Optimization of Dose Distribution for LINAC-based Radiosurgery with Multiple Isocenters

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The current LINAC technique for radiosurgery utilizes a single isocenter approach with multiple noncoplanar arcs. This approach results in spherical dose distributions in the target. Many arteriovenous malformations and tumors suitable for radiosurgical treatment have non-spherical or irregular shapes. The basic approach presented in this paper is to use two or multiple isocenters with standard arcs to shape irregular target volumes through the use of multiple spherical targets.

Selection of reasonable irradiation parameters in the first stage is critical to the success of real-time optimization. A useful guideline for optimum isocenter separation and collimator size is developed to shape the target margin uniformly with an desired isodose surface for an elongated target. The implementation of multiple isocenters with three dimensional dose model and application of multiple isocenters approach to several cases are discussed.

Key Words: Stereotactic Radiosurgery, LINAC, Dose Distributions, Multiple Isocenters

INTRODUCTION

The aim of stereotactic 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 using LINAC were decribed in many literatures[1~6].

Radiosurgical treatment of the brain requires a detailed three-dimensional (3-D) treatment planning system, and intervening and surrounding tissues must be protected from unwanted irradiation while a high dose which conforms to the shape of the target is produced. The design of an optimal radiosurgery planning system which uses 3-D patient data and treatment parameters 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 beam parameters involved in treatment planning. Recently, many techniques have been developed and proposed to optimize dose distributions in radiosurgery[7~9].

Many arteriovenous malformations and tumors suitable for radiosurgical treatment have non-spherical or irregular shapes. Thus, single isocenter approach is not efficient technique, since dose shape is spherical with a single isocenter approach. The basic approach presented in this paper is to use two or multiple isocenters with standard arcs to shape irregular target volumes through the use of multiple spherical targets.

MATERIALS AND METHODS

Before we discuss the multiple isocenter approach of LINAC-based radiosurgery, we must present some information on dose modelling. First, we discuss the dose model for a fixed single beam. This is basic background for developing an efficient 3-D dose algorithm for multiple moving beams. The 3-D dose algorithm for multiple moving beams will be considered in the next. Finally, a brief discussion about multiple isocenters is given.

1. Dose Model for a Fixed Single Beam

An isocentric model for single circular treatment is given by[10]

$$D_m(C, STD, d, r) = D_{ref} \times ROF(C) \times TMR(w, d) \times (SAD/STD)^2 \times OAR(C, STD, d, r) \quad (1)$$

where

m=point of interest in a medium
C=collimator size defined at SAD
STD=source to target distance
w=field size at point of interest m expressed by

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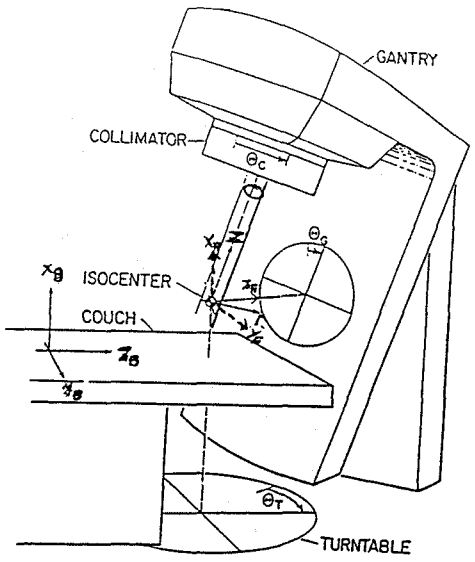

Fig. 1. Linear accelerator with the three coordinate systems. z_F, x_F and Z indicates axis of rotation of the gantry, turntable, and the collimator. These three axis intersect at the center of the target.

w=C (STD/SAD)
d=depth of point of interest m
r=off-axis distance
SAD=source to axis distance=100 cm
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_m, r=0)/D(C_{ref}, SSD=100, d_m, 0)
TMR=tissue maximum ratio defined by D(w d)/D(w, d_m)
OAR=Off-axis ratio defined by D(C, STD, d, r)/D (C, STD, d, r=0)

The measurement data for tissue-maximum-ratio (TMR) and offaxis-ratio (OAR) are the main function data for the dose model developed. These measurements are identified as basic beam data. Early work on basic beam data included two main parts. The first part was to determine the detector system for our small beam measurement. The second part was to formulate basic beam data from our limited mesasurements[11].

2. 3-D Dose Algorithm for Multiple Moving Beams

From the single isocentric dose model given by

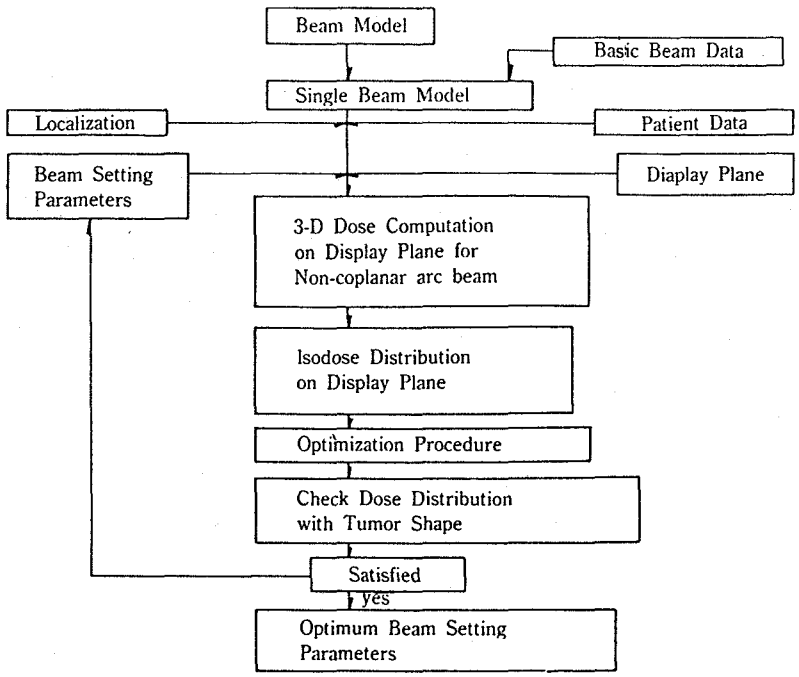

Fig. 2. The procedure for dose planning in stereotactic radiosurgery.

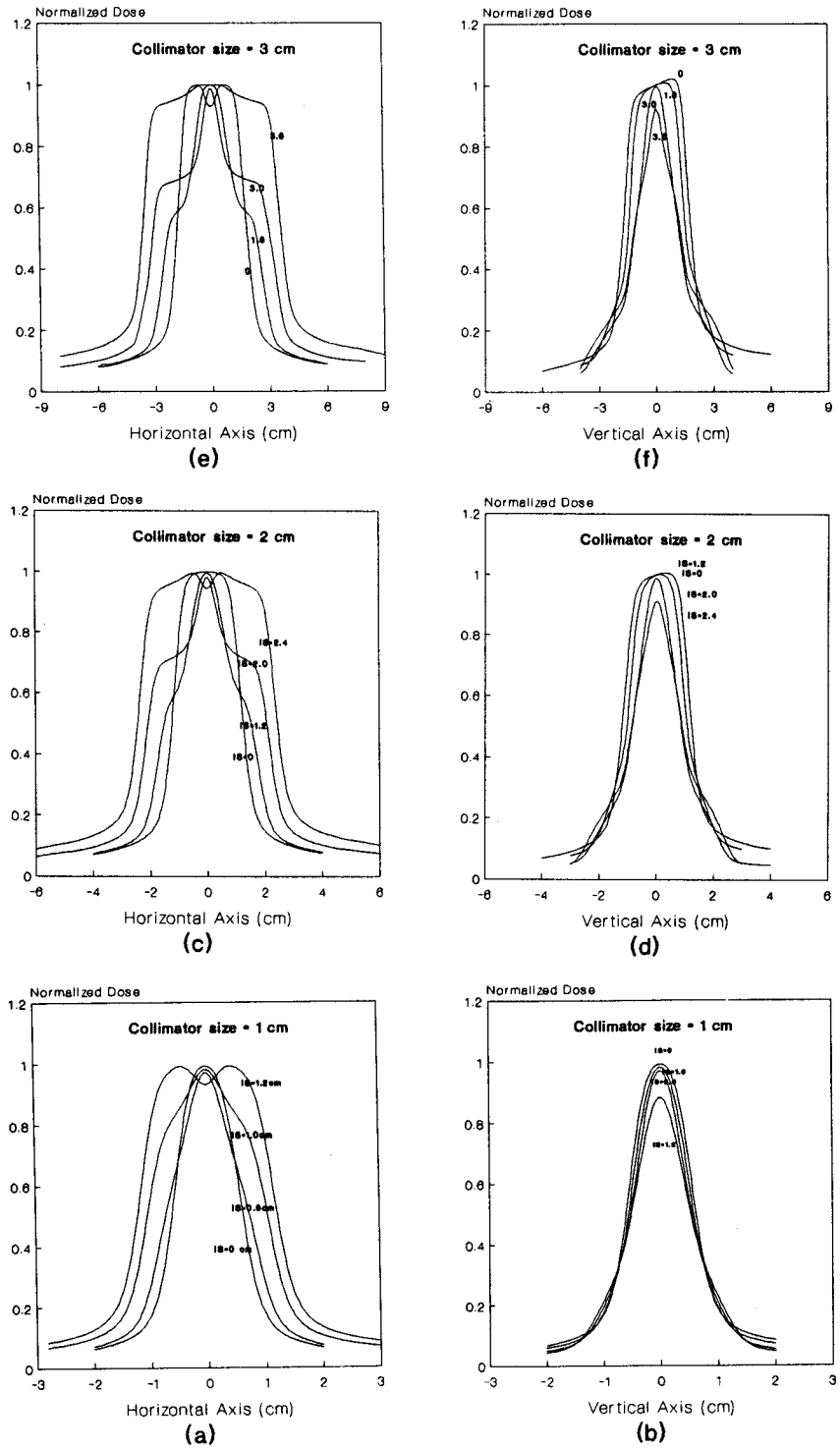

Fig. 3. Dose profoles through horizointal axis (a, c, e) and vertical axis (b, d, f) for three different collimator sizes and four different isocenter separation using two isocenters. The numbers shown represent the isocenter separation (IS) in cm. The relative dose is normalized at midpoint of two isocenter.

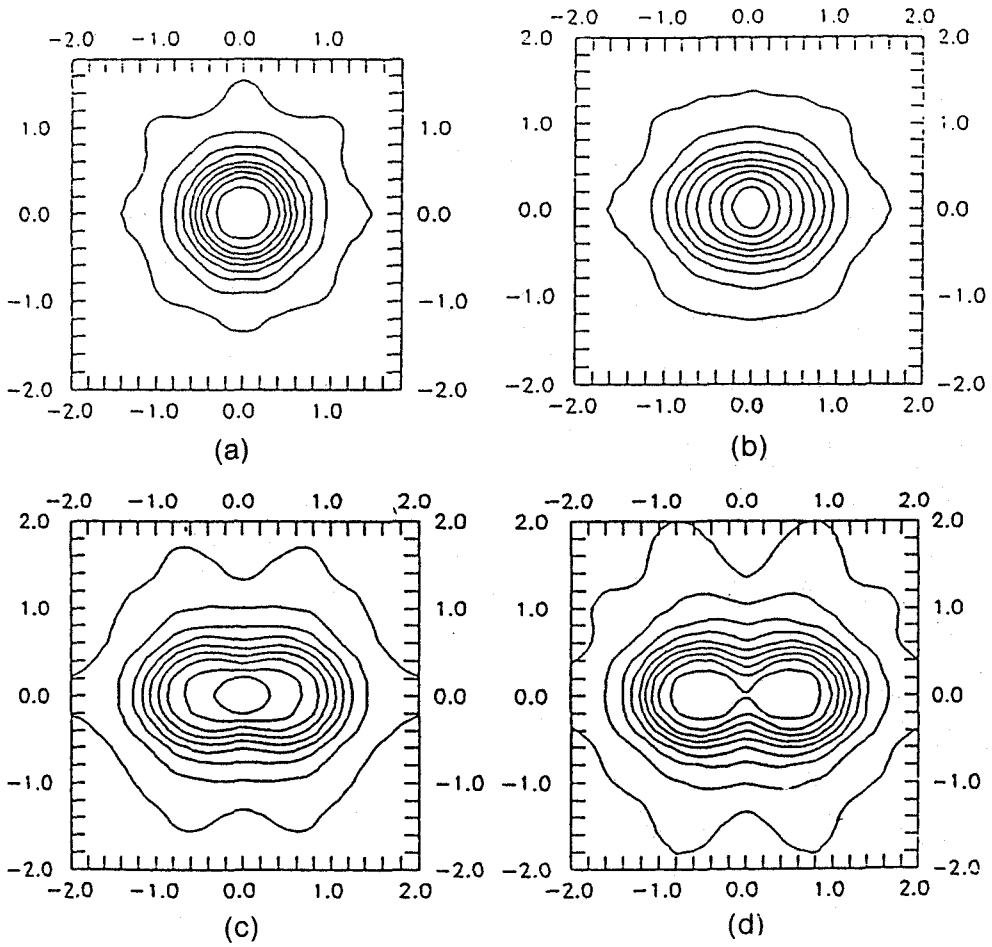

Fig. 4. Isodose distributions on the coronal plane with 1 cm collimator size for various isocenter separation: (a) 0 cm, (b) 0.4 cm, (c) 1 cm, (d) 1.2 cm. The isodose lines displayed are from 90 to 10 in 10 decrements and normalized by maximum.

Eq. (1), the calculation of the dose at each point of interest m requires the depth d, the off-axis distance r, the source to target distance STD, and the collimator size C with gantry and turntable orientation Θ_G, ϕ_T. From these parameters the field size w at each point is easily calculated by the relationship: w=C (STD/SAD). When we use different isocenter positions for different arcs, the depth d and off-axis distance r of each point on the dose grid for each increment of gantry rotation Θ_G in the algorithm are the only parameters which need to be derived from the patient contour and isocenter position l_j for each arc j.

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 method is based primarily on the definitions of the three-dimensional space. A more detailed discussion is shown in other literature[12,13].

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

$$D_t = \sum_T \sum_G D_m \qquad (2)$$

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 values are then obtained from the measured data

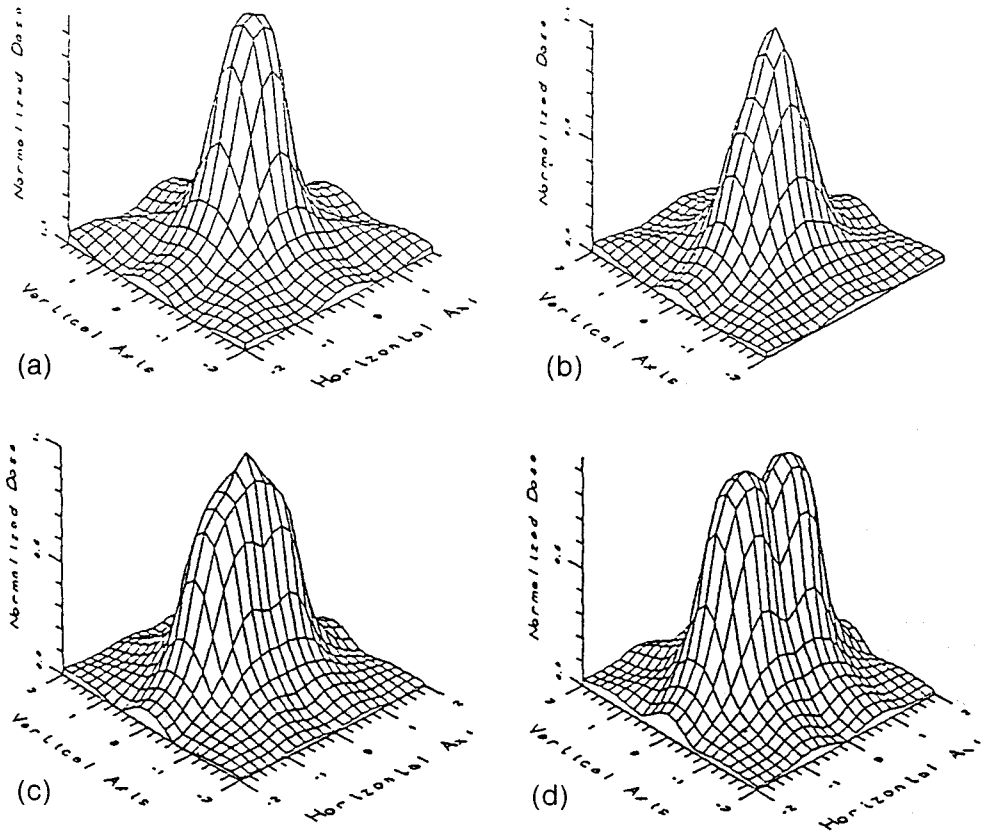

Fig. 5. 3-D dose profiles on the coronal planes for various isocenter separation in Fig, 4.

or fitting function developed. The procedure needed for dose planning in stereotactic radiosurgery is shown in Fig. 2

3. Multiple Isocenters Approach

A brief description of a multiple isocenter approach is given, and a useful guideline for optimum isocenter separation and collimator size is developed to shape the target margin uniformly with an desired isodose surface for an elongated target. The method is based on the relationship between an isodose shape and optimum variables. The current technique utilizes a single isocenter approach with multiple noncoplanar arcs. This approach results in spherical dose distributions in the target and dose fall-offs outside the target, which depend on the arrangement of the arc system. The method presented here is to use multiple isocenters with standard arcs to shape target volumes through the use of multiple spherical targets.

The test is based on the use of two isocenters in parallel for 1-D shape about an elongated target. In addition, more than two isocenters are used to shape 2-D or 3-D target shape with the proper arrangement. Dose distributions were inspected for different isocenter separations and collimator sizes. Four standard arcs (three 100° and one 180°) with equal arc spacing (45°, 270° 315°, and 0°turntable angle) were used for each isocenter. After checking the dose shape, including field uniformity and dose fall-off, the useful combinations of isocenter separations and collimator sizes were considered.

RESULTS

The dose distributions were generated by the 3-D dose model discussed in materials and methods. The application of multiple isocenters approach to several cases are discussed. Fig. 3 represent a series of two orthogonal dose profiles for three different collimator sizes and different

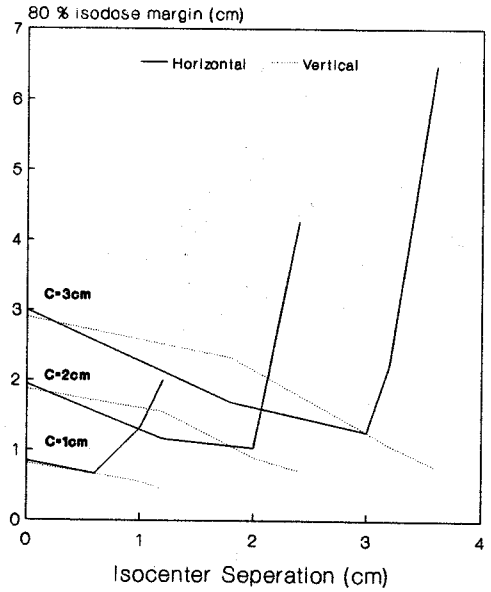

Fig. 6. Guidelines for two isocenters. The solid lines represent the longest margin (L), and shortest margin (S) of the elongated target, which can bve fitted to the 80% isodose surface.

isocenter separations with two isocenters: horizontal axes along two isocenters on the coronal plane; and vertical axes perpendicular to horizontal axes at the mid-point of two isocenters on the coronal plane. Fig. 4 represent isodose distributions on the coronal plane for different isocenter separations with 1 cm diameter collimator size.

The dose shapes are changed into spherical (a), elliptical (b), cylindrical (c), dumbbell shape (d) as isocenter separation varies. Fig. 5 show 3-D dose profiles on the same coronal plane. A reasonable optimization criteria for the target dose could be to fit the target margin within the 80% isodose surface in single isocenter approach, and 50 to 80% in multiple isocenter approach. When we use two isocenters in parallel, the isodose surface can be elongated-shape.

The elongated target shape can be approximated by a elliptical, a cylindrical or dumbbell shape with the longest and shortest margin. Fig. 6 represents longest (L) and shortest distances (S) of the target, which can be fitted to the 80% isodose surface for different isocenter separations and collimator sizes. Although other isodose lines can be used to fit the target volume according to the

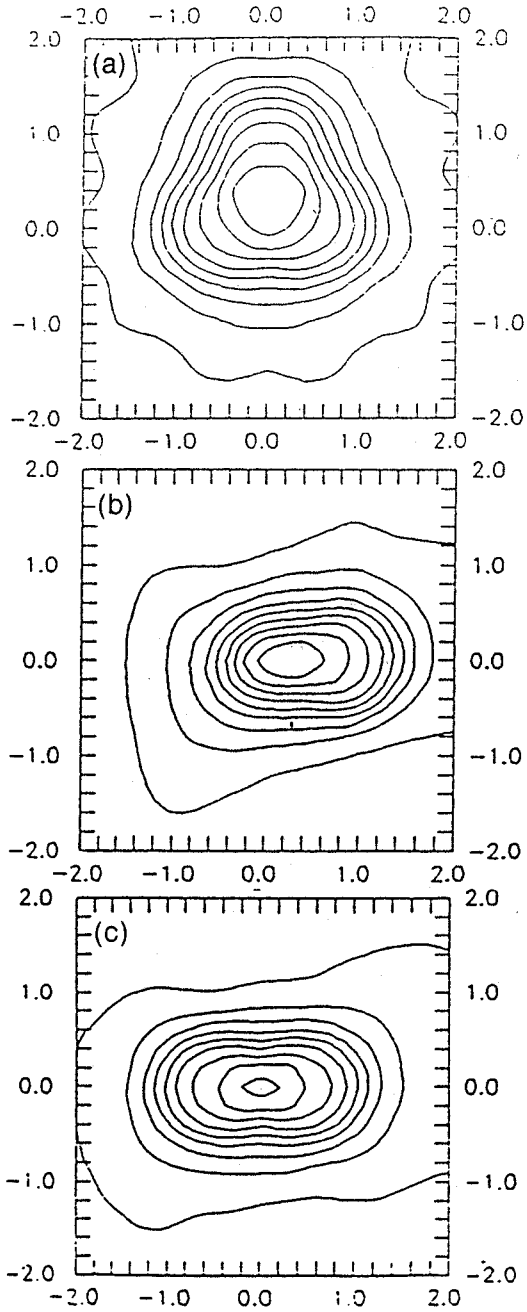

Fig. 7. Isodose distribution on the three orthogonal planes: coronal (A), sagittal (B), axial (C) using three isocenters in triangle geometry on the coronal plane with 1 cm collimator size and 1 cm isocenter separation. The isodose lines displayed are from 90 to 10 in decrement 10 and normalized by maximum.

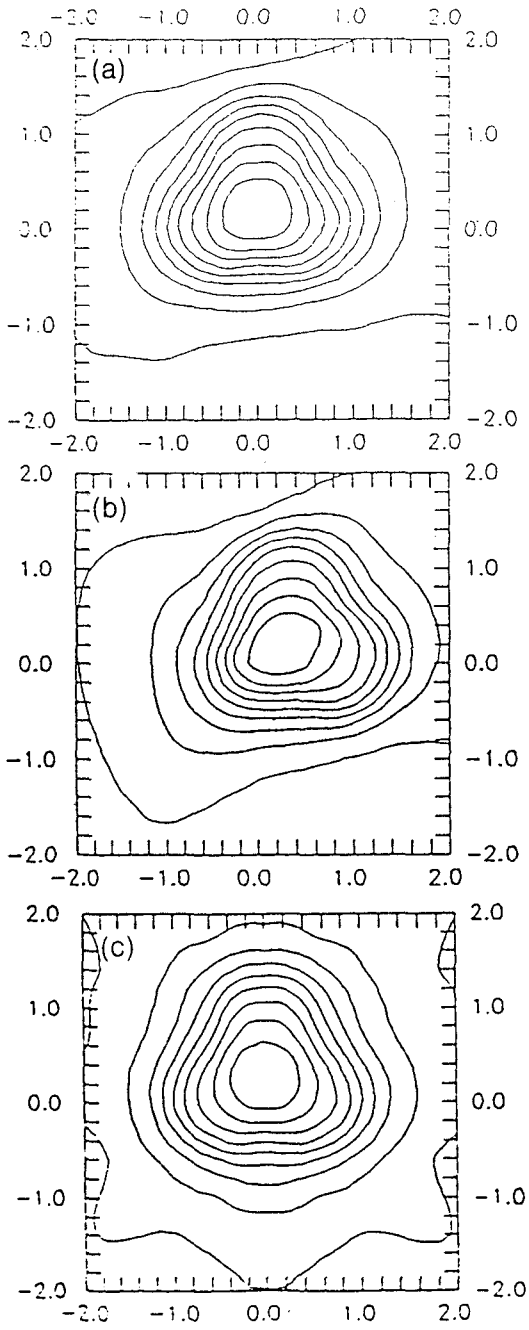

Fig. 8. Isodose distribution on the three orthogonal planes: axial (A), sagittal (B), coronal (C) using four isocenters in tetrahedra geometry with 1 cm collimator size and 1 cm isocenter separations. The isodose lines displayed are from 90 to 10 in decrement 10 and normalized by maximum.

shape of the dose, the guideline for 80% may give some basic idea to obtain the best target corresponding dose. These guidelines can be used to determine the isocenter positions and collimator sizes for the target of interest. For a more elongated target, we can add another isocenter to obtain the desired height and diameter. It is possible to use more than three isocenters in parallel, however there is no increased benefit if the isocenter separation is small.

Two potential studies are suggested for the use of multiple isocenters. One is to fit isodoses to the 2-D or 3-D shape of a target such as a thin plate or arbitrary target by constructing multiple isocenters geometrically on coplanar planes or in 3-D space. Fig. 7 represent dose distributions on three orthogonal planes, which forms a thin triangular plate isodose volume and gives uniform target dose with 1.0 cm isocenter separation and 1 cm diameter collimator. This isocenter separation configuration will be a basic unit to fit the 2-D shape of a target by arranging or adding isocenters. Fig. 8 represent dose distributions on the three orthogonal planes through four isocenters which form a pyramid geometry. This isocenter separation configuration will be a basic unit to fit the 3-D shape of a target by arranging or adding isocenters. However, it may not be desirable to develop guidelines for these asymmetric target shapes, since the benefit of using too many isocenters is small.

DISCUSSION

The experimental approach with multiple isocenters is a suitable treatment technique for elongated target shapes. Potential studies for shaping 2-D (thin plate) or 3-D (arbitrary) targets using multiple isocenters are expected. Another possible study is to utilize conformal therapy using beam's eye view and field shaping. The study of this technique is ongoing in many research centers. Possible solutions will be expected in near future.

The guidelines in Figs. 6 is useful in determining the optimum isocenter position and collimator size for elongated target shapes. Much more benefit is obtained from the multiple isocenter approach rather than the single isocenter approach especially, to fit the elongated target shape within an 80% isodose surface (Fig. 9a, b with c, d). Figure 9e, f represent isodose distributions on two orthogonal planes for two different isocenters and collimator sizes to fit a cone shaped target with

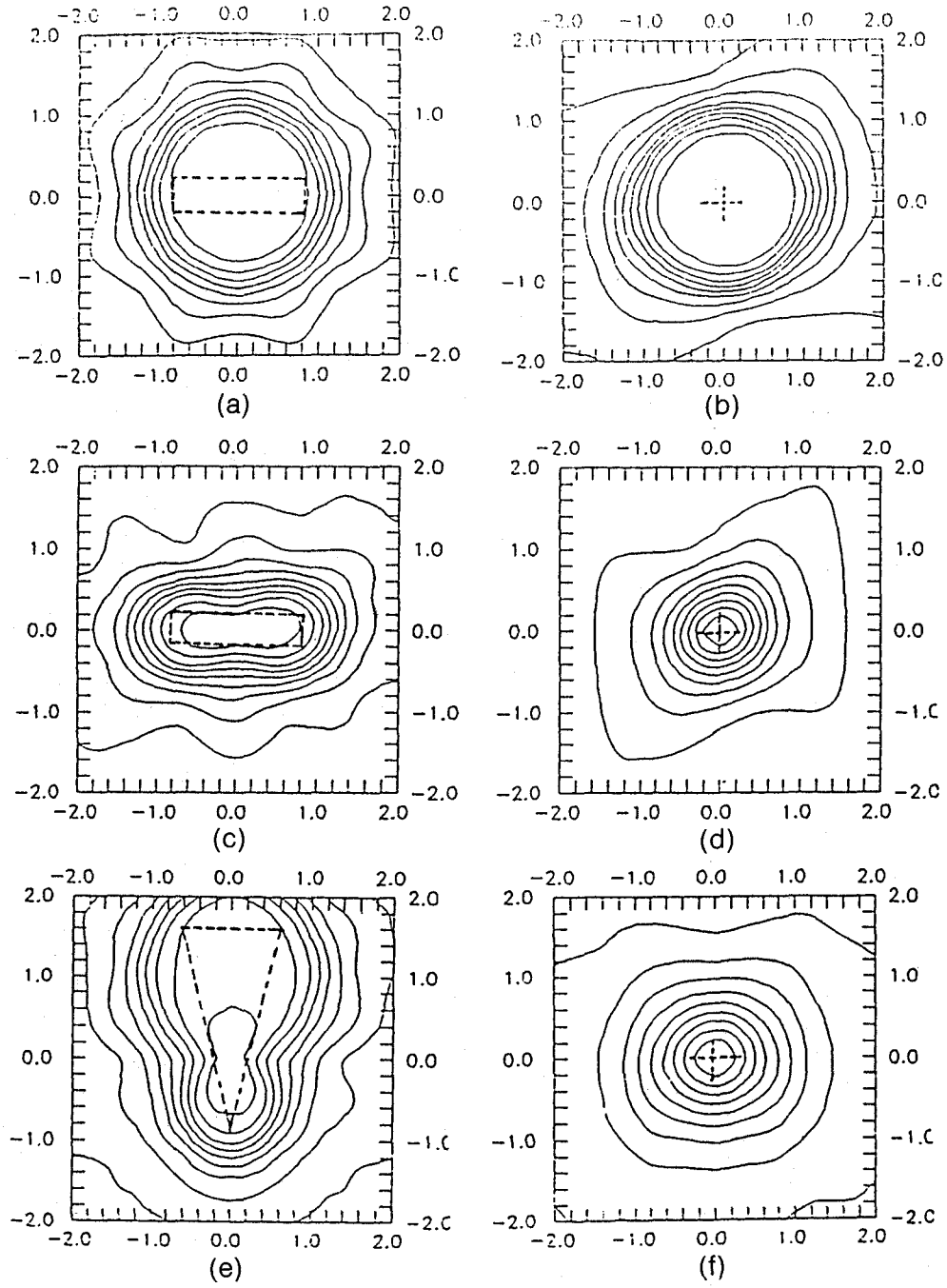

Fig. 9. Isodose distributions on two orthogonal planes for single isocenter technique (a, b) and two isocenters technique (c, d) with a cylindrical target (length=1.6 cm, diameter=0.4 cm) covered by 80% isodose surface. (e) and (f) represent isodose distribution on two orthogonal planes for two isocenters with two different collimator sizes. 80% isodose surface covered cone shaped target (length=1.6 cm, diameter=1.2 cm). The isodose lines displayed are from 90 to 10 in decrement 10 and normalized by maximum.

80% isodose surface.

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= 국문초록 =

LINAC 뇌정위적 방사선 수술시 Multiple Isocenters를 이용한 최적 선량분포 계획

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서태석 · 윤세철 · 신경섭 · 박용휘

LINAC 뇌정위적 방사선 수술은 주로 multiple noncoplanar arc를 이용한 single isocenter를 이용하고 있다. 이러한 방법에 의하면 구형선량 분포를 얻게 되는데, 뇌동정맥 기형이나 뇌종양의 경우 구형이 아닌 임의의 형태를 가진 경우도 많다. 본 논문에서는 임의의 병소형태에 대하여 multiple isocenters를 이용하여 병소모양과 같은 형태의 선량분포를 얻는 방법에 대하여 논하고져 한다.

적당한 조사변수들을 처음에 잘 선정하는 것은, 빠른 시간내에 최적선량 계획을 수행하는데 중요하다. 긴 병소모양에 대하여 같은 형태의 선량분포를 얻기 위한 isocenter 간격 및 조사면에 대한 guideline이 만들어졌다. 특히, 3차원 선량분포를 이용한 multiple isocenters의 응용에 대하여 논하여진다.