Rapid Optimization of Multiple Isocenters Using Computer Search for Linear Accelerator-based Stereotactic Radiosurgery

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= Abstract =

The purpose of this paper is to develop an efficient method for the quick determination of multiple isocenters plans to provide optimal dose distribution in sterotactic radiosurgery. A Spherical dose model was developed through the use of fit to the exact dose data calculated in a 18cm diameter of spherical head phantom. It computes dose quickly for each spherical part and is useful to estimate dose distribution for multiple isocenters. An automatic computer search algorithm was developed using the relationship between the isocenter move and the change of dose shape, and adapted with a spherical dose model to determine isocenter separation and collimator sizes quickly and automatically. A spherical dose model shows a comparable isodose distribution with exact dose data and permits rapid calculations of 3-D isodoses. the computer search can provide reasonable isocenter settings more quickly than trial and error types of plans, while producing steep dose gradient around target boundary. A spherical dose model can be used for the quick determination of the multiple isocenter plans with a computer automatic search. Our guideline is useful to determine the initial multiple isocenter plans.

Key Words : Stereotactic Radiosurgery, Multiple Isocenter, Dose Model, Optimization

INTRODUCTION

The use of LINAC-based stereotactic radiosurgery for small tumors and AVM of the brain was already reported in several institutes[1-6]. Since many targets have nonspherical or irregular shapes and three dimensional dose calculations included in dose optimization, it reguires lengthy computation time to determine the optimum isocenter separation and collimator sizes to shape the irregular target through the multiple isocenter approach by trial and error types of methods.

Recently, many techniques have been developed and proposed to optimize dose distributions in radiosurgery[7-9]. However, most methods are based on trial and error type of optimization using interactive modification of treatment using experimental test or graphic displays.

Another possible solution for 3-D treatment

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plan optimization is to utilize analytical optimization techniques with proper objective functions to represent the physical optimization criteria. The use of analytic formalism as an objective function for automatic optimization has been tried in radiation therapy. This effort, however, was limited to optimizing simple linear variables such as beam weights or treatment times, and reflected only two-dimensional considerations[10-13]. The automatic computer search was based on linear programming or quadratic programming including least square fit. LINAC-based radiosurgery uses many noncoplanar arcs and a 3-D evaluation technique. Accordingly many important nonlinear beam parameters and complex 3-D calculation procedures are included in the dose optimization. A more efficient search method is necessary to handle these kinds of multi-dimensional non-linear parameters. Furthermore, to accelerate the speed of calculation a fast dose computation model is more helpful for optimization procedure. The theoretical basis of this technique was fully discussed[14]. The aim of this work is to demonstrate a computer optimization technique and a fast dose model to find improved isocenter positions and collimator sizes quickly and automatically.

MATERIALS AND METHODS

1. Spherical Dose Model

From the modification of single isocentric dose model[15], the formula to express the dose at defined point for a single beam with gantry and table orientation was derived[16]. Using 18cm diameter sphere head model and 3D dose model developed[16], a study of the spatial dose distribution for multiple arcs was carried out. The dose distribution generated by the 3D dose model could be represented by a spherical dose model in a simple analytic form which is convenient and very efficient for calculating dose distribution iteratively in the optimization procedure. A spherical dose model was developed for standard four arcs about a single isocenter with equal arc spacing. The analytic form for standard four arcs with fixed single isocenter is given by

$$D_s = 1 - s_1 \exp[-s_2 \times (c/2 - r) - s_3 \times (c/2 - r)^2] \quad \text{for } r \le c/2 \quad (1)$$

$$= s_4 + (1 - s_1 - s_4) \exp[-s_5 \times (r - c/s)] \quad \text{for } r > c/2 \quad (2)$$

The s parameters are fitting parameters. The parameters obtained by non linear least square (NLLS) fit for the diameter sizes of collimators are given in Table 1. This form dose fits well with the collimator size routinely used in stereotactic radiosurgery. s_3 quadratic term needs to be added to give an improvement to field sizes smaller than 1.6cm can be used for that small field sizes. r is a radial distance from the

Table. 1. Parameters of Spherical Dose Model

Coll(cm)	S_1	S_2	S_4	S_5
1	0.320	7.430	0.020	2.520
2	0.232	7.009	0.032	1.606
3	0.257	9.575	0.036	1.071
all	0.249	7.019	0.029	1.927

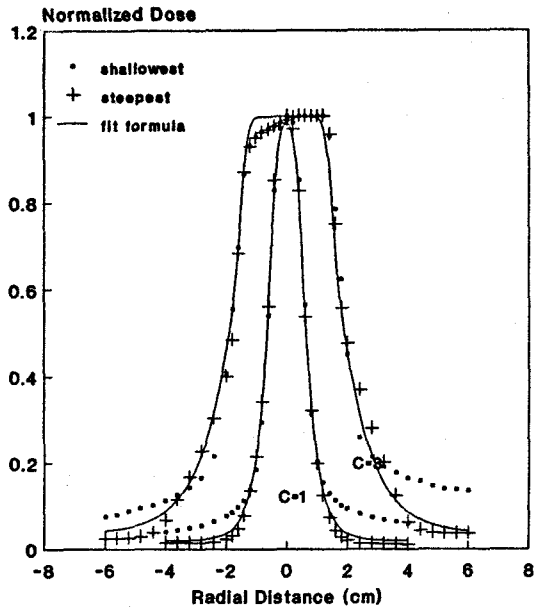

Fig. 1. Radial dose profiles with the analytic fits (solid curve) and exact dose data (data points) for standard four arc systems. The data points represent radial dose distributions for two different radial orientations: steepest and shallowest.

isocenter and C is the collimator diameter. The fits are shown by the curves in Fig. 1. The data points are radial dose distributions for different radial orientations, and are dertermined by the exact dose model.

Fig. 2 give montages of spatial contours of dose distribution from an exact (a, b), and a spherical dose model (c, d) on the coronal plane for two and three isocenters with standard four arcs for each isocenter. The programs reguired approximately less than 1 second using spherical dose model to calculate dose for standard four arcs on a $20\times20\times20$ matrix (8000 points) with 486/50 computer with floating point processor. The calculation speed of these approximate dose models are about 100times faster than the 3D dose model (80 sec). Thus, with the use of a spherical dose model optimum isocenter positions and collimator sizes can be found about 100 times faster than with the exact dose model.

2. Computer Optimization

Optimum irradiation parameters can be found automatically by using mathematical programming to minimize irradiation outside the target area while maximizing the target dose. An spherical dose model was used to simulate the 3D dose model and to find the optimum irradiation parameters quickly and automatically using computer-aided design (CAD) optimization. The objective function in radiosurgery can be either to maximize the dose gradient between the target boundaries and the surrounding normal structures or to minimize the dose to critical organs. In addition, the target dose and critical organ dose must be quaranteed by constraint conditions on the target and criticial organ. The side constraints that reguire a reasonable range of varibales such as upper or lower limits should also be considered.

In the following examples, we consider arbi-

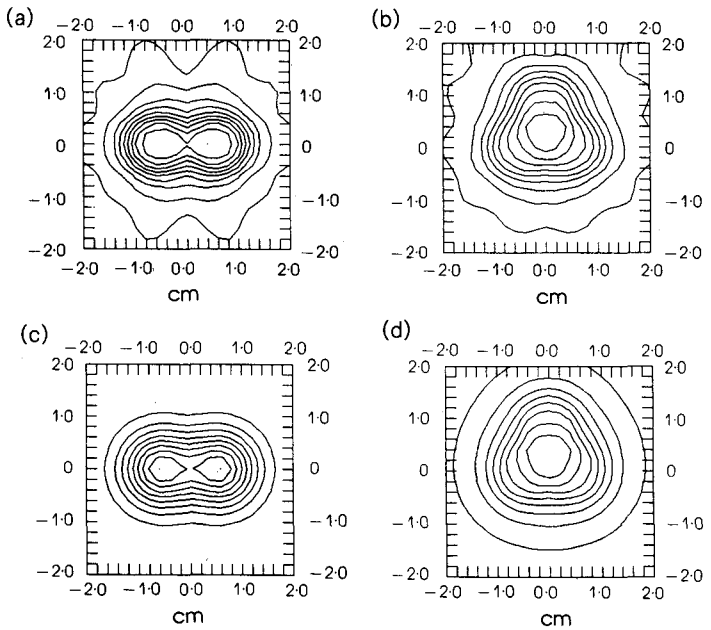

Fig. 2. Isodose distributions on the planes through two different isocenters positions (a) and three isocenter positions (b) with standard four arcs for each isocenter, calculated by 3D dose model and two (c) and three isocenters (d) calculated by spherical dose model. The isodose lines displayed are from 90 to 10 or 20% in 10 decrements and normalized by maximum. 10% lines are not shown in Fig. 4c and d.

trary 3-D patient data which can be represented by a series of transverse sectional contours along the patient. This set of 3-D patient data contains target cross-sections and relevant normal tissue outlines or critical points.

CASE : The target is assumed to be an elongated cone shape (height=2.4cm, diameter=1.2cm) which is represented by a series of contours from four slices of equal thickness (Fig. 3).

The aim in this example is to determine improved isocenter positions and collimator sizes with the standard four arcs such that the objective function:

$$\sum (D_t(X)-D_n(X))^2 \quad (3)$$

is maximized subject to constraint conditions described in Egs. (4-5).

$$D^l \le D_t(X) \le D^u \quad (4)$$

$$X^l \le X \le X^u \quad (5)$$

where

X=Disign vector(isocenter coordinates and collimator size)

$D_t(X)$=Dose to the target boundary at position t

$D_n(X)$=Dose to the surrounding normal structure at position n

D^l, D^u=Lower and upper limits of the desired dose

X^l, X^u=Lower and upper limits of the design variables

A more general category of algorithms, referred to as nonlinear programming (NLP), is needed to solve this general optimization prob-

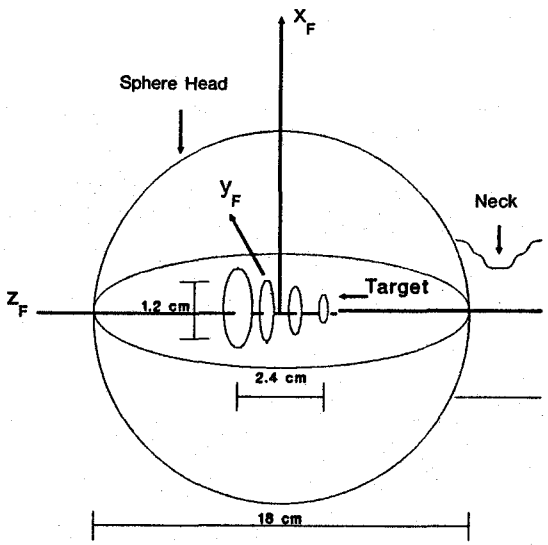

Fig. 3. The dimensions of the targets in sphere head for the example case.

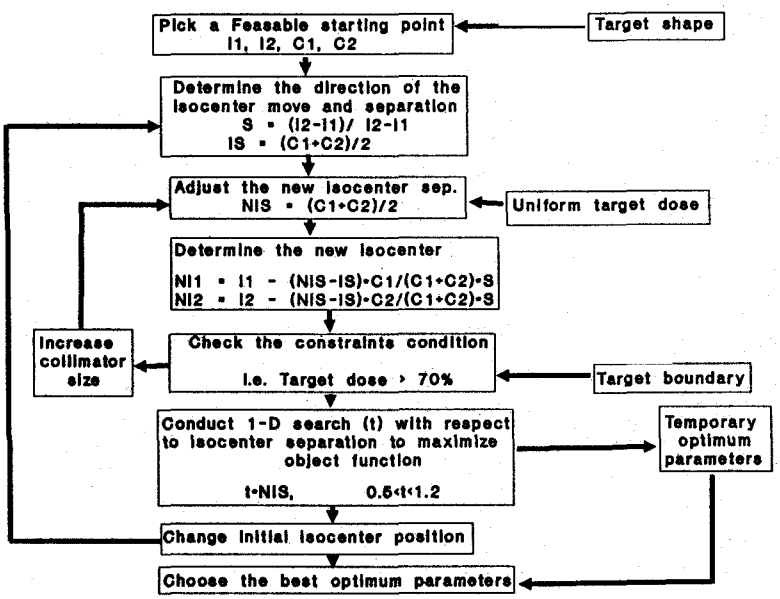

Fig. 4. Computer search algorithm to determine optimum isocenter positions and collimator sizes for two isocenter approach.

lem[17]. A rule-based search algorithm was developed using well developed idea from experimental dose experience to determine optimum isocenter positions and collimator sizes (Fig. 4).

RESULTS

The starting and final design values for the example are given in Table 2. Fig. 5 show montages of spatial contours of dose distribution of 6 MVX-ray on the coronal plane and axial plane from the 3D dose model with the initial and final search value for the example. Fig. 5a and b are the initial starting plan shown in the coronal and axial plane, while Fig. 5c and d show the same planes following optimization. The labels and levels of each plane shown in Fig. 5 were based on the geometry shown in Fig. 3. The dose distributions with the final search values for the example give a better distribution than that obtained with the starting design values. The isodose shapes in Fig. 5c and d show a comparable result with those obtained from the spherical dose model.

Table 2. Optimum Variable Values

Variable	Initial(cm)	final(cm)
x_1	0.1	0.13
y_1	−0.1	−0.13
z_1	−0.4	−0.58
c_1	1.0	1.0
x_2	−0.1	−0.17
y_2	0.2	0.17
z_2	0.5	1.06
c_2	1.0	2.4

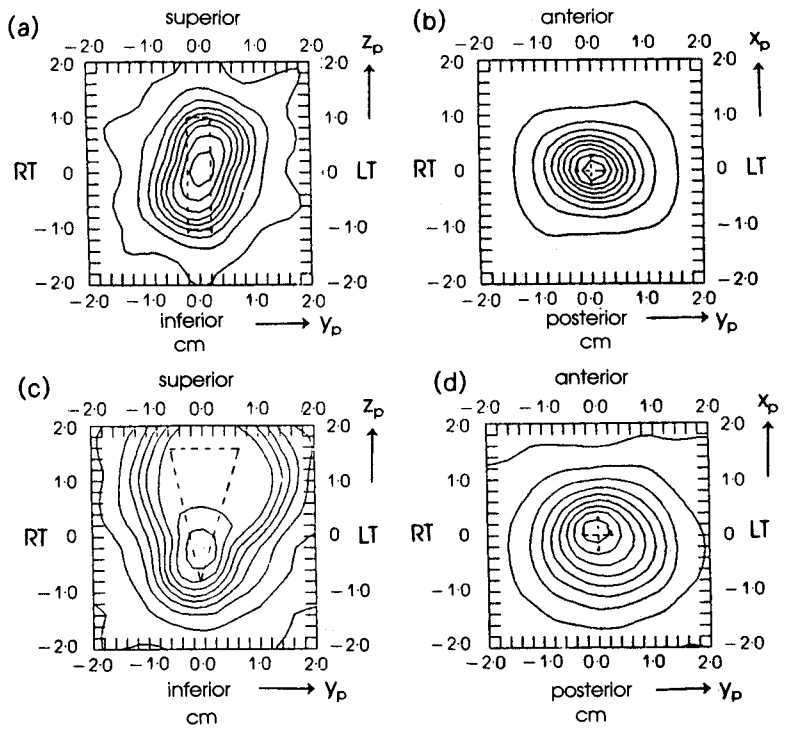

Fig. 5. Isodose distributions on the coronal (a, c) and axial planes (b, d): initial (a, b) and final search value (c, d) using 3D dose model. The isocenter positions and collimator sizes were searched by the rule-based search algorithm. The isodose lines displayed are from 90 to 10% in decrement 10 and normalized by maximum.

DISCUSSIONS

In the current work we use a spherical dose model to simulate the exact dose distribution for standard four arc system, and optimize dose distribution through the use of computer search optimization. Since the dose distribution from the simple dose model is similar to that from the exact dose model, we conclude that computer optimization with a spherical dose model is an efficient and practical alternative to the trial and error method with an exact dose model.

Since the dose distributions are not changed much as target position or head contour vary, it may not be necessary to correct for different target positions and head contours. Potential studies for shaping 2-D or 3-D such as thin plane or arbitrary targets using multiple isocenters are expected in the future. However, the use of too many isocenters is not desirable to shape the complicated target exactly, since it gives little benefit with much increased effort. A conformal therapy could be a better approach to shape the more complicated targets.

The present methods are based on physical optimization criteria. The statistical approach to optimization including the dose-response model, tumor control probabilities, and normal tissue complication probabilities could be appropriately applied to radiosurgery optimization if all major factors or statistical information can be accounted for.

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국문초록 =

Multiple isocenter를 이용한 뇌정위적 방사선 수술시 컴퓨터 자동 추적 방법에 의한 고속의 선량 최적화

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서태석 • 박찬일** • 하성환** • 윤세철 • 김문찬* • 박용휘 • 신경섭

본 연구의 목적은 뇌정위적 방사선수술시 최적 선량분포를 얻기 위하여 빠른 multiple isocenter 계획을 효과적으로 수행할 수 있는 방법을 개발하는 데 있다. 18cm 직경의 구형 머리 팬톰과 정확한 선량 알고리듬을 이용하여 선량값을 계산한 뒤 fitting 기술을 이용하여 빠른 구형선량 모델을 개발하였다. 구형선량 모델을 이용하여 single isocenter에 대한 선량값은 합산에 의하여 쉽게 얻어졌다. Isocenter들간의 이동에 따른 선량분포의 변화를 이용하여 컴퓨터 자동추적 방법이 개발되었으며, isocenter 간격 및 collimator 크기가 빠른 시간내에 결정될 수 있었다. 구형선량모델은 beam data에 의한 선량데이타와 같은 선량분포를 나타냈으며 고속으로 삼차원 선량계산을 가능하게 하였다. 컴퓨터 자동추적 방법은 지금까지의 시행착오적 방법에 비해 보다 빠르게 최적 isocenter setting을 제공할 수 있었다.

구형선량모델 및 컴퓨터 자동추적방법은 multiple isocenter를 이용한 수술 계획시 최적선량 분포를 보다 빨리 얻을 수 있었다.