New Techniques for Optimal Treatment Planning for LINAC-based Stereotactic Radiosurgery

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Since LINAC-based stereotactic radiosurgery uses multiple noncoplanar arcs, three-dimensional dose evaluation and many beam parameters, a lengthy computation time is required to optimize even the simplest case by a trial and error. The basic approach presented in this paper is to show promising methods using an experimental optimization and an analytic optimization. The purpose of this paper is not to describe the detailed methods, but introduce briefly, proceeding research done currently or in near future. A more detailed description will be shown in ongoing published papers.

Experimental optimization is based on two approaches. One is shaping the target volumes through the use of multiple isocenters determined from dose experience and testing. The other method is conformal therapy using a beam's eye view technique and field shaping. The analytic approach is to adapt computer-aided design optimization in finding optimum irradiation parameters automatically.

Key Words: Stereotactic radiosurgery, Optimization, Conformal therapy, Multiple isocenters, LINAC

INTRODUCTION

The main goal in radiosurgery is to deliver a level of radiation dose to the target volume sufficient to eradicate the tumor while at the same time minimizing the complications induced by unnecessary radiation throughout the irradiated volumes and particularly to critical normal structures. Stereotactic radiosurgery requeires the optimization of dose distribution since high dose is focussed on or near the target. The concept and mechanical design of stereotactic radiosurgery using LINAC were described in many literatures[1,6].

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 irradiation paramenters involved in treatment planning. It requires not only a fast 3-D dose calculation algorithm, but also a way of quickly evaluating the relative merits of various plans. Recently, many techniques have been developed and proposed to optimize dose distributions in radiosurgery[7~9].

In comparing optimum variables, multiple isocenter positions ad collimator size and shape are most useful for changing the shape and margin of the high isodose surface, which makes it possible to shape the field to the target by varying these paramenters. Since arc variables such as length, direction, and weighting do not change much about a high isodose shape within a restricted range of arc variables with fixed isocenter positions and collimator sizes, it is possible to change the low isodose shape encomassing critical organs while maintaining the shape of the target dose.

The current technique utilizes treating multiple isocenters or weighting various beams or arcs to change treatment volume shape. However, most of 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 plan optimization is to utilize analytical optimization techniques with proper objective functions to represent the physical optimization criteria.

MATERIALS AND METHODS

1. Multiple Isocenter Approach

In this section, a brief description of a multiple isocenter approach is given, and a sueful rule for optimum isocenter separation and collimator size was developed to shape the target margin uniformly with an 80% 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 or three isocenters in parallel for 1-D shape of an elongated target. 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 uniforimity and dose falloff, the useful combinations of isocenter separations and collimator sizes were considered. A more detailed description is shown in Suh et., al[10].

2. Confomation Therapy

In designing radiation treatment plans, the objective is to conform and confine the high dose regions to the shape of the target as closely as possible. It is necessary to shape the aperture of the beam and compensate for surface irregularities, internal inhomogeneities, and target shape to achieve desirable dose distibutions. Since radiosurgery uses a small beam to treat homogeneous brain tissues, the compensation problem is not important. Our concern in this section is field shaping using the beam's eye view projection technique and adjusting of the collimator (rotation and size). Instead of using irregular field shapes such as multileaf collimators, the variation of a rectangular field, which seems to be more practical in radiosurgery, is considered in this section.

For practival 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[11~15]. The patient structures which have been defined can be made into wire frame[16] or shaded 3-D views[17]. In this work, BEV is accomplished by displaying a wire-frame diagram of contours outlinig the patients'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 (i.e. reference frame) into beam coordinates (i.e. Collimator system). Next, beam coordinates were transformed into screen coordinates. The first is called viewing transformation, and second, perspective transformation.

3. Analytical Optimization

The puropse of this approach is to find optimum parameters automatically by using mathematical programming to minimize irradiation outside the target area while maintaining the target dose.

A computer-aided design (CAD) optimization is any use of an algorithmic approach to optimizing a dose distribution using a quantitative evaluation of the optimality of a treatment plan. In this category of optimization methods, one expresses the optimization criteria as some mathematical function of the relationship of the calculated dose distribution to the optimization criteria is known as the objective function.

The optimization criteria for the objective function in radiosurgery can be either to minimize the dose to critical organs or to maximize the dose gradient between the target boundaries and the normal structures near the target. In addition, the target shape dose must be guaranteed by constraint conditions on the target. The side constraints that require a reasonable range of variables (upper or lower limits) should also be considered.

The method to find optimum parameters is based on three steps. the first step is to find the isocenter position and collimator size with which the high dose region shapes well the target while minimizing the dose to the normal structure around target volume, or maximizing dose grdient between target boundary and normal structure. The second step is to find optimum arc parameters with which dose to critical organs or normal structures can be further minimized by varying arc spacing or arc weighting while maintaining target dose. The third step is to adjust optimum parameters obtained from the previous two steps by examining the dose distribution using exact dose model.

RESULTS

We discussed two main approaches and methods brifly to optimize dose distribution for stereotactic radiosurgery. The implementation of computer-aided design optimization with experimental optimization and it's application is discussed to illustrate the method and the results.

1. Multiple Isocenters

The guidelines in Fig. 6 in Suh et al.[10] is useful in determining the optimum isocenter position and collimator size for elongated target shapes, and

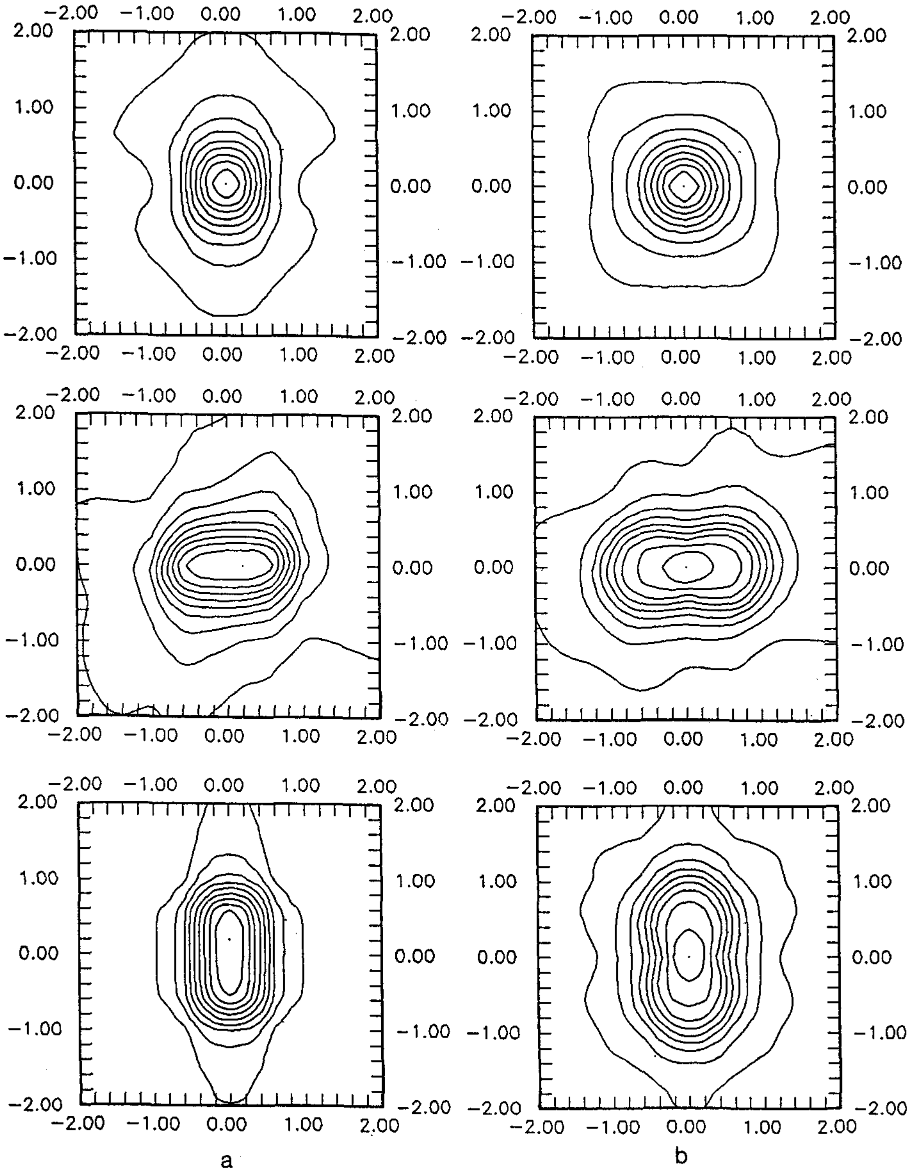

Fig. 1. Isodose curves on the three orthogonal planes (axial, sagittal, coronal) through the trarget point due to (a) conformal therapy using beam's eye view form two arcs and (b) multiple isocenter technique using twp standard-four arcs sysyem. Both 80% isodose surfaces covered the same margine of the elongated solid rectangular targets. The isodose lines displayed are from 10 to 90 in icrement 10 and normalized by the maximum.

much more benefit is obtained from the multiple isocenter approach rather than the single isocenter approach to fit the elongated target shape (e.g. within an 80% isodose surface, compare Fig. 9a, b with c,d in Suh et al. [10]).

2. Conformation Therapy

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[18].

However, the use of that algoritnm is more complicated and is not necessary for our study purpose. Using wire frame model, the program was written in BASIC language to display the beam's eye view for any structure.

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 minimizing 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. Another way to determine the arc position is to utilize dose volume histograms[19] or a volume matrix[20] through the information obtained from beam's eye view. A dose volume histogram, though less graphic than the isodose plots, can provide a complete summary of the entire 3-D dose matrix relative to the irradiated and unirradiated volume of the patient. This is especially helpful when evaluating how much of a normal organ is receiving an amount of dose. It is invaluable when several plans have to be evaluated and compared. 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. The outline of the aperture should conform to the shape of the target visible from the direction of incidence and provide adequate margins.

In practical cases, it is convenient to automatically specify the shape of the aperture enclosing

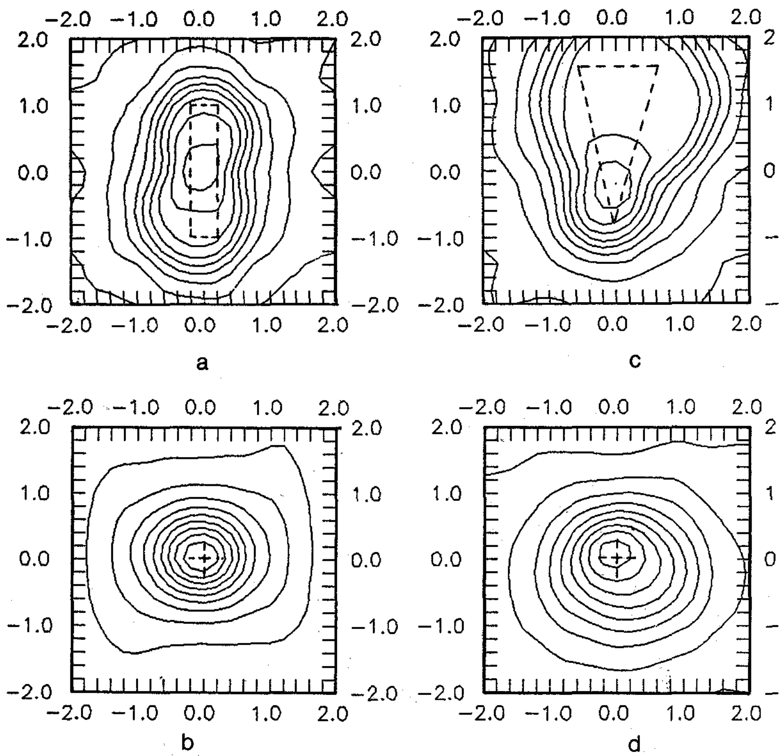

Fig. 2. Isodose distributions on the plane along two isocenters (a, c) and on the vertical plane (b, d) from a exact 3-d dose model with the optimum isocenter positions and collimator sizes searced by the rule-based search algorithms. The 70% isodose surfaces cover both elongated cylindrical (a, b) and cone (c, d) shape target. The isodose lines displayed are from 90 to 10 and normalized by maximum.

the target region. This is especially important for moving beam treatments using multi-leaf colliators. In this study, a rectangular collimator is used to fit the target margin instead of multi-leaf collimator, since the use of the rectangular collimator is easy, less time consuming, provides a simpler dose model, and quite accurate for a small target.

Figure 1 compares the treatment of a rectangular solid target with either two spherical isocenters or conformal therapy. Using only two arcs, the conformal dosimetry provides better dose gradient and superior dose homogeneity within the target[21].

3. Analytical Optimization

In the present work, the objective function is slected to minimize the weighted dose to the critical organs defined at different positions, or to maximize the dose gradient between target boundary and normal structure around target. We can now write our nonlinear constrained optimization problem mathematically.

The values obtained from the computer algorithm represent useful results. The initial variables were unreasonably assigned to undercover the target volume from the desired isodose surface (e. g. 50 to 70%). The final optimum isocenter positions and collimator sizes were searched to sufficiently cover the target volume within the desired isodose surface while maximizing the dose gradient between target region and surrounding normal structures. The number of iterations depend on the accuracy desired at the cost of time consumed.

Figure 2 show montages of spatial contours of dose distribution on the plane along two isocenters and on the vertical plane for cylindrical or cone shape target from a exact 3-D dose calculation and the optimum isocenters and collimator sizes searched by the rule-based search algorithm developed[21,22].

DISCUSSION

We discussed two approaches to optimize dose distribution for arc-based radiosurgery. 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 are expected in the future. 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 might be a better approach to shape the more complicated targets with an computer-aided design optimization in a future study.

We may consider the possibility of using computer-aided dsign optimization to find all the optimum parameters using rule-based or step search method. However, the use of too many variables is not efficient and may be ill-conditioned with the CAD optimization technique. The most important and difficult problem is how to find efficient optimization criteria and that of specifying the optimization criteria in the form of simple mathematical formalisms. It may be desirable to develop a few stadard plans to use as starting points and then search for an optimal result by varying some paramenters using multiple steps. The CAD optimizsation technique should be initiated on an expert system that will interface between the treatment planner and the three-dimensional treatment planning system

Our two approaches are based on physical optimization criteria other than complicated biologic optimization criteria. The statistical approach to optimization including the dose-response model, tumor control probabilities, and normal tissue complication probabilities may be appropriately applied to radioasurgery optimization if all major factors or statistical information can be accounted for. At the simplest level, the physical optimization criteria might be good to implement CAD optimization techniques, and could be used until all the biologic information are obtained. The slection coriteria and the cost of the function evaluation for the objective function and constraints are very important to the success of the computer analytic optimization.

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= 국문초록 =

LINAC 뇌정의적 방사선 수술시 새로운 최적 선량분포계획 시스템의 개발

가톨릭대학교 의과대학 방사선과학교실

서 태 석

LINAC 뇌정위적 방사선 수술은 multiple noncoplanar arc, 3 차원 선량 계산 및 많은 조사 변수들이 사용되기 때문에 간단한 경우에도 최적 선량분포를 얻기 위해서는 많은 시간이 요구된다. 본 논문에서는 실험적 방법과 분석적 방법을 통한 유용한 방법을 제시하기 위한 것으로서, 보다 자세한 방법 및 내용은 앞으로의 발표 논문에서 다루게 된다.

실험적 방법으로 2 가지 방법에의하면, 첫번째 방법은 multiple isocenter를 이용하는 것이고, 두번째 방법은 beam's eye view와 field shaping을 이용한 conformal therapy이다. 분석적 방법은 최적 조사조건을 찾기 위하여 computer-aided design optimization 방법을 이용하는 것이다.