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Original paper

Monte Carlo modeling of converging small-field contrast-enhanced radiotherapy of prostate

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ABSTRACT

Radiation therapy using a kilovoltage X-ray source to irradiate a target previously loaded with a radiological contrast agent, contrast-enhanced radiotherapy (CERT), has been shown both theoretically and in a preliminary experimental study to represent a potential alternative to high-energy treatments. It has also been shown, however, to produce an integral dose that can be up to twice that resulting from a conventional megavoltage treatment. In this work, using a realistic patient model and Monte Carlo simulation, a CERT prostate treatment plan is designed that makes use of a plurality of small circular beams aimed at the target in such a way as to minimize the radiological trajectory to the target volume. Gold nanoparticles are assumed to be the contrast agent. Two cases are examined, one with a concentration level in the target of 10 mg-Au per gram of tissue and the second with a concentration of 3 mg-Au per gram of tissue in the target. A background concentration of 1 mg of contrast agent per gram of tissue was assumed everywhere else in both cases. The Cimmino feasibility algorithm was then used to find each beam weight in order to obtain the prescribed target dose, set at 72 Gy to 100% of the tumor volume. It is shown that the approach using the small circular fields, a radiosurgery treatment, produces treatment plans with excellent absorbed dose distributions while at the same time it reduces by up to 60% the non-tumor integral dose imparted to the irradiated subject. A brief discussion on the technology necessary to clinically implement this treatment modality is also presented.

Introduction

A radiological contrast agent incorporated into a target volume subsequently irradiated with a kilovoltage X-ray beam has been shown to greatly enhance the local absorption properties of such a target by increasing in up to three orders of magnitude the absorption efficiency through the photoelectric effect [1–7]. This potential treatment modality, usually referred to as Contrast-Enhanced Radiotherapy (CERT) [8], has been shown to be able to treat tumors at depth with resultant absorbed dose distributions which compare favorably to those obtained with high-energy treatment machines [9–11]. However, while the absorbed dose distributions are acceptable, the non-tumor integral dose (NTID), the total energy deposited outside of the treatment volume, imparted to the irradiated subject can be up to twice as high as that delivered by the high-energy machine for an equivalent treatment, with the worst case being the irradiation of tumors at depths of about 10 cm, such as is the case for prostate [12,13]. Whereas integral dose is not typically a treatment parameter taken into consideration during the planning process, under some circumstances, particularly for younger patients, a higher NTID would represent a serious disadvantage for this treatment modality, since integral dose correlates with late reactions such as secondary malignancies.

Therefore, it might be desirable to determine if by means of a different treatment technique it would be possible to obtain CERT treatment plans which, without degrading the quality of the plan, could offer a lower NTID. For megavoltage therapy it has been shown that, regardless of the treatment site, the integral dose is basically insensitive to the number, weight, and angular orientation of the beams used in the treatment and that it increases with decreasing beam energy [14], and therefore, for a given treatment site and beam energy the only way to reduce the integral dose is to in turn reduce the amount of irradiated volume by the use of apertures that better conform to the target, a standard practice nowadays, and by shortening the radiological pathlength that the radiation beam must traverse before reaching the target. In CERT, due to the weak penetration power of kilovoltage X-ray, shortening the pathlength of the X-ray beam before reaching the target is furthermore necessary in order to increase the absorbed dose at

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depth per unit of fluence incident on the surface. Some radiosurgery treatment strategies make use of a plurality of circularly-shaped beams aimed to the target volume from positions distributed spherically around the patient [15]. We hypothesize that in CERT, by selecting the position of each of such beams, with small cross sections, so that the radiological distance from the entrance to the target point is minimized, it may be possible to irradiate a target volume to a desired level of absorbed dose while at the same time reducing the NTID. The purpose of this paper is to obtain the dosimetric characteristics of CERT treatments for which a converging small-field treatment approach has been employed and to determine if with such an approach a reduction in the NTID can be achieved. It will be shown that this is indeed the case and that, while the NTID is still higher when compared to a conventional megavoltage treatment, the reduction is nevertheless substantial and that therefore, if CERT treatments are to be clinically implemented, the technique and method presented in this paper should be used for the treatment planning of targets at depth.

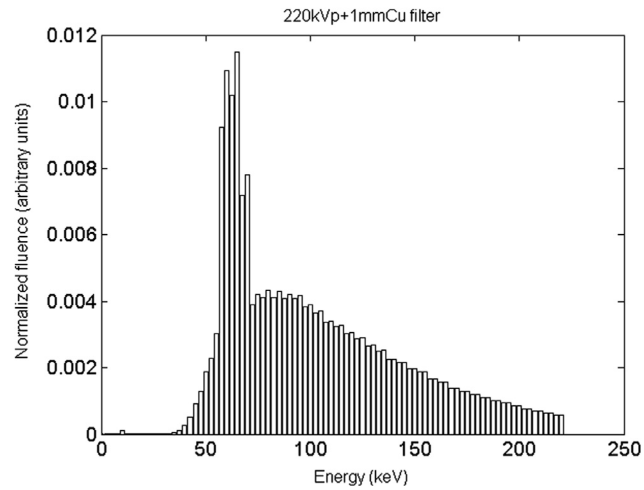

Figure 1. Geometry for the irradiation with 3 non-coplanar 360° arcs.

Materials and methods

Patient model

The voxelized Zubal phantom [16], from which a portion at the pelvis level had been previously extracted, was used to represent a realistic patient model. The voxel resolution in this phantom is 0.38 cm. The composition of the different tissues in the phantom was taken from ICRU report 44 [17] while water was used to model urine and feces. Gold nanoparticles were used as the contrast agent [5] and two clinical situations were examined: in the first, a concentration of 10 mg-Au/g of tissue is assumed to be present in the target, while in the second case a concentration of 3 mg-Au/g of tissue in the target is considered. In both situations, it is assumed that 1 mg-Au/g of tissue is present everywhere else except bone, in order to take into account the possibility of contrast agent leakage to adjacent structures and tissue.

The X-ray beam and energy spectrum

Monte Carlo simulation was used to model the X-ray source, a Phoenix XS225D (GE Inspection Technologies) which has a tungsten target and a beryllium window with a thickness of 0.5 mm. This system is capable of producing X-ray beams with a peak energy that can be continuously varied from 20 keV up to 225 keV. For this work, a 220 kVp spectrum filtered by 0.1 cm of copper was used, as it has been shown that it renders treatment plans with quite acceptable absorbed dose distributions for both prostate and brain tumors [11,13]. Figure 1 shows the X-ray spectrum produced by this source. We also calculated the number of photons per incident electron on the target when the beam is collimated to produce a circular beam 2 cm in diameter at a distance of 80 cm from the source. This will allow estimating treatment times.

Treatment plan design

In all the treatment plans presented in this work, a 2 cm margin was added to the prostate to form the planning target volume (PTV) in all directions except in the posterior direction where only a 1 cm margin was added in order to spare the rectum, as is customary in prostate radiotherapy [18].

Treatment plan with 3 non-coplanar 360° arcs

The non-coplanar arcs are modeled as if delivered from a standard CT scanner: standard CT scanners have the capability of tilting the whole gantry up to ±20° from the straight up position. In this work, we have assumed that the treatment arcs are delivered at −20°, 0° and 20° with a full rotation of the X-ray tube for each case. The full rotation is modeled by using 36 static beam ports uniformly distributed around the patient, so for this treatment a total of 108 beams are used. It has been assumed that the CT scanner is fitted with a beam shaping device so that from each direction the beam is collimated to project to the beam's eye view of the target. Raytracing [19] was used to determine the aperture for each beam port in order to conform to the PTV. Figure 2 shows the geometry of these simulations. The non-coplanar plans were used as the reference for the integral dose comparison.

Converging small-field treatment plan

A separate computer program was written to determine the position from which each of the circular small-field beams was aimed at the target. The program uses raytracing [19] to calculate the radiological pathlength between a given point inside the target and another point located on a grid laid out externally to the

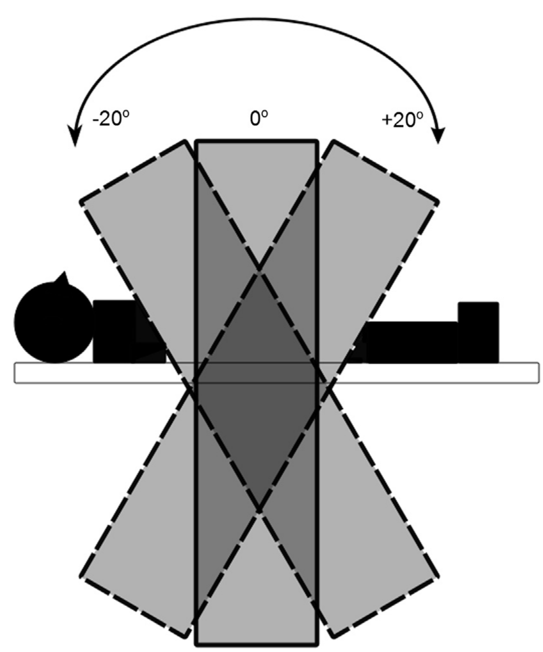

Figure 2. Spectrum from a Phoenix XS225D X-ray tube, calculated with Monte Carlos simulation.