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Original paper

Dosimetric analysis of Tomotherapy-based intracranial stereotactic radiosurgery of brain metastasis

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ABSTRACT

Purpose: This paper analyzes Tomotherapy-based intracranial stereotactic radiosurgery (HTSRS) of brain metastasis targeting two end-points: 1) evaluation of dose homogeneity, conformity and gradient scores for single and multiple lesions and 2) assay of dosimetric criticality of completion of HTSRS procedures.
Methods: 42 treatment plans of 33 patients (53 brain lesions) treated with HTSRS were analyzed. Dose to healthy brain, homogeneity, conformity and gradient indexes were evaluated for each lesion. Influence of Field Length and multiple lesions *cross-talk* effect were assessed. Treatment interruption and completion was investigated using radiochromic films in order to examine the delivered dose and its robustness to patient intrafraction movement.
Results: The average dose homogeneity index was 1.04 ± 0.02 (SD). Average dose conformity and gradient score indexes were 1.4 ± 0.2 and 50 ± 14 respectively. We found a strong correlation of the dose to healthy brain and conformity and gradient indexes with target(s) volume for which analytical functions were obtained. Field Length and *cross-talk* effect were significantly correlated with poor gradient scores, but were found not to affect dose conformity.
Conclusions: Homogeneity and conformity of HTSRS plans achieved excellent scores, while dose falloff and dose to healthy brain were slightly larger when compared with non-coplanar SRS techniques. Care should be given if treating large (> 3 cc) or multiple near *in-plane* lesions in order to reduce dose to healthy brain. Analysis of interrupted treatments suggests splitting HTSRS treatments in two consecutive fractions in order to prevent target miss and overdosage due to patient intrafraction movement.

1. Introduction

Stereotactic radiosurgery (SRS) is a well-attained treatment [1,2] of single and multifocal brain metastasis. Radiosurgical irradiation of brain lesions with an ablative dose in the range 18–21 Gy can be performed using dedicated systems like Gamma Knife and Cyber Knife or using conventional linear accelerators equipped with cones or multileaf collimators (MLC) by way of conformal or intensity modulated non-coplanar static fields or partial arcs. Helical Tomotherapy (HT) is a general-purpose radiotherapy technique whose advantages include built-in megavoltage CT for image guided set-up of the patient, powerful rotational intensity modulation of the photon beam and easy treatment of extended target volumes. Recently application of HT to intracranial SRS has been reported [3,4]. However some critical aspects of Tomotherapy-based SRS should be considered: i) the minimum longitudinal field length is 10 mm and the leaf width is 6.25 mm so treatment of very small lesions can lead to excessively large conformity indexes; ii) the target irradiation is purely coplanar so the dose gradient can be poor if compared to non-coplanar treatment techniques; iii) given that irradiation of the target is done by helical rotation of the beam, there is some concern about interruption of the treatment given that in SRS all the dose is given in a single fraction. This paper examines in depth the aforementioned critical aspects to answer some important questions: what is the expected performance of HTSRS in terms of homogeneity and conformity? Can HTSRS achieve steep dose gradients and satisfactory healthy brain sparing? Does the usage of the 25 mm longitudinal field to speed up the treatment significantly affect the amount of healthy brain tissue irradiated? Does irradiation of multiple

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Table 1
Summary of planning and treatment parameters.

All lesions		mean ± SD	n = 53
Prescription Dose (Gy)	15–21 Gy		
CTV volume (cc)	0.18–13.8	3.0 ± 3.1	
PTV volume (cc)	0.96–24.7	5.9 ± 5.4	
	< 1 cc		1
	1–5 cc		33
	5–10 cc		11
	> 10 cc		8
Lesions			n = 53
Single/multiple			20/33
isolated/x-talking			34/19
HT Treatment Parameters			n = 42
Field Length (static)	10 mm		35
	25 mm		7
Pitch	0.096–0.150	typical 0.108	
Modulation Factor	1.140–2.470	1.8 ± 0.3	
Gantry Period (s)	19–60	42 ± 11	
Couch Speed (cm/s)	0.002–0.010	0.004	
Beam On Time (s)	477–1985	1208 ± 375	

Abbreviations: SD = Standard Deviation; HT = Helical Tomotherapy; n = number of lesions.

lesions lying in the same axial planes significantly degrade the dose gradient or conformity? Can interruption and completion of HTSRS procedures be done safely?

2. Methods and materials

2.1. Dosimetric analysis

The treatment plans of 33 patients treated with HT (Accuray) SRS for brain metastasis were examined. A total of 42 plans for irradiation of 53 brain lesions were included in the study. Patients were immobilized using the InterFix Radiosurgery kit described in [5,6]. The treatments were planned on CT scans with slice thickness of 1.25 or 2.5 mm, depending on target size, using Tomotherapy Planning System v.4 and Fine resolution for optimization and Final Dose calculation. Target volumes and HT plan parameters are summarized in Table 1. In general the static 10 mm Field Length (FL) or SJ10 was used for planning, while in 7/42 of the plans the static 25 mm FL (SJ25) was used to reduce Beam On Time (BOT) and/or to include multiple disseminated lesions. Usage of Dynamic Jaws was not considered in this paper. In the case of multiple lesions with longitudinal (Y) separation greater than 2 cm the treatment was planned using two separate SJ10 plans. Each metastatic lesion was assigned to a distinct Planning Target Volume (PTV) and the dose prescription was hard constrained so to cover the 50% of the main PTV with the Prescription Dose (PD). Optimization was carried out using all relevant organs at risk (always including the whole brain and the posterior fossa) and a 1 cm ring help structure for improvement of the dose falloff, although the special optimization technique reported by Soisson et al. [7] was not used in this study. 17 (out of 53) lesions were lying in the same or adjacent transverse planes and were classified as *inplane* or *x-talking* lesions producing in general a slightly flatter dose falloff due to what we call the *cross-talk* effect between the dose to multiple lesions delivered in pure coplanar way by HT. The other lesions ("true" single lesions or multiple lesions with Y separation greater than 2 cm) were dubbed as *isolated*.

For all the lesions four different dose "quality" parameters were calculated: Homogeneity Index (HI), Conformity Index (*CI*), Gradient Score Index (*GSI*) and GSI_{80} Index.

Following RTOG radiosurgery guidelines [8,9] the Homogeneity Index was defined as:

$$HI = \frac{D_{max}}{D_{RX}}$$

where D_{max} and D_{RX} are the maximum and prescription doses for the PTV.

The Conformity Index was defined as in [10] as a modified inverse-Paddick index:

$$CI = V_{TV} \times V_{PTV}/V^2_{PTV,T}$$

where V_{TV} is the volume comprised in the 95% isodose (treated volume), V_{PTV} is the volume of the PTV and $V_{PTV,T}$ is the volume of the PTV covered by the 95% isodose.

The Gradient Score Index was defined as in [11]

$$GSI = 100-\{100 \times [(R_{Eff,50\%RX}-R_{Eff,RX})-0.3]\}$$

where $R_{Eff,RX}$ and $R_{Eff,50\%RX}$ are the effective radii (expressed in cm) of the volume encompassed by the 95% isodose and the 50% isodose. In order to compare fairly the *GSI* of multiple *inplane* lesions with the *GSI* values of *isolated* lesions we introduce the novel per-lesion Gradient Score Index (*plGSI*) as:

$$plGSI = \begin{cases} 100-\{100 \times [(R_{Eff,50\%RX}-R_{Eff,RX}) \\ \quad -0.3]\} \quad \text{if each lesion has separated 50\% isodose} \\ 100-\{100 \times [(R^n_{Eff,50\%RX}-R^n_{Eff,RX})-0.3]\} \quad \text{for each lesion if 50\%} \\ \quad \text{isodoses overlap} \end{cases}$$

where the R^n_{Eff} radii are calculated per-lesion dividing the volume encompassed by the entire 50% isodose by the number *n* of *inplane* lesions with 50% isodoses overlapping. The *plGSI* score is a good approximation of the "true" *GSI* if all lesions have similar sizes and spherical dose distributions: this assumption was approximately correct for all the examined cases in this paper.

To better discern the effect of the dose splash induced on the HT dose gradient by *cross-talking* lesions we introduced the novel GSI_{80} index defined as:

$$GSI_{80} = 100-\{100 \times [(R_{Eff,80\%RX}-R_{Eff,RX})-0.3]\}$$

where $R^n_{Eff,80\%RX}$ is the effective radii (expressed in cm) of the volume encompassed by the 80% isodose. Supposing a spherical isodose distribution the radii were calculated according the following formulas:

$$R_{Eff,iso} = \sqrt[3]{\frac{3}{4\pi} * V_{iso}}$$

$$R^n_{Eff,iso} = \sqrt[3]{\frac{3}{4\pi} * \frac{V_{iso}}{n}}$$

where V_{iso} is the volume of the considered isodose (95%, 80% or 50%) and *n* is defined as above for multiple lesions.

Finally, given that the volume of the 12 Gy dose received by brain/posterior fossa has been shown to be highly correlated with the risk of radiosurgery-induced radionecrosis [12–14], we calculated for each patient the net V9/V12/V15Gy volume which represents the volume of the healthy (excluding PTV volumes) brain/posterior fossa tissue irradiated with a dose not inferior to 9/12/15 Gy.

Dose and volume data were evaluated on Varian Eclipse v.6 Treatment Planning System, linking for each Tomotherapy plan the dose distribution exported through DICOM protocol to the original high-resolution (0.95 mm^2 pixels) planning CT. Statistical analysis of data was based on one-tailed Wilcoxon Rank Sum Test. Results with $p > 0.05$ were scored as Not Significant (NS).

2.2. Treatment interruption

To assess if completion of interrupted HTSRS treatments can be of concern (due to target-miss and/or overdosage) we performed film analysis of simulated interrupted treatments with radiochromic EBT2 (ISP Corporation) films. A real HTSRS treatment (P10) was selected as "typical" with PD = 18 Gy, SJ10 jaws, pitch = 0.096, BOT = 885 s and