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research article

Evaluation of two-dimensional dose distributions for pre-treatment patient-specific IMRT dosimetry

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Background. The accuracy of dose calculation is crucial for success of the radiotherapy treatment. One of the methods that represent the current standard for patient-specific dosimetry is the evaluation of dose distributions measured with an ionization chamber array inside a homogeneous phantom using gamma method. Nevertheless, this method does not replicate the realistic conditions present when a patient is undergoing therapy. Therefore, to more accurately evaluate the treatment planning system (TPS) capabilities, gamma passing rates were examined for beams of different complexity passing through inhomogeneous phantoms.

Materials and methods. The research was performed using Siemens Oncor Expression linear accelerator, Siemens Somatom Open CT simulator and Elekta Monaco TPS. A 2D detector array was used to evaluate dose distribution accuracy in homogeneous, semi-anthropomorphic and anthropomorphic phantoms. Validation was based on gamma analysis with 3%/3mm and 2%/2mm criteria, respectively.

Results. Passing rates of the complex dose distributions degrade depending on the thickness of non-water equivalent material. They also depend on dose reporting mode used. It is observed that the passing rate decreases with plan complexity. Comparison of the data for all set-ups of semi-anthropomorphic and anthropomorphic phantoms shows that passing rates are higher in the anthropomorphic phantom.

Conclusions. Presented results raise a question of possible limits of dose distribution verification in assessment of plan delivery quality. Consequently, good results obtained using standard patient specific dosimetry methodology do not guarantee the accuracy of delivered dose distribution in real clinical cases.

Key words: IMRT; 2D dose verification; gamma method; anthropomorphic phantom

Introduction

The accuracy of dose calculation and precise dose delivery are crucial factors in the radiotherapy treatment process. There is a common agreement that Monte Carlo (MC) simulation is the most promising method for accurate calculation of absorbed dose.[1,2] In MC based systems the absorbed dose calculated to be delivered by external photon beams can be reported either as dose-to-media (D_m) or dose-to-water (D_w), and there is still no general agreement regarding the choice of the calculation method.[1-3] Hence, experimental verification is essential to validate algorithms before clinical use.[4] These verifications need to be performed using different dosimetric techniques and phan-

toms of different complexity (*e.g.* homogeneous, semi-anthropomorphic, anthropomorphic). The complexity of the phantom is especially important since it has been shown[3,5,6] that performance of algorithms in the heterogeneous medium can differ significantly depending on reporting mode used. Namely, our earlier investigation confirmed previously published results when the calculated values according to respective reporting mode were compared with values measured using ionization chambers in media of various densities. In case of water equivalent media, dose differences were less than 2%.[2,3,7] Similar results were acquired in low-density media.[1,8] However, differences in absorbed dose between two reporting modes were found to be as high as 10–15% when calculated in high-density media[2,3,9] due to their inherent limitations and differences. Compared to the measured values, the differences between D_m and D_w approaches in high-density media (*e.g.* bones) were significant and of opposite sign.[2,3] This problem was of particular interest for our group, and extensive work was performed using a methodology based on absorbed dose measurements with ionization chambers. We found a plausible solution for this problem which can be of practical use when measurements for commissioning of different reporting modes of treatment planning system (TPS) algorithm are performed. Nevertheless, due to the comprehensiveness of this research, the results are prepared to be published as separate research elsewhere.

In addition to these point dose verifications, where ionization chamber was placed in the phantom volumes of different densities, we investigated the performance of the system for the 2D dosimetric verification of dose distributions, which is colloquially known as patient-specific dosimetry. It is well known that this type of verification should be performed before the first fraction of patient's therapy. Patient specific 2D dosimetry can be performed either using film or arrays of ionization chambers or diodes. One of the first 2D detectors was radiographic film, but it is energy dependent[10] and nowadays it is replaced by radiochromic film. Radiochromic film is a detector with a high spatial resolution and it is almost energy independent. Furthermore, it is almost water equivalent, which makes it convenient for measurements of dose distributions produced by high energy photon beams used for radiotherapy.[11] Nevertheless, handling and processing of radiochromic films using flatbed scanners makes its use rather complex for everyday patient specific dosimetry. Consequently, arrays of ionization chambers or diodes are devices of choice for routine patient dose distribution verifications. One of the methods that represent the current standard for patient-specific dosimetry is the evaluation of dose distributions measured with an ionization chamber array inside a homogeneous phantom using gamma method.[12,13] Because beams pass through homogeneous water equivalent media, this does not replicate the realistic conditions present when a patient is undergoing therapy. Therefore, to evaluate the accuracy of the TPS calculations more in detail, gamma methodology was used for verification of resulting dose distribution produced by photon beams passing through inhomogeneous phantoms in different geometries. Calculated dose distributions were obtained using D_m and D_w reporting modes. Also, to better differentiate the underlying reasons for possible discrepancies, a selection of several plans was evaluated, ranging from simple square field to intensity modulated radiation therapy (IMRT) plans of various complexity. The results and analysis of this research will be presented.

Materials and methods

In this study, the research was performed using devices which are in clinical use at Radiotherapy Department of University Hospital Rijeka, Croatia: linear accelerator Siemens Oncor Expression (6 MV photon beam) equipped with multileaf collimator with 160 leaves (leaf width 0.5 cm at isocentre), Somatom Open CT simulator (Siemens Healthineers, Erlangen, Germany) and-Monaco v. 5.11.02 TPS (Elekta, Stockholm, Sweden). Linear accelerator was commissioned and prepared for the clinical implementation of the IMRT according to international standards.[14-17]

A 2D detector array IBA MatriXX (IBA Dosimetry GmbH, Schwarzenbruck, Germany) with 1020 ion chambers spaced at approximately 0.7 cm distance one from another was used to evaluate TPS accuracy in homogeneous MultiCube phantom (IBA Dosimetry GmbH, Schwarzenbruck, Germany) and inhomogeneous phantoms: CIRS Thorax semi-anthropomorphic phantom (Computerized Imaging Reference Systems Inc., Norfolk, USA) and Alderson Radiation Therapy (ART) anthropomorphic phantom (Radiology Support Devices, Long Beach, USA). CIRS semi-anthropomorphic phantoms are well known to all involved in dosimetric verification of TPS performance for point measurements using ionization chambers.[18-21] In

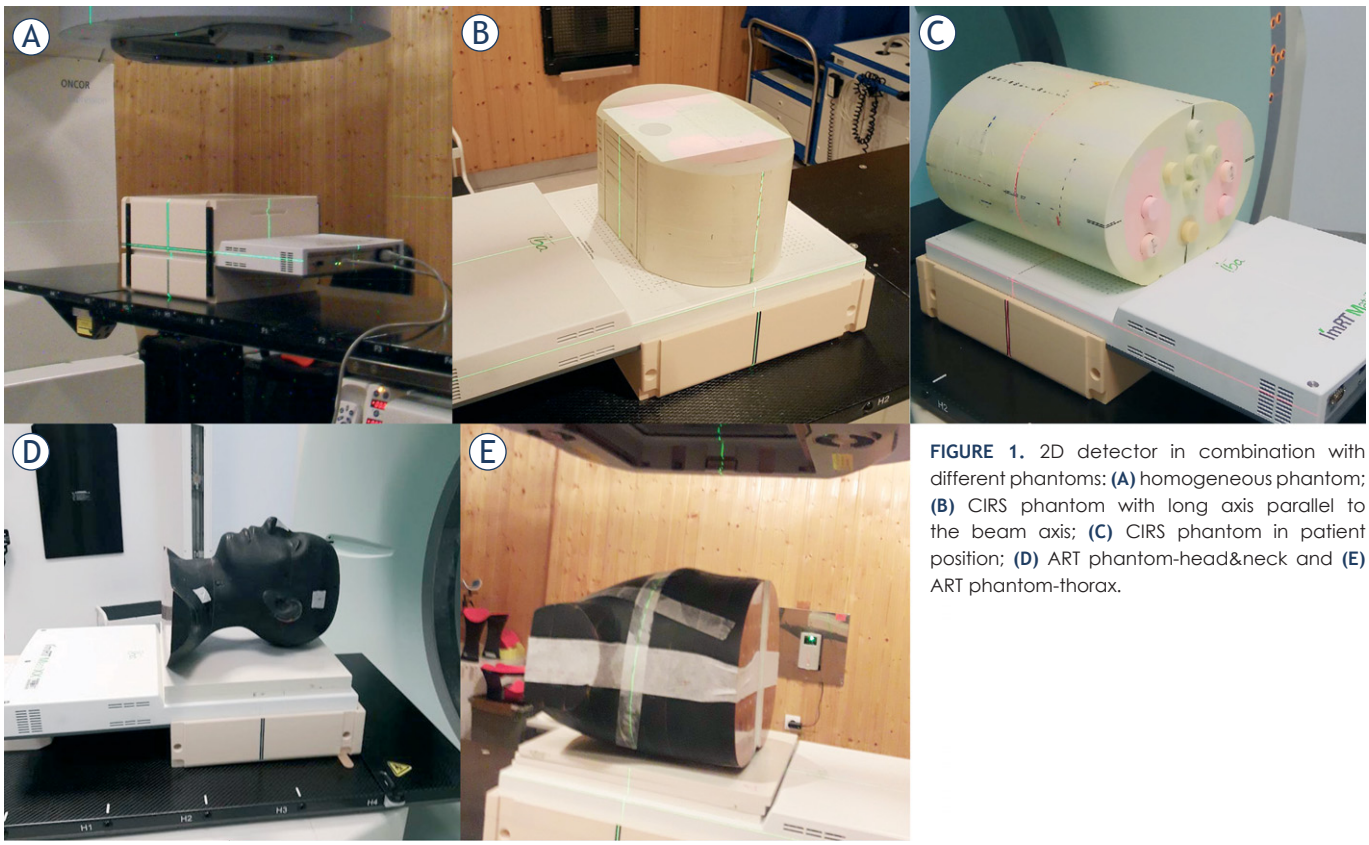

FIGURE 1. 2D detector in combination with different phantoms: **(A)** homogeneous phantom; **(B)** CIRS phantom with long axis parallel to the beam axis; **(C)** CIRS phantom in patient position; **(D)** ART phantom-head&neck and **(E)** ART phantom-thorax.

present study, the CIRS Thorax phantom, where volumes of three different densities (water equivalent, low-density and high-density) are built-in, was used along with a 2D detector for transit dosimetry. For a better resemblance to a realistic situation, the methodology was also verified using three parts of the Alderson phantom; head and neck (H&N), thorax and pelvis.

Gamma analysis was used to quantify the differences between measured and calculated dose distributions using criteria of 3 mm distance-to-agreement (DTA) and 3% relative dose difference (3%/3 mm).[17] To study the effects of more stringent criteria on the passing rate, we also used 2%/2 mm criteria. Gamma analysis was performed using commercial software OmniPro-I'mRT v. 1.7b (IBA Dosimetry GmbH, Schwarzenbruck, Germany). Therefore, measured planar dose distribution was taken as a reference distribution according to which calculated distribution is evaluated. The data were analysed according to following parameters- global gamma normalization, dose maximum to 100%; threshold: 10% of the maximum dose; search distance: 4.5 mm.

Calculated data along with data measured using a 2D detector were used for the evaluation of gamma analysis results considering the dependence on inhomogeneous media, different complexities of radiotherapy plans and different phantom configurations. Phantoms were scanned in all measuring set-ups, and the appropriate relative electron density tables were assigned. To increase the experimental complexity, a 2D detector was placed under different measuring conditions (Figure 1) using above mentioned phantoms. Patient specific dosimetry (PSD) is regularly performed by placing the detector (IBA Matrixx) in the homogeneous phantom MultiCube, which is shown in Figure 1A. This phantom is built of tissue equivalent plastic and 10 cm of it is placed in front of the detector, on the beam path. To increase the experimental complexity, a 2D detector was placed under different measuring conditions (Figure 1). Therefore, various thicknesses of semi-anthropomorphic

TABLE 1. Results of gamma analysis for measured and calculated dose distributions in homogeneous and CIRS thorax phantoms for different levels of plan complexity and different reporting modes

phantom	gamma criteria	15x15		IMRT1		IMRT2		IMRT3		IMRT4	
		% points passing with gamma<1									
		D_w	D_m	D_w	D_m	D_w	D_m	D_w	D_m	D_w	D_m
MultiCube	2mm/2%	93,12	95,62	98,68	96,75	99,53	98,62	97,32	96,01	89,59	84,68
	3mm/3%	98,74	99,97	99,94	99,33	99,99	99,81	99,65	99,31	98,22	95,93
5N CIRS	2mm/2%	90,13	91,51	96,63	94,94	99,03	98,72	93,68	88,49	78,74	70,37
	3mm/3%	97,55	98,71	98,26	98,44	99,94	99,92	98,64	96,19	92,03	84,99
10N CIRS	2mm/2%	88,61	86,14	95,11	92,39	99,14	97,9	93,25	84,54	77,51	70,52
	3mm/3%	97,18	96,15	96,07	97,17	99,98	99,64	97,76	92,57	89,48	84,19
15N CIRS	2mm/2%	85,73	86,06	96,35	94,45	98,42	97,42	89,67	84,66	72,16	64,7
	3mm/3%	96,44	96,46	99,33	98,17	99,99	99,36	96,97	93,32	86,69	79,06
CIRS	2mm/2%	85,05	81,5	91,72	89,16	97,66	97,09	88,25	82,93	67,29	59,28
	3mm/3%	96	95,91	93,98	95,52	99,83	99,27	96,43	92,34	86,72	76,6

phantom CIRS Thorax, with its long axis parallel to the beam central axis (CAX) were placed on top of 3 cm water equivalent RW3 plastic plates (PTW, Freiburg, Germany). The RW3 plates assure that the dose on the detector would not be affected by transitions between different media and potential lack of dose build-up. Different thicknesses of CIRS Thorax phantom, *e.g.* 5, 10 and 15 cm (Figure 1B) respectively, were used to verify the influence of inhomogeneities on measured dose distributions. Dose distribution using CIRS Thorax phantom with long axis of the phantom perpendicular to CAX ('clinical position') was also investigated (Figure 1C). RW3 plates were not used in this measuring arrangement since there was enough tissue equivalent material in front of the detector. Investigation was also performed on three 'anatomical parts' of interest (head&neck, thorax and pelvic) of anthropomorphic phantom in 'clinical position' (Figures 1D, E). Here, build-up material (RW3 plates) was also used due to large 'air gaps' between the phantom and the detector, to ensure consistency of dose measurement.

Dose calculations were performed using Monaco 5.11.02 TPS utilizing D_w and D_m reporting modes. Different dose distributions were calculated for different phantom geometries and configurations (Figure 2), having beams directed vertically to the measuring plane. Beam geometries ranged from simple square (reference) field (15×15 cm^2) to clinical IMRT plans of various complexities considering fluence maps modulation degrees: 1.25, 1.65, 2.25 and 3.65 respectively, which is in accordance with

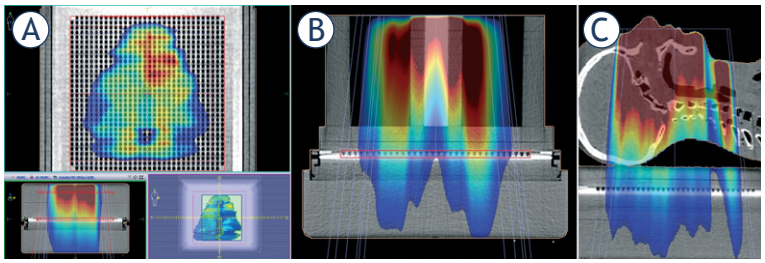

FIGURE 2. Calculated dose distributions for IMRT4 plan on homogeneous **(A)**, CIRS phantom with long axis parallel to the beam axis **(B)** and H&N part of ART phantom **(C)**.

number of segments (23, 40, 76 and 105 segments, respectively). To achieve an appropriate level of dose calculation accuracy and consistency, dose distributions were calculated with 0.2 cm grid size, 0.5% statistical uncertainty, and „per control point" calculation mode. Sequencing parameters were as follows: minimum segment area: 4 cm^2, minimum segment width: 1.5 cm, fluence smoothing: medium, minimum MU/segment: 2, maximum number of segments per plan: 110.

Results

Results of gamma analysis in the homogeneous phantom and different combinations of the semi-anthropomorphic phantom for various levels of plan complexity as well as different reporting modes are presented in Table 1 and Figure 3. The results for 3%/3mm and 2%/2mm criteria are shown in tables. Due to clarity, only the results

TABLE 2. Results of gamma analysis for measured and calculated dose distributions in the thorax, pelvic and head and neck parts of Alderson phantom for different levels of plan complexity and different reporting modes

phantom	gamma criteria	15x15		IMRT1		IMRT2		IMRT3		IMRT4	
		% points passing with gamma<1									
		D_w	D_m	D_w	D_m	D_w	D_m	D_w	D_m	D_w	D_m
Thorax Alderson	2mm/2%	86,39	86,18	97,6	96,79	95,02	94,2	86,3	84,59	75,44	73,62
	3mm/3%	94,24	96,19	99,26	98,89	97,6	97,07	94,07	93,19	93,57	90,8
Pelvic Alderson	2mm/2%	92,05	95,75	99,15	98,16	97,05	94,61	90,85	89,47	78,48	76,33
	3mm/3%	99,19	99,82	99,99	99,65	99,5	98,57	97,85	95,72	93,93	92,99
H&N Alderson	2mm/2%	91,59	91,82	98,14	97,65	95,96	94,83	95,45	94,1	83,51	79,86
	3mm/3%	97,2	98,01	99,65	99,53	99,12	98,14	98,82	98,34	94,73	93,03

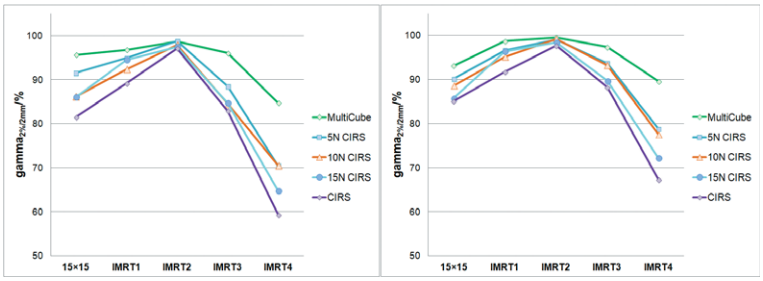

FIGURE 3. Gamma analysis with 2%/2mm criteria for dose-to-media (left) and dose-to-water (right) reporting modes related to the complexity of the particular plan, measured over homogeneous phantom and various set-ups of the semi-anthropomorphic phantom.

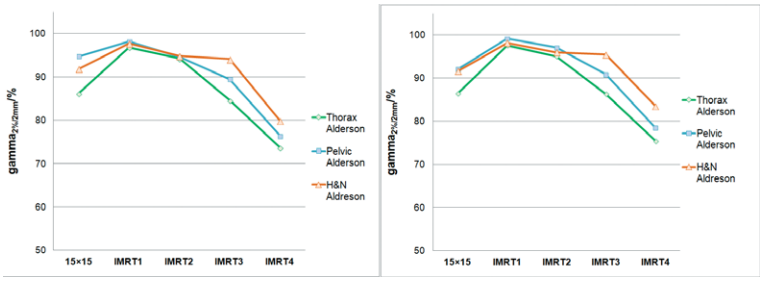

FIGURE 4. Gamma analysis with 2%/2mm criteria for dose-to-media (left) and dose-to-water (right) reporting modes related to plan complexity, measured over different parts of the anthropomorphic phantom.

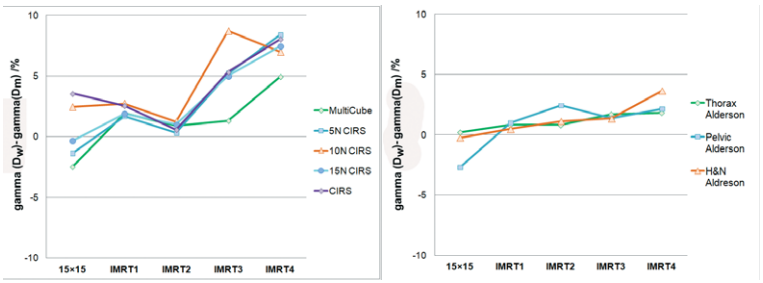

FIGURE 5. Gamma passing rate differences using 2%/2mm criteria between reporting modes related to plan complexity and phantom acquired over homogeneous phantom and different set-ups of the semi-anthropomorphic phantom (left) and different parts of the anthropomorphic phantom (right).

for 2%/2mm criteria were shown graphically. Percentage of points passing with gamma<1 for 3%/3mm criteria of the IMRT plans degrade depending on the thickness of non-water equivalent material up to 12% and up to 19% for dose-to-water and dose-to-media reporting mode, respectively. It also degrades for the most complex IMRT plan.

Percentage of points passing with gamma<1, when using 2%/2mm criteria, degrade depending on the level of complexity of plans, up to 30% for dose-to-water and up to 37% for dose-to-media reporting mode, for CIRS Thorax phantom in the patient position.

Results for anthropomorphic phantom are presented in Table 2 and Figure 4.

Considering more realistic situations in anthropomorphic phantom, gamma passing rates, when using 2%/2mm criteria, degrade depending on the level of complexity of plans, up to 22% for dose-to-water and up to 23% for dose-to-media reporting mode, both in ART Thorax (worst case scenario).

Percentage differences between gamma passing rates using 2%/2mm criteria of dose-to-water and dose-to-media reporting mode for different levels of plan complexity and different phantom set-ups are shown in Figure 5.

Discussion

The motivation for this work was related to a large number of very good gamma analysis results gathered while performing patient-specific dosimetry for IMRT clinical cases in a standard way using homogeneous phantom and 3%/3mm criteria. Obtained results were independent of dose reporting mode used. Thus, we were interested how the above-mentioned patient-specific dosimetry meth-

odology performs in a more realistic clinical situation.

From our results, it is evident that the gamma passing rate decreases with increasing plan complexity. It also depends on the level of inhomogeneity of the analysed region. Data in Table 1 shows that for the simplest case gamma passing rate (reference field and homogeneous phantom) is not as superior as expected in comparison to more complex plans and more complex measuring geometries. Further analysis of dose profiles shows that differences between calculated and measured values are insignificant at the exact positions of ionization chambers in the 2D detector. Nevertheless, in the regions of steep dose gradients, the interpolation between measuring points deteriorates passing rates when 2%/2mm criteria is used. These results, suggest that the resolution of the detector is one of the limiting factors of the analysis. Latter is less pronounced in complex multiple field geometries due to an averaging effect.

Comparing the data for all set-ups of semi-anthropomorphic (Table 1 and Figure 3) and anthropomorphic phantoms (Table 2 and Figure 4) one can conclude that passing rates are higher in the anthropomorphic phantom. Such observation indicates that the TPS calculates real situation more accurately than the extreme ones when different inhomogeneities are separated (Figure 2B). Exceptions are the passing rates for the IMRT2 plan, which are extremely high in all set-ups of the semi-anthropomorphic phantom since all fields that form this plan are small enough to pass through only the homogeneous part of the phantom.

From Figure 5 one can see that gamma passing rate depends on the dose reporting mode used. The magnitude of these differences increases as plan complexity increases. It also depends on the heterogeneity of the region of interest. The influence of heterogeneity on gamma passing rate differences of reporting modes is less pronounced in the anthropomorphic phantom (-2.7% to 3.6%) than in the semi-anthropomorphic phantom (-2.5% to 8.7%). These results raise a question of possible limits of dose distribution verification in the assessment of plan delivery quality. Consequently, one has to bear in mind the fact that good results obtained using standard patient-specific dosimetry methodology do not guarantee the accuracy of delivered dose distribution in real clinical cases.

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