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Original Paper

A general method for the definition of margin recipes depending on the treatment technique applied in helical tomotherapy prostate plans

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ABSTRACT

Purpose: To obtain specific margin recipes that take into account the dosimetric characteristics of the treatment plans used in a single institution.
Methods: We obtained dose-population histograms (DPHs) of 20 helical tomotherapy treatment plans for prostate cancer by simulating the effects of different systematic errors (Σ) and random errors (σ) on these plans. We obtained dosimetric margins and margin reductions due to random errors (random margins) by fitting the theoretical results of coverages for Gaussian distributions with coverages of the planned D99% obtained from the DPHs.
Results: The dosimetric margins obtained for helical tomotherapy prostate treatments were 3.3 mm, 3 mm, and 1 mm in the lateral (Lat), anterior-posterior (AP), and superior-inferior (SI) directions. Random margins showed parabolic dependencies, yielding expressions of $0.16\sigma^2$, $0.13\sigma^2$, and $0.15\sigma^2$ for the Lat, AP, and SI directions, respectively. When focusing on values up to $\sigma = 5$ mm, random margins could be fitted considering Gaussian penumbras with standard deviations (σ_p) equal to 4.5 mm Lat, 6 mm AP, and 5.5 mm SI.
Conclusions: Despite complex dose distributions in helical tomotherapy treatment plans, we were able to simplify the behaviour of our plans against treatment errors to single values of dosimetric and random margins for each direction. These margins allowed us to develop specific margin recipes for the respective treatment technique. The method is general and could be used for any treatment technique provided that DPHs can be obtained.

Introduction

Given the uncertainties involved in radiotherapy, a planning target volume (PTV) should be defined to ensure minimum coverage of the clinical target volume (CTV). CTV-to-PTV conversion is performed using the margins between both volumes. These margins should take into account all the uncertainties involved in a treatment planning. The approaches proposed to establish coverage criteria include dose-probability histograms [1] (with margins ensuring a probability of having a minimum dose in the CTV) and dose-population histograms (DPHs) [2,3] (in which a margin recipe is proposed to ensure that the CTV will receive a minimum dose in a given percentage of patients).

van Herk et al. [2] investigated the geometrical uncertainties (systematic and random) involved in radiotherapy and obtained their effects based on theoretical dose distributions. The authors assumed that systematic errors produced displacements of the dose distribution with respect to the CTV, while random errors were responsible for blurring the dose. This approach enabled the definition of a margin recipe that ensured that 90% of patients had a minimum CTV dose of 95%. Its simplified form was as follows [2]:

$$M = 2.5\Sigma + 0.7\sigma \quad (1)$$

The recipe assumed a series of simplifications, such as perfect conformation of the dose distribution to the PTV and modelling of the beam penumbra as cumulative Gaussian distributions.

Improvements on this recipe were proposed by McKenzie et al. [4], who presented different expressions for reduction of margins caused by random errors (random margins), depending on the beam setup of the plans. Witte et al. [5] also studied the dependence of random margins on target size and tissue density and compared random margins with those proposed in Eq. (1).

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These same principles can be directly applied to the analysis of real treatment plans. If systematic and random errors are applied to treatment plans, realistic DPHs can be obtained. van Herk et al. [6] used this method to evaluate the effect of geometric uncertainties on tumour control probability and equivalent uniform dose for perfectly conformal and realistic 3-field prostate plans.

Song and Dunscombe [7] also analysed the suitability of margins in a plan with both spherical CTV and organ at risk based on evaluation of the equivalent uniform dose in both volumes for different margins. Margin selection was based on the creation of plans with different CTV-to-PTV margins. The use of simple 3D conformal radiotherapy plans made this approach possible.

As for more complex techniques, Arnaud et al. [8] presented results for the dose delivered to the CTV in intensity-modulated radiation therapy (IMRT) for prostate cancer depending on the setup protocol and on the margins applied. Bos et al. [9] compared DPHs to determine which techniques of prostate IMRT were less sensitive to set-up errors. Gordon et al. [10] analysed the outcome of real IMRT plans for a series of geometrical uncertainties and found that clinical plans could absorb wider uncertainties than those predicted by the formula of van Herk et al. In a later study based on the same plans, Gordon and Siebers [11] attributed this discrepancy to imperfect conformance of the dose distributions and obtained the dosimetric margins of those plans by direct measurement of the distances between the PTV and the isodose of interest.

In this study, we attempt to obtain a margin recipe that takes into account the characteristics of the treatment plans obtained at specific institutions, by avoiding recipes that make general assumptions about the nature of the dose distributions. Our approach is to simulate various systematic and random errors in those plans, obtaining the DPHs for each of the error distributions. By analysing the coverage probability of a specific dose in our patient population, and comparing it with the theoretical probability given by certain margins based on Gaussian distributions, we can infer both mean dosimetric margins and mean random margins according to the treatment technique and the treatment site. Our methodology is general and can be used for any technique and treatment site, provided that simulations of the effect of geometrical uncertainties on plans are performed.

Methods

Treatment plans

We evaluated 20 tomotherapy plans delivered in our institution for prostate cancer, 11 of which involved irradiation of the prostate and seminal vesicles, 4 the prostate only, and 5 the pelvic nodes. The dose prescribed was 70.2 Gy (in 27 fractions) for prostate PTV, 54 Gy for seminal vesicles volume, and 48.6 Gy for pelvic volume. Only coverage of the prostate CTV was analysed. CTV-to-PTV margins were 7 mm in the lateral direction (Lat), 5 mm in the anterior-posterior (AP) direction, and 9 mm in the superior-inferior (SI) direction.

Calculation of dose-population histograms

DPHs represent the distribution of values of a specific dose parameter within a patient population [2]. These are characterised by geometric uncertainties that occur during the preparation of the treatment.

Two types of uncertainties – or errors – are usually defined: systematic errors and random errors. Systematic errors yield an average displacement during treatment. They are also called preparation errors, as they occur during preparation of treatment. Random errors do not imply an average error in treatment, but are responsible for the dispersion of the positions on each treatment day; therefore, they are also called execution errors [3].

The effects of systematic and random errors on dose distribution are well documented [2,3]. Random errors lead to blurring of the planned dose, while systematic errors produce a displacement of the CTV over the previously blurred dose matrix. Random and systematic errors are assumed to be normally distributed, with standard deviations σ and Σ, respectively.

In the present study, we focused on the distribution of the CTV coverage at D99% (as a representative of the minimum dose).

Random errors were simulated by convolution of the dose matrix, with 3-dimensional Gaussian matrices having standard deviations equal to σ, while the effect of systematic errors was based on the creation of 200 random displacements following Gaussian distributions with standard deviations equal to $\sum$. Two hundred displacements were used to ensure good reproducibility of results (SD = 0.3% in DPHs for D99% = 1).

This approach is valid if a series of requisites are fulfilled: the number of fractions should be sufficiently high [12], and the displacements of the beam setup inside the patient should produce only the effect of displacing the dose matrix inside the patient (shift invariance). Our treatments are administered in 27 fractions, and the characteristics of homogeneous density and anatomical situation of the CTV enable us to assume shift invariance [10,13,14].

A CTV dose-volume histogram (DVH) was obtained for each of these 200 displacements. Then, after obtaining the D99% of each DVH, DPHs representing the probability that a patient has a specific D99% or higher were calculated.

As stated above, target coverage was based on the D99% delivered to the PTV in the treatment plan. Therefore, all plans were normalised so that the D99% to the prostate PTVs had a value of 1. The coverage probability for a given systematic and random error is the value of the DPH of all plans (global DPH) at a normalised dose value of 1. The use of the planned D99% enabled us to avoid differences in dose normalisation of the plan and also has the advantage that data can be obtained based on the treatment plan itself.

Systematic error distributions were consecutively tested in each direction. This approach speeds up calculation time and allows for easy differentiation of the behaviour of the plans for each direction. Distributions of systematic errors were tested with $\sum$ from 3 mm to 15 mm in steps of 3 mm. As we were interested in values of errors that could cover a wide range of probabilities, values were chosen in order to find a suitable margin, even though they were not clinically relevant. In addition, the use of 1D Gaussian distributions (a margin of $2.5\sum$ in a 1D distribution gives a probability of 98.7% compared to 90% in a 3D distribution) and the presence of margins already applied in the treatment made it necessary to widen the $\sum$ used. In the case of random errors, the values used were $\sigma = 0$ mm, 3 mm, 4.5 mm, 6 mm, and 7.5 mm. Due to the low effect of random errors on margins, the lowest value of σ used was 3 mm. Below this, the effect on margin reduction is so small that it could not be calculated accurately. The largest values of σ were used (even though they are too high to be found in clinical practice) in order to achieve a sufficiently accurate empirical expression of margins.

Margin formula

Assuming that systematic errors follow a normal distribution, the DPH at a specific dose is the probability obtained from the integration of a normal 3D distribution function over the volume within certain limits, as follows:

$$Q = \frac{1}{\sqrt{(2\pi)^3 \Sigma_x \Sigma_y \Sigma_z}} \int_{\bar{M}_{tot}} e^{-\frac{1}{2}\left(\frac{x^2}{\Sigma_x^2}+\frac{y^2}{\Sigma_y^2}+\frac{z^2}{\Sigma_z^2}\right)} d^3\vec{x} \quad (2)$$