A Study for Optimal Dose Planning in Stereotactic Radiosurgery

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Introduction

Stereotactic radiosurgery is a technique for obliterating intracranial tumors which are inaccessible or unsuitable for open surgical techniques, using tgihtly collimated beams of ionoizing radiation. 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. At present, there are three types of radiation beam that can be used for radiosurgery : focused beams obtained from specially dsigned units incorporating several hundred cobalt sources (the Gamma Knife) (Larsson et al., 1974 ; Dahlin & Sarby, 1975 ; Leksell, 1983) : heavy charged particle beams (protons, deuterons, helium ions, etc.) obtained from cyclotrons or synchrocyclotrons (Lyman & Howard, 1977 : Lyman et al., 1986) : and x-rays obtained from medium energy (4 to 10 MV) isocentrically mounted linear accelerator (LINAC) (Heiftz et al., 1984 : Clolombo et al., 1985 : Hartmann et al., 1985 : Houdek et al., 1985 : Pike et al., 1987 : Lutz et al., 1988 : Friedman & Bova, 1989). LINAC-based stereotactic radiosurgery is a less expensive alternative to the two proven radiosurgical techniques. The LINAC method is based on the combination of multiple isocentric arc irradiation with small fields centered in the stereotactic target. This optimized the dose falloff outside the target volume.

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 lack of 3-D information about target volumes and anatomic structures, and also by the many beam parameters involved in treatment planning.

With the availability of computed tomography (CT) and magnetic resonance (MR) imaging devices, the ability to visualize anatomic structures has been greatly enhanced. Many new tools have been developed and evaluated which permit the generation of 3-D displays of these structures, the accurate specification of beam direction and size, the display of dose distribution in three dimensions, and the evaluation of treatments for optimization. these improvements, however, have also added to the complexity of evaluating a given plan. The full 3-D extent of the tumor, the neighboring anatomy, their relationship to the planned radiation fields, and the resulting dose distribution must all be considered.

The use of graphic displays to present the information obtained from improved 3-D planning can be helpful in acquiring an overall impression of the adequacy of a particular plan. However, 3-D planning uses a large volume of patient data and many beam parameters, which may vary with the treatment. Furthermore, since 3-D calculations take a very long time, interactive modification of treatment using graphic displays may not be practical. Another alternative to complex 3-D optimized treatment is to use an analytical method of handling treatment plans quantitatively. Sufficient information on biologic dose response, tumor control probability, and normal structure complication rate is needed to quantify optimal treatments. Since no detailed information about biologic optimization is avilable at present, the evaluation method is based on physically optimizing dose distribution.

A possible solution for 3-D treatment plan optimizaiton is to utilize computer-aided design optimizaiton techniques with proper objective functuions to represent the physical optimizaiton criteria. The use of analytic formalism as an objective function for automatic optimization has been tried with little clinical success and is still being studied. This effort, however, was limited to optimizing simple linear variables such as beam weights or treatment times, and reflected only two-dimensional considerations. 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. Although the most difficult problem is that of specifying the optimization criteria, the full use of 3-D treatment planning for radiosurgery may not be possible without the use of both visual and computer-adided design optimization.

The aim of this work is to investigate the feasibility of planning optimal dose distributions for LINAC-based stereotactic radiosurgery.

DISCUSSION

In order to investigate the possible solution associated with a comprehensive 3-D optimization in stereotactic radiosurgery, we discuss 3-D factors (patient data, beam setting parameters, optimum variables, optimization programming) in the following.

Patient Data

The final set of patient data is represented by a series of transverse sectional contours along the patient. This set of 3-D patient data contains external contours, target cross-sections, and relevant normal tissue outlines.

One difficulty in obtaining an optimal dose distribution is due to different patient head geometries and target positions. Another problem originates from the difficulty of outlining the 3-D solid shape of the target and critical organs. It is inconvenient to find the optimum parameters for each patient condition every time. A better approach is to use a general simplified patient model which can simulate accurately the real head shape or target shape without any significant difference between the simplified model and real patient geometry.

For example, a spherical or eliptical head model with a centered tarqet position can be assumed for the experimental optimization study, since it is geometrical simple, and represents a useful result with a RANDO head phantom. The dose shape is not much changed except in an extreme case (near the surface) as the target position varies. Therefore, useful information such as the isodose shape, or target margin, obtained from this reference model can be used as a guideline for an individual patient model.

The next problem is to identify a 3-D target shape and the critical organs. For simplicity, the target shape and critical organs are approximated by ideal geometries (e. g. cylindrical, spherical, cone, etc.), which sufficiently cover and simulate their physical shapes. The critical organs may be represented by a few discrete points.

This approximation technique can simplify the optimization problem while saving time, and can be used to develop a reference system to prepare standard guidelines. The method yields good results which can then be tailored to the individual case.

Optimum Variables

After defining the target volume and other structures, treatment planning involves selection of beam parameters that reduce the dose to the normal tissues while providing adequate target coverage. It is possible to use all the beam parmeters as the optimum variables ; however, most recent optimization methods use the most sensitive beam parameters as the optimum variables to obtain favorable results economically. Many noncoplanar arcs are used for stereotactic radiosurgery. Accordingly, many beam parameters (e. g. the position of isocenter, collimator size or shape, arc spacing, and the length and weight for each arc) are included in dose optimization. The problems are how to reduce the variables systematically and choose the optimum variables for the particular situation. Tests were done to find the effects of optimum variables on spatial dose distribution with noncoplanar arcs. The followings are some interesting points obtained from the tests :

(1) The shapes of high isodose surfaces were almost spherical with a single fixed isocenter, even with a change in the position of arc and weighting.

(2) The isocenter separation and collimator size with multiple isocenters or collimator shaping were sensitive variables in changing the high isodose shape.

(3) The shape of the beam profile or dose gradient was dependent on the isocenter separation and collimator size.

(4) Different arc weighting for each isocenter shifted all the isodose lines toward the more weighted isocenter.

(5) The shape of low isodose lines changed with a change in arc direction and weighting.

(6) The shape of high isodose lines did not change significantly with a change in patient contour and target position.

The tests stimulated ideas about the proper use of optimum parameters. In order to obtain the corresponding target dose, isocenter position and collimator size must be the active optimum variables. As an alternative, changing the collimator shape could be an effective

parameter in obtaining the desired target dose shape. Arc variables could also be useful optimum variables to minimize dose to the surrounding normal tissues after a uniform dose to the target volume is obtained, since those variables change low isodose lines without changing high isodose lines.

3-D Dose Calculational Model

After selection of beam parameters, dose distributions are calculated using the exact geometry of the patient and beam configurations. The 3-D dose algorithm is required to calculate doses at any point in the patient for any specified gantry angle, turntable angle, collimator angle and collimator size. 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.

The use of the exact dose model in optimization is not efficient, especially when we utilize mathematical optimization programming. A faster and more efficient dose calculation algorithm is required for the optimization to simulate the exact dose model. This finds the optimum parameters much faster when using computer-aided design optimization.

Optimization Criteria

An essential goal of radiosurgery is to reach the optimum dose distribution within the target volume and surrounding healthy tissue. The most important subject is optimization criteria for the optimal dose distribution. Criteria for optimal external beam radiation therapy can be separated into two stages : clinical optimization and physical optimization. Optimal treatment planning at clincal stages requires a knowledge of the relative response of tumor and normal tissues to irradiation in terms of dosage and fractionation. Physical optimization consists of the development of a treatment plan which will produce a preferred dose distribution. Our concern here is physical optimization, since it is difficult to obtain necessary biologic response information on the single fraction treatments used in radiosurgery at present.

Defining optimization criteria in a mathematical form and determining the relative importance of different criteria are the most serious obstacles to performing automated optimization. Much of physical optimization is the specification of maximum and minimum dose to the target and maximum dose to normal structures at risk. Table 1 is a list of some of the quantitative parameters that have been used to evaluate physical dose distributions.

Guidelines for Optimum Parameters

Many variables are used in radiosurgery. It is very important to obtain an optimal dose distribution within a reasonable time. Selection of reasonble optimum variables in the first stage is critical to the success of real time optimization in both visual and computer-aided design optimization.

The pre-study for the selection of optimum variables must be analyzed to find the relationship between dose distribution and optimum variables. This information must be stored so

that it can be used to determine the optimized parameters, such as isocenter separation or collimator size, to shape the dose distribution to the target. Furthermore, these guidelines are useful in determining the initial values for the computer-aided design optimization.

Table 1 Quantitative Evaluation of Physical Dose Assessment

- Target volume shape
- 80 or 90% dose volume
- Degree of overlap between volumes, i. e., target volume vs. 90% isodose volume
- Maximum dose, minimum dose, mean dose in target·
- Dose gradient
- Dose volume histogram
- Treatment volume
- Integral dose
- Therapeutic ratio, i. e., target volume dose over treatment volume dose

The Optimization with Constraints Problem

The main limitations in planning are tolerance doses of neighboring tissues and critical organs as well as the tolerance dose of the normal connective tissue within the tumor region. Most earlier optimization methods were based on least square fitting to minimize the variance of dose distributions within the applied target volume, subject to constraining doses at nearby critical structures.

Radiosurgeons may be more interested in minimizing dose to the critical organ with constraining points for the desired dose to the target, since it is always possible to deliver a lethal dose to the tumor, and a large amount of dose is delivered to the brain within a short time. An additional constraint is the limit on variables, which must be specified with reason after consideration of mechanical limitations or other parameters.

Optimization with Nonlinear Programming

Some optimization techniques, such as linear or quadratic programming, have been applied to deal with specific classes of optimization with constraints problems in radiation therapy. However, all of these optimization attempts have incorporated a fairly limited set of linear variables such as beam weights and dose rates because of lengthy recalculation time and the difficulty of dealing with nonlinear variables. Most of the variables used in radiosurgery are nonlinear parameters such as isocenter position, field size, and arc position, which are very important factors in modifying dose distributions to fit the target shape while avoiding dose to the critical organ. A more general category of algorithms referred to as nonlinear programming must be consideared for the solution of the optimization problem in LINAC-based radiosurgery.

Since nonlinear programming shows some disadvantage in time required to find the optimum parameters, and it is sometimes difficult to find the global optimum, using too many variables is not efficient. However, nonlinear programming used with a good estimate of initial

variables and a simple objective function could be a very powerful technique in the search for optimum variables. Therefore, the fast 3-D dose algorithm with a proper optimization criteria, which makes the objective function simple, is an important factor. The proper selection of optimum variables which change isodose shape is also important factor.

SUMMARY

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 article 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 normal 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 prerequisite for treatment plan optimization. It must cover 3-D methods for representing the patient, the dose distributions, and beam settings.

The major problems and possible modelings about 3-D factors and optimization technique were discussed to simplify and solve the problems associatied with 3-D optimization, with relative ease
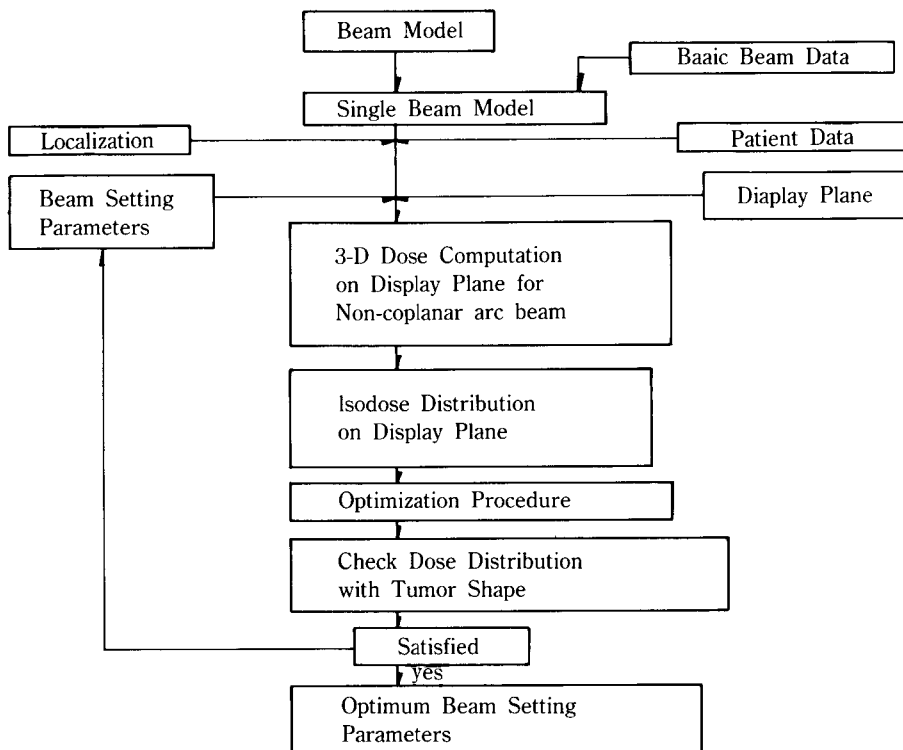
Figure 1. The procedure for optimal dose planning in stereotactic radiosurgery.

and efficiency. These modification can simplify the optimization problem while saving time, and can be used to develop reference dose planning system to prepare standard guideline for the selection of optimum beam parameters, such as the target position, collimator size, arc spacing, the variation in arc length and weight. The method yields good results which can then be simulated and tailored to the individual case. The procedure needed for dose planning in stereotactic radiosurgery is shown in figure 1.

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