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Inter fraction motion

Intra-fraction motion of the prostate during treatment with helical tomotherapy

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ABSTRACT

Background and purpose: To measure the geometric uncertainty resulting from intra-fraction motion and intra-observer image matching, for patients having image-guided prostate radiotherapy on TomoTherapy.

Material and methods: All patients had already been selected for prostate radiotherapy on TomoTherapy, with daily MV-CT imaging. The study involved performing an additional MV-CT image at the end of treatment, on 5 occasions during the course of 37 treatments. 54 patients were recruited to the study. A new formula was derived to calculate the PTV margin for intra-fraction motion.

Results: The mean values of the intra-fraction differences were 0.0 mm, 0.5 mm, 0.5 mm and 0.0° for LR, SI, AP and roll, respectively. The corresponding standard deviations were 1.1 mm, 0.8 mm, 0.8 mm and 0.6° for systematic uncertainties (Σ), 1.3 mm, 2.0 mm, 2.2 mm and 0.3° for random uncertainties (σ). This intra-fraction motion requires margins of 2.2 mm in LR, 2.1 mm in SI and 2.1 mm in AP directions. Inclusion of estimates of the effect of rotations and matching errors increases these margins to approximately 4 mm in LR and 5 mm in SI and AP directions.

Conclusions: A new margin recipe has been developed to calculate margins for intra-fraction motion. This recipe is applicable to any measurement technique that is based on the difference between images taken before and after treatment.

The TomoTherapy treatment system [1] combines intensity modulated radiotherapy (IMRT) with image guided radiotherapy (IGRT). An MV-CT scan taken immediately before treatment is matched to the planning kV-CT used to align the patient for each fraction. Even when daily IGRT is performed, a margin is still needed between the clinical target volume (CTV) and the planning target volume (PTV), to allow for intra-fraction motion, for the uncertainties in the image matching process, and for other components of uncertainty in planning and delivery [2]. Studies on intra-fraction motion of the prostate have mainly been performed with electromagnetic tracking [3,4], with planar seed imaging [5–9] or with kV CT imaging [8,10]. The only reported study on intra-fraction motion with TomoTherapy [11] contained only four prostate patients, giving insufficient data for calculation of the standard deviations of systematic and random uncertainties, as required for margin calculation [2].

We have performed a study on 54 patients, to provide data to inform decisions on appropriate margins for prostate patients being treated on TomoTherapy. Studies based on imaging before and after treatment have calculated margins using a recipe that implicitly assumes that all the intra-fraction motion happens immediately after the first image. We describe a new margin recipe that does not make this assumption.

Materials and methods

Study design and treatment technique

All patients in the study had already been selected for prostate radiotherapy with TomoTherapy, involving daily MV-CT imaging. The study involved performing an additional MV-CT image at the end of treatment, on five occasions during the course of 37 fractions; the interval between these 5 occasions was typically weekly. The study was given ethical approval by a Research Ethics Committee. All patients gave informed consent. 74 Gy was prescribed to a PTV consisting of the prostate plus a 5 mm margin, with 60 Gy prescribed to a PTV consisting of prostate + seminal vesicles (or base of seminal vesicles) plus a 10 mm margin.

54 patients were recruited to the study, with an average age of 68 years (standard deviation = 5 years). Of these 54 patients, 50 had the additional MV-CT image taken 5 times as per protocol, 2

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had it taken 4 times, and 2 had it taken 3 times, giving a total of 264 measurements.

Patients were asked to follow a low fibre diet and exercise advice sheet from one week prior to CT planning to minimize rectal distension [12]. At the time of the planning CT, patients were advised to void their bowels and to have a comfortably full bladder by drinking 2–3 cups of water about 1 h before the scan, and to do the same before each treatment fraction. A CT scanning protocol was used to ensure that patients were not planned when the maximum rectal diameter at the level of the prostate gland exceeded 5 cm. For imaging and treatment, patients were immobilized with knee supports and ankle stocks and asked to breathe normally. Delineation was performed on CT. In some cases the diagnostic MRI (pre-androgen deprivation) was reviewed to aid the CT delineation.

The patients were imaged each day before treatment and the MV-CT scan compared to the planning kV-CT treatment planning scan. Soft-tissue prostate match was performed with 4 degrees of freedom (x, y, z and roll) to give relevant couch moves, using the methods described by Burnet et al. [13]. Once couch and roll adjustments were made the patient underwent the planned treatment fraction. On the five days selected for a second scan, this was performed at the end of the fraction, re-matched to the planning kV by the same radiographers as performed the original match, and the values of x, y, z and roll noted.

The mean time between the start of the first image and the end of the second was 12 min. The mean duration of the treatment beam was 3 min 40 s, with the mean mid-point of beam being 55 s after the mid-point between the start of the first image and the end of the second.

Statistical analysis of results

The methods described by Greener [14] were used to calculate the standard deviations, Σ and σ, of systematic and random errors respectively, for each of the three orthogonal directions and for the roll. The methods of de Boer et al. [15] were used to correct for the overestimation of Σ due to the influence of random errors with a small number of observations per patient.

The mean values of the displacements and roll were also calculated. To test whether these were significantly different from zero, a two-sided Student's t-test was used.

Calculation of margins

The difference between the match on the first and second image is subject to the uncertainties in the image matching process (twice) and intra-fraction motion (once). Let us first consider the random uncertainties. Denoting these uncertainties σ_{image} and σ_{intra}, respectively, then adding errors in quadrature

$$\sigma_{\text{diff}} = \sqrt{2\sigma_{\text{image}}^2 + \sigma_{\text{intra}}^2} \tag{1}$$

The uncertainty in patient treatment position is subject to only one image matching process. It will not on average be subject to the full intra-fraction motion, since that would only be true if the motion always occurred in the interval between the image and the start of the treatment. Fig. 1 shows two possible scenarios, one in which the move happens as a step change at a random point between the two images, and one in which the motion happens continuously during the time between the two images. The treatment is assumed to occur at a point in time half way between the two images; this is close to the observed mean mid-point of treatment which is 55 s after the half way point.

In scenario A, in half the cases the shift happens before treatment and in half it happens after, hence half the moves do not contribute to the variance or to the mean shift. Therefore the variance of treatment-affecting intrafraction motion goes from $\frac{1}{n}\sum_{i=1}^{n}\Delta^2$ to $\frac{0.5}{n}\sum_{i=1}^{n}\Delta^2$ giving a standard deviation of $\frac{1}{\sqrt{2}}\sigma_{\text{intra}}$. The mean move at the point of treatment will be half the measured shift between images. In scenario B, where moves are assumed linear with time, the standard deviation reduces to $\frac{1}{2}\sigma_{\text{intra}}$. Electromagnetic tracking studies [4,16,17] suggest that the linear model does not match reality, and that a model in which the moves occur over a short time is nearer to reality. We have therefore chosen to use scenario

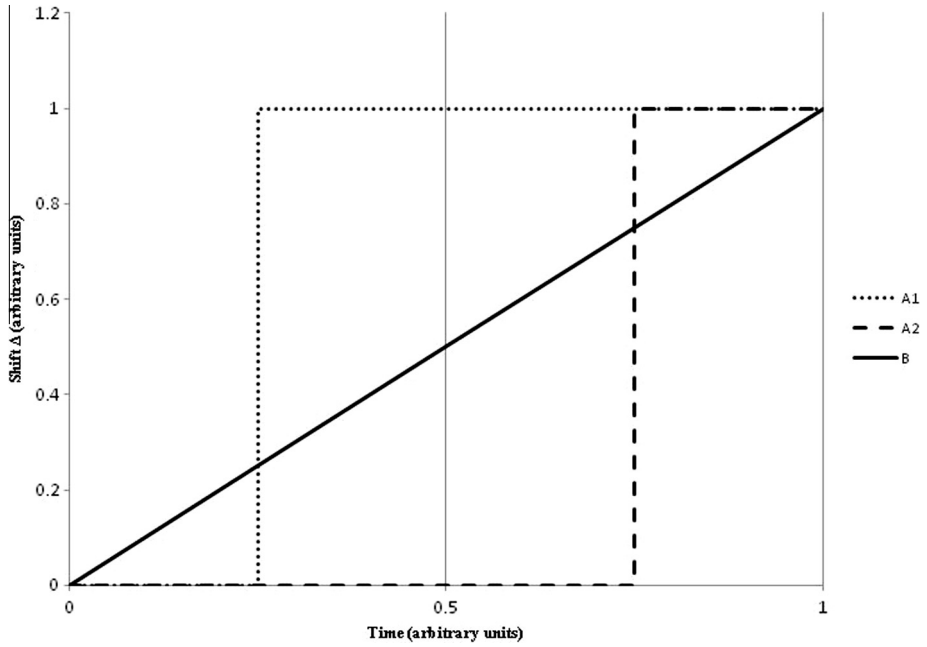

Fig. 1. Schematic presentation of possible patterns of prostate movement. The x-axis represents time, with the two images happening at times zero and 1.0, with the treatment at time 0.5. The y-axis represents shift Δ – in scenario A (dotted and dashed lines) this happens at a random time between 0 and 1, whilst in scenario B a continuous motion takes place.