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A dosimetric comparison of 3D-CRT, IMRT and IMAT treatment techniques — assessment from radiation protection point of view

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ABSTRACT

Background: The purpose was to assess the impact of irradiation technique type and beam energy on the mixed radiation field around the medical linear accelerator (linac) in terms of radiation quality and related radiation protection quantities.

Materials and methods: Seven radiotherapeutic plans with Alderson-Rando anthropomorphic phantom [different techniques: conventional three-dimensional conformal radiotherapy (3D-CRT), intensity-modulated radiotherapy (IMRT) and intensity modulated arc therapy (IMAT), different beams: 6 MV or 18 MV, and their arrangements) were prepared for the case of prostate malignancy. Recombination chambers REM-2 and GW2 were positioned on the treatment couch 100 cm from the beam axis at the height of the isocentre. Recombination chambers REM-2 and GW2 were used for recombination index of radiation quality Q_4 determination, measurement of total tissue dose D_t and calculation of gamma and neutron components to D_t. Estimation of D_t and Q_4 allowed for the ambient dose equivalent H*(10) calculations for each plan.

Results: For plans prepared with 6 MV beams, Q_4 values within the limits of uncertainty were equal to one, which confirms the correctness of the measurement method. For plans implemented with 18 MV beams, the value of Q_4 was in the range of 3.7–5.7. Comparison between treatment techniques indicates that the lowest exposure resulting from out-of-field doses comes from 6 MV IMAT (0.7 mSv), whereas the highest one is from 18 MV IMRT (55.1 mSv).

Conclusion: With the recombination chambers technique it was confirmed that the choice of beam energy directly affects the generation of photoneutrons. The treatment plan technique can have a significant impact on the out-of-field dose.

Key words: photon external beam radiotherapy; recombination chambers; radiation quality; secondary radiation; radiation protection

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Introduction

The generation of secondary and scattered radiation in the vicinity of operating medical linear accelerators (linacs) is primarily related to the interaction of high-energy photons with the elements of the accelerator head, elements located in the beam path outside the head, or objects located in the therapeutic bunker and its structural elements [1]. In particular, when a certain threshold of photon energy is exceeded, secondary neutrons are generated as a result of photonuclear reactions (γ,n). In high-energy photon external beam radiotherapy (EBRT), photonuclear reac-

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tions are observed for photons with energies above the threshold of 8 MeV, which results mainly from the threshold of reaction energy of structural materials (tungsten or lead) used in the construction of medical linear accelerators [2]. For this reason, for 6 MV photon beams, the occurrence of photonuclear reactions and the formation of photoneutrons are practically not observed. However, small amounts of neutrons can be generated in reactions with beryllium atoms which typically constitute the accelerator exit window [3].

From the point of view of dosimetry in radiation protection, the radiation field in the vicinity of linac is a mixed radiation field. In this field, apart from the scattered photons, photoneutrons generated in the reactions described above are observed. These neutrons can be dispersed and/or moderated, resulting in additional exposure of the patient and medical personnel [2]. For that reason, scattered photons and photoneutrons in the vicinity of linacs have been the subject of research for many years [4–5]. They reported data on neutron and photon fluence, their energy spectrum or average energy. On this basis, using appropriate conversion factors, one can estimate, for example, organ dose equivalent H_T or ambient dose equivalent H*(10). It should be noted that H*(10) is an operational quantity, which can be measured, conservatively estimating the effective dose [6]. More about the utility of H*(10) for exposure assessment during a radiotherapy course (a justification, but also a discussion of the limitations of such an approach) could be found in [7].

An important problem in the dosimetry of mixed radiation fields around medical linear accelerators, where we deal with highly intense and pulsed photon beams, is an experimental measurement of the neutron component of the total absorbed dose. The National Council on Radiation Protection and Measurements (NCRP) in its report 116 recommends the use of a radiation weighting factor of 20 for photoneutrons generated in the medical linear accelerator head [8]. Consequently, despite the much smaller contribution of neutrons to the total absorbed dose compared to the photon component, the biological effect of photoneutron interaction on healthy tissues may be significant.

In EBRT, three techniques using high-energy photons are the most commonly used: conventional three-dimensional conformal radiotherapy (3D-CRT), intensity-modulated radiotherapy (IMRT) and its more advanced variant, the intensity modulated arc therapy (IMAT). For most malignant lesions, intensity-modulated techniques (IMRT and IMAT) are characterized by better coverage of planning target volume (PTV) and lower doses in organs at risk (OAR) compared to the 3D-CRT technique. On the other hand, highly specialized techniques are associated with an increase in the number of monitor units (MU) generated in one therapeutic fraction and with a greater number of normal tissues through which the radiation passes. In consequence, an increased risk of radiation-induced malignancies may be of concern [9, 10]. This risk seems to be more and more important with the use of beams of accelerating voltage above 6 MV. One can expect greater radiation penetration through the medical linear accelerator head shields and the contribution to exposure from both scattered photons and generated photoneutrons. Nevertheless, the use of high-energy photon beams of accelerating voltages from 10 MV up and highly specialized radiotherapeutic techniques is often justified in the case of neoplasms deep sited in the patient's body, because the skin dose is lower, the depth dose is larger, the scattered dose to tissues outside the target volume is smaller, and the isodose curves are less round [11]. Therefore, the question can be asked whether the choice of the irradiation method (in particular the irradiation technique and beam energy) affects the mixed radiation field around linacs and the out-of-field doses important from the radiation protection point of view.

The objectives of the presented study were to assess the impact of irradiation technique type and beam energy on the mixed radiation field around the medical linear accelerator. Moreover, we also determined H*(10), as a conservative estimation of effective dose relevant from the radiation protection point of view during one radiotherapeutic session (fraction).

Materials and methods

Linac

The Varian Clinac 2300 C/D system installed in the Maria Sklodowska-Curie National Research Institute of Oncology, Krakow Branch, was used. Calibration of the medical linear accelerator was

carried out so that the absorbed dose of 1 cGy corresponded to 1 MU for a 10×10 cm^2 field and a cylindrical Farmer ionization chamber placed at a depth of 5 cm for 6 MV beam and at a depth of 10 cm for 18 MV beam in a water phantom [12]. Dose optimization and calculations were performed using the Varian Eclipse treatment planning system and the AAA algorithm [13].

Recombination chambers

REM-2 and GW2 cylindrical, parallel-plate recombination chambers were used for all measurements. Due to their construction, REM-2 is sensitive both to photons and neutrons, while GW2 is sensitive only to photons. The REM-2 recombination chamber can be considered equivalent to the International Commission on Radiation Units and Measurements (ICRU) sphere and can be used for direct measurement of H*(10) without any corrections to the calibration factor in most measurements for radiation protection purposes. Detailed information on the construction and properties of REM-2 and GW2 recombination chambers can be found in other publications [14–17]. In particular, as detectors with a LET-dependent response, they give the unique opportunity for an experimental measurement of the quantity representing the radiation quality (a function of the unrestricted linear energy transfer Q(L) in water). This quantity is called the recombination index of radiation quality Q_4. They also allow for the determination of gamma and neutron radiation contributions to the total ambient-absorbed dose D_t in an unknown mixed radiation field. Having such information, other dosimetric quantities, like H*(10) or the dose equivalent in a distant organ H_T, can be assessed. Above all, they are active detectors that allow monitoring results on an ongoing basis, without the need for long waits for readout, and can be used in relatively intense radiation fields, not suffering from saturation or dead-time effects. Recombinant methods are included in the lists of available neutron measurement methods recommended by the International Atomic Energy Agency (IAEA) and ICRU [18–20].

Recombination chambers were calibrated in the accredited calibration laboratory at the National Centre for Nuclear Research, Poland, with ^{137}Cs and ^{239}Pu–Be reference sources in terms of the ambient-absorbed dose D*(10) and the ambient dose equivalent H*(10).

Linac set-up

To assess the mixed radiation field and the exposure associated with the choice of radiotherapy technique and beam energy, seven plans were prepared for the case of prostate malignancy. The beam configurations for each plan are shown in Table 1.

The anatomical structures necessary for the preparation of radiotherapy plans (PTV covering the prostate with required margin, rectum, urinary bladder, femoral heads) were drawn on tomographic cross-sections of the pelvic part of an anthropomorphic phantom (Alderson-Rando, RSD Radiology Support Devices, Long Beach, CA, USA). A total dose of 63 Gy in 21 fractions (in fractional doses of 3 Gy) was planned. The dose distribution was normalized to the mean dose in PTV. The dose distribution was planned so that the minimum dose in PTV was greater than 95% and the maximum dose was less than 107% (at least 98% of the PTV volume was covered with 95% isodose). In the case of OARs, the protocol valid at the Maria Sklodowska-Curie National Research Institute of Oncology, Krakow Branch, at the time of conducting the measurements was followed and was the same for all irradiation techniques.

The anthropomorphic phantom was positioned on the treatment couch in such a way that the isocentre of the medical linear accelerator was located in the vicinity of the PTV centre, as planned. The arrangement of the phantom on the therapeutic couch did not change during subsequent radiotherapy sessions. The REM-2 and GW2 recombination chambers were placed on the treatment couch 100 cm from the beam axis at the height of the isocentre (the position of the treatment table was 0°).

Recombination methods

The method of the recombination index of radiation quality Q_4 determination has been described in detail previously [21]. Briefly, comparing an ion collection efficiency at a specially chosen polarizing voltage U_R (ensuring 96% saturation in the reference ^{137}Cs gamma radiation field) for investigated mixed radiation field in the vicinity of linac and the reference gamma field, the recombination index of radiation quality Q_4 was calculated. The total ambient-absorbed dose D_t and relative contribution

to D_t delivered by the gamma component (D_γ/D_t) were determined by the twin-detector method [22]. Additionally, the value of the recombination index of radiation quality only for photoneutrons $(Q_4)_n$ was evaluated. In particular, it could be calculated from equation (1), assuming that Q_4 is an additive quantity and $(Q_4)_\gamma = 1$ for gamma radiation by the definition:

$$Q_4 = k_n(Q_4)_n + k_\gamma(Q_4)_\gamma \quad (1)$$

where k_n and k_γ are the relative contributions of the neutron and photon components, respectively, of the radiation field to the saturation current [14].

The ambient dose equivalent H*(10) per MU for each beam in the plan was determined as the product of the total ambient-absorbed dose D_t and the recombination index of radiation quality Q_4 divided by the number of monitor units for the beam [14, 21]. The total ambient dose equivalent $H^*(10)_t$ for each plan was determined as the product of the total number of monitor units in the plan and the sum of H*(10) per MU for all beams in the plan.

Results and discussion

The values of Q_4 and $(Q_4)_n$, which reflect the radiation quality for each beam in each plan, are presented in Table 2. The estimated total expanded uncertainty of Q_4 is ± 0.5. The estimated total expanded uncertainty of $(Q_4)_n$ is ± 1.0.

According to the authors' knowledge, this is the first experimental measurement of radiation quality in the vicinity of a linear medical accelerator during a radiotherapeutic session. As expected for plans prepared with the use of 6 MV beams, Q_4 values within the limits of uncertainty were equal to one. This fact should be highlighted as confirmation of the correctness of the measurement method and results, as contamination of the therapeutic beam by neutron radiation is assumed to be negligible for radiation energies below 10 MeV [23]. For plans implemented with the use of 18 MV beams, the value of Q_4 was in the range of 3.7–5.7. The lowest value of Q_4 was achieved for a single beam of the 3D-CRT plan. For the rest of the 18 MV beams (even for the 3D-CRT plan), the value of Q_4 was within the range of 4.6–5.7. Therefore, it is worth noting the compliance of these results, treating the result of 3.7 probably as an outlier. Additionally, the majority of estimated $(Q_4)_n$ values are similar. However, the results for $(Q_4)_n$ are higher than the others for one position (108°). Most likely, it is related to the bunker equipment or the structure of the bunker itself, on which the radiation beam falls at this angle, slightly affecting the spectrum of generated neutrons. The $(Q_4)_n$ values presented in Table 2 are consistent with the results presented in other studies performed with the use of recombinant detectors and methods [16, 24]. Altogether, it indicates that the main source of photoneutron generation is the primary elements of the medical linear accelerator head (even considering different positions and movements of multileaf collimator leaves, while maintaining the same neutron scatter conditions in the patient). So the influence of the selected radiotherapy technique at the point of measurement and of course for the same machine may be assessed as negligible on photoneutrons generation and their energy spectrum. Naseri and Mesbachina reviewed articles on Monte Carlo simulation concerning photoneutron generation sources in linear medical accelerators [1]. It can be concluded from different studies discussed in this article that the primary collimator has the highest contribution among different components to pho-

Table 1. Beams arrangement for conventional three-dimensional conformal radiotherapy (3D-CRT), intensity-modulated radiotherapy (IMRT) and intensity modulated arc therapy (IMAT) treatment plans

Technique	Beams arrangement	Total MU
3D-CRT	4 fields: 270°, 0°, 90°, 180° all beams 6 MV	431
3D-CRT	4 fields: 270°, 0°, 90°, 180° all beams 18 MV	347
Sliding window IMRT	5 fields: 180°, 108°, 36°, 324°, 252° all beams 6 MV	911
Sliding window IMRT	5 fields: 180°, 108°, 36°, 324°, 252° all beams 18 MV	810
Sliding window IMRT	5 fields: 180° (6 MV), 108° (18 MV), 36° (6 MV), 324° (6 MV), 252° (18 MV)	885
IMAT	one arc of 360° (from 181° to 179°) without gaps with 6 MV	765
IMAT	One arc of 360° (from 181° to 179°) without gaps with 18 MV	604

MU — monitor unit

Table 2. The total ambient-absorbed dose D_t, the relative contribution to D_t delivered by photon component D_γ, the recombination index of radiation quality (Q_4), the recombination index of radiation quality for photoneutrons $(Q_4)_n$, the ambient dose equivalent H*(10) per monitor unit (MU) in each beam and the total dose equivalent $H^*(10)_t$ for each plan

Technique	Beam arrangement	MU	Q_4	$(Q_4)_n$	D_t [μGy/MU]	D_γ/D_t	H*(10) [μSv/MU]	$H^*(10)_t$ [mSv]
3D-CRT	270° 6 MV	95	1.1		1.41		1.50	2.2
	0° 6 MV	123	1.0		1.18		1.22	
	90° 6 MV	132	1.0		1.15		1.11	
	180° 6 MV	81	1.1		1.19		1.32	
3D-CRT	270° 18 MV	79	4.9	12.5	3.09	0.66	15.06	19.2
	0° 18 MV	99	5.1	12.7	2.98	0.65	15.08	
	90° 18 MV	97	5.6	12.0	3.29	0.58	18.36	
	180° 18 MV	72	3.7	10.6	1.80	0.72	6.72	
Sliding window IMRT	180° 6 MV	156	0.9		0.64		0.60	4.2
	108° 6 MV	171	1.0		0.96		0.95	
	36° 6 MV	210	1.0		1.00		1.04	
	324° 6 MV	202	1.0		0.95		0.98	
	252° 6 MV	172	1.1		0.98		1.03	
Sliding window IMRT	180° 18 MV	138	4.6	11.0	1.45	0.64	6.61	55.1
	108° 18 MV	157	5.2	13.9	2.57	0.68	13.3	
	36° 18 MV	180	5.4	11.6	2.75	0.59	14.76	
	324° 18 MV	183	5.6	11.6	2.89	0.56	16.3	
	252° 18 MV	152	5.7	11.0	3.01	0.54	17.03	
Sliding window IMRT	180° 6 MV	159	1.0		0.63		0.61	29.5
	108° 18 MV	156	5.2	13.8	2.56	0.67	13.35	
	36° 6 MV	211	1.2		1.00		1.23	
	324° 6 MV	205	1.2		0.96		1.11	
	252° 18 MV	154	5.7	11.1	3.00	0.53	17.03	
IMAT	one arc 6 MV	765	1.0		0.95		0.97	0.7
IMAT	one arc 18 MV	604	5.4	12.0	2.64	0.60	14.30	8.6

3D-CRT — three-dimensional conformal radiotherapy; IMRT — intensity-modulated radiotherapy; IMAT — intensity modulated arc therapy

toneutrons generation. The second contributors are secondary collimator jaws and the target. Other contributors are multi-leaf collimator, shielding and flattening filter to a lesser extent. Kry et al. evaluated fluence, energy spectra, and quality factors as a function of depth and examined the importance of field size and source-to-surface distance SSD on the absolute neutron dose equivalent and the percentage depth-dose equivalent PDDE in tissue with the use of Varian 2100 Clinac, 18 MV photon beam and Monte Carlo simulations [25]. They found that the quality factor did not change drastically as a function of depth in tissue. However, a slight decrease in the average quality factor with increasing depth was observed, due to the decreased number of fast neutrons relative to epithermal and thermal neutrons. Overall, the quality factor for neutrons decreased from 17.1 at a depth of 0.1 cm to 13.8 at a depth of 19.5 cm. Additionally, they found the energy of fast neutrons was quickly degraded and thermalized over the first 5 cm of tissue depth. At depths greater than 7–8 cm, the neutron energy became nearly constant because equilibrium was achieved between the absorption of thermal neutrons and the thermalization of the remaining fast neutrons. So, the shape of the energy spectrum remained nearly constant at this and greater depths and only reduced in magnitude with increasing depth. In a Monte Carlo study on photoneutron production for a 15 MeV Primus linac, Pena et al. calculated the neutron spectra at different locations in the treatment room [26]. They observed that the epithermal neuron fluence does not vary significantly inside the treatment room as well as the maze. On the other hand, for fast neutrons, the neutron fluence is high for isocentre, but drops down and remains almost constant in other locations in the treatment room. Consequently, the radiation quality of photoneutrons might be considered unchanged, except for the very close vicinity of the beam itself.

The values of D_t and relative contributions of photon and neutron radiation components to the total absorbed dose D_γ/D_t, along with $H^*(10)$ per MU for each beam in each plan and $H^*(10)_t$ for each plan are presented in Table 2. The total expanded uncertainty of D_t measurements did not exceed 5%. The choice of irradiation technique and beam energy at the selected measurement point was very important from the point of view of radiation protection. This is mainly related to the total number of monitor units for a given plan, as well as the radiation quality characterizing beams of different energies. An obvious observation is that regardless of irradiation technique, 6 MV photon beams generate a lower exposure outside the radiation field. Taking into account all other parameters characterizing a good plan and capabilities of a given radiotherapeutic centre, the best choice from the radiological protection point of view is IMAT using a 6 MV photon beam. Even when it is necessary to use a photon beam of higher energy, IMAT is still a good option. However, when choosing IMRT and photon beams with energies higher than 6 MV, one must take into account a significantly higher exposure outside the radiation field. In this case, it should be considered whether the implementation of a 3D-CRT plan would not be a better option if IMAT cannot be applied. Similar conclusions were made by other authors. Di Fulvio et al. measured peripheral secondary neutron doses for IMRT to be nearly four times those caused by 3D-CRT, at 18 MV primary photon maximum energies [3]. Hauri and Schneider concluded that for intensity-modulated treatments, IMAT should be used instead of IMRT because of its shorter beam-on time, which reduces the out-of-field dose [27]. Rezaian et al. stated that among equivalent IMRT treatment plans, the one with less MU should be favoured [28].

Although recombination chambers and methods are more a tool for scientific research than for routine use in radiotherapy facilities, they can be useful for special applications and needs. Recombination chambers offer the possibility of fast measurements of the radiation quality and the components of the absorbed dose in terms of LET and then to compare relatively intense radiation fields. Such specific measurements are of interest not only for EBRT but also for hadron therapy (e.g. ion therapy and boron-neutron capture therapy) [15, 16, 29–31].

Conclusions

The use of recombination methods and detectors allows us to obtain important information about the mixed radiation field around linear medical accelerators. Firstly, this field was characterized by

the value of the recombination index of the quality, which is a reflection of the value of radiation quality. Secondly, together with data on the total absorbed dose and the gamma and neutron components of this dose, it allows us to estimate exposure at a selected point in the radiation field.

An additional important conclusion from the conducted research is that the main source of photoneutron generation is the elements of the medical linear accelerator head. Using the example of prostate malignancy and seven different treatment plans, it was shown that a treatment plan technique can have a significant impact on the out-of-field dose, especially for 18 MV plans, where radiation quality of the fields increases due to neutron contamination. Comparison of the treatment techniques, in terms of H*(10), shows that for both 6 MV and 18 MV beam energies, the lowest exposure from secondary radiation was observed for one fraction of IMAT (0.7 mSv and 8.6 mSv), than 3D-CRT (2.2 mSv and 19.2 mSv) and the highest one for IMRT (4.2 mSv and 55.1 mSv). So, the choice of irradiation technique and beam energy is very important from the radiation protection point of view, as well as for secondary doses delivered to non-target organs during the radiotherapy session

Conflicts of interest

Authors declare no conflict of interest.

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