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Evaluation of Dose Calculation Algorithms Accuracy for Eclipse, PCRT3D, and Monaco Treatment Planning Systems Using IAEA TPS commissioning tests in a Heterogeneous Phantom

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ABSTRACT

Introduction: The accuracy of dose calculation algorithm (DCA) is highly considered in the radiotherapy sequences. This study aims at assessing the accuracy of five dose calculation algorithms in tissue inhomogeneity corrections, based on the International Atomic Energy Agency TEC-DOC 1583.

Material and Methods: A heterogeneous phantom was scanned using computed tomography and tests were planned on three-dimensional treatment planning systems (3D TPSs) based on IAEA TEC-DOC 1583.Doses were measured for 6- and 18-MV photon beams with ion chambers and then the deviation between measured and calculated TPS doses were reported. The evaluated five DCAs include Monte Carlo (MC) algorithm employed by Monaco, pencil beam convolution (PBC) and anisotropic analytical algorithms (AAA) employed by Eclipse and Superposition (SP), and Clarkson algorithms employed by PCRT3D TPSs.

Results: In Clarkson algorithm, low and high energy photons indicated 7.1% and 14.8% deviations out of agreement criteria, respectively. The SP, AAA, and PBC algorithms indicated 0.9%, 7.4%, and 13.8% for low energy photon and 9.5%, 21.3%, and 23.2% for high energy photon deviations out of agreement criteria, respectively. However, MC algorithm showed 1.8% and less than 1% deviations at high and low energy photons, respectively.

Conclusion: The DCAs had different levels of accuracy in TPSs. Some simple DCAs, such as Clarkson, showed large deviations in some cases. Therefore, the transition to more advanced algorithms, such as MC would be desirable, particularly for the calculation in the presence of inhomogeneity or high energy beams.

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Introduction

Radiation therapy is ionizing radiation treatment for various types of cancers [1, 2]. The maximization of therapeutic benefit for radiation treatments is critically dependent on the delivery of the prescribed dose to the entire planning target volume (PTV), while the dose received by the surrounding uninvolved tissues is simultaneously minimizing. To achieve this goal, it is essential to either accurately specify the spatial localization of all pertinent structures, or calculate the absorbed dose [3].

The accuracy of dose deliveryis importance in radiotherapy treatment [4]. According to the report 46 of the international commission on radiation units (ICRU), the error of radiotherapy treatment (including contouring parts, treatment planning and calculation, patient adjustment, and dose delivery) should be less than 5% [5]. In order to achieve this level, several task groups over the past decades have extended protocols for systematic quality assurance (QA) of three-dimensional (3D) radiotherapy treatment planning systems (TPSs). Various recommendations have been raised by those reports for specific QA characteristics of a TPS, including anatomical and beam descriptions, dose calculations, as well as data output and transfer.

Nowadays, 3D TPS is commonly applied in radiotherapy, which has different dose calculation algorithm (DCAs).A bulk of studies addressed specific problems associated with treatment planning and DCAs [6-8]. Additionally, manystudies have been performed on the precision of inhomogeneity correction algorithms in simple geometries [9, 10]. Based on the obtained results of these studies, DCAs might be clinically unacceptable in heterogeneities, especially in the Thorax region [11]. In the past few years, some studies dealt with theoperation of a particular TPSs [12-14], while few researchers, including Kappas and Rosenwald[15], Venselaar and Welleweerd[16], and Carrasco et al. [17],presented the comparative results of different TPSs.

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In general, DCAs are divided into three categories: a) correction-based algorithms, b) model-based algorithms, and c) Monte Carlo-based algorithms. Each of these methods can be used in 3D treatment planning although they are different in terms of accuracy and speed. Correction-based algorithmsare semi-experimental, which relies on the measured data derived from a water phantom. Model-based algorithms, such as convolution/superposition, calculate the dose distribution from a physical model [18]. A set of clinically practical tests for TPSs has been developed by International Atomic Energy Agency (IAEA) to assist users in the verification of the dosimetric accuracy of their systems [19].

Sincemost of the TPSs have been commercially available and are currently in use by different radiotherapy centers in Iran, it is of great importanceto have a comprehensive review of these devices. The objective of current study was to evaluate the dosimetric accuracy of DCAs in clinically relevant geometries in the presence of low/high-density area according to IAEA TPS commissioning tests (TEC-DOC 1583) in Eclipse v13.7.14 (Varian, Palo Alto, California, USA), PCRT3D v6.0.2 (TécnicasRadiofísicas, Zaragoza, Spain), and Monaco v5.10 (Elekta Oncology Systems, Stockholm, Sweden) TPSs.

Materials and Methods

All tests were conducted in two centers with similar machines for highand low energy photon beams using an ionization chamber.

Phantom

In this study, the phantom was chosen if it was realistic in shape and consisted of heterogeneities, capable of performing all dosimetric test cases, easy to apply and set-up, and was easily transported and shared between different institutions. The comparison of different phantoms for clinical commissioning of TPSs was accomplished according to an IAEA guideline given in TEC-DOC 1583[20]. In this study, a semi-anthropomorphic 002LFC CIRS Thorax phantom (Norfolk, USA) was used for clinical test measurements.

The CIRS phantom has a body made of tissue, bone, and lung equivalent materials with an electron density of 1.003, 1.506, and 0.207, respectively. Moreover, it has cavities for the dose measurement using an ionization chamber. The phantom contains 10 holes to hold interchangeable bar inserts for an ionization chamber. The holes were identified as shown in Figure 1. The phantom was scanned by a 16-slice helical GE computed tomography (CT) scanner (General Electric, USA). Next, CT images were converted to DICOM format for all the TPSs and used to design the IAEA tests. Electron density proportional to CT number and the highest difference between CT numbers for the same relative electron density was 20 Hounsfield units (HUs).

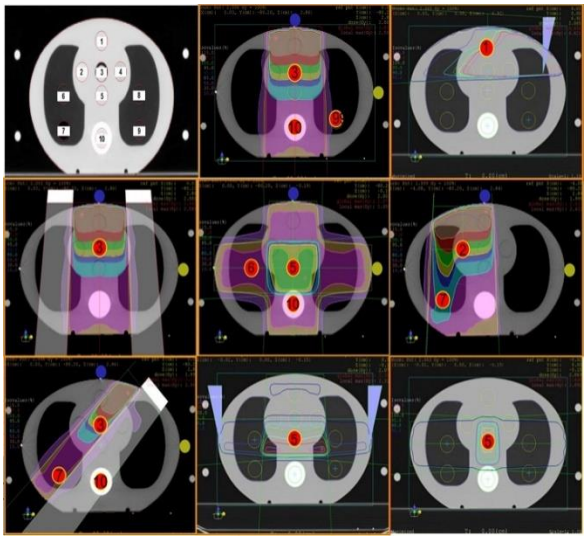

Figure1. Measurement holds in anthropomorphic 002LFC CIRS thorax phantom and eight clinical test cases

Clinical tests

The IAEA TEC-DOC 1583 has recommended a set of clinical tests through which a range of basic treatment techniques exerted in the clinical practice is verified.Table 1 tabulates the details of these tests and measurement points. As a result, planning test cases were carried out and the number of monitor units/time was calculated for the delivery of 2Gy prescribed dose to the reference point. Dose calculations for the studied algorithms were performed based on the grid size routinely used in the clinic.Test 5 was not implemented in algorithm types (a) and (b) due to the lack of Multi-Leaf Collimator in the mentioned machines. Similarly, tests 2 and 7 were not implemented by this algorithm since the Monaco Monte Carlo algorithm does not calculate the dose in the presence of wedge in the field.

Treatment planning system

Table 2 indicates five different calculation algorithms implemented on Eclipse v13.7.14, PCRT3D v6.0.2, and Monaco v5.10 TPSs with the same machine configures. The complete explanation of the implemented DCAs was beyond the aims of this study and more details about algorithms can be found in Knoos et al. [13].The algorithms in the current study were divided into three types:

(a) Measured- based algorithms, including Clarkson method.

(b) Model-based algorithms, including Superposition (SP) and Anisotropic Analytical Algorithm (AAA)methods when changes in lateral electron and photon transport (with lateral transport) and pencil beam convolution (PBC) method when changes in lateral electron and photon transport are not modeled (no lateral transport).

(c) Monte Carlo-based algorithms (MC).

Table1. Description of test cases

Description of test cases	Test no.	Reference. Point	Measurement. points	Agreement criteria (%)
Single field: SSD=100 cm, size of field=10×10 cm^2, gantry angle 0°, Coll angle 0° Deliver 2 Gy to point 3	1	3	3	2
			9	4
			10	3
Single field: SAD technique. Size of field=10×15 cm^2, wedge angle=45°, gantry angle 90°, coll angle depend on wedge orientation. Deliver 2 Gy to point 1	2	1	1	3
Significant of the field corners: SSD=100cm, fieldsize=14×14 cm^2 blocked to a 10×10 cm^2, gantry angle 0°, coll angle 45°. Deliver 2 Gy to point 3	3	3	3	3
Four field box, SAD technique. Deliver 2 Gy to point 5	4	5	5	*F1:0° 2
				F2:90° 3
				F3:180° 3
				F4:270° 3
				∑ 3
			6	F1:0° 4
				F2:90° 3
				F3:180° 4
				F4:270° 3
				∑ 3
			10	F1:0° 3
				F2:90° 4
				F3:180° 3
				F4:270° 4
				∑ 3
MLC block of cylinder 10 cm: SAD, set-up at point 2, gantry angle 0°, coll angle 0°. Deliver 2 Gy to point 2	5	2	2	3
			7	4
L-shaped field with oblique incidence: SAD technique, Deliver 2 Gy to point 3	6	3	3	3
			7	5
			10	5
Asymmetric fields with a wedge. SAD technique, Deliver 2 Gy to point 5	7	5	5	F1:0° 2
				F2:90° 4
				F3:270° 4
				∑ 3
Non-coplanar field. SAD technique, deliver 2 Gy to point 5	8	5	5	F1:30° 3
				F2:90° 3
				F3:270° 3
				∑ 3

*F: field size

Table2. Treatment planning systems used in the study

TPS vendor	Algorithm	Version	Type of accelerator	Beam energies (MV)
PCRT3D	Clarkson	6.0.2	Varian Clinac 2100 C/D	6 and 18
PCRT3D	Superposition	6.0.2	Varian Clinac 2100 C/D	6 and 18
Varian Eclipse	Anisotropic Analytical Algorithm	13.7.14	Varian Clinac 2100 C/D	6 and 18
Varian Eclipse	Pencil Beam Convolution	13.7.14	Varian Clinac 2100 C/D	6 and 18
Monaco	Monte Carlo	5.10	Elekta Precise	6 and 18

Measurements

Dose measurements were performed in two centers using Varian Clinac 2100C linear accelerator (Varian, Palo Alto, California, USA) and Elekta Precise accelerator (Elekta Oncology Systems, Stockholm, Sweden) with nominal photon energies of 6 MV and 18 MV. Regarding the type of energy, photon beams were divided into two categories, namely lower energy X-ray (6 MV) and higher energy X-ray beams (18MV). Each measurement was performed three times to gain higher precision and fewer personal mistakes. Farmer-type ionization chamber PTW30010 with UNIDOS electrometer (PTW, Freiburg, Germany) was used for dose measurements in the CIRS phantom. The

calibration of chamber and electrometer was fulfilled atSecondary Standard Dosimetry Laboratory (SSDL). Pressure and temperature were also measured during all measurement condition.

Analysis of the results

The criteria specified in IAEA TEC-DOC 1583 were used to evaluate the measured D_{meas}, and TPS was employed to calculate D_{cal}. Dose differences were normalized to the dose measured at the reference point for each test case*Equation1*:

$$Error[\%] = 100 \times \left(\frac{Dcal - Dmeas}{Dmeas,ref}\right) (1)$$

Where, $D_{meas,ref}$ presents the measured dose value at the reference point. The agreement criteria for each test case are listed in Table 1.

Results

A total of 66 test datasets were developed for the 2 energy groups of 6 MV and 18 MV with the implementation of DCAs. The differences between the calculated and measured doses for several measurement points and test cases are presented in figures 2-6. In order to have a clear demonstration of the data, the results for each algorithm were plotted on 2 beam energy groups of 6 MV and 18 MV. The linear red line depicted the value of agreement criteria for each measurement point. The results were grouped according to the energies and the calculation algorithms implemented at the studied TPS.

The results pertained to the single square field test (case1) were within the agreement criteria (±2%) at points inside the tissue equivalent material (point3) for all of the TPSs, except for MC algorithm in high photon beam energy. In the lung, out of the field (point 9), Clarkson, AAA, and PBC algorithms indicated higher deviations reflecting the underestimation of the dose with the increase of beam energy. However, the differences between measured and calculated doses were within the agreement criteria (±4%) for MC and SP algorithms.

For point number 10 (bone equivalent material), the Clarkson and MC algorithms complied with the agreement criteria (±3%). Nevertheless, deviations derived from other algorithms showed underestimation as the energy increased.

In the tangential fields (case 2), Clarkson algorithm overestimated the dose up to 3.5%, however, the differences between measured and calculated doses were within the agreement criteria (±3%) almost for all tests and the studied TPSs.

For case 3, a blocked field test, all algorithms had an acceptable level of accuracy, and their errors were within the acceptable limits (±3%).

On the basis of the results, three dosimetry points existed in the four-field box test (case 4). These points were located at the isocenter in tissue equivalent material **(**Point number 5**)**, equivalent to the lung (Point number 6), and equivalent to the bone **(**Point number10). The results of point 6 (lung) were within the agreement criteria (±4%) for the type (c) algorithm while algorithm types (a) and (b) showed deviations outside agreement criteria for all energy groups.

According to the results, in lower energy beam, the largest deviations for algorithm types (a) and (b) in the lung (point6) were up to 4% and 16.1% as overestimation, respectively. However, in higher energy beam, deviations at this point for algorithm types (a) and (b) yielded up to 11.4% and 17.9% as overestimation, respectively. Results indicated that differences increased as photon beam energy increased.

At point 10 (bone equivalent material), AAA, PBC, SP, Clarkson, and MC have deviations out of agreement criteria for 18 MV beam with their maximum differences of -4.6%, -5.3%, -6.9%, -5.5%, and −4%, respectively. Except for SP, in other algorithms, these deviations decreased as the energy decreased.

For the L-shaped field (case 6), three points were tested. Most of the algorithms passed and performed well at the prescription point 3; however, the results of MC algorithm were within the agreement criteria inside the equivalent lung material (point 7; Figure2). In other algorithms, the obtained results were out of the mentioned limit and failed, as can be seen in figures 3-6. The number of errors increased with photon beam energy. All algorithms passed successfully at the point 10 (bone equivalent media).

In the asymmetrical wedge field (case 7), the difference between measured and calculated doses was within the agreement criteria (±4%) for most algorithms. While in Clarkson, the measured dose was lower than the calculated one, indicating that Clarkson overestimates the dose for 18 MV beam in this case. In the noncoplanar field test (case 8) for the lateral field, AAA had an error that exceeded the agreement limits. However, deviations outside the agreement criteria were observed for the two studied algorithms (Clarkson and MC) for anterior (coach rotation) position. Generally, the evaluation of results revealed that for MC algorithm, the range of observed deviations between measured and calculated doses was within the agreement criteria approximately for all the tests, while larger deviations were observed for other types of algorithms.

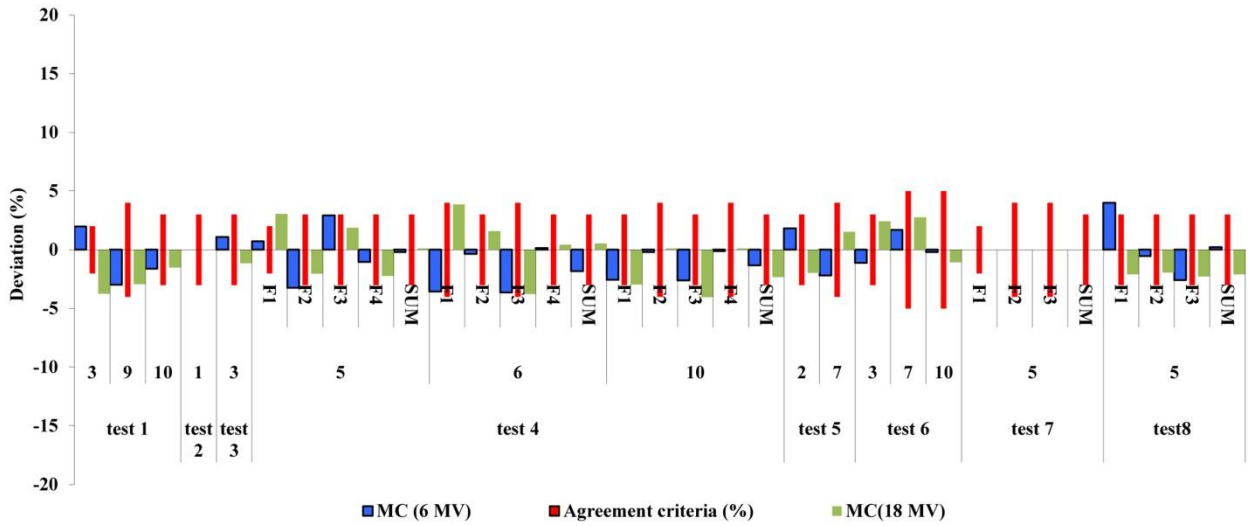

Figure 1. Differences between measured and calculated point doses for Monte Carlo algorithm in different photon energies

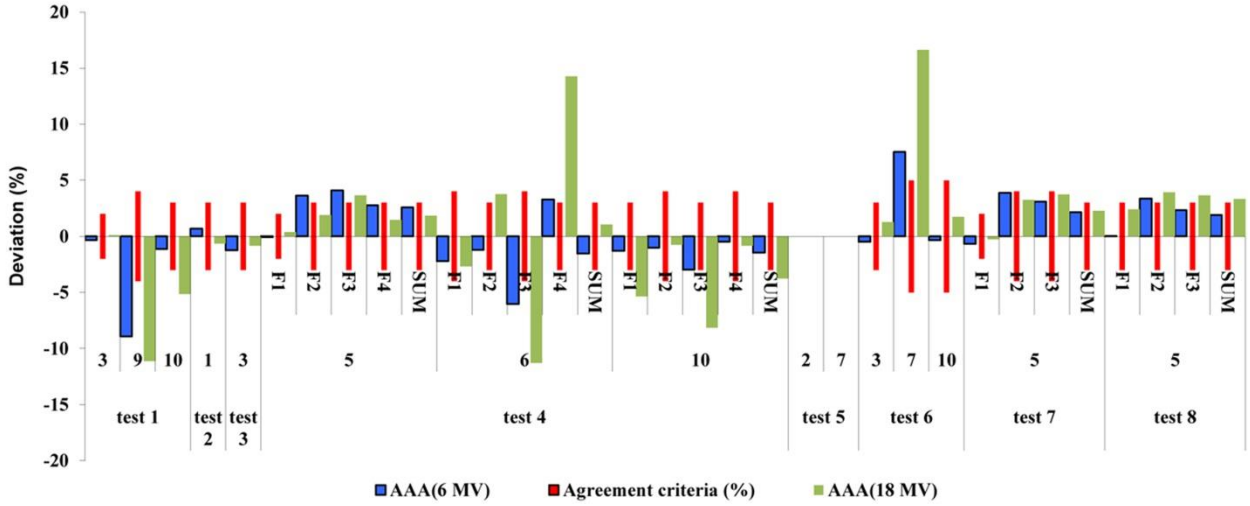

Figure 2. Differences between measured and calculated point doses for anisotropic analytical algorithm in different photon energies

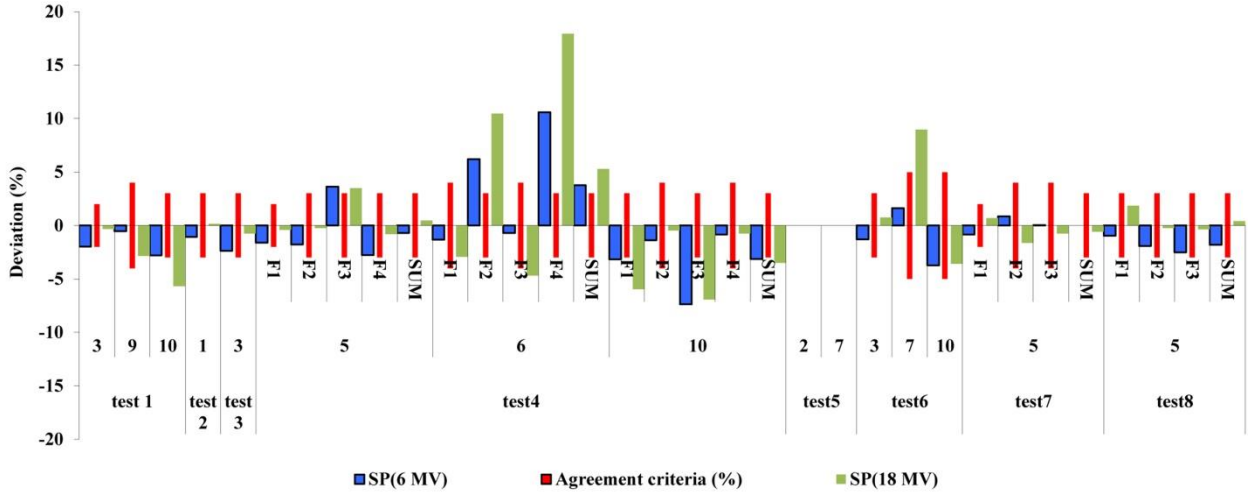

Figure 3. Differences between measured and calculated point doses for the superpositionalgorithm in different photon energies

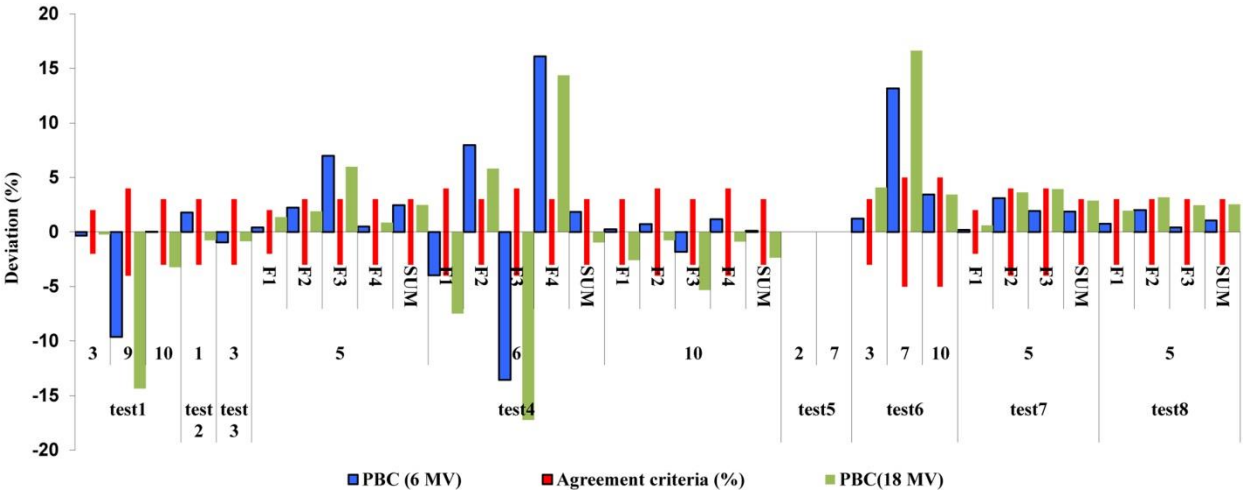

Figure 4. Differences between measured and calculated point doses for pencil beam convolution algorithm in different photon energies

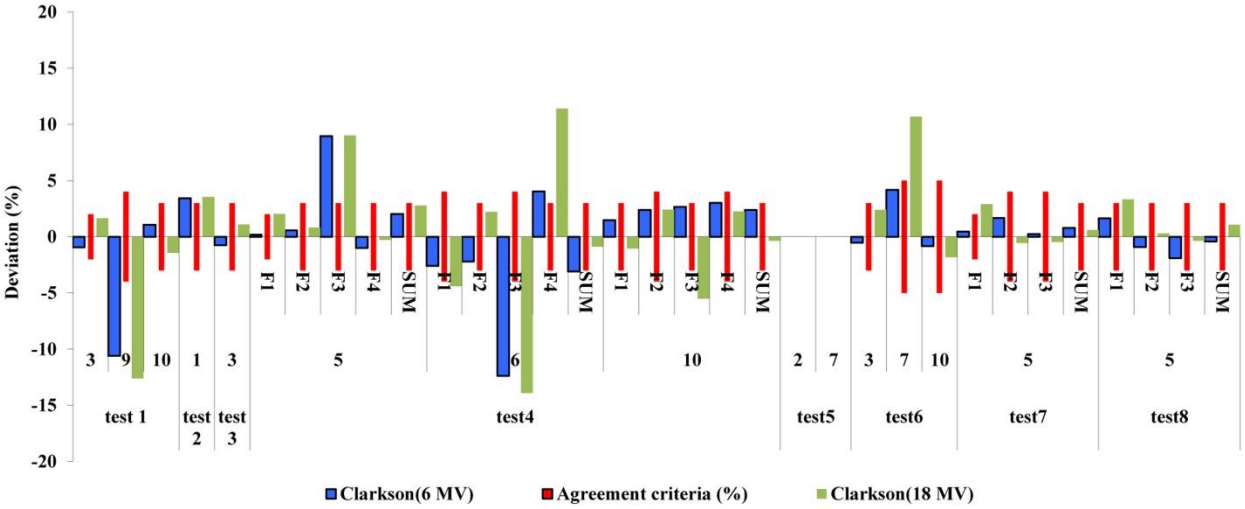

Figure 5. Differences between measured and calculated point doses for Clarkson algorithm in different photon energies

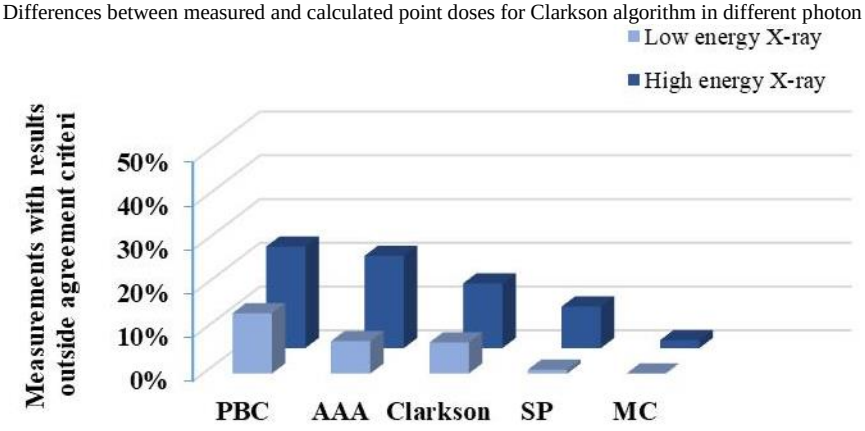

Figure 7. Percentage of deviations outside the agreement criteria depending on the algorithm types and energies

The results of the studied algorithms and energies are summarized in Figure 7. As can be seen in this figure, the number of deviations increased by the enhancement of radiation energy and declined by advanced algorithms (e.g. SP, AAA, and MC), except the PBC algorithm.

According to Figure 7, in Clarkson algorithm, low and high energy photons indicated 7.1 % and 14.8 % deviations out of agreement criteria, respectively. The SP, AAA, and PBC algorithms indicated 0.9 %, 7.4%, and 13.8 % for low energy photon and 9.5%, 21.3%, and 23.2% for high energy photon deviations outside agreement criteria, respectively. While in the MC algorithm, these values were 1.8% for high energy photons.

Discussion

It is essential to carry out various tests in order to verify the accuracy of DCAs in TPSs [21-24]. The implementation of such tests results in either the identification of the problems or fewer mistakes in the patient-treating process. In the current study, the dosimetric accuracy of different DCAs (AAA, PBC, SP, Clarkson, and MC) was evaluated for three different TPSs (Eclipse, PCRT-3D, and Monaco) in Iran according to the IAEA TEC-DOC 1583 TPS commissioning tests.

In the previous section, the differences between the measured and calculated doses of all cases calculated with AAA, PBC, Clarkson, SP, and MC were compared to each other. In Clarkson algorithm, lower energy beam (6 MV) showed up to 4% overestimation in lung. However, higher energy beam (18 MV) resulted in overestimation in lung (up to 11.4%) and underestimation in bone (-5.5%). In addition, out-of-field lung doses were underestimated for both 6 MV and 18 MV beams. Therefore, there was a relationship between the range of deviations and the beam energy, meaning that larger deviations were in compliance with higher beam energy.

These results were consistent with those obtained from a study conducted by Miften et al. [22]. Type (a) algorithm overestimated doses at all dose points in the lung of the anthropomorphic phantom [25]. However, this study did not address any changes in radiation scatter and electron transport in a heterogeneous region. Moreover, it failed to investigate the deviations increased with the enhancement of the photon energy.

In lower energy, the results of AAA and SP algorithms beam indicated an overestimation up to 10.6% in lung and -7.4% underestimation in bone for SP algorithm. In a higher energy beam, the overestimations in lung were up to 5.8% and 17.9%, and the underestimations in bone were -6.2% and -6.9% for AAA and SP algorithms, respectively. The outcomes presented here were in line with the findings of studies conducted by Robinson [3] and Van Escha et al.[12], which revealed the capability of AAA algorithm in yielding substantial overestimations for the dose beyond low-density heterogeneities. Furthermore, the deviation mean of 6% using the SP algorithm was reported by Rutonjski et al. [26].

In PBC algorithm, the overestimation was up to 16.6% in lung for 6 MV beam. Furthermore, the overestimation in lung and underestimation in bone for 18 MV beam were 14.4% and -5.3%, respectively. These results complied with the ones reported by Rutonjski et al. [26]. The basic limitation of this method was related to changes in lateral electron scattering and photon transport, which were not modeled (no lateral transport). The observed differences between doses calculated with the above-mentioned groups of algorithmsprimarily originated from changes in electron transport in the heterogeneous medium (lung), which were not sufficiently considered by PBC algorithms [27, 28].

Regarding type (c) algorithm, as it directly modeled particle transport, the obtained results were better than algorithm types (a) and (b). In this algorithm, the maximum differences were seen in bone equivalent materials, which led to insignificant differences between algorithm types (a) and (b), at this point. Results of these algorithms complied with those obtained from studies[29, 30].

All dosimetry points placed equivalent to the lung material overestimated the dose in both types (a) and (b) algorithms. Algorithm type (a) displayed fewer variations in comparison with two particular algorithm type (b) (SP and PBC).

It was observed that the value of the points outside the agreement criteria was dependent on the beam energy. Accordingly, higher beam energies led to larger deviations, which were in agreement with several studies [31, 32]. Type (c) algorithm showed a good performance in the applied IAEA cases with most of the results located inside the agreement criteria that were better than those of algorithm types (a) and (b). For all types of algorithm, the dose deviations in high energy photon beams inside bone equivalent material were underestimated, which complied with a study conducted by Gershkevitsh et al. [31].

Transition to more sophisticated algorithms provided a good consistency between the measured and calculated doses, which led to a more precise dose-volume relationship for tumors and normal tissues [26]. The results revealed the deficiency of the algorithm types (a) and (b) in evaluating dose calculation in the presence or inside low-density inhomogeneities (in an inhomogeneous region like lung) at high-energy beams calculation. Type (c) algorithm showed better accuracy in the applied test cases.

The final results of tests may be utilized as reference data for the periodically continuing QA checks by different TPSs users. However, it is worth emphasizing that different factors, namely dose calculation grid, incomplete input data, choosing applied phantom, may affect the final dose calculation results.

There are still some restrictions in the dosimetry of the ionization chamber with a limited number of points, in which the achievement of the final results requires the

selection of individual points. The end-to-end approach, however, is thought to be adequate for the evaluation of the overall quality of dose calculations and exploring TPS limitations [19, 33, 34]. The implication of film dosimetry may provide better discovery in some aspects, including the penumbra widening in low-density materials at higher energy beams (test 1, point 9), but this is beyond the scope of the current study.

Conclusion

The methodology described in IAEA TEC-DOC 1583 [19] was used in two different centers of Iran. The comparison of experimental and calculated data indicated some discrepancies. Significant differences were found between the behaviorof different DCAs in low-density and high-density heterogeneous regions, particularly in conditions with the lack of lateralelectronic equilibrium. This study has verified that the Model-based algorithms (e.g. SP or AAA) could result in a better accuracy, compared to the correction-based algorithms (e.g. Clarkson). In addition, the obtained results of the current study have demonstrated a superior precision of MC algorithm in Monaco TPS, compared to the other tested DCAs. To conclude, the IAEA test cases could assist the users in the enhancement of the capabilities of the systems and identification of their limitations.

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References

1. Li J, Zhang T. Implementation of convolution/superposition model of photon dose calculation. In7th Asian-Pacific Conference on Medical and Biological Engineering. 2008 ; 442-446.
2. Wieslander E. Verification of dose calculation algorithms in treatment planning systems for external radiation therapy: a Monte Carlo approach. Lund University; 2006.
3. Robinson D. Inhomogeneity correction and the analytic anisotropic algorithm. Journal of Applied Clinical Medical Physics. 2008 Mar;9(2):112-22.
4. Farhood B, Bahreyni Toossi MT, Soleymanifard S. Assessment of Dose Calculation Accuracy of TiGRT Treatment Planning System for Physical Wedged fields in Radiotherapy. Iranian Journal of Medical Physics. 2016 Sep 1;13(3):146-53.
5. Scott JA. Photon, electron, proton and neutron interaction data for body tissues ICRU report 46. International Commission on Radiation Units and Measurements, Bethesda, 1992, $40.00. Journal of Nuclear Medicine. 1993 Jan 1;34(1):171.
6. Cheng CW, Das IJ, Tang W, Chang S, Tsai JS, Ceberg C, et al. Dosimetric comparison of treatment planning systems in irradiation of breast with tangential fields. International journal of radiation oncology, biology, physics. 1997 Jul;38(4):835-42.
7. Paelinck L, Reynaert N, Thierens H, De Neve W, De Wagter C. Experimental verification of lung dose with radiochromic film: comparison with Monte Carlo simulations and commercially available treatment planning systems. Physics in Medicine & Biology. 2005 Apr 20;50(9):2055.
8. Mesbahi A, Zergoug I. Dose calculations for lung inhomogeneity in high-energy photon beams and small beamlets: a comparison between XiO and TiGRT treatment planning systems and MCNPX Monte Carlo code. Iranian Journal of Medical Physics. 2015 Sep 1;12(3):167-77.
9. El-Khatib EE, Evans M, Pla M, Cunningham JR. Evaluation of lung dose correction methods for photon irradiations of thorax phantoms. International Journal of Radiation Oncology* Biology* Physics. 1989 Oct 1;17(4):871-8.
10. Ekstrand KE, Barnes WH. Pitfalls in the use of high energy x-rays to treat tumors in the lung: International Journal of Radiation Oncology, Biology, Physics, Vol. 18, No. 1, January 1990, pp. 249‑252. Medical Dosimetry. 1990 Jan 1;15(4):239.
11. García-Vicente F, Miñambres Á, Jerez I, Modolell I, Pérez L, Torres JJ. Experimental validation tests of fast Fourier transform convolution and multigrid superposition algorithms for dose calculation in low-density media. Radiotherapy and oncology. 2003 May 1;67(2):239-49.
12. Van Esch A, Tillikainen L, Pyykkonen J, Tenhunen M, Helminen H, Siljamäki S, et al. Testing of the analytical anisotropic algorithm for photon dose calculation. Medical physics. 2006 Nov;33(11):4130-48.
13. Knoos T, Ceberg C, Weber L, Nilsson P. The dosimetric verification of a pencil beam based treatment planning system. Physics in Medicine & Biology. 1994 Oct;39(10):1609.
14. Aspradakis MM, Morrison RH, Richmond ND, Steele A. Experimental verification of convolution/superposition photon dose calculations for radiotherapy treatment planning. Physics in Medicine & Biology. 2003 Aug 20;48(17):2873.
15. Kappas C, Rosenwald JC. Quality control of inhomogeneity correction algorithms used in treatment planning systems. International Journal of Radiation Oncology· Biology· Physics. 1995 Jun 15;32(3):847-58.
16. Venselaar J, Welleweerd H. Application of a test package in an intercomparison of the photon dose calculation performance of treatment planning systems used in a clinical setting. Radiotherapy and Oncology. 2001 Aug 1;60(2):203-13.
17. Carrasco P, Jornet N, Duch MA, Weber L, Ginjaume M, Eudaldo T, et al. Comparison of dose calculation algorithms in phantoms with lung equivalent heterogeneities under conditions of lateral electronic disequilibrium: dose calculation algorithms in lung heterogeneities. Medical physics. 2004 Oct;31(10):2899-911.
18. Khan FM ,Gibbons JP. Khan's the physics of radiation therapy. Lippincott Williams & Wilkins. 2014.
19. I. A. E. Agency. Commissioning and Quality Assurance of Computerized Planning Systems for

Radiation Treatment of Cancer: IAEA Technical Report Series 430. IAEA Vienna. 2003.
20. TecDoc IA. 1583: commissioning of radiotherapy treatment planning systems: testing for typical external beam treatment techniques. Vienna: International Atomic Energy Agency. 2008.
21. Asnaashari K, Nodehi MR, Mahdavi SR, Gholami S, Khosravi HR. Dosimetric comparison of different inhomogeneity correction algorithms for external photon beam dose calculations. Journal of Medical Physics/Association of Medical Physicists of India. 2013 Apr;38(2):74.
22. Miften M, Wiesmeyer M, Kapur A, Ma CM. Comparison of RTP dose distributions in heterogeneous phantoms with the BEAM Monte Carlo simulation system. Journal of applied clinical medical physics. 2001 Dec;2(1):21-31.
23. Knöös T, Wieslander E, Cozzi L, Brink C, Fogliata A, Albers D, et al. Comparison of dose calculation algorithms for treatment planning in external photon beam therapy for clinical situations. Physics in Medicine & Biology. 2006 Oct 24;51(22):5785.
24. Golestani A, Houshyari M, Mostaar A, Arfaie AJ. Evaluation of dose calculation algorithms of Isogray treatment planning system using measurement in heterogeneous phantom. Reports of Radiotherapy and Oncology. 2015;2(3).
25. Ding W, Johnston PN, Wong TP, Bubb IF. Investigation of photon beam models in heterogeneous media of modern radiotherapy. Australasian Physics & Engineering Sciences in Medicine. 2004 Jun 1;27(2):39.
26. Rutonjski L, Petrović B, Baucal M, Teodorović M, Čudić O, Gershkevitsh E, et al. Dosimetric verification of radiotherapy treatment planning systems in Serbia: national audit. Radiation Oncology. 2012 Dec;7(1):155.
27. Yorke E, Harisiadis L, Wessels B, Aghdam H, Altemus R. Dosimetric considerations in radiation therapy of coin lesions of the lung. International Journal of Radiation Oncology· Biology· Physics. 1996 Jan 15;34(2):481-7.
28. Klein EE, Morrison A, Purdy JA, Graham MV, Matthews J. A volumetric study of measurements and calculations of lung density corrections for 6 and 18 MV photons. International journal of radiation oncology, biology, physics. 1997 Mar;37(5):1163-70.
29. Woon YL, Heng SP, Wong JH, Ung NM. Comparison of selected dose calculation algorithms in radiotherapy treatment planning for tissues with inhomogeneities. InJournal of Physics: Conference Series 2016 ; 694(1): 012024.
30. Zhuang T, Djemil T, Qi P, Magnelli A, Stephans K, Videtic G, et al. Dose calculation differences between Monte Carlo and pencil beam depend on the tumor locations and volumes for lung stereotactic body radiation therapy. Journal of applied clinical medical physics. 2013;14(2):38-51.
31. Gershkevitsh E, Schmidt R, Velez G, Miller D, Korf E, Yip F, et al. Dosimetric verification of radiotherapy treatment planning systems: Results of IAEA pilot study. Radiotherapy and oncology. 2008 Dec 1;89(3):338-46.
32. Alam R, Ibbott GS, Pourang R, Nath R. Application of AAPM Radiation Therapy Committee Task Group 23 test package for comparison of two treatment planning systems for photon external beam radiotherapy. Medical physics. 1997;24(12):2043-54.
33. Schiefer H, Fogliata A, Nicolini G, Cozzi L, Seelentag WW, Born E, et al. The Swiss IMRT dosimetry intercomparison using a thorax phantom. Medical physics. 2010 Aug;37(8):4424-31.
34. Asnaashari K, Gholami SO, Khosravi HR. Lessons learnt from errors in radiotherapy centers. Int J Radiat Res. 2014 Oct 1;12(4):361-7.