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Kairn, Tanya, Crowe, Scott, Kenny, John, & Trapp, Jamie (2011) Investigation of stereotactic radiotherapy dose using dosimetry film and Monte Carlo simulations. *Radiation Measurements*, *46*(12), pp. 1985-1988.

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http://dx.doi.org/10.1016/j.radmeas.2011.06.024

Investigation of stereotactic radiotherapy dose using dosimetry film and Monte Carlo simulations

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Abstract

This study uses dosimetry film measurements and Monte Carlo simulations to investigate the accuracy of type-a (pencil-beam) dose calculations for predicting the radiation doses delivered during stereotactic radiotherapy treatments of the brain. It is shown that when evaluating doses in a water phantom, the type-a algorithm provides dose predictions which are accurate to within clinically relevant criteria, γ(3%,3mm), but these predictions are nonetheless subtly different from the results of evaluating doses from the same fields using radiochromic film and Monte Carlo simulations. An analysis of a clinical meningioma treatment suggests that when predicting stereotactic radiotherapy doses to the brain, the inaccuracies of the type-a algorithm can be exacerbated by inadequate evaluation of the effects of nearby bone or air, resulting in dose differences of up to 10% for individual fields. The results of this study indicate the possible advantage of using Monte Carlo calculations, as well as measurements with high-spatial resolution media, to verify type-a predictions of dose delivered in cranial treatments.

Keywords: computer simulation, dosimetry, pencil beam, radiochromic film, stereotactic radiosurgery

1. Introduction

Cancerous and benign lesions of the brain can be treated with radiotherapy, by using very small (stereotactic) radiation fields. Because the brain is

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composed of tissues with a nearly uniform density and does not contain any substantial volumes of either air or bone, the use of a pencil-beam single-convolution algorithm that does not account for changes to electron transport caused by density heterogeneities (designated 'type-a' by Knoos et al. (2006)) seems to be an efficient means to perform accurate treatment planning calculations for cranial cases. Type-a treatment planning calculations of small-field radiation doses delivered to tumors in more heterogeneous tissues (most obviously the lungs (Knoos et al., 1995) but also the head and neck (Seco et al., 2005; Partridge et al., 2006)) are known to have limited accuracy. For stereotactic fields, the accuracy of treatment planning dosimetry is difficult to verify by standard measurement alone due to the physical limitations of the measuring devices available (Das et al., 2008). There is therefore an obvious advantage to being able to verify the planned dosimetry of stereotactic treatments using continuous dosimetry media such as gels and films (Kairn et al., 2010c) in conjunction with an established Monte Carlo code, such as BEAMnrc (Rogers et al., 1995).

This study uses radiochromic film measurements and Monte Carlo dose calculations to test the assumption that a type-a radiotherapy treatment planning algorithm is sufficient to predict the dosimetry of small-field radiotherapy treatments in the brain. Here, the accuracy of type-a dose predictions made using Version 3.0.2 of the iPlan treatment planning system (Brainlab, Feldkirchen, Germany) are evaluated, for sample stereotactic radiotherapy treatments delivered to a planar solid water phantom and to heterogeneous human tissue using the Brainlab m3 micro-multileaf collimator (Brainlab, Feldkirchen, Germany) (Cosgrove et al., 1999).

2. Methods

The dose predictions made by iPlan's type-a (pencil-beam) dose calculation algorithm were compared with (a) radiochromic film measurements and the results of Monte Carlo simulations of a treatment delivered to solid water and (b) Monte Carlo simulations of a hypothetical treatment to a stereotactic radiotherapy patient. Using iPlan, a sample treatment plan for an arteriovenous malformation treatment, which had an average field width of 1.5 cm and a minimum field width of 0.2 cm (measured at the isocenter), was mapped onto a computed tomography (CT) scan of a Virtual Water phantom (Standard Imaging, Middleton, USA) and recalculated, with gantry angles and couch angles set to zero (according to local quality assurance protocol). This

treatment plan, including dose grids, was exported for delivery to film and for comparison with Monte Carlo calculations. A nine field conformal treatment plan for a meningioma treatment, which had an average field width of 2.5 cm and a minimum field width of 0.2 cm (measured at the isocenter), was directly exported from iPlan (including patient CT data, calculated dose grids and regions of interest) in DICOM format, for comparison with Monte Carlo simulations.

The radiochromic film images were obtained using eight sheets of Gafchromic EBT2 dosimetry film (International Specialty Products, Wayne, USA). The film sheets were cut and pre-scanned using an Epson Perfection V700 Photo flatbed scanner (Seiko Epson Corp., Nagano, Japan) as recommended by Kairn et al. (2010b). For irradiation, each film was placed within the block of Virtual Water used in iPlan's recalculated treatment plan. Each film was irradiated using a different field from the arteriovenous malformation treatment, with all beams delivered from a zero gantry angle. Irradiations were performed using a Varian Clinac iX linear accelerator (Varian Medical Systems, Palo Alto, USA), producing a nominal 6 MV photon beam, with the 120-leaves of its Millennium MLC fully retracted (to $\pm$20.08 cm, projected to the isocenter) and the BrainLAB m3 micro-multileaf collimator (μMLC) attached at its exit. After waiting 24 hours from the time of irradiation, the films were re-scanned and their optical densities converted to two-dimensional maps of absorbed dose (Kairn et al., 2010b).

The Varian linear accelerator and BrainLAB m3 μMLC used in this study were modeled as previously described (Kairn et al., 2010c,a,d) using the BEAMnrc and DOSXYZnrc Monte Carlo code, with corrections for output deviations due to collimator backscatter into the monitor chamber based on previous work (Kairn et al., 2009). This study relied on the use of the MCDTK package (Crowe et al., 2009): to convert the DICOM-format treatment plans obtained from iPlan into BEAMnrc and DOSXYZnrc input files with the correct jaw and μMLC positions; to convert the CT images of the Virtual Water and meningioma patient into a voxelised text format suitable for use with DOSXYZnrc; and to generate isodoses, two-dimensional dose maps, dose profiles and dose-volume histograms for the patient treatment, to allow quantitative comparisons between the Monte Carlo and iPlan results.

3. Results

3.1. Water phantom treatment

Figure 1(a) typifies the dose profiles measured using radiochromic film and calculated using the accurate Monte Carlo model and the type-a treatment planning algorithm, for fields delivered to Virtual Water. Like Figure 1(a), results for all eight beams used in this part of the study showed that: there is agreement between film measurements and Monte Carlo calculations to within strict acceptance criteria, γ(2%,1mm); there are details in profiles from both the Monte Carlo calculations and the film measurements, which are not apparent in the type-a predictions (for example, see the feature -1.0 cm from the central axis in Figure 1(a)); the film and the Monte Carlo calculations show that the beams have narrower penumbrae than the type-a algorithm predicts; and the doses at the centers of the fields obtained from film measurements and Monte Carlo simulations differ by up to 3% from the doses predicted using the type-a algorithm. Importantly, the film measurements and Monte Carlo calculations for all fields consistently agree with the type-a predictions within clinically relevant acceptance criteria, γ(3%,3mm), and certainly within internationally recommended acceptance criteria, γ(5%,5mm) (ICRU, 2010). It can be concluded that when used to predict the doses delivered by small fields to a planar, homogenous block of Virtual Water, the type-a algorithm provides a degree of accuracy that is acceptable for clinical use, although its dose predictions are subtly but measurably different from doses obtained from both dosimetry film and Monte Carlo simulations.

3.2. Meningioma patient treatment

When used to evaluate the doses delivered by a hypothetical treatment to a meningioma patient, the type-a algorithm produces more substantial inaccuracies. In the profiles through the isocenter of this patient treatment, an example of which is shown in Figure 1(b), the Monte Carlo calculations show narrower and steeper penumbrae than the pencil beam predicts, which is similar to the results discussed above, for the water phantom, and which may be due to slight inaccuracies in the micro-ion chamber measurements that were used to commission the iPlan treatment planning system. Monte Carlo dose calculations at the treatment isocenter for each beam range from from 3% below to 10% above the type-a predictions, with the larger differences being apparent in the profiles for beams that have passed though bone

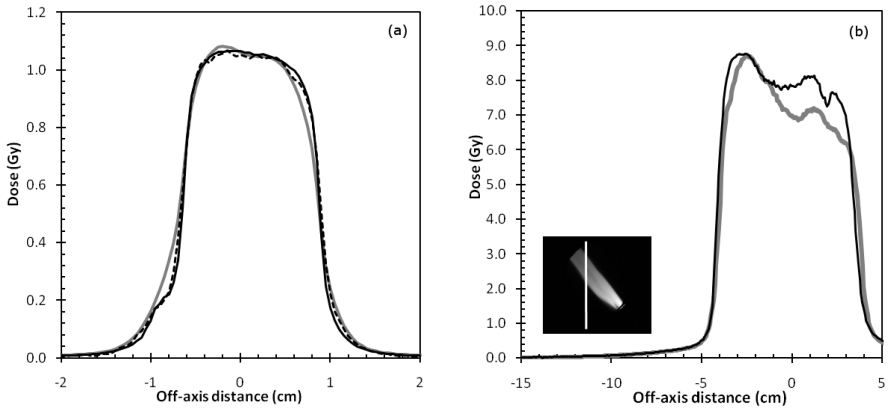

Figure 1: Dose profiles in (a) a water phantom and (b) heterogeneous patient tissue, for dose calculated using the type-a algorithm (heavy grey line) and the Monte Carlo simulations (fine black line) as well as, for figure (a), dose measured using radiographic film (fine, dotted line). The inset in figure (b) shows the location of the radiation field and the plotted profile (vertical white line) in relation to patient anatomy (compare with CT images in figure 2).

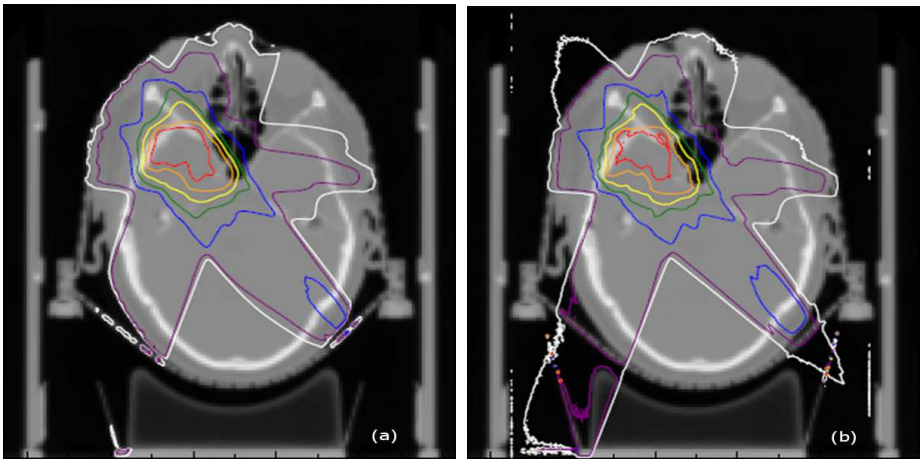

Figure 2: Patient CT image overlaid with isodoses lines derived from (a) the iPlan type-a dose predictions and (b) a Monte Carlo simulation of the treatment. (Note that in the Monte Carlo data, dose to the air outside the patient is not automatically set to zero as it is in the type-a data.)

or air cavities. The profiles shown in Figure 1(b) were generated at the sphenoid bone, for a beam that had traversed almost the entire cranial cavity, partially intersecting the paranasal sinuses. Consequently, the data shown in Figure 1(b) show obvious disagreement and represent a worst-case-scenario for this treatment.

Despite the clear disparity that is apparent when individual beam profiles were compared, the overall result of calculating the dose for the entire treatment using the Monte Carlo model and the type-a algorithm show relatively good agreement. Figures 2(a) and (b) show sets of isodose lines obtained from three dimensional dose grids produced by the type-a algorithm and from a Monte Carlo simulation of the treatment. Both sets of isodoses indicate that the tumor is covered by the prescription dose, although there are noticeable deviations in the volumes of tissue within lower isodoses, especially in regions close to bone.

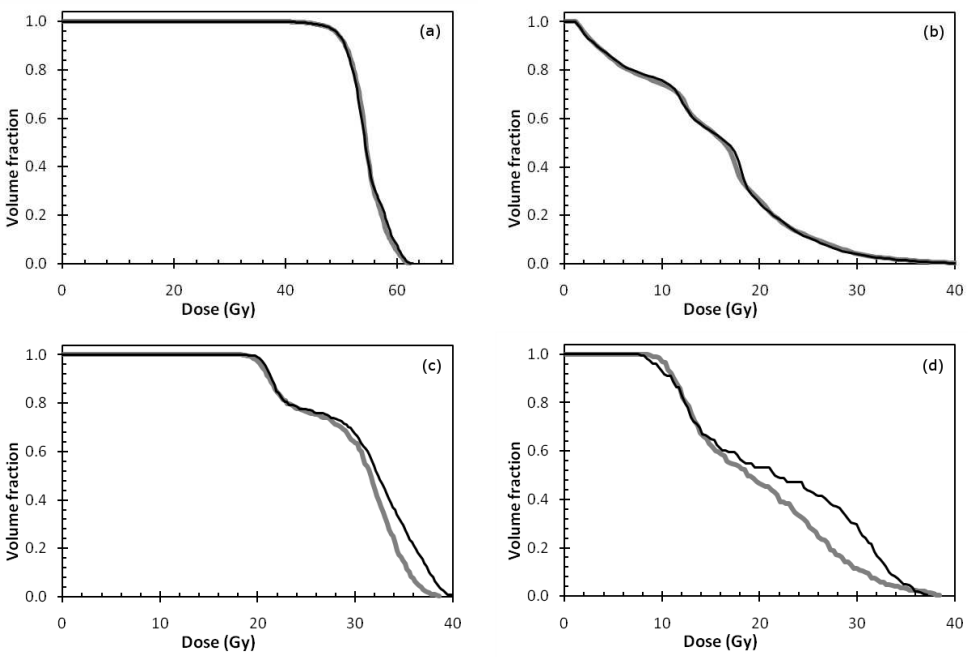

Figure 3: Cumulative dose-volume distograms, plotted using data calculated using the type-a algorithm (heavy, grey lines) and the Monte Carlo model (fine, black lines), for (a) the tumour, (b) the brain stem, (c) the optic nerve and (d) the optic chiasm.)

Examination of the cumulative dose-volume histogram (DVH) data il-

lustrated in Figures 3(a) and (b) shows that the type-a calculations for the different beams combine to produce a relatively accurate prediction of the overall doses to both the tumor and the brain stem. Examination of DVH data for other critical structures, exemplified in Figures 3(c) and (d), show that the type-a algorithm has underestimated the volumes of these tissues that would receive radiation doses of up to 40 Gy, if this treatment was delivered to the patient. The clinical relevance if these differences can be elucidated through examination of the data in Table 1.

Table 1 lists the maximum doses as well as the doses received by 90% and 50% of the volumes of the tumor, brain stem, optic nerve and optic chiasm, as calculated using the type-a algorithm and Monte Carlo simulations. Like the DVH data (from which they were derived) the values in Table 1 show good agreement in the doses calculated for the tumor and brain stem, with poorer agreement between the doses calculated for the optic nerve and optic chiasm. It should be noted, however, that all doses to critical structures calculated using both methods are below levels linked to a 3-5% of necrosis or neuropathy (Marks et al., 2010). For this patient, all doses to the tumor and critical structures evaluated using the both type-a and Monte Carlo calculations conform to the original treatment planning objectives and constraints.

Table 1: Doses (in Gy) calculated in the tumour and critical structures, using the type-a algorithm and the Monte Carlo model.

Region	D(V=90%)		D(V=50%)		D_{max}	
	Type-a	MC	Type-a	MC	Type-a	MC
Tumour	50.8	50.5	54.3	54.2	62.2	62.9
Brain stem	3.3	3.3	16.2	16.6	44.8	44.8
Optic nerve	21.2	21.4	31.7	32.3	38.6	40.4
Optic chiasm	11.2	11.0	18.8	21.4	38.4	37.1

4. Conclusion

When evaluated in comparison to Monte Carlo simulations and radiochromic film measurements, type-a predictions of the doses delivered by very small fields can be measurably inaccurate, even when these doses are evaluated in water. When predicting stereotactic radiotherapy doses to the brain, the

inaccuracies of the type-a algorithm can be exacerbated by inadequate evaluation of the effects of nearby bone or air.

Although the patient treatment examined here conformed to treatment planning objectives and constraints, the results of this study indicate the possible advantage of using Monte Carlo calculations to verify type-a predictions of dose delivered in cranial treatments in addition to treatments delivered to more heterogeneous regions, such as lung. Measurements made using a medium with a high spatial resolution, such as dosimetric film, can also be used to test and verify the predictions made using type-a algorithms, such as that used by the iPlan stereotactic radiotherapy treatment planning system.

5. Acknowledgements

This research was funded by the Wesley Research Institute, Australia. The authors wish to thank Andrew Fielding, Rick Franich, Peter Johnston, Richard Knight, Christian Langton, David Schlect and Michael Taylor for valuable discussions of aspects of this work. The authors are also grateful to Jo Mitchell for designing the clinical meningioma treatment plan and to Muhammad Basim Kakakhel for commissioning the Monte Carlo model of the Varian linear accelerator. Computational resources and services used in this work were provided by the High Performance Computing and Research Support Unit, QUT, Brisbane, Australia.

6. Role of funding source

The Wesley Research Institute funded this research, though a project grant (2008/11). The Wesley Research Institute played no role in study design; in the collection, analysis, and interpretation of data; in the writing of the report; or in the decision to submit this paper for publication.

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