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Clinical simulations of prostate radiotherapy using BOMAB-like phantoms: Results for photons

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HIGHLIGHTS

► Dosimeters used (TLD, OSL and RPL) are suitable for out-of-field dosimetry.
► Generally agreement is within 3% compared with ion chamber reference measurements.
► Peripheral doses for the same PTV can vary by a factor of 4 for various modalities.
► Results revealed that the TPS used, regularly underestimated out-of-field doses.

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ABSTRACT

In this part of work carried out by Working Group 9 (Radiation Protection Dosimetry in Medicine) of the European Radiation Dosimetry Group (EURADOS), water tank experiments described in this issue (Bordy et al., 2013) were extended to a BOMAB-like phantom. This phantom is more clinically realistic than a water tank, sufficiently to allow the simulation of some clinical treatments. In the experiments to be described, four types of prostate treatment were simulated: Volumetric Modulated Arc Therapy (VMAT, 6 MV), Tomotherapy (6 MV), IMRT (6 MV and 18 MV), 5-field conformal radiotherapy (15 MV) and 4-field conformal radiotherapy (6 MV and 18 MV). Irradiations were performed in two centres, University Hospital of Santa Chiara, Pisa, Italy and Centre of Oncology M. Skłodowska-Curie Memorial Institute, Krakow, Poland. Whatever the difficulties and uncertainties in risk estimation, its foundation lies in the knowledge of the absorbed dose to the irradiated organs. Thus the measurement of out-of-field doses is a crucial pre-requisite for risk estimation and is the subject of the EURADOS Working Group 9. For photon out-of-field dose measurements TLD, OSL and RPL dosimeters were used. Comparison of dosimeters under the same irradiation conditions showed that dosimeters generally agreed to within 3% compared with ion chamber reference measurements. Other comparisons were possible with these data. They include a comparison of doses (beam profiles) in different positions in the BOMAB phantom, a comparison of different treatment modalities in the two contributing clinical centres (Pisa and Krakow) and a comparison of dose profiles resulting from the different treatment techniques and the corresponding doses calculated by the treatment planning systems used to generate the treatment plans. Finally, preliminary measurements of surface doses at selected points on the trunk of the BOMAB phantom were made using diode detectors. Comparison of out-of-field doses for different modalities in the two clinical centres shows that differences in out-of-field doses for the same Planning Treatment Volume (PTV) can be even a factor of 4. For sparing adjacent organs-at-risk the best results were obtained for IMRT. On the other hand the lowest out-of-field doses were for MLC conformal therapy.

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1. Introduction

The greatest challenge for radiation therapy or any cancer therapy is to attain the highest probability of cure with the least morbidity. The simplest way in theory to increase this therapeutic ratio with radiation is to encompass all cancer cells with sufficient doses of radiation during each fraction, while simultaneously sparing surrounding normal tissues. The induction of cancers following radiotherapy (second cancers) has been known for many years although the estimation of the probability of radiation carcinogenesis is not straightforward. The overall cancer risk is influenced by the (usually non-uniform) dose to several radiosensitive organs distant from the radiotherapy target volume. Improvements in cancer treatment have increased survival times and thus increased incidence of second cancers may be expected in the future. In addition, increased whole body exposure may result from developments in radiotherapy. Starting with two-dimensional (2D) treatments, external radiotherapy consisted of a single beam from one to four directions. Beam setups were usually quite simple; plans frequently consisted of opposed lateral fields or fourfield "boxes". 3D conformal radiotherapy (3DCRT) is the term used to describe the design and delivery of radiotherapy treatment plans based on 3D image data with treatment fields individually shaped (advanced types use multi-leaf collimators (MLCs)) to treat only the target.

Conformal radiotherapy permits the delivery of a radical tumour dose while limiting the dose to normal tissue structures, thus minimising the adverse effects of treatment. As its name implies, Intensity-Modulated Radiation Therapy (IMRT) allows modulation of the intensity of each radiation beam, so that each field may have one or many areas of high intensity radiation and any number of lower intensity areas within the same field, thus allowing for greater control of the dose distribution with the target. In conjunction with Image-Guided Radiotherapy (IGRT) this approach should give better clinical results, with regard to both improved tumour control and sparing of organs-at-risk (OAR). On the other hand, increased whole body exposure may result (IAEA, 2008; Bucci et al., 2005). In addition, a variety of novel IMRT delivery methods have been investigated. One of these is Tomotherapy (or Helical Tomotherapy), in which the radiation is delivered slice-by-slice. Tomotherapy achieves higher spatial resolution than step-and-shoot IMRT, but requires longer delivery time and more monitor units (MUs) during daily treatment. As the number of MUs required for treatment delivery increases, so does the primary beam leakage dose (Mackie et al., 1993; Mutic and Low, 1998). Another approach, called "Volumetric Modulated Arc Therapy" (VMAT) proposed by Otto (2008) uses a dynamic modulated arc to deliver IMRT. The VMAT technology simultaneously coordinates gantry rotation, MLC motion, and dose rate modulation, facilitating highly conformal treatment and optimal sparing of the critical structures around the target (Pardo-Montero and Fenwick, 2009). VMAT appreciably reduces beam-on times in comparison with IMRT (Zhang et al., 2010). Recently there have been a number of published papers dealing with comparison of 3DCRT, IMRT and novel forms of IMRT: VMAT and Tomotherapy with regard to plan qualities and treatment efficiency for prostate cancer (Aoyama et al., 2006; Palma et al., 2008; Wolff et al., 2009; Aznar et al., 2010; Zhang et al., 2010; Tsai et al., 2011) and for other cancer types (Bertelsen et al., 2010; Viellot et al., 2010; Lee et al., 2011; Lu et al., 2012). However, there are still insufficient data on the comparative measurement of out-of-field doses for these radiotherapy modalities and their influence on second cancer risk.

In the experiments to be described, four types of prostate treatment were simulated: VMAT, 6 MV, Tomotherapy (6 MV), IMRT (6 MV and 18 MV), 5-field conformal radiotherapy (15 MV) and 4-field conformal radiotherapy (6 MV and 18 MV). Irradiations were performed in two centres, University Hospital of Santa Chiara, Pisa, Italy and Centre of Oncology M. Skłodowska-Curie Memorial Institute, Krakow, Poland.

Whatever the difficulties and uncertainties in risk estimation, its foundation indisputably lies in the knowledge of the absorbed dose to the irradiated organs. Thus the measurement of out-of-field (sometimes referred to as peripheral) doses is a crucial prerequisite for risk estimation. Prostate treatments have been identified as a valuable benchmark for analysis by this Working Group. The prognosis for these patients (and those undergoing some other cancer treatments involving radiotherapy) has steadily improved (Harrison, 2013 according to CRUK, 2012). This means that an increasing number of patients will survive for periods comparable to or greater than the latent period (5 years–10 years or more) for expression of a second cancer, thus suffering a finite risk of carcinogenesis.

Dosimetry measurements were extended from water tank experiments to a BOMAB-like phantom. This phantom is more clinically realistic than a water tank, sufficiently to allow the simulation of some clinical treatments as it is composed of body, legs, arms and head sections in the form of water tanks of circular or elliptical cross section. The reason for using the BOMAB design was to have an intermediate phantom between a water tank and a realistic anthropomorphic phantom. It has the advantage of being "body" shaped, but its elliptical cross section makes it easier to model. Thus the results from this phantom are useful mainly for comparison with dose calculation algorithms (not for organ dose and risk estimates) and for comparison between dosimeters.

For photon dose measurements, thermoluminescence (TL), optically stimulated luminescence (OSL) and radiophotoluminescence (RPL) dosimeters were used. Dosimeters were first irradiated under the same irradiation conditions in a water tank and compared with ion chamber reference measurements. Other comparisons were possible with this data. They include a comparison of doses (beam profiles) in different positions in the BOMAB phantom, a comparison of different treatment modalities in the two contributing clinical centres (Pisa and Krakow) and a comparison of dose profiles resulting from the different treatment techniques and the corresponding doses calculated by the treatment planning systems used to generate the treatment plans. Finally, preliminary measurements of surface doses at selected points on the trunk of the BOMAB phantom were made using diode detectors. The aim is to investigate the possible relationships between surface doses and underlying doses within the phantom and thus to explore potential practical ways in which organ and tissue doses may be estimated when full-scale simulation is not possible in the clinic.

2. Material and methods

2.1. Treatment features

Treatment modalities for the clinical simulation of prostate therapy shown in Table 1 were performed mainly in two centres, University Hospital of Santa Chiara, Pisa, Italy and Centre of Oncology M. Skłodowska-Curie Memorial Institute, Krakow, Poland. Only Tomotherapy was performed in Campo di Marte Hospital in Lucca, Italy. For 15 MV 5-field MLC and 6 MV IMRT in Pisa, the treatment planning system (TPS) was a CMX XiO Rel. 4.40.05. For VMAT ("RapidArc" Varian implementation) a VARIAN Eclipse External beam Planning vers. 8.6 was used and for Tomotherapy (HI-ART TomoTherapy), a TomoHD treatment system – TomoDirect™ Treatment Delivery Mode. For 4-field MLC and IMRT in Krakow, the TPS was Eclipse 8.6 (Varian). The value of monitor