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Influence of the electron energy and number of beams on the absorbed dose distributions in radiotherapy of deep seated targets

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HIGHLIGHTS

- Technical requirements to be met in VHEET are established for the irradiation of prostate tumors.
- Optimization of beam energy as a function of number of beams is provided.
- Behavior of the non-tumor integral dose as a function of both energy and number of beams is examined.

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ABSTRACT

With the advent of compact laser-based electron accelerators, there has been some renewed interest on the use of such charged particles for radiotherapy purposes. Traditionally, electrons have been used for the treatment of fairly superficial lesions located at depths of no more than 4 cm inside the patient, but lately it has been proposed that by using very high energy electrons, i.e. those with an energy in the order of 200–250 MeV it should be possible to safely reach deeper targets. In this paper, we used a realistic patient model coupled with detailed Monte Carlo simulations of the electron transport in such a patient model to examine the characteristics of the resultant absorbed dose distributions as a function of both the electron beam energy as well as the number of beams for a particular type of treatment, namely, a prostate radiotherapy treatment. Each treatment is modeled as consisting of nine, five or three beam ports isocentrically distributed around the patient. An optimization algorithm is then applied to obtain the beam weights in each treatment plan. It is shown that for this particularly challenging case, both excellent target coverage and critical structure sparing can be obtained for energies in the order of 150 MeV and for as few as three treatment ports, while significantly reducing the total energy absorbed by the patient with respect to a conventional megavoltage x-ray treatment.

1. Introduction

The use of electron beams in radiotherapy has been usually confined to the treatment of superficial lesions, namely skin cancer, chest wall irradiation in breast cancer patients, and head and neck cancers. One disadvantage of electrons when compared to other types of charged particles, such as protons or heavy ions, is their relatively low mass, which in turn results in highly irregular trajectories as they scatter through a medium at the energy range currently employed in radiotherapy, namely 4–20 MeV. Although the use of very high energy electron beams in radiotherapy (VHEET), ranging from 150 to 250 MeV, has been suggested by several authors in the last 12 to 14 years (DesRosiers et al., 2000; Yeboah and Sandison, 2002), it has not been until more recently, with the advent of compact laser-based electron accelerators, that researchers and clinicians are starting to consider VHEET as a feasible alternative to current radiotherapy technologies based on x-rays and heavy charged particle accelerators (DesRosiers et al., 2008; Fuchs et al., 2009; Moskvin et al., 2010). As the latter technologies are quite established and mature, it is important to fully assess the characteristics of the resultant absorbed dose distributions of VHEET as a function of both beam energy and number of treatment ports in order to establish a baseline of technological requirements to be met if this treatment modality is to be clinically implemented. While several of the previously cited works have explored different aspects of the electron irradiation of deep-seated targets, prostate in particular, a systematic analysis with regards to the effect that a variation in both the electron energy and number of beams has on the absorbed dose distributions for this type of treatment is lacking. In this work, using a realistic patient model and full Monte Carlo

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simulation of the electron transport in such a patient, we evaluate these two important treatment parameters in order to determine their impact on target coverage, sparing of critical structures and the total energy absorbed by the patient, i.e. the non-tumor integral dose (NTID).

2. Materials and methods

2.1. Patient model

The voxelized Zubal phantom (Zubal et al., 1994) was used to model a prostate radiotherapy treatment. This phantom consists of segmented CT scan images of a male patient and has a voxel resolution of 0.38 cm in each of the main axes. A portion of the phantom at the pelvis level was extracted and the arms were digitally removed. The total number of transverse slices used in this work is 80. The composition of 7 different materials present in the phantom was taken from ICRU Report 44 (1989), the materials being air, bone, skeletal muscle, soft tissue, blood, and bone marrow. Water was used to model the urine and feces. For the prostate treatment, the planning target volume (PTV) was formed by the addition of a 1 cm margin in all directions around the prostate, the gross target volume (GTV), except towards the rectal wall where a margin of 0.5 cm was used, as it is customary in this type of treatment (Bentel, 1996). The PTV thus obtained was used in all the treatments reported in this work.

2.2. Electron beam model

It is assumed that a collimation device is available that produces electron beams that conform to the PTV. This collimation could be achieved, for example, by magnetically scanning an electron pencil beam (Fuchs et al., 2009) or by an external collimating device (Ma, 2004; Gauer et al., 2006). A separate computer program was written to determine each beam aperture by means of raytracing through the Zubal phantom using the Siddon algorithm (Siddon, 1984). It is further assumed that the geometry of the accelerating machine is such that it permits an isocentric delivery of the treatment, with the isocenter located at 100 cm from the electron source and that the electrons travel in air before reaching the patient. With regards to the electron energy spectra, it has been previously shown that, for the electron beams produced in laser-based accelerators, the use of a mono-energetic beam or one with the full energy spectrum is virtually indistinguishable in terms of the dose distributions (Fuchs et al., 2009), so in this work we restrict ourselves to the use of mono-energetic electron beams of energies 75, 100, 150, 200, and 250 MeV. Following the work of Fuchs et al. (2009) the electron source is assumed to be a point located at 100 cm from the isocenter, with a Gaussian angular distribution and a divergence of 6 mrad at FWHM. As a reference, a standard 6-field 15 MV x-ray prostate 3D conformal radiotherapy treatment (3DCRT) was also calculated in order to make a comparison between the high energy electrons and the current clinical practice with photons, using the same PTV as for the electron beam treatments. The source is placed at 100 cm from the isocenter and again raytracing was used to determine the beam aperture to conform to the PTV for each beam. The x-ray spectrum for these simulations was taken from the literature (Garnica-Garza, 2008).

2.3. Monte Carlo simulations

The Monte Carlo code PENELOPE (Salvat et al., 2006) and its auxiliary set of subroutines from the PenEasy suite (Sempau, 2006), which allows the simulation of radiation transport in voxelized geometries, were used to determine the absorbed dose distributions in the patient model. For each beam, at least 1×108 histories were simulated, achieving an uncertainty at the 1% level for those voxels receiving at least 50% of the maximum dose. Electron and photon cutoff energies were set at 100 keV, while parameters c1 and c2 were both set at 0.1. These latter parameters determine the mean free path between hard elastic collision and the maximum fraction of the electron energy lost in each step respectively.

2.4. Cimmino optimization algorithm

In order to determine each beam weight according to the prescription goals, an in-house optimization program based on the Cimmino algorithm was used (Garnica-Garza, 2011). Table 1 shows the prescription parameters used for the optimization runs. Upon termination, the software delivers each beam weight as well as treatment plan evaluation metrics such as cumulative dose volume histograms (cDVH) for the structures of interest and the NTID. In order to perform a meaningful comparison among all the different treatment plans, after the optimization each plan was renormalized so that the minimum dose imparted to the GTV is the prescribed dose, 72 Gy in this case. In order to assess the influence of the number of treatment ports on the absorbed dose distributions, the algorithm was separately run with 9, 5 and 3 beams made available to the optimization engine. The beam entrance angles for each beam in ever treatment plan calculated in this work are shown in Table 2.

3. Results and discussion

3.1. GTV dose uniformity and PTV coverage versus beam energy

Fig. 1a) and b) shows the cDVH for the GTV, the prostate gland, and the PTV, for the 9 beam treatment technique, normalized to the prescribed dose of 72 Gy, while Fig. 2 shows the relevant data with regards to minimum, maximum and average absorbed doses in these two target structures. With regards to GTV dose uniformity, Figs. 1 and 2a), show that for electron energies at or above 150 MeV, the GTV dose uniformity is virtually the same as that for

Table 1
Parameters used in the beam weight optimization algorithm. The structure weight refers to the importance assigned to the dose objectives for each structure, and their sum equals 1.

Structure	Minimum dose (Gy)	Maximum dose (Gy)	Structure weight
GTV	72.0	75.0	0.4
PTV	65.0	75.0	0.4
Rectal wall	0.0	65.0	0.18
Bladder	0.0	65.0	0.01
Femoral heads	0.0	40.0	0.005
Skin	0.0	40.0	0.005

Table 2
Beam entrance angles in each of the treatment techniques modeled in this work. The 0° beam is defined as the left lateral beam.

Treatment technique	Beam entrance angle
VHEET 3 beams	90°, 235°, 305°
VHEET 5 beams	45°, 90°, 135°, 235°, 305°
VHEET 9 beams	45°, 90°, 135°, 170°,215°, 235°, 270°, 305°, 350°
15 MV photons	0°, 45°, 90°, 135°, 225°, 315°