Clinical Experience in Conformal Stereotactic Radiotherapy of Irregularly Shaped Intracranial Tumors

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Purpose: The dosimetric advantages of multiple non-coplanar stationary fields for stereotactic radiotherapy or radiosurgery (SRT/S) are well known. However, this technique is not widely used due to the logistical problems associated with producing and testing customized collimators. We report our experience of SRT/S using multiple non-coplanar stationary fields (conformal SRT/S).

Materials and Methods: Between August 1997 and February 2002, we performed frameless SRT/S in 63 patients. We chose conformal SRT/S when the tumor was of a very irregular shape or larger than 4 cm. We obtained three pieces of information: 1) the couch translations required to bring the target point to the isocenter, 2) the distance between the stereotaxic markers in the CT study, and the distance between the markers determined from orthogonal beam films, taken in the anterior-posterior and lateral directions, and 3) the rotational movement of the head position between the CT study and actual treatment position. We evaluated two kinds of data: 1) the precision of the isocenter setup, and 2) the reproducibility of the head position in the a) translational and b) rotational components.

Results: Twenty-six of the 63 patients receiving stereotactic treatment received conformal SRT/S. The precision of the isocenter setup for the conformal SRT/S was $x=0.03\pm0.26$ mm, $y=0.19\pm0.25$ mm and $z=0.20\pm0.27$ mm. The reproducibilities of the head position with the conformal SRT/S were 0.5 mm and less than 1°, for the translational and rotational components, in any plane.

Conclusion: We were able to apply conformal stereotactic irradiation, which has a dosimetric advantage, to irregularly shaped intracranial tumors, with precision and reproducibility of head position for the isocenter setup nearly equivalent to that of frame-based SRS or multiple-arc SRT/S. (Cancer Research and Treatment 2003; 35:69-74)

Key Words: Intracranial tumors, Conformal stereotactic radiotherapy

INTRODUCTION

Stereotactic radiosurgery (SRS) is a one-day, non-invasive, outpatient procedure that delivers a high dose of radiation to a small intracranial target, while minimizing the dose to the surrounding normal tissue. Using arc based linac SRS, or a Gamma-knife unit, spherical isodose distributions are produced sufficient to treat a benign disease, such as trigeminal neuralgia or arteriovenous malformation (AVM).

Malignant tumors invade into the surrounding normal tissue and are usually irregular in shape. If SRS, having spherical isodose distributions, is applied to a malignant disease, a considerable portion of surrounding normal tissue will inevitably receive an unnecessarily high radiation dose (Fig. 1A). As the tumor shapes become more irregular, this phenomenon is more prominent. Linac radiosurgery, with multiple non-coplanar stationary fields, has a dosimetric advantage compared with that of multiple arcs SRS for irregularly shaped tumors (Fig. 1B) (1). However, to implement this method, more time is required to produce the plan, and fabricate and test the collimators. We applied implanted fiducials in a radiosurgery system, and performed conformal stereotactic radiotherapy/surgery (SRT/S). We report our experiences of conformal SRT/S using multiple non-coplanar stationary fields.

MATERIALS AND METHODS

Between August 1997 and February 2002, we performed frameless SRT/S in 63 patients, with various brain tumors.
Fig. 1. (A) The spherical isodose distributions applied to SRS for malignant disease, showing considerable portion of surrounding normal tissue receiving unnecessary high radiation dose. (B) The isodose distribution with multiple non-coplanar stationary fields showing a dosimetric advantage relative to multiple arcs SRS in irregularly shaped tumors.

Fig. 2. The determination of a stereotactic coordinates in the skull of a patient in the image study processs. (A) marker 1 coordinates, (B) marker 2 coordinates, (C) marker 3 coordinates, (D) Target coordinates.

Twenty-six patients of the 63 received conformal, instead of multiple arcs, SRT/S.

1) Imaging study

To define the stereotaxy, three gold markers, 2.0 mm in diameter, were implanted in the cranium. The location of the markers was not critical, but two were generally placed on the left and right temporal sides of the skull, with the third in the mid-anterior hairline region. The patient was immobilized in the standard head holder provided with the CT scanner. There was no requirement to fix a particular head position as the target would be localized with respect to the gold markers.
After verifying the gold markers in the Anterior-Posterior and lateral scout views, a series of image scans of the patient was started to define the marker coordinates (Fig. 2). A 1mm slice thickness was used in order to obtain high spatial resolution.

An intravenous contrast media was injected, at a dose of 200 cm³, to identify the tumor region. Target volume slices were acquired with a 1mm slice thickness and 3 mm spacing. The upper and lower general anatomy series were acquired at a 1mm thickness and 10mm spacing.

The CT study was reviewed to ensure the patient’s immobilization during scanning, and the coordinates of each marker identified. The image matrix size and field of view (FOV) were 512 by 512 and 25×25 cm², respectively

2) Simulation

Frameless SRT entailed establishing the relationship between the marker coordinates in the treatment machine and the CT coordinate systems; accordingly the treatment position was defined at the simulation session, with a marker fitted in the small field collimator of the radiotherapy machine, a Clinac 2100C/D (Varian, Palo Alto, CA) (Fig. 3). After immobilization was achieved, with a thermoplastic mask and back support, a cassette holder was attached to the linac table for the anterior-posterior and lateral beam films. The cooperation of the patient was of the utmost importance in this procedure, and we found it advantageous to make the patient as comfortable as possible to promote immobilization. A small-field SRT collimator was attached into the wedge slot of the machine. Index marks, defining the axis of the radiotherapy machine, were built into the collimator assembly. The radiation field size was set at 30×30 cm².

After the beam films had been produced, the implanted marker coordinates were defined by digitization of the beam films between the anterior-posterior and lateral directions (Fig. 4). A micropositioner was attached to the cassette holder, and set to the zero position on each of its three axes. A pointer on a floor stand was then aligned to the micropositioner. Following this, the couch translation movements, required to bring the target point to the isocenter, were adjusted into the micropositioner and the couch carefully moved to bring the pointer on the micropositioner back into alignment with the pointer on the floor stand.

3) Conformal SRT/S

The CT data was imported to a treatment planning computer, and the surface area and volume of the target computed. We calculated an irregularity factor, which was the ratio of the surface area of the target, to that of the surface area of a sphere having the same volume as the target. A target with an irregularity factor less than 1.2 was judged sufficiently spherical to use multiple arcs SRT/S, if the target was more than 1.3 it was treated better with conformal SRT/S. However, multiple arcs SRT/S was used for small targets less than 10mm in size. The following rules were generally applied in developing a conformal SRT/S plan. 1) Use a minimum of six fields. 2) Separate each field as widely as possible over the head. 3) Do

Fig. 3. The setup of a patient in the process of simulation.

Fig. 4. The verification of a stereotaxy in the skull of a patient in the simulation session using two orthogonal port films with a cassette holder attached linac table. (A) Anterior-posterior direction, (B) Lateral direction.
not oppose fields which would decrease the dose gradient at the target edge. 4) Minimize the path through any critical structures. The angulation of beams in an oblique treatment plane was useful for this purpose (2). 5) Apertures with a 3mm margin within a beam's-eye-view (BEV) projection of the target produce a dose distribution where the 90% isodose shell is about 1mm from the target.

BEV plots of the fields were produced with a magnification factor 1.45, which was used to produce Styrofoam forms, using standard block cutting techniques. A real-size plot was also created, which was used to verify the accuracy of the Styrofoam cutting. A special jig was used to hold the Styrofoam and collimator housing. The real size plot was aligned to a prescribed center marking on the base plate, the Styrofoam was aligned to the plot, and the collimator housing fixed around the Styrofoam, which was clamped in place by a large rod from above. Figure 5 is a typical set of small field inserts for the case of conformal SRT/S. This assembly was held firmly in place while a low melting point alloy was poured around the Styrofoam. The location of the screw hole was indexed to the collimator as collimator rotations were occasionally used to take advantage of the diagonal dimension of the 65 mm square jaw setting on the linac.

4) 

Isocenter setup error analysis

The treatment set up procedure was a reproduction of the process used at the simulation. The final isocenter location in the CT study was defined in the treatment planning process, which would substitute for the original estimate. Beam port films were produced, and the ISOLOC program (NMPE, Lynnwood, WA) used to adjust the couch to within 1mm of each axis of the target. We defined the medio-lateral direction as the x axis, the anterior-posterior direction as the y axis, and the crano-caudal direction as the z axis. For a given axis, the overall displacement was defined as the mean of all the setup displacements for all the patients. The distribution of the overall displacement was determined by the standard deviation. Using the ISOLOC program, we obtained three pieces of information: 1) the couch translations required to bring the target point to the isocenter, 2) the distance between the stereotaxic markers in the CT study, and between the markers determined from the orthogonal beam films, taken in the anterior-posterior and lateral directions, and 3) the rotational movement of the head position between the CT study and the actual treatment. We evaluated two kinds of data: 1) precision of isocenter setup, and 2) reproducibility of head position in the a) translational and b) rotational components.

RESULTS

1) Precision of isocenter setting

The precision of a setup point, defined in the CT study, to the linac isocenter was the same at each treatment, since port films were produced, and the ISOLOC program was used to align the patient based on the navigational markers.

The precision of the isocenter setup for the conformal SRT/S was $x = 0.03 \pm 0.26$ mm, $y = 0.19 \pm 0.25$ mm and $z = 0.20 \pm 0.27$ mm. Fig. 6a shows an isocenter displacement histogram.

Fig. 5. A typical set of small field inserts in the case of conformal SRT/S.

Fig. 6. The isocenter distribution histogram for a (A) x direction, (B) y direction, and (C) z direction.
in the medio-lateral direction (x), with the positive direction defined as the left in the room coordinates in the supine position. Fig. 6A shows a broad normal distribution relative to the isocenter coordinates. Fig. 6B shows an isocenter displacement histogram in the anterior-posterior direction (y), with the positive direction defined as an anterior in the room coordinates, in the supine position. Fig. 6B shows a shift in the anterior direction relative to isocenter coordinates. Fig. 6C shows an isocenter displacement histogram in the cranio-caudal direction (z), with the positive direction defined as a cranial in the room coordinates in the supine position. Fig. 6C shows a general shift in the cranial direction relative to isocenter coordinates.

2) Reproducibility of head position

The reproducibilities of the head position for the conformal SRT/S were nearly 0.5 mm and less than 1°, for the translational and rotational components, in any plane (no showing data).

DISCUSSION

The original focus in the development of radiosurgery, with a linear accelerator, was the beam penumbra, and the production of a method that would produce a steep gradient, as obtained with the Leksell Gamma unit. To accomplish this, it is necessary for beams to have a large angle of convergence, as demonstrated by Podgorsak et al. (3). Under these conditions, spherical isodose distributions are produced. Various methods to obtain non-spherical isodose distributions, with arcing fields, have been described, and Serago et al used elliptical, rather than round, collimators (4). McGinley et al. also shaped the fields by blocking segments of a circular field (5). Luxton and Josel showed that careful selection of the number of arcs, the arc angle, the relative weighting of arcs and the collimator size, could be used to obtain good coverage of a prolate ellipsoid revolution 25 mm in diameter and 35 mm in length, and maintain a sharp dose gradient (6). Columbo et al obtained a cigar-shaped dose distribution by rotating and translating the couch, while irradiating with fixed gantry angles (7). Another method of dose conformation, borrowed from Gamma Knife users, is to set multiple isocenters. Shaw et al compared the number of isocenters used in these radiosurgery techniques, and reported a median value of 5, ranging from 1 to 14, for Gamma Knife treatments, and a median value of 1, ranging from 1 to 4, for linac treatments. They hypothesized that neurotoxicity was associated with a low number of isocenters, and thus poor conformity of the dose distribution in the linac group (8). The possibility of shaping the field during arc therapy has been investigated by Leavitt et al., who devised a dynamic collimator, with four independent blocks, that could exclude segments of the circular field (9). Shiu et al. described a miniature multileaf collimator (MMLC), and have evaluated its potential for dynamic therapy. The goal is for the MMLC to conform to a BEV the target during moving beam therapy. The staircase effect of the leaves will be minimized by the collimator rotation. The orchestration of the MMLC and collimator rotation is not complete, and the system has been evaluated by simulating arc therapy using multiple stationary fields (10).

The use of multiple stationary fields, shaped to conform the target, is commonplace in radiotherapy, and was applied to linac radiosurgery by Schlegel et al. (11), and Griffin et al. (12) applied it to radiosurgery with a neutron beam, using nine non-coplanar, non-opposing isocentric fields, to treat 15 patients with an intracranial AVM, using stationary conformal fields, instead of multiple arcs. They proposed a target diameter of 40 mm as the break point. In a later report by the same group (13), irregularly shaped targets, as small as 20 mm in diameter, were better treated by static conformal fields, as the grading was based on the dose to normal tissue at various dose levels. Rieke evaluated the margin that should be placed in a BEV of the target for the production of stationary field collimators (14).

Intensity modulated beams have been used to treat irregularly shaped targets, and Cardinale et al. (15) calculated the dose distribution obtained by five non-coplanar arcs, six conformal non-coplanar stationary beams and five coplanar intensity modulated beams. They compared various dosimetric parameters, and demonstrated the detrimental results of using a single isocenter arc. The differences between 3D stationary beams and intensity modulation techniques did not appear significant.

Columbo and his colleagues (16), first described the advantage of separating the localization from the treatment, using implanted fiducials in a radiosurgery system. The dosimetric advantages gained from using multiple non-coplanar stationary beams, for stereotactic radiotherapy or radiosurgery, are well known. This technique is not widely applied due to the logistical problems associated with the production and testing of these customized collimators. The use of implanted fiducials allows enough time to accomplish the task we have described.

The reproducibility of head position was not critical for stereotactic multiple arc therapy since the correct isocenter is set at each fraction, and the variation in average path length to the target is minimal when many arcs are used for treatment. However, for conformal SRT/S the collimators are designed with a 3 mm margin in the BEV of the target, as defined by the geometry of the machine viewing the target at the simulation session. Thus, it is important that the head position should be reproduced for each treatment. The ISOLOC program provides information on the rotation of the CT axes at each treatment. The accuracy of the dose delivery by our method is equivalent to a frame based system (17, 18). In fact, it can be argued that there is a fundamental advantage in using implanted fiducials, over stereotactic frames, in that the relationship of the target to the fiducials is fixed, and the fiducials are localized within the treatment beam. With a frame based system, even though the pins may be fixed to the bone, there is the potential for flexing of the arms attaching the stereotactic ring, which is used as the reference (19). The frame based systems rely on the careful alignment of the stereotactic frame to the linac, which requires considerable Q.A. checks prior to treatment. In the method described here, the coordinate system is defined by the fiducials incorporated in the small field collimator. Using implanted fiducial markers for stereotaxy, there is concern about head movement during SRT/S, due to the use of a flexible thermoplastic mask to immobilize the patient in a position that is as comfortable as possible. However, we found the degree
of head movement was acceptable in our experience (20).

CONCLUSIONS

We were able to apply conformal stereotactic irradiation, which has a dosimetric advantage, to irregularly shaped intracranial tumors, with an isocenter setup precision and reproducibility of the head position nearly equivalent to frame-based SRS or multiple-arc SRT/S.

REFERENCES