Dose Distributions for LINAC Radiosurgery with Dynamically Shaping Fields

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An important problem in radiosurgery is the utilization of the proper beam parameters, to which dose shape is sensitive. Streotactic radiosurgery techniques for a linear accelerator typically, use circular radiation fields with multiple arcs to produce an spherical radiation distribution. Target volumes are irregular in shape for a certain case, and spherical distributions can irradiate normal tissues to high dose as well as the target region. The current improvement to dose distribution utilizes treating multiple isocenters or weighting various arcs to change treatment volume shape. In this paper another promising study relies upon dynamically shaping the treatment beam to fit the beam's eye view of the target.

This conformal irradiation technique was evaluated by means of visual three dimensional dose distribution, dose volume histograms to the target volume and surrounding normal brain. It is shown that using even less arcs than multiple isocenter irradiation technique, the conformal therapy yields comparable dose gradients and superior homogeneity of dose within the target volume.

Key Words: Stereotactic radiosurgery, LINAC, Conformal therapy, Beam's eye view

INTRODUCTION

Stereotactic radiosurgery using linear accelerator have been developed and are clinically used for treatment of arteriovenous malformations and brain tumors. The essence of this technique is to deliver a high radiation dose to the target volume while limiting the dose to surrounding normal tissues. The concept and machanical design of LINAC-based stereotactic radiosurgery were described in many literatures[1~6].

The design of an optimal planning system which uses enormous 3-D patient data and many treatment parameters is very important in radiosurgery and represents a significant challenge. This is in part due to the lengthy calculation time for 3-D information of dose distribution about target volumes and anatomic structures, and also by the many irradiation parameters involved in treatment planning. It requires not only a fast 3-D dose calculation algorithm, but also a way of quick evaluation of the relative merits of various plans. Recently, many techniques have been developed and proposed to optimize dose distributions in radiosurgery[7~12]. The most of current techniques utilize treating multiple isocenters or weighting various beams or arcs to change treatment volume shape. It has been shown that the effect of changing beam energy or the number of arc is minimal to modify dose distribution[13,14]. Even moderate modification of arc weight and orientation from standard arc system with equal arc spacing doesn't significantly change dose distribution from spherical shapes in the high dose region, while it may provide desired change in low dose region. Although the use of multiple target points is useful to shape the irregular target, it introduces large dose inhomogeneities within target[12]. The possibility of shaping the dose distribution using conformation of the target has been investigated using the beam's eye view and change of field shape[11,12,15].

The aim of this work is to develop dose planning procedures for the determination of irradiation parameters with a dynamically shaping field technique. The basic approach of this prototype work limits to develop a beam's eye view algorithm, dose calculation algorithm for dynamic varying field, and

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optimization procedure using field shaping.

MATERIALS AND METHODS

It is necessary to shape the aperture of the beam and compensate for surface irregularities, internal inhomogeneities, and target shape to achieve desirable dose distributions. Radiosurgery uses a small beam to treat homogeneous brain tissues and thereby, the compensation problem is not critical. Field shaping using the beam's eye view and adjusting of the collimator are discussed. Instead of using irregular field shapes such as multileaf collimators, the variation of a rectangular field, which seems to be more practical for study purpose, is considered in this article.

1. Beam's Eye View Projection

For practical 3-D treatment planning, one of the most important perspectives to be used is the Beam's Eye View (BEV), since it displays the relationship of the target volume to the proposed radiation beams. Beam's eye view is a display of relevant anatomical, dosimetric and beam data from the perspective of the radiation source, looking down the radiation beam. Discussion of the beam's eye view concept and it's implementation at other sites can be found in the literature[16~20]. The patient structures which have been defined can be made into wire frame[21] or shaded 3-D views[22]. In this work, BEV is accomplished by displaying a wire-frame diagram of contours outlining the patient's anatomic structures in three dimensions as if being viewed from the source of radiation along the central axis of the beam.

In order to display the defined anatomy in beam's eye view, transformation was performed from the anatomical coordinate systems into beam coordinates. Next, beam coordinates were transformed into screen coordinates. The first is called viewing transformation, and second, perspective transformation.

The viewing coordinate system is affixed to the collimator of the treatment machine with its x_c-axis pointing from the isocenter to the source and y_c and z_c-axes parallel to the jaws defining the field size. The origin of this collimator system is at isocenter. The contour points defining the structures are given in the patient coordinate system $[V]_B$, which are transformed from the original coordinate system of the CT images. These points undergo a series of rotational and translational transformations to be expressed in terms of the collimator system. The collimator coordinates can be expressed in more detail in terms of patient coordinates.

$$[V]_c = R_x(r_k)\, R_z(\theta_i)\, R_x(\phi_j)\, \{[V]_B - [I_j]_B\} \qquad (1)$$

where $R_x(r_k)$, $R_z(\theta_i)$, $R_x(\phi_j)$, are rotation operator of collimator, gantry, and turntable. $[I_j]_B$ represent coordinate of isocenter in frame coordinate system. A complete mathematical expression is more or less tedious, and could be referred to the reference[26].

After the viewing transformation, those points are then projected on the defined imager screen. To take into account the beam divergence, the objects nearer to the source than screen are proportionally magnified and those farther than the screen are demagnified. In our implementation of the beam's eye view, the isocenter is assumed to be the view point. A more advanced display method could also be used with the beam visualization algorithm[23]. Using wire frame model and equation, the program was written in BASIC language to display the BEV for any structure.

2. Field Shaping Using BEV

The basic idea of BEV is to determine the optimum directions and field sizes of oblique noncoplanar beams so as to maximize the coverage of the target region while manimizing the inclusion of healthy critical organs in the high dose region. The best arc direction in radiosurgery can be determined among the possible directions by observing the dose distribution through the entire volume in the patient.

Once directions of incidence of the radiation beams have been selected, the collimator opening is adjusted to the smallest size that covers the target volume with the proper collimator rotation. The outline of the aperture should conform to the shape of the target visible from the direction of incidence and provide adequate margins. Presently, a rectangular collimator is used to fit the target margin instead of multi-leaf collimator, since the use of rectangular collimator is simple and quite enough to estimate the efficiency of conformal radiosurgery. Later, improved field shaping technique such as multi-leaf technique will be discussed in elsewhere.

From the single isocentric dose model, the calculation of the dose at each point of interest requires the depth d, the off axis distances y_c and z_c, the source to target distance STD, the collimator size W_Y and W_Z, and field size w_y and w_z with gantry, turntable, and collimator orientation θ_i, ϕ_j and r_k. The field size w_y and w_z at each point is easily

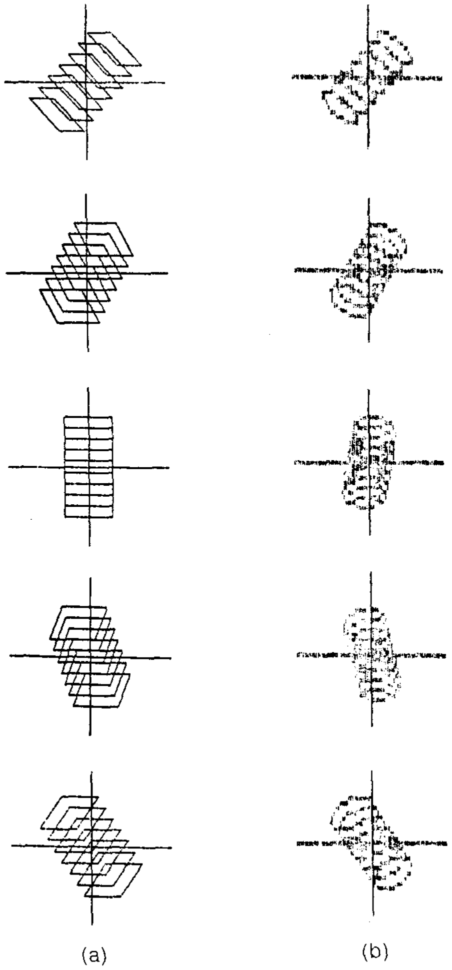


Fig. 1. Beam's eye view of a rectangular (a) and cylindrical (b) target in Fig. 2 at 45° couch position. The target has a 3-D description including 7 slices using a wire-frame model.

calculated by the relationship, $w_y = W_Y$ (STD/SAD). When we use different isocenter positions for different arcs, the depth d and off axis distance y_c and z_c of each point on the dose grid for each increment of gantry rotation θ_i in the algorithm are the only parameters which need to be derived from the patient contour and isocenter position I_j for each arc j. The formula to express the dose at defined point m with three additional variables θ_i, ϕ_j and r_k can be written by:

$$D(W_Y, W_Z, STD, d, y_c, z_c) = D_{Ref} \times ROF(W_Y, W_Z) \times TMR(w_y, w_z, d) \times (SAT/STD)^2 \times OAR(W_Y, W_Z, STD, y_c, z_c) \quad (2)$$

An explicit set of algebraic equations were developed for the determination of beam parameters on the cartesian frame coordinate dose grid with the patient head in terms of the known parameters θ_i, ϕ_j, r_k, W_Y, W_Z AND i_j. A more detailed description could be referred to references[26)].

RESULTS

Fig. 1' shows the projection of BEV superimposed on a set of elongated rectangular and cylindrical targets as seen from the source. The targets have a 3-D description including 7 target contours on CT slices using a wire-frame model. The center of a target is located at isocenter in the spherical head model. The dimension of the target and all other geometry are shown in Fig. 2. The objective in each view is changed as the collimator rotates at table orientation of 45°. The fields in Fig. 1 is selected to encompass the target plus some margin, and are shown as dashed lines. Dose distributions are then calculated. We developed an explicit dose model with the BEV in terms of the gantry angle, table angle, collimator angle, collimator size, and isocenter position.

Fig. 3 and 4 show three orthogonal dose distributions for elongated solid rectangular targets using one arc (eithor table angle 0 or −90) or two arcs (table angle 0 and −90) and four arcs. Dose distributions in Fig. 4a show results comparable with that obtained from the multiple isocenter approach[25)]. The collimator was rotated and adjust-

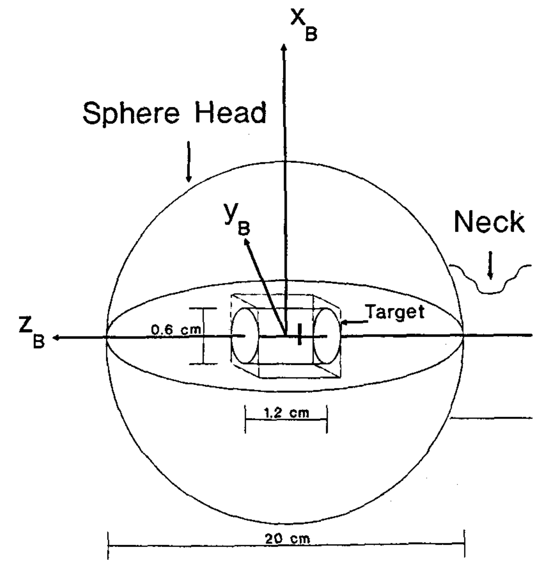


Fig. 2. The dimensions of the target and sphere head.

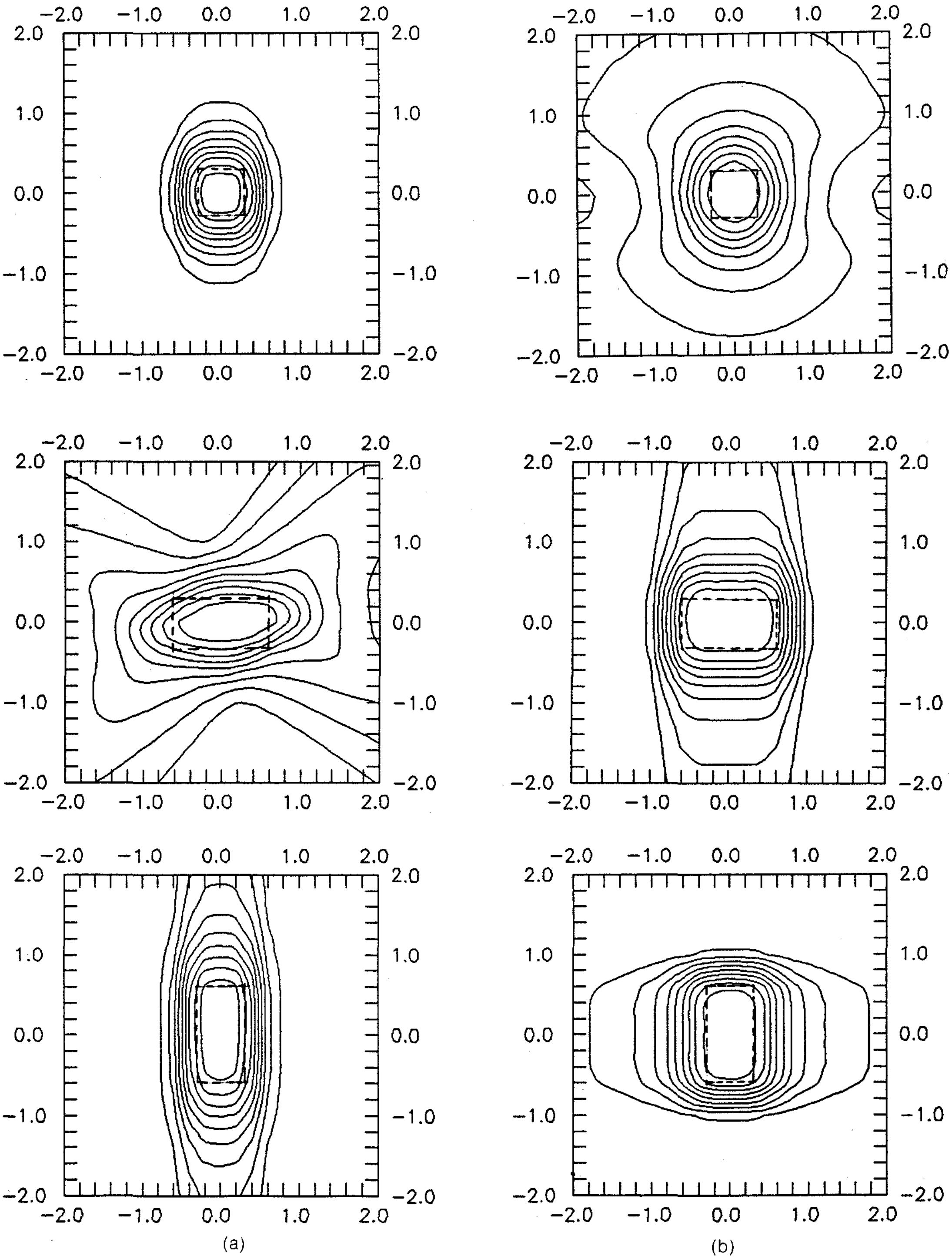
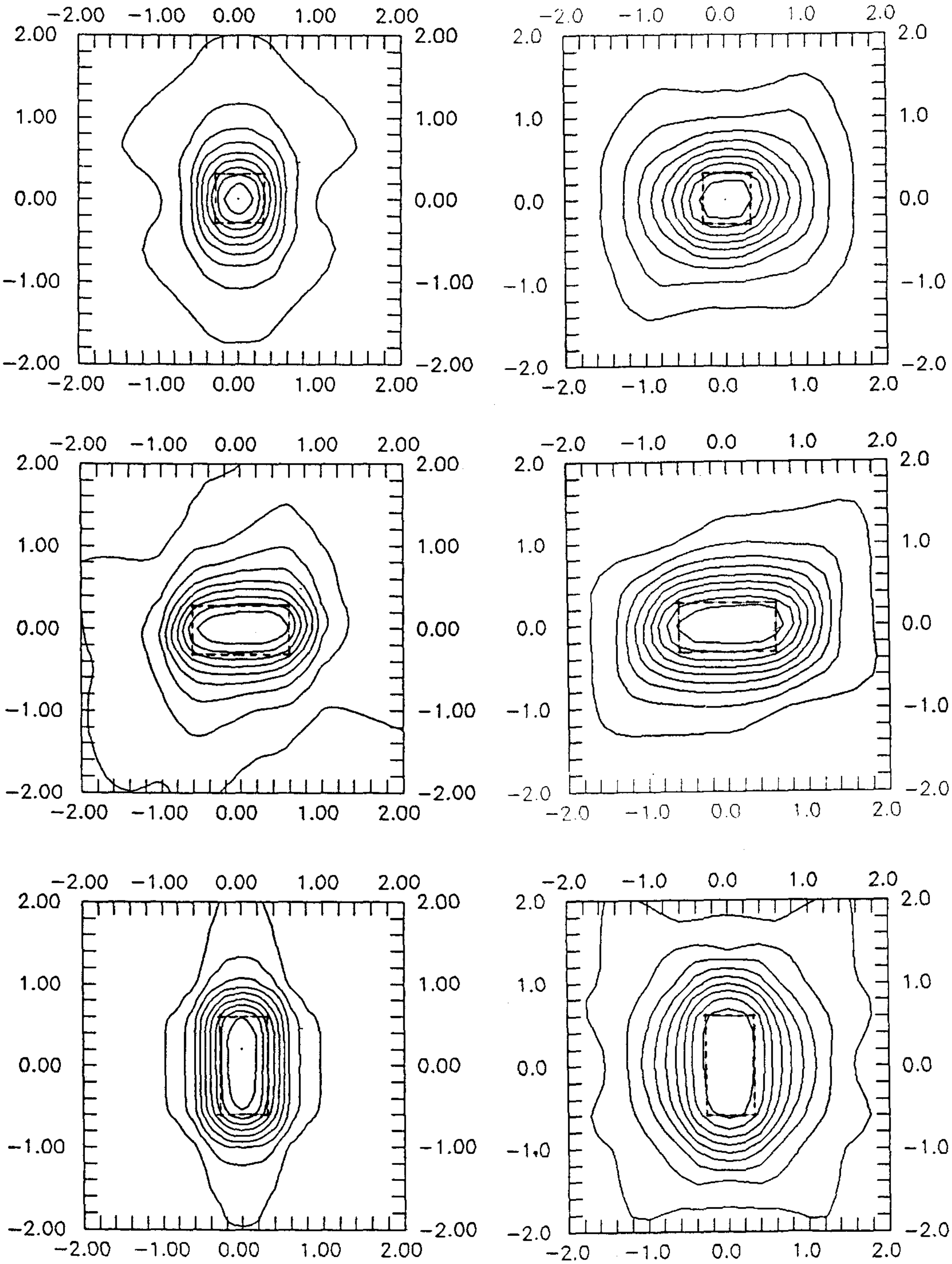


Fig. 3. Isodose curves in the three orthogonal planes (axial, sagittal, coronal) through the target point due to the field shaping technique using beam's eye view from one arc at either (a) table orientation 0° with gantry angle (−80° to 80°) or (b) left 90° with gantry angle (30° to 130°).



(a) (b)

Fig. 4. Isodose curves in the three orthogonal planes (axial, sagittal, coronal) through the target point due to the field shaping technique using beam's eye view. (a): two arcs at table orientation 0° and left 90° (b): four arcs at table orientation 0°, right 45°, left 45° and 90°.

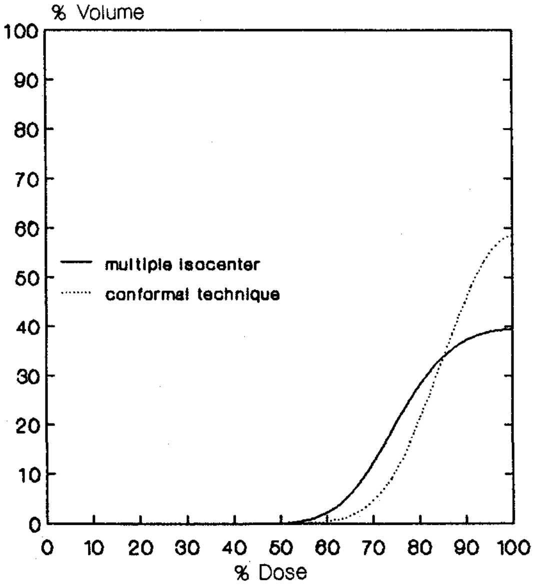


Fig. 5. Dose volume histogram for rectangular target ($1.2 \times 0.6 \times 0.6$ cm^3).

ed to achieve proper field matching. Fig. 5 shows a dose volume histogram for a rectangular target in two cases (4 arc field shaping and 2 multiple isocenter).

DISCUSSION

We discussed field shaping rtechnique to optimize dose distribution for arc-based radiosurgery. The multiple isocenters has been used as a suitable treatment technique for irregular target shapes. It was discussed extensively in previous paper[24]. However, the use of too many isocenters may not be desirable to shape the complicated target exactly, since it gives little benefit with much increased effort. A conformal therapy using beam's eye view was a better approach to shape the more complicated targets with a field shaping technique. Ideally, the optimal soultion to improving the radiosurgery technique with regard to matching the target volume and dose distribution is to develop a multileaf collimator which may be dynamically controlled to match the shape of the beam to the target volume as the beam rotates about the target. The use of a built-in rectangular collimator may be a possible method to improve the dose distribution for the radiosurgery technique, until a multileaf system is available for radiosurgery.

REFERENCES

1. **Colombo F, Benedetti A, Pozza F, et al:** External Stereotactic Irradiation by Linear Accelerator. Neurosurgery 16:154-160, 1985
2. **Hartmann GH, Schlegel W, Sturm V, et al:** Cerebral Radiation Surgery Using Moving Field Irradiation at a Linear Accelerator Facility. Int J Radiat Oncol Biol Phys 11:1185-1192, 1985
3. **Heiftz MD, Wexler M, Thompson R:** Single Beam Radiotherapy Knife; A Practical Theoretical Model. J Neurosurg 60:814-818, 1984
4. **Lutz W, Winston KR, Maleki N:** A System for Stereotactic Radiosurgery with a Linear Accelerator. Int J Radiat Oncol Biol Phys 14:373-381, 1988
5. **Pike B, Podgorsak EB, Peters TM, et al:** Dose Distributions in Dynamic Stereotactic Radiosurgery. Med Phys 14:780-789, 1987
6. **Friedman WA, Bova FJ:** The University of Florida Radiosurgery System. Surg Nuerol 32:334-342, 1989
7. **Flickinger JC, Lunsford LD, Wu A, et al:** Treatment Planning Gamma Knife Radiosurgery with Multiple Isocenters. Int J Radiat Oncol Biol Phys 18:1495-1501, 1990
8. **Flickinger JC, Maitz A, Kalend A, et al:** Treatment Volume Shaping with Selective Beam Blocking Using the Leksell Gamma Unit. Int J Radiat Oncol Biol Phys 19:783-789, 1990
9. **Bova FJ:** Radiation Physics. Neurosurgery Clinics of North America 1:909-931, 1990
10. **Kooy HM, Nedzi LA, Loeffler JS, et al:** Treatment Planning for Stereotactic Radiosurgery of Intracranial lesions. Int J Radiat Oncol Biol Phys 21:683-693, 1991
11. **Serago CF, Lewin AA, Houdek PV, et al:** Improved LINAC Dose Distribution for Radiosurgery with Elliptically Shaped Fields. Int J Radiat Oncol Biol Phys 21:1321-1325, 1991
12. **Leavitt DD, Gibbs FA, Heilbrun MP, et al:** Dynamic Field Shaping to Optimize Stereotactic Radiosurgery. Int J Radiat Oncol Biol Phys 21:1247-1255, 1991
13. **Pike GB, Podgorsak EB, Peters TM, et al:** Dose Distributions in Radiosurgery. Med Phys 17:296-304, 1990
14. **Serago CF, Houdek PV, Lewin AA, et al:** Stereotactic Radiosurgery: Dose-Volume Analysis of Linear Accelerator Techniques (Abstract). Radiology 173:362, 1989
15. **Friedman WA:** LINAC Radiosurgery. Neurosurgery Clinics of North America 1:991-1008, 1990
16. **Fraass BA, Mcshan DL, Weeds KL:** 3-D Treatment Planning: III. Complete Beam's Eye View Planning Capabilities. Proc. 9th Int. Conf. on the Use of

Computers in Radiotherapy 9:193, 1987
17. **Goitein M, Abrams M, Rowell D, et al:** Multi-Dimensional Treatment Planning: II. Beam's Eye View, Back Projection through CT Sections. Int J Radiat Oncol Biol Phys 9:789, 1983
18. **Purdy JA, Wong JW, Harms WB, et al:** Three Dimensional Radiation Treatment Planning System. Proc. 9th Int. Conf. on the Use of Computers in Radiotherapy, 9:277, 1987
19. **Chin LM, Sidden RL, Svensson GK, et al:** Progress in 3-D Treatment Planning for Photon Beam Therapy. Int J Radiat Oncol Biol Phys 11:2011, 1985
20. **Mohan R, Barest G, Brewster LJ, et al:** Three-Dimensional Radiation Treatment Planning System. Int J Radiat Oncol Biol Phys 15:481, 1988
21. **Houlard JP, Dutreix A:** 3D Display of Radiotherapy Treatment Plans. Proc. 8th Int. Conf. on the Use of Computers in Radiotherapy, 8:219, 1984
22. **Bauer-Kirpes B, Schlegel W, Boesecke R, et al:** Display of organs and Isodoses as Shaded 3-D Objects for 3-D Therapy Planning. Int J Radiat Oncol Biol Phys 13:135, 1987
23. **Reynolds RA, Sontag MR, Chen LS:** An Algorithm for Three-Dimensional Visualization of Radiation Therapy Beams. Med Phys 15:24, 1988
24. **Suh TS, Yoon SC, Shinn KS, et al:** Optimization of Dose Distribution for LINAC-based Radiosurgery with Multiple Isocenters, J Korean Soc Ther Radiol 9:351-359, 1991
25. **Suh TS:** New Techniques for Optimal Treatment Planning for LINAC-based Stereotactic Radiosurgery, J Korean Soc Ther Radiol 10:95-100, 1992
26. **Suh TS:** Optimization of Dose Distribution for the System of LINAC-baced Sterotactic Radiosurgery, Ph. D Dissertation, University of Florida, 1990

＝국문초록＝

선형가속기를 이용한 방사선 수술시 Dynamical Field Shaping에 의한 선량분포

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박 찬 일**·하 성 환**·강 위 생**

방사선 수술에 있어서 선량 형태를 변형시키기 위한 조사변수들의 선택은 중요한 문제이다. 선형가속기를 이용한 뇌정위적 방사선 수술은 통상 원형 조사면과 다중 arc를 이용하여 구형 형태의 선량을 얻는 방법을 이용하고 있다. 그러나, 병소가 임의의 형태인 경우 구형의 선량으로서는 병소 이외에 정상조직도 많은 선량이 가해지게 된다. 현재 병소형태의 선량을 얻기 위한 방법으로 multiple isocenters를 이용하거나, 각 arc에 달리 weights를 주는 방법을 사용하고 있다. 본 논문에서는 병소의 beam's eye view를 이용하여 조사 위치에서 조사면을 shaping하는 새로운 방법에 대하여 논의하고자 한다.

이러한 conformal 조사 방법은 병소와 정상조직의 가시적인 3차원 선량분포와 dose volume histogram의 분석 방법을 통하여 검증되었다. conformal 방법을 이용한 경우 multiple isocenter를 이용한 경우보다 적은 arc 수를 가지고도 상응하는 dose gradient와 더 나은 선량의 균질성을 얻을 수 있었다.