의학물리. 제2권 2호 1991

Three-Dimensional Dose Distribution for the System of Linear Accelerator-based Stereotactic Radiosurgery

Tae suk Suh, Ph. D.
Department of Radiology, Catholic University Medical College Seoul, Korea

Abstract. Radiosurgery treatment in the brain requires detailed information on three-dimensional dose distribution. A three-dimensional treatment planning is a prerequisite for treatment plan optimization. It must cover 3-D methods for representing the patient, the dose distributions, and beam settings.

Three-dimensional dose models for non-coplanar moving arcs were developed using measured single beam data and efficient 3-D dose algorithms for circular fields. The implementation of three dimensional dose algorithms with stereotactic radiosurgery and the application of the algorithms to several cases are discussed.

Keywords : Stereotactic Radiosurgery, LINAC, Three-dimensional Treatment Planning

1. Introduction

The aim of steteotactic radiosurgery is to deliver, with a high degree of spatial accuracy, a large radiation dose to the target volume within the brain, while maintaining the smallest possible dose to the remainder of the brain tissue. the concept and mechanical design of stereotactic radiosurgery usng LINAC were described in many literatures[1-6)].

Some experience with the treatment of brain tumors using multiple moving beams shows the necessity and efficiency of a three-dimensional radiotherapy treatment planning system. Noncoplanar beams enter the patient in an arbitrary configuration in stereotactic radiosurgery. This type of treatment technique requires a 3-D planning system. This system must employ calculational techniques for four individual model representations : patient, dose computational, treatment beam seup, and visualization. Three-dimensional planning systems and beam optimization studies are based on 3-D dose computation algorithms, which compute the 3-D dose distribution for muliple beam arrangements by adding the beams and combining the relationship between the four model representations.

Several dose algorithms have been described which calculate three-dimensional dose distributions for LINAC-based radiosurgery recently[2,5,8]. These 3-D algorithms are based on an isocentric model by Khan et al.[7], which is one of the empirical dose models that describe the dose for a single field, and is used as a basis for superimposed fields. For radiosurgery planning, an algorithm is needed that permits the calculattion of dose distribution for any single fixed circular field in any orientation, as well as of a number of superimposed fields. According to Hartman et al.[2,8], the dose was considered only near isocenter. The dose model of a single field was represented by a measured relative dose file and a measured depth dose curve in a cylindrical coordinate system. The entire 3-D dose distribution was approximated by that of penil-like beam. The resulting dose distribution was calculated by superimposing single fields. Rice et al.,[9] used a simple isocentric dose model similar to that used by Hartmann et al., ; however, he used somewhat different measured factors. The scatter correcton factor, tissue maximum ratio and off-axis ratio were used as basic beam data by that group. Since those two models actually ignored the inverse square factor, dose computation may not be accurate at points far from the isocenter. Pike et al.,[5] used a dose model based on the 2-D Milan and Bentley algorithm[10] which uses measured central axis percentage depth doses and beam profiles at several depths in water. The TMR was calculated from the percentage depth dose data using Khan's expression[7], and renormalized to the isocenter. This model is a more accurate method of obtaining the dose within the single field than the previous three beam models. One disadvantage of this model is the enormous effort for the measurements. Many other groups have mentioned the use of a 3-D dose cimputational algorithm in their papers ; however, they were not described in detail.

MATERIALS AND METHODS

From the single isocentric dose model, The formula to express the dose at defined point m for a single beam with gantry and table orientation Θ_G, ϕ_T can be written by

$$D(C,\ STD,\ d,\ r)_m = D_{Ref} \times TMR(w,\ d) \times (SAD/STD)^2 \times OAR(C,\ STD,\ r) \cdots\cdots (1)$$

Where

Θ_G = gantry angle orientation
ϕ_T = turntable angle orientation
m = poont of interest in a medium
C = Collimator size defined at SAD
STD = source to target distance
SAD = source to axis distance = 100cm
w = field size at point of interest m expressed by $w = C\ (STD/SAD)$
d = depth of point of interest m
r = off-axis distance
D_m = the dose at point of interest m
D_{ref} = the dose for the reference set-up
ROF = relative output factor defined by $D(C, STD=100, d_{max}, r=0)/D(C_{ref}, SSD=100, d_{max}, O)$
TMR = tissue maximum ratio defined by $D(w,d)/D(w,d_{max})$

OAR = off-axis ratio defined by $D(C,STD,d,r)/D(C,STD,d,r=0)$

If the dose matrix and beam setting parameters are determined, the calculation of the dose on the dose grid requires d, r, STD, and w from our dose model in Eq.(1). The unknown beam parameters can be determined from the geometrical relationship between a cartesian frame coordinates defined in the patient head and beam position (Fig. 1). The Eqs. (2-6) were derived as an explicit set of algebraic equations for the determination of unknown beam parameters on the cartesian coordinates (x_B, y_B, z_B) in terms of the known irradiation parameters ; gantry orientation, table orientation, collimator size, and isocenter position (X_j, Y_j, Z_j) for each arc j. The method is based primarily on the definitions of the three coordinate systems, transformations and vector analysis in three-dimensional space. A more detailed discussion is shown in other literature[11].

$$Z=(x_B-X_j)\cos\Theta_G+(y_B-Y_j)\sin\Theta_G\cos\phi_T$$
$$=(z_B-Z_j)\sin\Theta_G\sin\phi_T\cdots\cdots\cdots\cdots\cdots\cdots(2)$$

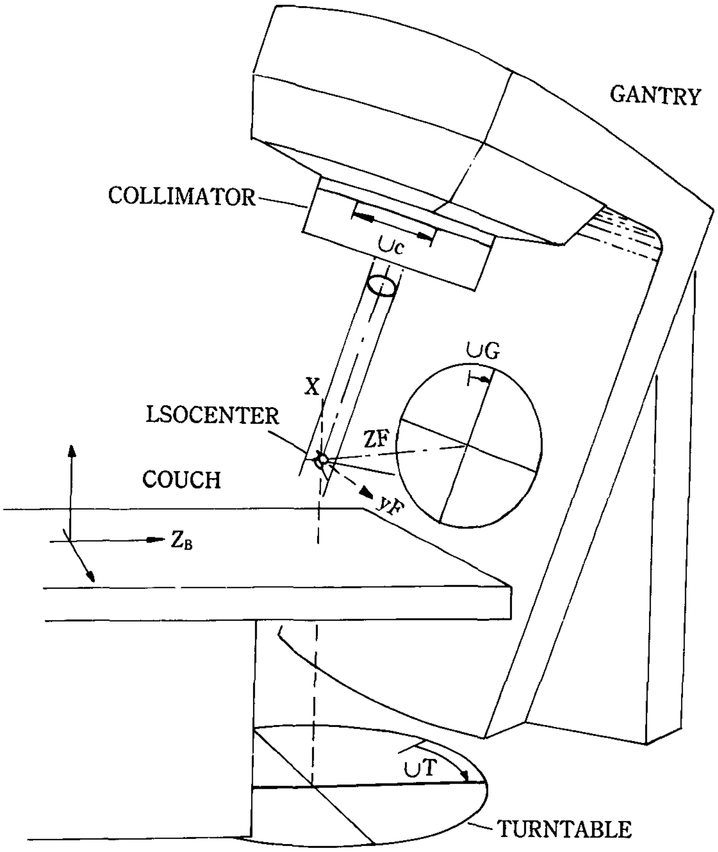

Fig. 1. Linear accelerator with the three coordinate systems. z_F, x_F and Z indicates axis of rotation of the gantry, turntable, and the collimator, These three axis intersect at the center of the target.

$$d = d_I - Z \quad (3)$$

$$r = [(x_B - X_j)^2 + (y_B - Y_j)^2 + (z_B - Z_j)^2 - Z^2]^{1/2} \quad (4)$$

$$STD = SAD - Z \quad (5)$$

$$W = C_j \; (STD/SAD) \quad (6)$$

where d_I is the depth of isocenter. The problem of finding the depth, d is now reduced to finding the depth of isocenter, d_I at each increment of the gantry rotation Θ_G and turntable rotation ϕ_T about isocenter position I_j. The depth of isocenter is dependent on the individual patient contour, isocenter position, and transformation of CT data to frame coordinate system, etc. To calculate the depth of the isocenter, d_I, a simple algorithm has been developed which is based on a database containing a sampling of points on the surface of the patient's head using a ray tracing technique[12] by the UF research team[6] and other institute[5].

The final algorithm to express total dose D_t at the point of interest m in the defined dose grid for multiple arcs is expressed in the form given by

$$D_t = \sum_T \sum_G D_m \quad (7)$$

where D_m is given by Eq.(1). The unknown beam parameters for one gantry (Θ_G) and turntable orientation (ϕ_T) of each arc j are determined in the cartesian frame coordinate system. TMR and OAR vales are then obtained from the measured data or fitting function developed[13]. The procedure needed for dose planning in stereotactic radiosurgery is shown in Fig. 2

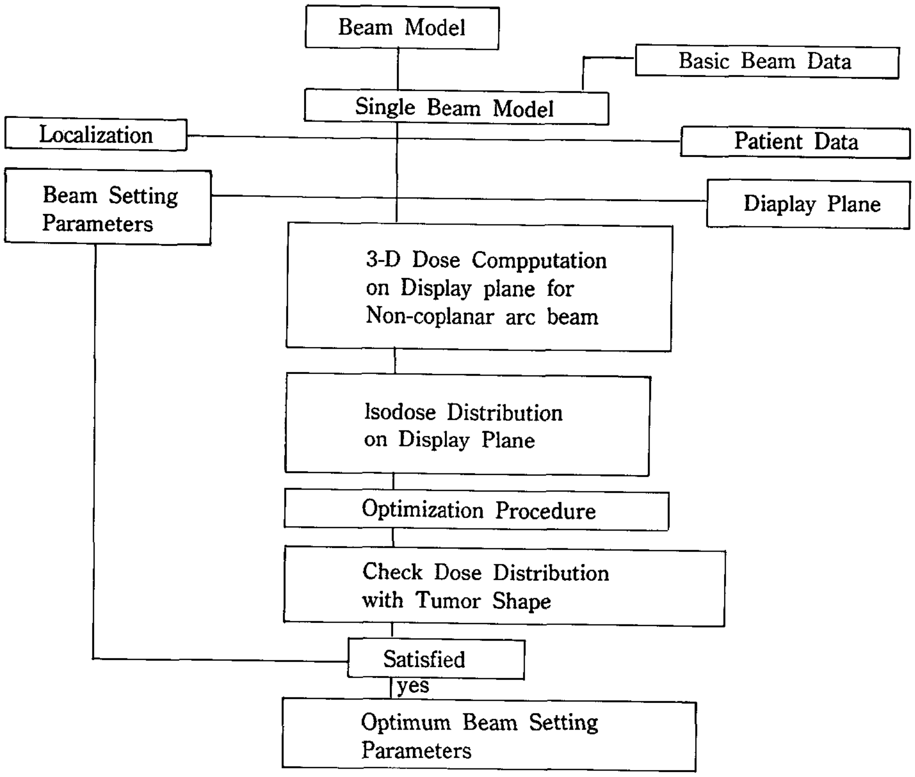

Fig. 2. The procedure for dose planning in stereotactic radiosurgety.

RESULTS

We discussed detailed methods to develop three-dimensional dose algorithm for LINAC-based stereotactic radiosurgery. The implementation of three-dimensional dose algorithms with stereotactic radiosurgery and dose distributions for various irradiation techniques are illustrated.

Figure 3 gives montages of spatial contours of dose distribution on major arc planes for 100° and 180° partial rotation arcs with isocenter position (0, 0 ,0) and collimator size 1cm. Figure 4 gives a montage of the spatial contours of the dose disstribution on the coronal plane in cartesian frame coordinates from two orthogonal arcs (0° and 90° turntable) with isocenter position (0, 0, 0) and collimator size 1cm. Figure 5 gives montages of spatial contours of dose distribution on three orthogonal planes (axial, sagittal and coronal) for standard four arcs (100° arc length with 45° equal arc spacing used in routine stereotactic radiosurgery) with single isocenter position (0, 0, 0) and collimator size 1cm. Single isocenter approach results in spherical dose distributions in the target and dose falloff outside the target, which depend on the arrangement of the arc system. Figure 6 gives montage of spatial contours of dose distribution on the three orthogonal planes for two standard four arcs system with two different isocenters, (0, -0.6, 0) and (0, 0.6, 0) (four arcs about each isocenter) and

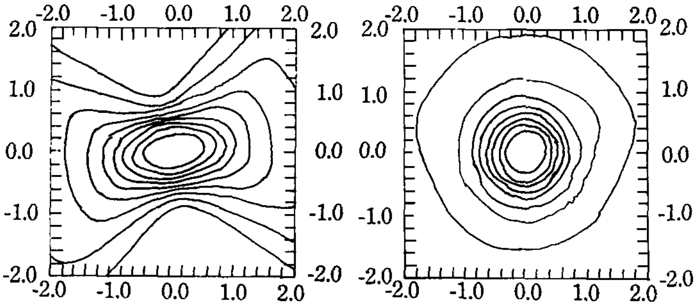

Fig. 3. Isodose distributions for 100° arc (a) and 180° arc (b). Isodose lines displayed are from 90 to 10 in decrements 10.

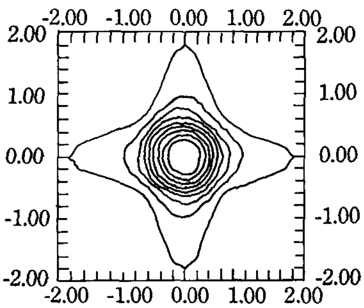

Fig. 4. Isodose distributons on the coronal plane for two orthogonal arcs (100° arc with 30°-130° gantry for two turntable positions, 0° and 90°) with 1cm diameter collimator size. Isodose lines displayed are from 90 to 10 in decrements 10.

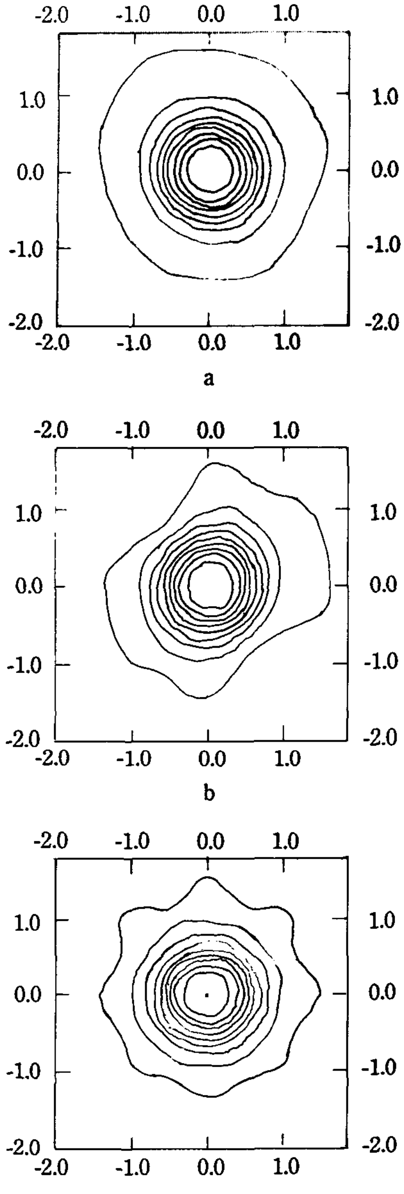

Fig. 5. Isodose distributions for standard four arcs (100, arc with equal arc spacing) with 1cm diameter collimator sizes : (a) axial, (b) sagittal, (c) coronal. Isodose lines displayed are from 90 to 10 in decrements 10.

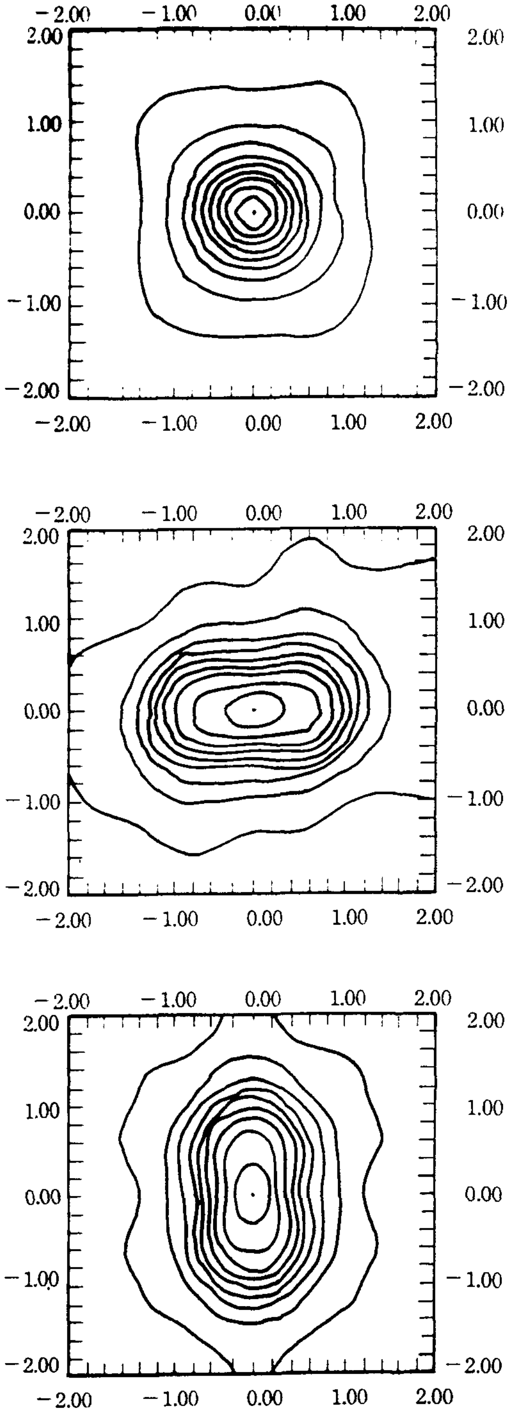

Fig. 6. Isodose curves for two standard four arcs system with two different isocenters and 1cm diameter collimator sizes : (a) axial, (b) sagittal, (c) coronal. Isodose lines displayed are form 90 to in decrements 10.

collimator size 1cm. Using two isocenters is presently a useful technique in radiosurgery to fit the treatment isodose volume to the elongated target shape.

As a consequence, the programs required approximately 30 seconds to calculate dose for for standard four arcs on a 20×20 matrix (400 points) and an additional 10 seconds to perform grid generation to represent isodose curves with386/59 personal computer with floating point processor. This is fast enough to perform real-time optimization during computer dosimtry treatment planning.

DISCUSSIONS

In order to explane the stereotactic procedure, the three steps of the procedure (target localization, dose planning and radiation treatment) must be examined separately. The ultimate accuracy of the full procedure is dependent on each of these steps and on the consistancy of the approach. The concern in this paper was about dose planning, which is a important factor to the success of radiation treatment. The major factor in dose planning is a dosimetry system to evaluate the dose delivered to the target and normall tissues in the patient, while it generates an optimal dose distribution that will satisfy a set of clinical criteria for the patient. A three-dimensional treatment planning program is a prerequite for treatment plan optimization. It must cover 3-D methods for representing the patient, the dose distributions, and irradiation settings. The development of 3-D dose algorithm was discussed. The resulting dose distributions were shown for possible irradiation techniques used in stereotactic radiosurgery. In addition, since the dose algorithm operates on a 3-D patient representation stored as set of multiple transverse sectional contours, calculating dose in 3-D space using the exact 3-D dose model is time consuming. A faster and more efficient dose calculation algorithm is required for the optimization to simulate exact dose model and to determine optimum irradiation parameters in the future.

REFERENCES

1. Colombo F, Benedetti A, Pozza F, et al : External Stereotactic Irradiation by Linear Accelerator, Neurosurgery, 16 : 154, 1985
2. Hartmann GH, Schlegl W, Sturm V, et al : Cerebral Radiation Surgery Using Moving Field Irradiation at a Linear Accelerator Facility, Int J Radiat Oncol Biol Phys, 11 : 1185, 1985
3. Heiftz MD, Wexler M, and Thompson R : Shngle Beam Radiotherapy Knife ; A Practical Theoretical Model, J. Neurosurg, 60 : 814, 1984
4. Lutrz W, Winston KR, and Maleki N : A System for Stereotactic Radiosurgry with a Linear Accelerator, Int J Radiat Oncol Biol Phys, 14 : 373, 1988
5. Pike B, Podgorsak EB, Peters TM, et al : Dose Distributions in Dynamic Stereotactic Radiosurgery, Med Phys, 14 : 780, 1987
6. Ffiedman WA, and Bova FJ : The University of Florida Radiosurgery System, Surg Neurol, 32 : 334, 1989
7. Khan FM, Sewchand W, Lee J, et al : Revision of Tissue-Maximum Ratio and Scatter-Maximum

Ratio Concepts for Cobalt 60 and Higher Energy X-Ray Beams, Med Phys, 7 : 230, 1980

8. Hartmann GH, Schlegel W, Strum V, et al : A Fast Algorithm to Calculate Three Dimensional Dose Distributions for Radiosurgery, Proc 8th Int Conf on the Use of Computers in Radiotherapy, pp 99, 1984
9. Rice Rk, Hansen JL, Svensson Gk, et al : Measurement of Dose Distribution in Small Beams of 6 MV X-rays, Phys Med Biol, 32 : 1087, 1987
10. Milan J, and Bentley RE : The Storage and Manipulation of Radiation Dose Data in a Small Digital Computer, Brit J Radiol, 47 : 115, 1974
11. Suh TS : Optimization of Dose Distribution for the System of Linear Accelerator-Based Stereotactic Radiosurgery, Ph. D. Dissertation, University of Florida, 1990
12. Siddon RL : A 3D Ray-Tracing Algorithm for Radiotherapy Applications, Phys Med Biol 30 : 817, 1985
13. Suh TS, Yoon SC, Shinn KS, et al : Measurement of Dose Distribution in Small Beams of Philips 6 8 MVX Linear Accelerator, J Korean Soc Ther Radiol 9 : 143, 1991

LINAC을 이용한 뇌정위적 방사선 수술에 대한 3 차원 선량분포

서태석
가톨릭 대학 의학부 방사선과

뇌정위적 방사선 수술 시 정확한 3차원적 선량분포에 대한 정보가 필요한다. 3차원적 치료계획은 최적선량분포를 얻기위한 것이며 환자 데이타, 선량분포, 방사선 조사 요소들에 대한 3차원적인 관계를 다루어야만 한다.

원형 조사면에 대한 single 조사면 선량 데이타와 3차원 선량 알고리듬을 이용하여 non-coplanar moving arcs에 대한 3차원적 선량 모델이 개발되었다. 뇌정위적 방사선 수술시 3차원 선량 알고리듬의 적용과 여러경우에 대한 응용에 대하여 논의되어진다.