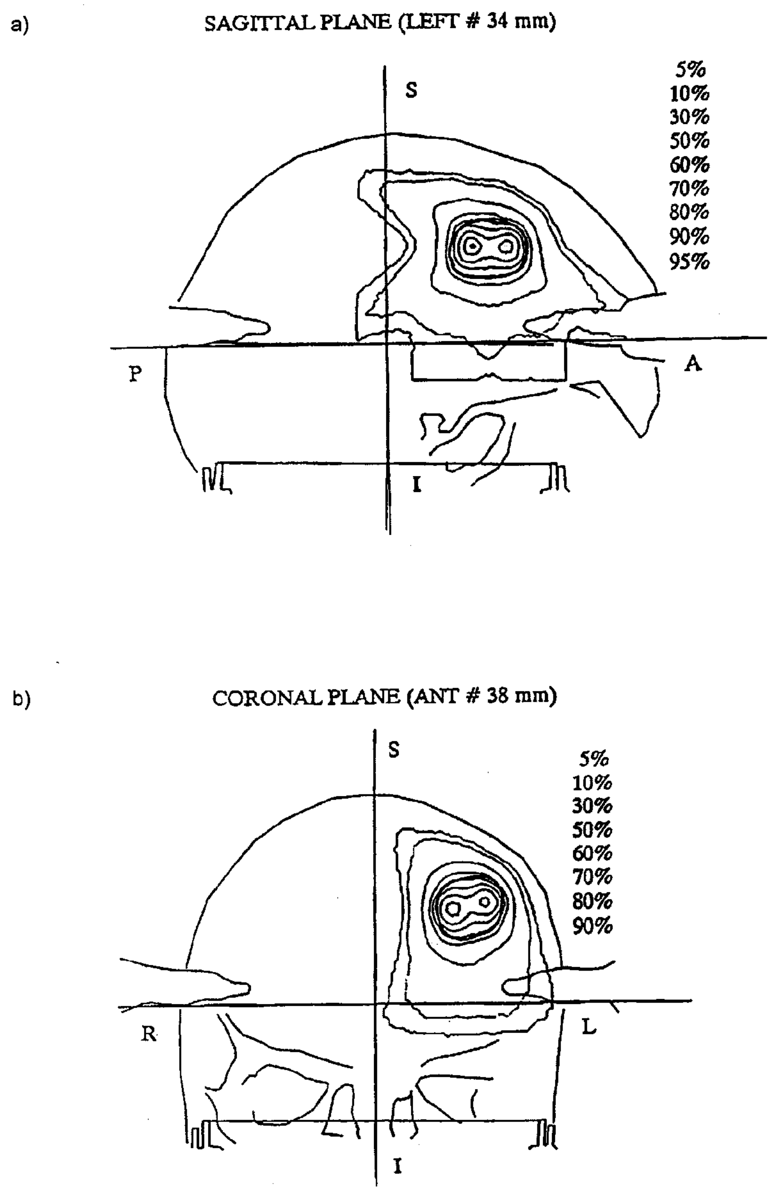

Fig. 3. Example of a final dose distribution in (a) sagittal and (b) coronal planes for a four-isocentre irradiation. The thick dark line represents the contours of the arteriovenous malformations(own results).

CONCLUSIONS

The general availability of linear accelerators and advances in stereotactic methods for stereotactic radiosurgery localization techniques have stimulated a great interest in radiosurgery in the last decade.

Dose distributions obtained with multiple-arc therapy planning are similar to those defined usually for "the gamma knife" technique. Special techniques are being developed to operate with nonspherical treatment volumes, if required.

A treatment planning system for radiosurgery should take into account a large number of irradiation parameters such as the collimator diameter, number of arcs, their angular positions and angular lengths and the weight of the arcs, in order to obtain dose distributions appropriately adapted to each individual treatment plan.

Radiosurgical treatment planning is based on 3-dimensional data obtained from CT, MRI or DSA in conjuction with stereotactic frames, and precise dosimetric data of narrow photon beams. One of the aims of treatment planning is the estimation of the effectiveness of the radiosurgery method in terms of the dose-volume histogram of dose to target and surrounding tissue. The results of these estimations confirm the advantages and the attractiveness of linear accalerator-based methods for stereotactic radiosurgery.

REFERENCES

Betti O O, Derechinsky Y E. Hyperselective encephalic irradiation with linear acelerator. Acta Neurochirurgica (1984); 12: 385-390.

Bova F J, Friedman W A. Stereotactic angiography: an inadequate database for radiosurgery? Int. J. Rad. Oncol. Biol. Phys. (1991); 20: 891-895.

Chierego G, Marchetti C, Avanzo R C, Pozz F and Colombo F. Dosimetric considerations on multiple arc stereotaxic radiotherapy. Radiother. Oncol. (1988); 12: 141-152.

Colombo F, Benedetti A, Pozza F, Avanzo R C, Marchetti C, Chierego G and Zanardo A. External stereotactic irradiation by linear accelerator. Neurosurgery. (1985); 16: 154-160.

Colombo F, Benedetti A, Pozza F, Marchetti C, Chierego G. Linear accelerator radiosurgery of cerebral arteriovenous malformations. Neurosurgery (1989); 24: 833-839.

Hartmann G H, Schlegel W, Sturm V, Kober B, Pastyr O and Lorenz W J. Cerebral radiation surgery using moving field irradiation at a linear accelerator facility. Int. J. Rad. Oncol. Biol. Phys. (1985); 11: 1185-1192.

Henri C, Collins L, Peters T M, Evans A C, Marrett S. Three-dimensional interactive display of medical images for stereotactic neurosurgery planning. Proc. SPIE. (1989); 1092 (Medical Imaging 3: Image Processing): 67-74.

Herbert M H, Froder M. Digital tumour fluoroscopy (DTF)- a new direct imaging system in the therapy planning for brain tumours. Int. J. Rad. Oncol. Biol. Phys. (1990); 18: 221-231.

Houdek P, Van Buren J M, Fayos J V and Ginsberg M S. Stereotaxic radiotherapy technique for small intracranial lesions. Med. Phys. (1985); 12: 469-472.

Kubsad S S, Mackie T R, Gehring M A, Misisco D J, Paliwal B R, Mehta M P, Kinsella T J. MonteCarlo and convolution dosimetry for stereotactic radiosurgery. Int. J. Rad. Onclo. Biol. Phys. (1990); 19: 1027-1035.

Leavitt D D, Gibbs F A, Heilbrun M P, Moeller J H, Takach G A. Dynamic field shaping to optimise stereotactic radiosurgery. Int. J. Rad. Oncol. Biol. Phys. (1991); 21: 1247-1255.

Lefkopoulos D, Schlienger M, Touboul E. A 3-D radiosurgical methodology for complex arteriovenous malformations. Radiother. Oncol. (1993); 28: 233-240.

Lefkopoulos D, Schlienger M, Merienne L, Levrier M, Touboul E. The assocciated targets methodology and the multi-isocenters radiosurgery treatment planning system Artemis-3D. Bull Cancer/Radiother. (1994); 81: 111-125.

Lutz W, Winston K R, Maleki N. A system for stereotactic radiosurgery using a linear accelerator. Int. J. Rad. Oncol. Biol. Phys. (1988); 14: 373-381.

Luxton G, Jozsef G, Astrahan M A. Algorithm for dosimetry of multiarc linear-accelerator stereotactic radiosurgery. Med. Phys. (1991); 18: 1211-1221.

McGinley P H, Butker E K, Crocker I R, Landry J C. A patient rotator for stereotactic radiosurgery. Phys. Med. Biol. (1990); 35: 649-657.

Philips M H, Kessler M, Chuang F Y S, Frankel K, Lyman J T, Fabrikant J L, Levy R P. Image correlation of MRI and CT in treatment planning for radiosurgery of intracranial vascular malformations. Int. J. Rad. Oncol. Biol. Phys. (1991); 20: 881-889.

Pike B, Podgorsak E B, Peters T M, Pla C, Oliver A, Souhami L. Dose distributions in radiosurgery. Med. Phys. (1990); 17: 296-304.

Podgorsak E B, Olivier A, Pla M, Lefebvre, Hazel J. Dynamic stereotactic radiosurgery. Int. J. Rad. Oncol. Biol. Phys. (1988); 14: 115-126.

Rogers D W, Faddegon B A, Ding G X, Ma C M, We J, Mackie T R. BEAM: a Monte Carlo code to simulate radiotherapy treatment units. Med. Phys. (1995); 22: 503-524.

Schlegel W, Pastyr O, Boesecke R, Bortfeld T, Schad L, Gademann G, Doll J, Lorenz W J. Computer systems and mechanical tools for stereotactically guided conformation therapy with linear accelerators. Int. J. Rad. Oncol. Biol. Phys. (1990); 19, suppl. 1: 133.

Walton L, Hampshire A, Forster D M C, Kemeny A A. Stereotactic localization using Magnetic Resonance Imaging. Stereotact. Funct. Neurosurg. (1995); 64, suppl 1: 155-160,

Winston K R, Lutz W. Linear accelerator as a neurosurgical tool for stereotactic radiosurgery. Neurosurgery. (1988); 22 (3): 454-464.

Wu A, Lindner G, Maitz A H, Kalend A M, Lunsford L D, Flickinger J C, Bloomer W D. Physics of gamma knife approach on convergent beams in stereotactic radiosurgery. Int J. Rad. Oncol. Biol. Phys. (1990); 18: 941-949.

Wysocka A. Physical aspects of stereotactic radiosurgery with application of the linear accelerator arc method. Nukleonika. (1996); 41: 11-20.