research article

Experimental validation of Monte Carlo based treatment planning system in bone density equivalent media

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Radiol Oncol 2020; 54(4): 495-504.

Received 10 June 2020
Accepted 9 July 2020

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Disclosure: No potential conflicts of interest were disclosed.

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Introduction. Advanced, Monte Carlo (MC) based dose calculation algorithms, determine absorbed dose as dose to medium-in-medium ($D_{m,m}$) or dose to water-in-medium ($D_{w,m}$). Some earlier studies identified the differences in the absorbed doses related to the calculation mode, especially in the bone density equivalent (BDE) media. Since the calculation algorithms built in the treatment planning systems (TPS) should be dosimetrically verified before their use, we analyzed dose differences between two calculation modes for the Elekta Monaco TPS. We compared them with experimentally determined values, aiming to define a supplement to the existing TPS verification methodology.

Materials and methods. In our study, we used a 6 MV photon beam from a linear accelerator. To evaluate the accuracy of the TPS calculation approaches, measurements with a Farmer type chamber in a semi-anthropomorphic phantom were compared to those obtained by two calculation options. The comparison was made for three parts of the phantom having different densities, with a focus on the BDE part.

Results. Measured and calculated doses were in agreement for water and lung equivalent density materials, regardless of the calculation mode. However, in the BDE part of the phantom, mean dose differences between the calculation options ranged from 5.7 to 8.3%, depending on the method used. In the BDE part of the phantom, neither of the two calculation options were consistent with experimentally determined absorbed doses.

Conclusions. Based on our findings, we proposed a supplement to the current methodology for the verification of commercial MC based TPS by performing additional measurements in BDE material.

Key words: treatment planning system; dose-to-medium; dose-to-water; experimental validation of dose calculation; Monte Carlo

Introduction

Implementation of advanced radiation therapy techniques into clinical practice has set high demands on the quality and accuracy of various devices used for radiation treatment planning, treatment delivery, and dose verification. Besides the required high performance of medical linear accelerators and their ancillary systems, there are also strict requirements on dose calculation and optimization using treatment planning systems (TPS). Precise dose calculation is one of the most critical steps in the radiation therapy process since it is the basis for accurate and safe treatment delivery using high-energy photon beams. To provide necessary dosimetric accuracy, the verification of the calculated doses should be performed using a reproducible and reliable methodology. To ensure acceptable reliability of the verification results, an appropriate methodology for dose verification

 doi: 10.2478/raon-2020-0051

should be carefully selected, while the limitations of the specific method must be fully understood. The latter is essential for an adequate interpretation of the verification results.

Comprehensive verification methodology for the evaluation of calculation algorithms built in the TPSs has been proposed by the International Atomic Energy Agency (IAEA).[1,2] However, the rapid development of treatment delivery devices and, consequently, the utilization of the advanced radiation therapy techniques call for further development of the verification methods. In some published studies and documents[3-5], methodologies for the verification of dosimetry parameters for the implementation of Intensity Modulated Radiotherapy (IMRT) have been proposed. However, neither the means of verification nor the methods were explicitly spelled out.

Presently, Monte Carlo based dose calculation algorithms built in the TPS are assumed to be the most accurate computational systems for the appropriate simulation of particle transport and dose calculation.[6,7] Those algorithms offer two alternative options for the calculation and reporting of the absorbed dose: dose-to-medium as calculated by Monte Carlo algorithms, referred as dose to medium-in-medium, $D_{m,m}$, and dose-to-water converted from dose-to-medium using stopping power ratios water-to-medium, referred as dose to water-in-medium, $D_{w,m}$, or sometimes "biological dose to water".[8-10] The first approach calculates absorbed energy in a medium voxel divided by the mass of the medium element, while the second calculates the absorbed energy in a small cavity of water divided by the mass of that cavity. For brevity, $D_{m,m}$ and $D_{w,m}$ calculation options will be denoted as D_m (dose-to-medium) and D_w (dose-to-water) respectively in the rest of the paper.

Since it is a matter of debate whether to use D_m or D_w calculation approach for dose planning[9-13], the American Association of Physicists in Medicine (AAPM) Task Group 105[10] recommended that the material to which the dose is computed should be explicitly indicated and conversion between dose-to-medium and dose-to-water calculation modes should be available. Several previously published studies[9,12,14-16] were dedicated to comparisons of the two mentioned calculation modes built in the contemporary TPSs. Those studies have shown that differences between dose-to-medium and dose-to-water calculation modes can be expected in bone density equivalent (BDE) material. While D_m is the quantity inherently computed by MC dose algorithms, D_w calculation approach is still indispensable in clinical radiation therapy due to some practical and historical experience of prescribers.[10] Because there is still no agreement regarding the calculation approach that should be used as a clinical standard and due to the absence of the appropriate verification methodology, the present work aimed to propose a supplement to the existing verification methodology to establish the validity of both approaches. For that purpose, calculated absorbed doses using D_m and D_w options were compared to those determined experimentally in the semi-anthropomorphic phantom focusing on the dose differences in the part of the phantom having density close to the bone density.

The ultimate goal of the study was to define and propose an additional verification procedure as a supplement to the set of existing preclinical commissioning tests provided in the IAEA TECDOC 1583[2], for the specific case where TPS uses Monte Carlo based calculation algorithms. Such additional test may well eliminate potential misinterpretations of the commissioning results for bone density material, where D_m and D_w calculation approaches lead to different conclusions.[9,12,14-16]

We have to note that the proposed addendum to the verification methodology has no intention to be an answer to which reporting mode, D_m or D_w, should be used for radiotherapy treatment prescription or dose calculation, neither to discuss possible limitations of the conversion methodology from D_m to D_w, which is based on stopping power ratios water-to-medium.[8]

Materials and methods

In this work we used 6 MV photon beam generated by Siemens Oncor Expression (Siemens Healthineers, Erlangen, Germany) linear accelerator, Siemens Somatom Open Computerized Tomography (CT) simulator (Siemens Helthineers, Erlangen, Germany) and Elekta Monaco treatment planning system version 5.11 (Elekta, Stockholm, Sweden). Monaco TPS is a Monte Carlo based system which calculates absorbed dose using the D_m approach that can be converted to D_w mode using water-to-medium stopping power ratios to account for different energy absorption in both media.[17] Linear accelerator and Elekta Monaco ver. 5.11 TPS were commissioned and prepared for the clinical implementation of Intensity Modulated Radiotherapy according to the international recommendations.[1,2,4,18-21] All dosimetric measure-

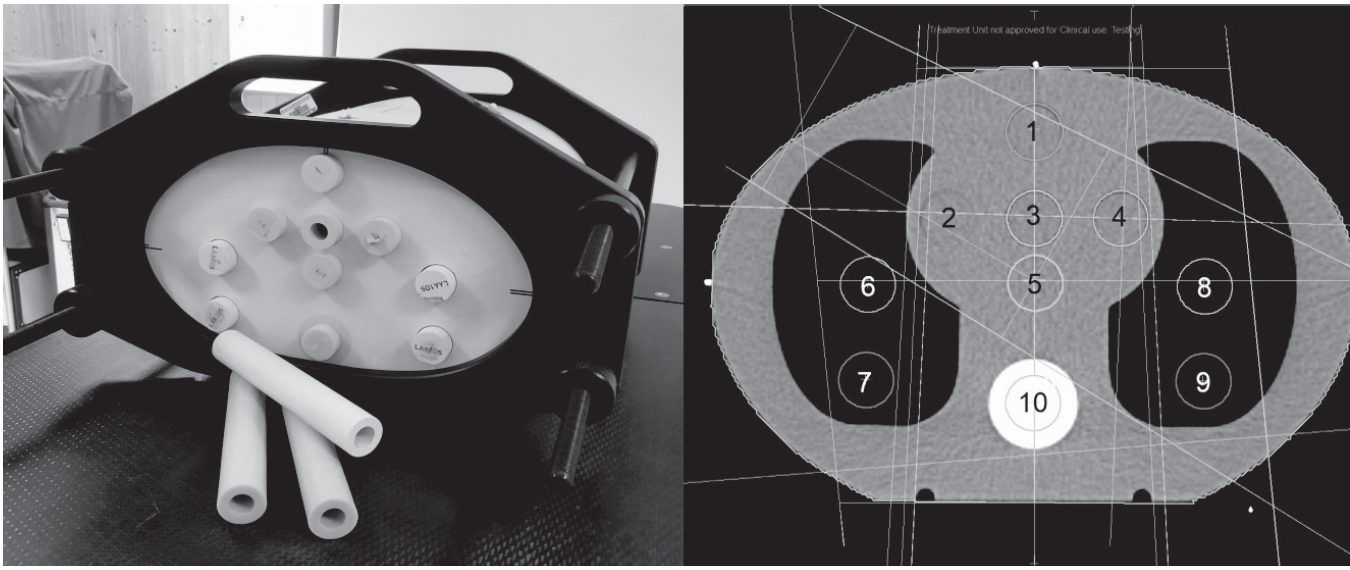

FIGURE 1. Photo of the semi-anthropomorphic CIRS Thorax phantom with interchangeable rod inserts (left) and its CT image (right). Positions of 10 interchangeable rod inserts are marked with numbers from 1 to 10. Five measuring points are in the water equivalent part of the phantom (grey area), four points are in the lung density equivalent material (black area), and one point is in the bone density equivalent part of the phantom (white area).

ments were performed using a PTW 30013 Farmer type ionization chamber and PTW UNIDOS electrometer (PTW, Freiburg, Germany).

Standard measurements in the CIRS Thorax phantom

Accuracy of the TPS Monaco ver. 5.11 calculation algorithm was experimentally verified using a semi-anthropomorphic CIRS Thorax phantom (CIRS Inc., Norfolk, VA, USA) consisting of a body made of water equivalent material (ρ = 1.003 g/cm^3), lung equivalent parts (ρ = 0.207 g/cm^3), and bone equivalent part (ρ = 1.506 g/cm^3) with cylindrical holes for placement of ionization chamber into interchangeable rod inserts having three different densities.[2] The phantom was scanned using the Somatom Open CT simulator. Acquired CT images were used for the delineation of volumes of interest and subsequent dose calculations. Measurements of absorbed dose were performed at ten measuring positions within the phantom (Figure 1) for 15 different irradiation set-ups (Table 1), using a PTW Farmer-type ionization chamber. All measurements were carried out at the central part of the selected radiation fields, excluding the regions of high dose gradients.

Measured doses were compared to the corresponding doses obtained by both calculation options, D_m and D_w. Dose differences δD_m and δD_w between measured and calculated values for dose-to-medium and dose-to-water calculation approach, were calculated according to the IAEA methodology[1,2] as:

$$\delta D_m = 100 \cdot \frac{D_m - D_{meas}}{D_{meas,ref}} \quad [1]$$

$$\delta D_w = 100 \cdot \frac{D_w - D_{meas}}{D_{meas,ref}} \quad [2]$$

where D_{meas} denotes measured absorbed dose at the selected measuring point, while $D_{meas,ref}$ stands for the absorbed dose measured at the reference point, which was chosen on the central axis of the beam at the isocenter (Table 1).

Dose differences δD_m and δD_w between calculated and measured doses were analysed for both calculation options through the comparison of the respective average values $\overline{\delta D_m}$ and $\overline{\delta D_w}$

$$\overline{\delta D_m} = \frac{1}{n}\sum_{i=1}^{i=n} \delta D_{m,i} \quad [3]$$

$$\overline{\delta D_w} = \frac{1}{n}\sum_{i=1}^{i=n} \delta D_{w,i} \quad [4]$$

The index i stands for a particular dose difference for i-th dose measurement and corresponding calculated dose for two different calculation modes in the selected part of the CIRS Thorax phantom (water equivalent part, lung equivalent part, or bone density equivalent part).

TABLE 1. Irradiation set-ups for measurements in 6 MV photon beam used for experimental verification of the Monaco ver. 5.11 treatment planning systems (TPS) calculation algorithm in the semi-anthropomorphic CIRS Thorax phantom. Reference and measuring points (I_1 to I_{10}) are shown in the last two columns; subscripts 1 to 10 correspond to the labelling in Figure 1

Set-up	Irradiation geometry	Field size [cm²]	SSD/SAD	Gantry angle [°]	reference point	measuring points
1		10×10	SSD	0	I_5	I_1, I_3, I_{5-10}
2	Single square fields	10×10	SAD	0	I_5	I_1, I_3, I_{5-10}
3		4×4	SAD	0	I_5	I_{1-9}
4		10×10	SAD	90	I_3	I_{2-10}
5	Rectangular field	10× 15	SAD	300	I_1	I_1, I_4, I_{6-8}, I_{10}
6		(6+8)×15	SAD	0	I_5	I_{1-10}
7	Single asymmetric fields	(3+8)×15	SAD	90	I_5	I_1, I_{5-10}
8		(4+10)×15	SAD	180	I_5	I_{1-3}, I_{5-10}
9		(3+7)×15	SAD	300	I_5	I_{2-10}
		12×10	SAD	0		
10	4 fields (box)	12×10	SAD	180	I_5	I_{2-5}
		12×8	SAD	90		
		12×8	SAD	270		
		4×4	SAD	30		
11	3 fields	16×4	SAD	90	I_5	I_2, I_{5-9}
		16×4	SAD	270		
12	Diamond-shaped field	14×14	SAD	0	I_3	I_1, I_3, I_{5-10}
13	Irregular L shaped field	/	SAD	45	I_1	I_{1-2}, I_{4-6}, I_{8-10}
14	MLC cylinder shaped field	/	SAD	0	I_2	$I_{1,2}$, I_5, $I_{8,9}$, I_{10}
		16×4	SAD	90		
15	3 non-coplanar fields	16×4	SAD	270	I_5	I_1, I_{5-6}, $I_{8,}$ I_{10}
		4×4[a]	SAD	30		

[a] Couch angle = 270°
SAD = source to axis distance; SSD = source to surface distance

Throughout the study, all calculations within Monaco TPS were performed on a 0.2 cm calculation grid, with 0.5% statistical uncertainty per control point.

Differences between D_m and D_w calculation modes in the bone density equivalent part of the CIRS Thorax phantom

In the second part of the study, we were aiming to determine differences between D_m and D_w calculation approaches in the Monaco ver. 5.11 TPS in the bone equivalent part of the CIRS Thorax phantom, following the same methodology as described in the preceding section.

Three irradiation geometries (single asymmetric rectangular fields having different gantry angles: 0°, 90°, and 180°) were selected for this part of the study (Table 1, set-ups 6, 7, and 8). For each of those irradiation geometries, two phantom assemblies were used to analyze differences between the two calculation approaches with respect to the measurements performed by PTW 30013 Farmer type ionization chamber in the bone density equivalent (BDE) part of the CIRS Thorax phantom. In the first assembly, referred to as *non-standard*, the water equivalent insert with the ionization chamber was placed into the BDE part of the phantom (Figure 2A). In this way, the measuring point in the phantom was surrounded by water equivalent material of sufficient thickness to fulfill conditions required by the Bragg-Gray cavity theory for the determination of absorbed dose in terms of dose to water. In the second assembly, referred to as *standard*, the BDE insert was placed in the BDE part of the phantom (Figure 2B).

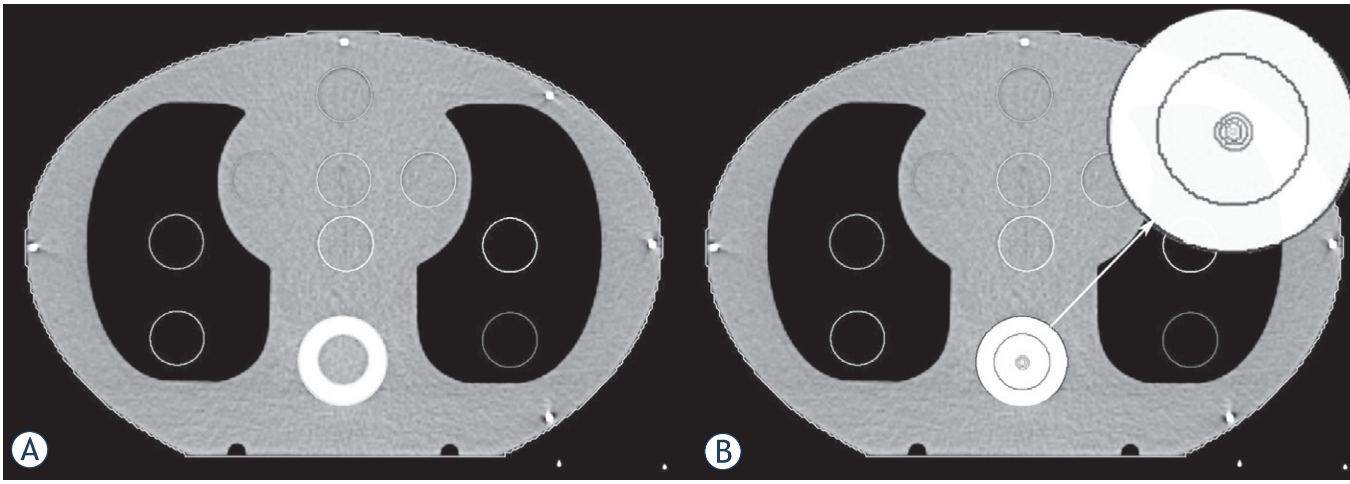

FIGURE 2. CT image of the CIRS Thorax phantom: water equivalent insert inside BDE part of the phantom **(A)**; a BDE insert inside bone density equivalent (BDE) part of the phantom **(B)** and cross-section of small "water cylinders" of different dimensions delineated inside BDE part of the phantom to find limits for calculating geometry where cavity theory applies (top right).

In the last part of the study, the phantom assembly was additionally virtually modified for the calculation purposes in the Monaco TPS: cylinders of various volumes (constant length and different diameters) were delineated inside the BDE insert on the CT scans (Figure 2, top right). This approach was utilized to obtain the limits above which the differences between D_m and D_w calculation approaches become non-significant and in agreement with experimentally determined absorbed doses. The length of the cylinders was set equal to the length of the cavity volume of the PTW 30013 ionization chamber, while the electron density of such cylinders was set to be equal to the electron density of the water. According to the IAEA TRS-398 Code of practice[22], the charge measured by an ionization chamber calibrated in terms of absorbed dose to water is directly proportional to the absorbed dose in water at the point of measurement in the absence of the chamber. By delineating cylinders having the electron density of water inside the BDE part of the phantom, we have tried to simulate the mentioned theoretical situation to different degrees.

To verify the accuracy of dose-to-medium and dose-to-water calculation modes, we have analyzed differences δD_m and δD_w between calculated and measured absorbed doses for both calculation modes and different volumes of "water cylinders" smaller than the volume of the PTW 30013 ionization chamber's cavity volume (0.6 cm^3), using Eqs. [1] to [4]. We were aiming to find the volume of "water cylinder," above which there will exist an agreement between calculated and measured doses without a statistically significant difference between both calculation approaches. Our final challenge was to define an addendum to the existing TPS verification methodology based on the described method and experimental findings from the present work.

Evaluation of results and estimation of uncertainties

The uncertainty of $\overline{\delta D_m}$ was estimated as the combination in quadrature of the statistical uncertainty of $\overline{\delta D_m}$ and the uncertainty of Monte Carlo calculation of 0.5% (1 SD) for D_m, using a coverage factor k = 2 (2 SD). The uncertainty of $\overline{\delta D_w}$ was calculated in the same manner.

We considered that the D_m and D_w calculation modes differed significantly within 95% confidence limits (two standard deviations – 2 SD, *i.e.*, coverage factor k = 2) if the relation

$$\left|\overline{\delta D_m} - \overline{\delta D_w}\right| > u_C(k = 2) \quad [5]$$

was satisfied. u_C is a combined uncertainty which was determined as the combination in quadrature of the individual uncertainties of $\overline{\delta D_m}$ and $\overline{\delta D_w}$. This estimation was considered conservative due to the fact that the uncertainties of the terms $D_{meas}/D_{meas,ref}$ were included in the compute of the individual uncertainties $\overline{\delta D_m}$ and $\overline{\delta D_w}$.

Secondly, we considered that the dose calculations within Monaco TPS were in agreement with the experimentally determined doses if the conditions

$$\left|\overline{\delta D_m}\right| < 1\% \quad [6]$$

$$\left|\overline{\delta D_w}\right| < 1\% \quad [7]$$

were satisfied. At this point we note, that throughout the rest of the paper all combined uncertainties are stated within two standard deviations, *i.e.*, using a coverage factor k = 2.

Results

Standard measurements in the CIRS Thorax phantom

Differences between calculated and measured absorbed doses for two calculation modes, dose-to-medium D_m and dose-to-water D_w, were determined using Eqs. [1] and [2] for all 15 standard irradiation configurations and ten measurement points in the CIRS Thorax semi-anthropomorphic phantom (Table 1). Mean values of percentage dose differences $\overline{\delta D_m}$ and $\overline{\delta D_w}$ calculated by Eqs. [3] and [4] are presented with corresponding uncertainties in terms of two standard deviations in Figure 3, separately for the water equivalent part (five measurement points), lung density equivalent part (four measurement points), and BDE part (one measurement point) of the phantom. Statistical significance of the obtained differences between $\overline{\delta D_m}$ and $\overline{\delta D_w}$ was evaluated using the relations shown in Eqs. [5] to [7].

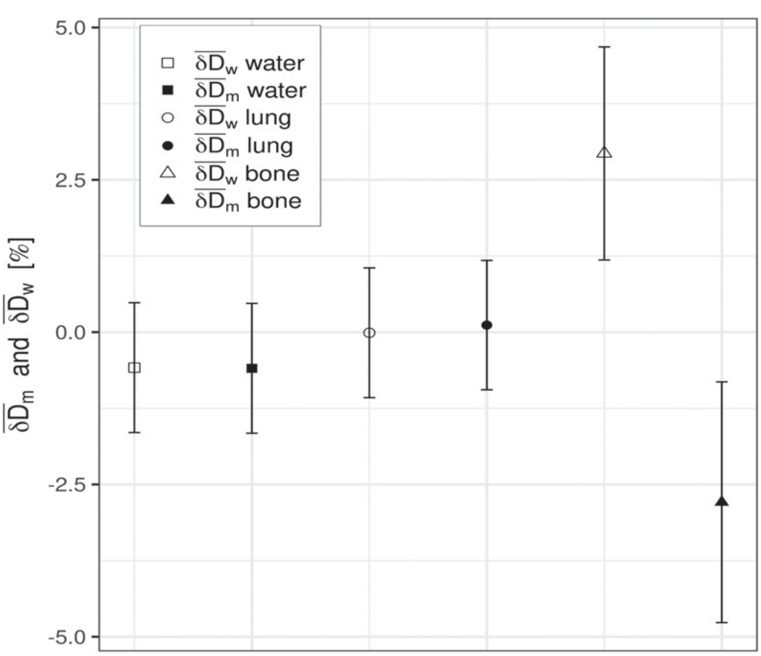

FIGURE 3. Mean percentage dose differences $\overline{\delta D_m}$ and $\overline{\delta D_w}$ between calculated and measured doses in different parts of the CIRS Thorax phantom (water, lung, and bone density equivalent materials) for both calculation options built in the Monaco TPS: dose-to-medium D_m and dose-to-water D_w. Error bars represent corresponding combined uncertainties.

Comparison of measured and calculated doses in the water equivalent part of the phantom showed that the mean percentage dose difference for all points was - 0.6% ($u_C = 1.1\%$) for the dose-to-medium calculation mode and - 0.6% ($u_C = 1.1\%$) for the dose-to-water calculation mode (Figure 3). The two calculations were found not to be significantly different within 95% confidence limits since the condition from Eq. [5] was not satisfied: $\left|\overline{\delta D_m} - \overline{\delta D_w}\right| = 0.0\% \, (u_C = 1.5\%)$.

Comparison of measured and calculated doses in the lung density equivalent part of the phantom showed that $\overline{\delta D_m}$ = 0.1% ($u_C = 1.1\%$) for the dose-to-medium calculation approach, while $\overline{\delta D_w}$ = 0.0% ($u_C = 1.1\%$) for the dose-to-water mode (Figure 3). Also in this case, the difference between both applied calculation approaches was statistically non-significant within 95% confidence limits: $\left|\overline{\delta D_m} - \overline{\delta D_w}\right| = 0.1\% \, (u_C = 1.5\%)$.

In the bone density equivalent part of the CIRS Thorax phantom, the percentage dose differences between the two calculation options were larger than in the previous two cases (Figure 3). Mean difference $\overline{\delta D_m}$ for the dose-to-medium calculation mode was - 2.8% ($u_C = 2.0\%$), while for the dose-to-water calculation approach the mean difference $\overline{\delta D_w}$ was 2.9% ($u_C = 1.8\%$). Consequently and importantly, in the BDE part of the phantom, the absolute differences between the two calculation modes were found to be statistically significant within 95% confidence limits: $\left|\overline{\delta D_m} - \overline{\delta D_w}\right| = 5.7\% \, (u_C = 2.6\%)$.

Dose calculations within Monaco TPS were in agreement with experimentally determined doses for water equivalent and lung equivalent parts of the CIRS Thorax phantom, since the conditions from Eqs. [6] and [7] were satisfied. On the contrary, for the BDE part of the phantom, conditions from Eqs. [6] and [7] were not satisfied. Therefore, we can conclude that the dose calculations in Monaco TPS ver. 5.11 were not in agreement with measured absorbed doses for the BDE part of the phantom, regardless of the calculation mode.

Differences between D_m and D_w calculation modes in the bone density equivalent part of the CIRS Thorax phantom

The second part of the study was focused on the differences between calculated and measured absorbed doses in the BDE part of the CIRS Thorax phantom. Three simple asymmetric fields with different gantry angles were selected for that purpose utilizing two different phantom assemblies, *standard* and *non-standard,* as described in the section Materials and methods and shown in Table 1 (set-ups 6, 7, and 8) and Table 2.

For *non-standard* phantom geometry, we did not find statistically significant differences between measured and calculated absorbed doses: $\overline{\delta D_m} = -0.3\%$ ($u_C = 1.3\%$) and $\overline{\delta D_w} = 0.3\%$ ($u_C = 1.3\%$). In this case, the absolute difference $|\overline{\delta D_m} - \overline{\delta D_w}|$ between both approaches was 0.6% and was statistically non-significant within 95% confidence limits ($u_C = 1.8\%$).

In the *standard* phantom geometry, however, the differences $\overline{\delta D_m}$ and $\overline{\delta D_w}$ between measured and calculated doses were larger and statistically significant (Table 2). $\overline{\delta D_m} = -3.9\%$ ($u_C = 2.1\%$) and $\overline{\delta D_w} = 4.4\%$ ($u_C = 1.9\%$).

The absolute value of the difference between both approaches was in this case statistically significant: $|\overline{\delta D_m} - \overline{\delta D_w}| = 8.3\%$ ($u_C = 2.8\%$).

As a final point, we investigated differences between calculated and measured doses in the phantom, which was virtually modified for the calculation purposes, as described in the section Materials and methods. Results for five delineated "water cylinders," including the results for *standard* geometry (V = 0 cm^3), are presented in Table 3. Differences gradually decrease as the volumes of delineated "water cylinders" become larger. The maximal difference was $|\overline{\delta D_m} - \overline{\delta D_w}| = 8.3\%$, for V = 0 cm^3 (*i.e.*, BDE plug without delineated "water cylinder"). The smallest difference of 0.1% between $\overline{\delta D_m}$ and $\overline{\delta D_w}$ was found for the largest investigated "water cylinder" of volume 0.573 cm^3. This difference was statistically non-significant within 95% confidence limits ($u_C = 1.9\%$).

Discussion

Standard measurements in the CIRS Thorax phantom

Differences between calculated and measured doses in the water equivalent part of the CIRS Thorax semi-anthropomorphic phantom were within 1% and not significantly different from zero (Eqs. [6] and [7]), regardless of the applied calculation option. The latter is in good agreement with previously published data.[9,16] Similarly, in lung density equivalent material, the calculated mean percentage dose differences were not significantly different than zero for both calculation modes, confirming the results from previously published studies.[3,9,13]

TABLE 2. Differences δD_m and δD_w between two different calculation options in the Monaco ver. 5.11. treatment planning systems (TPS) and measured data obtained in the bone density equivalent (BDE) part of the CIRS Thorax phantom, according to Eqs. [1] and [2]. Two phantom assemblies and three simple beam set-ups were considered for this part of the study

Irradiation geometry (field, gantry)	Phantom assembly	δD_m[%]	δD_w[%]
(6+8) x 15 cm^2 Gantry = 0°	standard[a]	- 2.9	2.9
	non-standard[b]	- 0.7	- 0.2
(3+8) x 15 cm^2 Gantry = 90°	standard[a]	- 3.0	5.1
	non-standard[b]	- 0.7	- 0.1
(4+10) x 15 cm^2 Gantry = 180°	standard[a]	- 5.7	5.4
	non-standard[b]	0.5	1.3

[a] BDE insert with the ionization chamber placed in the BDE part of the phantom
[b] Water equivalent insert with the ionization chamber placed in the BDE part of the phantom

TABLE 3. Mean differences, $\overline{\delta D_m}$ and $\overline{\delta D_w}$, between calculated and measured doses in the bone density equivalent (BDE) part of the CIRS Thorax phantom for D_m and D_w calculation approaches, respectively. The absorbed doses were calculated using the Monaco ver. 5.11 treatment planning systems (TPS) in the center of delineated "water cylinders" of volume V, in the BDE part of the phantom. Corresponding combined uncertainties are denoted as $u_{C,m}$ and $u_{C,w}$ for dose-to-medium and dose-to-water calculation options, respectively

V [cm^3]	$\overline{\delta D_m}$ [%]	$u_{C,m}$ [%]	$\overline{\delta D_w}$ [%]	$u_{C,w}$ [%]
0	- 3.9	2.1	4.4	1.9
0.035	- 2.6	1.5	2.5	1.9
0.141	- 1.4	1.3	1.8	1.7
0.279	- 0.3	1.2	1.2	1.5
0.573	0.3	1.4	0.4	1.3

The differences between the two calculation approaches, dose-to-medium and dose-to-water, were, however, significant in BDE media (Table 2 and Figure 3). Andreo *et al.*[9] have shown that a 10% difference in ICRP bone can be expected for Monaco ver. 5.0 TPS between two calculation modes after conversion of D_m to D_w. Results of the present study confirm those findings as well as the opposite signs of mean percentage dose differences for D_m and D_w reporting modes in the case when Monaco ver. 5.11 TPS has been used. Considerable differences between calculated dose distributions using D_m and D_w calculation approaches have also been reported in clinical studies.[15,23]

Differences between D_m and D_w calculation modes in the bone density equivalent part of the CIRS Thorax phantom

In the BDE part of the CIRS Thorax semi-anthropomorphic phantom, mean percentage dose differences $\overline{\delta D_m}$ and $\overline{\delta D_w}$ were calculated by applying

Eqs. [1] and [2] for two phantom assemblies - *standard* and *non-standard* and three selected irradiation geometries, as shown in Table 2. In the case of *non-standard* geometry, both $\overline{\delta D_m}$ and $\overline{\delta D_w}$ were within 1%, demonstrating that there is a negligible difference between applied calculation modes.

However, differences between the respective mean values $\overline{\delta D_m} = -3.9\%$ and $\overline{\delta D_w} = 4.4\%$ were statistically significant if *standard* geometry was utilized. The latter case was also assumed as our first result in the part of the study where we attempted to find the volume of "water cylinder" delineated in the Monaco ver. 5.11 TPS for which the difference between $\overline{\delta D_m}$ and $\overline{\delta D_w}$ would become non-significant.

For further discussion, analysis, and graphical presentation, the exponential function was selected to fit the data from Table 3. The general form of the fitting function is given as

$$y = a + b \cdot e^{cx} \qquad [8]$$

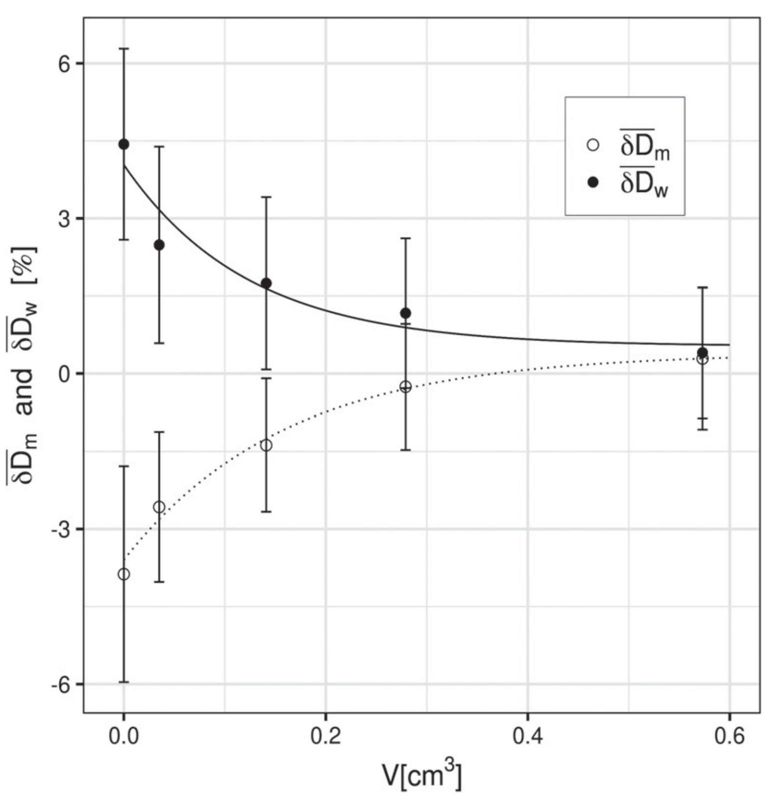

FIGURE 4. Average differences $\overline{\delta D_m}$ and $\overline{\delta D_w}$ between calculated and measured doses in the bone density equivalent (BDE) part of the CIRS Thorax phantom, as a function of the volumes of the simulated "water cylinders" (see Figure 2 and Table 3). $\overline{\delta D_m}$ and $\overline{\delta D_w}$ are presented as individual values/points calculated using Eqs. [1] to [4], and in the form of two analytical functions from Eqs. [9] and [10]. Error bars represent corresponding uncertainties within 95% confidence limits.

with fitting coefficients, a, b, and c. The dependent variable y denotes average values $\overline{\delta D_m}$ and $\overline{\delta D_w}$, while x stands for volumes of delineated "water cylinders". The explicit forms of the exponential fitting functions obtained were

$$\overline{\delta D_m} = 0.397 - 3.995 \cdot e^{-6.274 \cdot V} \qquad [9]$$

$$\overline{\delta D_w} = 0.526 + 3.510 \cdot e^{-8.131 \cdot V} \qquad [10]$$

for D_m and D_w reporting modes, respectively. Both functions from Eqs. [9] and [10] are graphically presented in Figure 4 having residual standard errors of the fit equal to 0.340% and 0.165% (on two degrees of freedom) for D_m and D_w calculation modes, respectively.

Applying Eqs. [9] and [10] for large volumes, we can see that $\overline{\delta D_m}$ and $\overline{\delta D_w}$ converge to the values of the free fitting coefficients a, *i.e.*, $\overline{\delta D_m} = a_m \cong 0.397\%$ and $\overline{\delta D_w} = a_w \cong 0.526\%$. a_m and a_w denote free fitting coefficients in Eqs. [9] and [10], respectively. Those values are non-significantly different from zero, thus in agreement with experimentally determined absorbed doses. From the latter observations, we can deduct two key facts, which form a basis for the recommended additional procedure to the existing methodology for the verification of the accuracy of the Monte Carlo based TPS we were aiming at. Briefly:

(i) Differences $|\overline{\delta D_m} - \overline{\delta D_w}|$ between dose-to-medium and dose-to-water calculation approaches gradually fade away as the volumes of "water cylinders" become larger and closer to the volume of the Farmer chamber;
(ii) $|\overline{\delta D_m}|$ and $|\overline{\delta D_w}|$ fall below 1% for volumes of delineated "water cylinders" larger than 0.3 cm^3.

Irrespective of the fact that the ionization chamber is calibrated in terms of dose to water, we propose an additional verification test of the accuracy of the Monaco TPS calculation modes for BDE regions considering the mentioned observations:

1. One can select three simple irradiation geometries (single fields, different gantry angles) and perform measurements of absorbed doses with the Farmer type ionization chamber in the BDE part of CIRS Thorax semi-anthropomorphic phantom, using a BDE insert ("standard" geometry). The ionization chamber should be positioned at the central part of the radiation field, where the measured signal is sufficiently large.

2. Measured doses are compared to the calculated ones using both calculation modes, D_m and D_w, applying Eqs. [1] to [4] for the additional four "water cylinders" delineated in the TPS.
3. Obtained mean values $\overline{\delta D}_m$ and $\overline{\delta D}_w$ of the percentage dose differences are fitted by the analytical function from Eq. [8].

Finally, the acceptability of the tested TPS algorithm is based on two conditions, which have to be fulfilled concurrently:

i) Differences $\left|\overline{\delta D}_m - \overline{\delta D}_w\right|$ between dose-to-medium and dose-to-water calculation approaches should fall within 1% for the "water cylinder" of volume 0.6 cm^3,*i.e.*,

$$\left|\overline{\delta D}_m(V = 0.6\ cm^3) - \overline{\delta D}_w(V = 0.6\ cm^3)\right| < 1\% \quad [11]$$

Fulfilment of this condition means that both calculation options yield to the same results within statistical uncertainty for large volumes, as expected. Since significant differences do exist for small volumes of delineated "water cylinders," we have to consider this fact as well. The maximal difference $\left|\overline{\delta D}_m - \overline{\delta D}_w\right|$ can be obtained from the corresponding fitting functions for V = 0 cm^3 (in our study, the maximal difference between both calculation options was 7.6%).

ii) Obtained values $\left|\overline{\delta D}_m\right|$ and $\left|\overline{\delta D}_w\right|$ have to fall below 1% (see Eqs [6] and [7]) for large volumes of delineated "water cylinders". If this condition is fulfilled, one can conclude that TPS dose calculations are in agreement with experimentally determined doses for both calculation modes.

It is important to note that our investigation was limited to the region of charged particle equilibrium (CPE) and for 6 MV photon beam only.

Conclusions

In the present study, a Monte Carlo based calculation algorithm built in the Elekta Monaco ver. 5.11 TPS was analyzed for 6 MV photon beam. It was confirmed that both calculation approaches, dose-to-medium and dose-to-water, yield to the similar results in the water equivalent and lung density equivalent parts of the semi-anthropomorphic phantom and are in agreement with experimentally determined absorbed doses.

In the bone density equivalent part of the phantom, significant differences were observed when calculations were compared to the measured absorbed doses. While the dose-to-medium approach yields to lower doses compared to the measured ones, calculations utilizing the dose-to-water computing approach revealed similar differences but of opposite sign. The observed differences can lead to ambiguity regarding the acceptability of the verification results before the clinical implementation of a newly commissioned TPS Monaco.

To overcome the ambiguity on the pertinence of the verification results in the bone density equivalent material, a supplement to the current TPS commissioning methodology has been proposed, having in mind inherent differences between the two calculation modes. This supplement relies on the findings from the present study. We consider it as a consistent and efficient method for the experimental verification of the absorbed dose calculation in both calculation modes D_m and D_w. A proposed supplementary test to the present verification methodology of the algorithm built in the Monaco TPS can assure higher accuracy and confidence compared to the current methodology.

While the selection of beams in this study assumes conditions of charged particle equilibrium, it would be highly interesting and worthwhile to set-up the study where CPE is violated, e.g., for small fields where lateral CPE does not exist. However, an experimental determination of absorbed doses in small fields is demanding. It requires determination of detector specific correction factors, which have to be utilized individually for the selected detector and are associated with additional uncertainties.[24-26] The latter can pose a problem to conduct such a study with sufficient reliability and robustness.

Acknowledgement

Bozidar Casar acknowledges the financial support from the Slovenian Research Agency through the research Grant P1-0389.

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