

Out-of-field dose measurements in radiotherapy – An overview of activity of EURADOS Working Group 9: Radiation protection in medicine

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Out-of-field dose measurements in radiotherapy - Activity of EURADOS WG9: Radiation Protection in Medicine

Abstract

This review of dosimetry for second cancer risk estimation introduces work carried out by Working Group 9 (WG9: Radiation Protection Dosimetry in Medicine) of the European Radiation Dosimetry Group (EURADOS). The work concentrates on the measurement of outof-field doses in water tanks and BOMAB-like phantoms using a variety of dosimeters to measure photon and neutron doses. These include optically stimulated luminescence (OSL), radiophotoluminescence (RPL) and thermoluminescence (TLD) dosimeters for photon dosimetry (together with ion chambers for reference measurements) and track etch and superheated emulsion detectors for neutron measurements. The motivation of WG 9 was to assess undue, non-target patient doses in radiotherapy and the related risks of secondary malignancy. Improvements in cancer treatment have increased survival times and thus increased incidence of second cancer may be expected in the future. In addition, increased whole body exposure may result from some developments in radiotherapy. This means that radiotherapy clinics will need to simulate their treatments in order to estimate and minimize doses to healthy tissues and organs. The proposed work is designed to generate a robust dataset of out-of-field dose measurements which can be used for the development and validation of dose algorithms.

Keywords: Out-of-field doses in radiotherapy; RPL; TLD; OSL, Superheated emulsion detectors, Track etch PADC detectors, IMRT; VMAT; Tomotherapy

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 (IGRT) and associated developments in dose delivery, e.g. Tomotherapy and Volumetric Modulated Arc Therapy (VMAT). However, there are still insufficient data on the comparative measurement of out-of-field doses for these radiotherapy modalities to determine their influence on second cancer risk.

Irrespective of difficulties and uncertainties in risk estimation, its foundation undoubtedly lies in the knowledge of the absorbed dose to irradiated organs. Thus the measurement of outof-field (sometimes referred to as peripheral) doses is a crucial pre-requisite for risk estimation. The main photon contributions to out-of-field doses are (i) scattered radiation from the interaction of the primary beams with the patient (ii) scattered radiation from the treatment head, including the collimators and (iii) leakage from the target. The determination of patient whole-body exposures requires experimental measurements since treatment planning software is rarely accurate beyond some centimeters from the edge of the treatment volume (Cadman et al., 2002; Martens et al., 2002; Sohn et al., 2003; Molineu et al., 2005; Howell et al., 2006; Howell et al., 2010). Two additional limitations of treatment planning software are that radiation leakage through the accelerator head is not always considered and that the possible photoneutron contamination of the X-ray or electron beam is never included. For endpoint energies greater than approximately 8 MV, there are dose contributions from fast neutrons from (γ, n) reactions in high-Z materials in the treatment head. The average energy of neutrons produced in the X-ray target and in the beam flattening filter are similar to those of fission neutrons, i.e. in the 1-2 MeV range. Once transmitted through the massive shielding and collimation systems (usually of lead or tungsten) of the accelerator head, these

neutrons present a strong spectral degradation. Their average energy is typically below 1 MeV (NCRP, 1984). In addition, a "cloud" of lower energy neutrons is generated in the treatment room due to multiple scattering events in the walls, floor, and ceiling and in other large structures such as accelerator gantry, patient couch, and shielding maze. The result is a broad polyenergetic neutron field, with a strong spatial dependence of the spectrum.

Prostate cancer was considered a good case to study because it involves a solid tumor, with a well-defined target volume, and because it affects a large population of patients whose life expectancy is increasing both thanks to improving treatment techniques and to earlier diagnosis (Harrison, 2013).

Dosimetry measurements were started at the calibration facility for radiotherapy dosimeters of the CEA/LIST Laboratoire National Henri Becquerel (LNHB), which is the French national laboratory of metrology for ionising radiations. The objective of this work was to evaluate the current methods of measuring three-dimensional dose distributions in and around the target volume using a water tank, to derive the leakage dose from the head of the medical linear accelerator (LINAC) and the doses due to scattered radiation from the collimator edges and the body (simulated by a water tank phantom)

In the clinical simulations which followed this work, four types of prostate treatment were simulated: VMAT (6 MV), Tomotherapy (6 MV), IMRT (6MV 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, the University Hospital of Santa Chiara, Pisa, Italy and the Centre of Oncology M. Skłodowska-Curie Memorial Institute, Krakow, Poland. Dosimetry measurements were extended from water tank experiments to a BOMAB-like phantom. This phantom is more clinically realistic than a water tank and sufficient to allow the simulation of some clinical treatments (Fig 1). However, 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. The photoneutron dose measurements were carried out by means of superheated emulsions (SE) and Poly-Allyl-Diglicol-Carbonate (PADC) solid state nuclear track detectors from the Universitat Autònoma de Barcelona (UAB). Two types of SE detectors were used: superheated drop detectors (SDD - UNIPI) and bubble damage detectors (BDT and BD PND), produced by Bubble Technology Industries (BTI).

2. Material and Methods

2.1 Calibration facility

Prior to irradiations using a reference clinical linac, photon dosimeters were calibrated under standard calibration conditions using a 60 Co source as described in IAEA TRS 398 (2000). Then, dosimeters (both photon and neutron) were compared in a reference clinical linac (Saturn 43) beam in a water tank at CEA-LIST/ LNHB, Saclay. Radiation qualities of 6, 12 and 20 MV were used. The reference calibration point in the water phantom was at a depth of 10 cm in water, on the central axis of the beam, with a field size of 10 x 10 cm². Doses were measured in the water tank over an axial distance of approximately 50 cm, at positions along a pipe (the beam axis was at 13.5 cm distance from the phantom inner wall). The reference values were measured with an ionisation chamber (type NE 2571) traceable to French national standards. (Bordy et al., 2013).

2.2 Radiation treatment features

Simulated clinical treatment regimens were then carried out at two large medical centers, the Santa Chiara University Hospital in Pisa, Italy (6 MV IMRT and VMAT, 15 MV 5-field MLC) and the Centre of Oncology M. Sk1odowska-Curie Memorial Institute in Krakow, Poland (6 and 18 MV IMRT and 6 and 18 MV 4-field MLC). Both centers are equipped with Varian 2300 CD linear accelerators (Varian Medical Systems, Palo Alto, CA) and complementary ancillary equipment. The IMRT treatments were designed with the same planning software in Pisa and Krakow; conversely, different software was used for the multileaf-collimator irradiations, which were based on 5 fields in Pisa and on 4 fields in Krakow.

The full range of X-ray beam energies and further details on the treatment modalities, including the treatment planning systems (TPSs), are reported in papers by Di Fulvio et al. (2013a) and Miljanić et al. (2013). All results are presented for a dose of 2 Gy at the isocentre.

2.3 Phantom and dosimeter positioning

In the experiments conducted at the CEA/LIST metrology laboratory, a 60 cm \times 30 cm \times 30 cm water-filled phantom with 15 mm thick (except along the beam axis where they were 4

mm thick) PMMA walls was used. The axis of irradiation was horizontal, and the beam size at 10 cm depth in phantom was 10 cm x 10 cm. A thickness of about 40 cm of water lay outside the direct beam. In this phantom, the dosimeters were mounted in "pipes" and their position fixed using PMMA spacers. Five frames were laid out at depth increments of 5 cm along the beam axis. Each frame contained 5 pipes mounted in a vertical plane. Therefore, depth doses along the beam axis and profile at various depths were measured.

The clinical treatment simulation campaigns were conducted using a modified version of the BOttle Mannikin ABsorber (BOMAB) phantom (Bush, 1949) developed at the University of Pisa for this work (Di Fulvio et al., 2013a) (Fig. 1). The reproducible positioning of the dosimeters inside the phantoms was achieved thanks to a series of polymethyl methacrylate (PMMA) channels ("pipes") forming a square lattice geometry; positioning was consistent with the water tank phantom used in Saclay. Doses were measured in the BOMAB phantom over an axial distance of approximately 50 cm, at positions along five pipes, one on the longitudinal axis of the phantom and the remaining four adjacent and parallel. Rod elements with recesses for dosimeters were placed in the pipes. A BOMAB CT scan and simulated organs are shown in Fig. 2. We should emphasise some limitations of the "organ" dose concept using BOMAB phantom. These organs ("prostate", "bladder", "rectum") will receive scatter from the PMMA "lungs" whereas in reality we might expect these doses to be lower because of the decreased scatter from real lung. Also, positions and dimensions representing the rectum and bladder in the rods are only approximate. The organs' positions and dimensions were exactly the same in Pisa and Krakow irradiations but it was not possible to have exactly the same treatment plans.

2.3 Dosimetry methods

Photon dosimetry methods applied were thermoluminescence (TL), types MTS-7 and TLD-700, radiophotoluminescence (RPL) rod glass elements type GD-352M and optically stimulated luminescence (OSL) type nanoDotTM. The basic principles of the methods, their characteristics, methods of their calibration and use have been described by Knežević, Stolarczyk, et al. (2013).

Neutron detectors applied in this work were superheated emulsions (superheated drop detectors - SDD and bubble damage BTI-detectors) and Poly-Allyl-Diglicol-Carbonate (PADC) solid state nuclear track detectors. The basic principles of the methods, their characteristics, procedures of their calibration and readout have been described by Di Fulvio et al. (2013b).

2.4 Estimation of the components of the peripheral doses

In a second set of experiments performed with the water tank in Saclay, the objective was to estimate the components of the peripheral doses; scattered radiation from the interaction of the primary beams with the water, scattered radiation from the treatment head, including the collimators and the leakage from the head of the LINAC. Details of the experiment similar to that previously carried out by Kase et al. (1983) have been described by Bordy et al. (2013).

3. Results

3.1 Comparison of dosimetry systems

Comparison of the profile measured with the 4 types of passive dosimeter and the ionisation chamber at 10 mm depth for 12 MV radiation quality (Bordy et al., 2013) is shown in Fig. 3.

The over-response of OSL dosimeters for energies lower than 200 keV, leads to an overestimation of the absorbed dose in the scatter region (Fig. 3) whilst a good agreement is found between TLD, RPL and ionisation chamber measurements; this over response of OSL is larger as the distance from the beam axis increases. The proportion of the fluence and the energy fluence for energies lower than 200 keV were calculated using the Monte Carlo code PENELOPE (Bordy et al., 2013). Correction factors for OSL were used for the second set of experiments and for the clinical irradiations.

For the dose at the isocentre, compared to the ionisation chamber the deviation for the TLDs is less than 1.5%, for corrected OSL a systematic underestimation up to 4% is found while for the RPL dosimeter (type GD-352M) a systematic overestimation of 13.5%, 23.0% and 27.5% is found for the radiation qualities 6, 12 and 20 MV, respectively (in Fig. 3 this is shown for 12 MV). This can be attributed to the influence of the tin cap covering the RPL detector. A correction similar to the one provided for OSL could be calculated if this dosimeter is used for measurements inside the beam without a dedicated calibration. Another posibility is to use RPL types GD-301 or GD-302M (without a Sn filter) in the target volume which did not show an over-response for high energy photons (Mizuno et al, 2008 and Rah et al, 2009). Since the objective is to measure out-of-field doses, corrections for this over-response have not been made as part of this work.

Comparison of TLD and RPL with a reference ionisation chamber (IC) for all three radiation qualities gives the following results: The mean ratios with standard deviations for doses in the out-of-field region in the range from 1.5 to 150 mGy were within 3%: (i) 6 MV:

TLD/IC = 0.982±0.027; RPL/IC = 0.976±0.034, (ii) 12 MV: TLD/IC = 0.997±0.025; RPL/IC = 1.029±0.025, (iii) 20 MV: TLD/IC = 0.999±0.046; RPL/IC = 1.027±0.041.

Variation of dosimeter measurements in BOMAB-like phantoms for different modalities was larger, with standard deviations ranging from 6 to 10%. (Miljanić et al., 2013)

The distribution of neutron dose equivalent as a function of penetration depth in the phantom along the beam axis and 10 cm off-axis is shown in Fig. 4, for 20 MV photon irradiation (Di Fulvio et al., 2013a). Data are reported as the ratios between neutron dose equivalent, in mSv, and photon absorbed dose at the isocentre, in Gy. The isocentre is placed at a depth of 10 cm in water, on the beam axis. Data acquired with different systems agree within their 1SD uncertainties, which are not shown, but estimated to be in the order of 20%. Taking into account different energy responses as well as different calibration procedures (and uncertainties) for used dosimeters types (Di Fulvio et al., 2013a,b), agreement between them is very satisfactory.

3.2 Components of out-of-field doses

The results of the secondary radiation and their components are summarised in Table 1 (Bordy et al., 2013) which presents the evaluation of the scattered components due to water and collimator as well as the leakage, as a function of the radiation quality of the beam. Water scatter decreases with energy while leakage increases with energy, and collimator scatter increases only slowly with energy. The combined result is that total peripheral doses decrease as the incident energy increases (Bordy et al., 2013, Figure 6).

A similar finding was seen in clinical BOMAB phantom irradiations. Comparison of the same modalities with different energies (MLC 6 MV and 18 MV; IMRT 6 MV and 18 MV) in Krakow irradiations (Fig. 5) shows that the peripheral photon doses are always significantly lower for higher energies. The lower photon peripheral doses from 18 MV in comparison with 6 MV photon beams equipped with MLC were also reported by Stern (1999) and Mazonakis et al. (2008).

3.3 Comparison of Treatment Planning System (TPS) calculations and dosimeters

Dose profiles from different treatment plans in Pisa and Krakow are shown in Miljanić et al. 2013, Figure 9. The shape of the TPS curves corresponds to the results of peripheral doses measured with dosimeters, but generally dosimeters show larger doses then the TPS as distance from isocentre increases. Dose distributions by the TPS are given for distances up to about 15 cm from the isocentre. Beyond this distance, dosimeters show much larger doses than could be predicted by the TPS as shown for example in Fig. 6, where comparison of TPS and dosimeters for 6 MV VMAT, 6MV IMRT and 15 MV 5-fields MLC all from irradiations in Pisa is given. The results are for "prostate" pipe. Dose profiles for the planning target volumes for prostate show that out-of-field doses are quite different for different modalities and their order from the highest to the lowest values is the same as with dosimetry measurements. At a distance of 4.6 cm from the field edge, the ratios of doses measured by dosimeters and that from TPS vary from 1.15 up to 2.25.

The estimation of the sparing of adjacent sensitive organs from PTV dose data is shown in Fig. 7. Maximum doses for "bladder" pipe and "rectum" pipe as the percentage of TPS dose for the "prostate" pipe are given for modalities in Pisa (P) and Krakow (K). Generally doses in the "rectum" pipe are lower than in the "bladder" pipe, with the exception of 4-field MLC and also for IMRT in Pisa. The reasons lie in the beam angles applied which give the same doses in the rectum and bladder for 4-field MLC and higher doses for the rectum in case of IMRT in Pisa. The best results for sparing bladder and rectum are obtained for IMRT in both hospitals and for 5-field MLC in Pisa.

3.4 Neutron measurements

As average neutron energy and production efficiency increase with maximum energy of the Bremstrahlung photon spectrum (Tosi et al., 1991), higher photon energies result in higher out-of- field neutron doses per unit photon dose at the isocentre. This is confirmed by the comparison of MLC treatment modality at different energies, (Di Fulvio et al. 2013, Figure 10) for irradiations in Pisa and in Krakow.

Intensity modulated radiotherapy is nowadays considered one of the most effective modes of treatment delivery. However, we measured peripheral secondary neutron dose for IMRT nearly four times those observed in 3DCRT, at 18 MV primary photon maximum energies. On the other hand, IMRT shows a better sparing of OARs close to the treatment volume compared to arc-techniques at photon energies as low as 6 MV, because of the finite number of beam positions. In fact, in the assessment of radiotherapy treatments, 6 MV radiation quality is often chosen, being considered free of photoneutrons. In this work, a non-negligible photoneutron dose has been measured also with 6 MV primary photon beam. The probability of photonuclear reactions decreases with photon energy, however it is not zero as long as it is higher than nuclei of interacting materials separation energy. At 6 MV, tens of microsivert per unit photon Gy are delivered to target organs and surrounding OARs as well. This unwanted neutron dose for radiotherapy patients is non-negligible especially in high dose-per-fraction treatments.

4. Discusion and Conclusions

The estimation of second cancer risk is a difficult and extensive task and it is impracticable to simulate all possible treatment types and techniques for all patient geometries. The development of algorithms for out-of-field use is therefore of considerable importance and these requires validation against dose measurements, for both photons and neutrons.

Dosimetric methods used in this study (TLD, OSL and RPL for photons and SE and PADC for neutrons) can be used for out-of-field dosimetry. All show good uniformity, good reproducibility, and can be used down to low doses expected at distances remote from the subsequent radiotherapy target volume.

Comparison of out-of-field doses for different modalities in two RT centres shows that differences in out-of-field doses for the same PTV can be as high as a factor of 4. For sparing adjacent OARs the best results for IMRT were obtained. On the other hand, the lowest out-of-field doses were for MLC conformal therapy. Further investigations are needed, especially for new radiotherapy modalities since results revealed the fact that the TPS used regularly underestimated out-of-field doses.

The measurement of neutron doses should be continued and extended, particularly as treatment planning systems do not routinely include neutron dose calculations in their standard algorithms. In addition, it has been shown that photoneutron doses are non-negligible even at accelerating energies as low as 6 MV.

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dosimeters for 6 MV VMAT (upper), 6 MV IMRT (middle) and 15 MV 5-field conformal therapy (lower).



dose for "prostate" pipe 1 given for modalities in Pisa (P) and Krakow (K) (Miljani c et al., 2013).

References

- Bordy, J. M., d'Agostino, E., Bessiere, I., Domingo, C., d'Errico, F., di Fulvio, A., Knežević,
 Ž., Miljanić, S., Olko, P., Ostrosky, A., Poumarede, B., Sorel, S., Stolarczyk, L.,
 Vermersse D., Harrison, R., 2013. Radiotherapy out-of-field dosimetry: Experimental and computational results for photons in a water tank. Radiat. Meas. 57, 29-34.
- Bush F., 1949. The integral dose received from a uniformly distributed radioactive isotope. British J Radiol. 22, 96-102.
- Cadman, P., Bassalow, R., Sidhu, N.P.S., Ibbott, G., Nelson, A., 2002. Dosimetric considerations for validation of a sequential IMRT process with a commercial treatment planning system. Phys. Med. Biol. 47 (16), 3001e3010.
- Di Fulvio, A., Tana, L., Caresana, M., D'Agostino, E., de San Pedro, M., Domingo, C., d'Errico, F., 2013a. Clinical simulations of prostate radiotherapy using BOMAB-like phantoms: Results for neutrons. Radiat. Meas. 57, 48-61.
- Di Fulvio, A., Domingo, C., de San Pedro, M., D'Agostino, E., Caresana, M., Tana, L., d'Errico, F., 2013b. Superheated emulsions and track etch detectors for photoneutron measurements. Radiat. Meas. 57, 19-28.
- Harrison, R. M., 2013. Introduction to dosimetry and risk estimation of second cancer induction following radiotherapy. Radiat. Meas. 57, 1-8.
- Howell, R. M., Hertel, N. E., Wang, Z., Hutchinson, J., Fullerton, G. D., 2006. Calculation of effective dose from measurements of secondary neutron spectra and scattered photon dose from dynamic MLC IMRT for 6 MV, 15 MV, and 18 MV beam energies. Med. Phys. 33(2) 360-368.
- Howell, R. M., Scarboro, S. B., Kry, S. F., Yaldo, D. Z., 2010. Accuracy of out-of-field dose calculations by a commercial treatment planning system. Phys.Med.Biol. 55, 6999-7008.
- IAEA, 2000. Absorbed Dose Determination in External Beam Radiotherapy. An International Code of Practice for Dosimetry Based on Standards of Absorbed Dose to Water. Technical Reports Series No. 398. International Atomic Energy Agency, Vienna.
- Kase, K. R., Svensson, G. K., Wolbarst, A. B., Marks, M. A., 1983. Measurements of dose from secondary radiation outside a treatment field. International Jornal of Radiation Oncology Biology Physics 9(8), 1177-1183.

- Knežević, Ž., Stolarczyk, L., Bessiere, I., Bordy, J. M., Miljanić, S., Olko, P., 2013. Photon dosimetry methods: Optically stimulated luminescence (OSL), thermoluminescence (TL) and radiophotoluminescence (RPL) dosimetry. Radiat. Meas. 57, 9-18.
- Martens, C., Reynaert, N., De Wagter, C., Nilsson, P., Coghe, M., Palmans, H., Thierens, H., De Neve, W., 2002. Underdosage of the upper-airway mucosa for small fields as used in intensity-modulated radiation therapy: a comparison between radiochromic film measurements, Monte Carlo simulations, and collapsed cone convolution calculations. Med. Phys. 29 (7), 1528e1535.
- Mazonakis, M., Zacharopoulou, F., Varveris, H., Damilakis, J., 2008. Peripheral dose measurements for 6 and 18 MV photon beams on a linear accelerator with multileaf
- Miljanić, S., Bessieres, I., Bordy, J. M., d'Errico, F., Di Fulvio, A., Kabat, D. Knežević, Ž., Olko, P., Stolarczyk, L., Tana, L., Harrison R. 2013. Clinical simulations of prostate radiotherapy using BOMAB-like phantoms: results for photons. Radiat. Meas. 57, 35-47.
- Mizuno, H., Kanai, T., Kusano, Y., Ko, S., Ono, M., Fukumura, A., Abe, K., Nishizawa, K., Shimbo, M., Sakata, S., Ishikura, S., Ikeda, H., 2008. Feasibility Study of Glass Dosimeter Postal Dosimetry Audit of High- Energy, Radiotherapy Photon Beams. Radiot. and Oncol. 85, 258-263.
- Molineu, A., Followill, D.S., Balter, P.A., Hanson, W.F., Gillen, M.T., Huq, M.S., Eisbruch, A., Ibbott, G.S., 2005. Design and implementation of an anthropomorphic quality assurance phantom for intensity-modulated radiation therapy for the Radiation Therapy Oncology Group. Int. J. Radiat. Oncol. Biol. Phy. 63 (2), 577e583.
- NCRP, Neutron Contamination From Medical Accelerators, 1984. National Council on Radiation Protection and Measurements Report 79. Washington, DC, USA.
- Newhauser, W.D., Durante M., 2011. Assessing the risk of second malignancies after modern radiotherapy. Nature Reviews Cancer 11, 438-448.

Newhauser, W.D., et al., 2011 (?)

- Rah, J.-E., Hong, J.-Y, Kim,G.-Y., Kim, Y.-L., Shin, D.-O., Suh, T.-S., 2009. A Comparison of the Dosimetric Characteristics of a Glass Rod Dosimeter and a Thermoluminescent Dosimeter for Mailed Dosimeter. Radiat. Meas. 44, 18-22.
- Sohn, J.W., Dempsey, J.F., Suh, T.S., Low, D.A., 2003. Analysis of various beamlet sizes for IMRT with 6 MV photons. Med. Phys. 30 (9), 2432e2439.

- Stern, R. L., 1999. Peripheral dose from a linear accelerator equipped with multileaf collimation. Med. Phys. 26(4), 559-563.
- Tosi, G., Torresin, A., Agosteo, S., Foglio Para, A., Sangiust, V., Zeni, L., Silari, M., 1991. Neutron measurements around medical electron accelerators by active and passive detection techniques. Med. Phys. 18 (1), 54e60.

Figure captions

- Fig. 1. Modified version of the BOMAB phantom developed at the University of Pisa
- Fig. 2. BOMAB CT scan and simulated organs.
- Fig. 3. Comparison of the profile measured with the 4 passive dosimeters and the ionisation chamber at 10 mm depth for 12 MV radiation quality (Bordy et al., 2013)
- Fig. 4. Neutron dose equivalent along the central axis and 10 cm off the axis of 20 MV X-ray beam (normalized to 1 Gy of photons at the isocentre) measured with SDD, BD PND and PADC (Di Fulvio et al., 2013).
- Fig. 5. Comparison of out-of-field doses for different energies (irradiations in Krakow, central "prostate" pipe); left: 6 and 18 MV IMRT; right: 6 and 18MV 4-field MLC.
 For IMRT irradiations the mean values of three types of dosimeters were used (MTS-7, RPL, TLD-700); for 6 MV MLC only results measured by MTS-7 and for 18 MV MLC mean value of OSL and MTS-7.
- Fig. 6. Comparison of TPS curves and dosimeters for 6 MV VMAT (upper), 6 MV IMRT (middle) and 15MV 5-field MLC (lower).
- Fig.7. Maximum doses for "bladder" pipe and "rectum" pipe as a percentage of PTV dose for "prostate" pipe 1 given for modalities in Pisa (P) and Krakow (K). (Miljanić et al., 2013)

Table caption

Table 1. Comparison of the out-of-field doses due to water scattering, collimator scattering and leakage for the three radiation qualities between 18 and 40 cm from the beam axis (ionisation chamber measurements). Measurements at the reference clinical linac, Saturn 43 Varian (Bordy et al., 2013).

Table 1.

Radiation quality	% out-of-beam-dose		
	water scatter	collimator scatter	"leakage" estimate
6 MV	45 to 55	28 to 36	11 to 24
12 MV	37 to 42	29 to 43	17 to 30
20 MV	26 to 37	34 to 49	19 to 40







Fig. 2. BOMAB CT scan and simulated organs.







Fig. 4



Fig.5



Fig. 6



