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ARTICLE

TomoTherapy Hi-Art Machine Matching: Verification and Quality Assurance

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Abstract: This work aims to check the similarities between two TomoTherapy machines: TomoTherapy I and TomoTherapy II (TomoTherapy Inc. Madison, WI). A strategy to match the two machines is developed to facilitate patient transfer between them. Ensuring smooth patient transfer between the two machines improves clinic workflow and reduces the time needed to complete treatments as scheduled. It also reduces the risk of errors during patient transfer between machines.
Keywords: Tomotherapy, Radiation therapy, Twinning, Treatment planning.

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1. Introduction

In a busy clinical department with multiple radiation treatment machines, it is sometimes necessary to transfer patients from one machine to another due to unavoidable machine downtime. When the treatment machines within the same clinic have matching beam characteristics and identical treatment delivery accessories, such as multi-leaf collimators (MLC), the treatment plan transfer is assumed to be straightforward. This allows for efficient patient transfer between machines, optimizing daily clinical operations.

The TomoTherapy Hi-Art system is an advanced inverse-planning radiation treatment system designed to deliver image-guided intensity-modulated radiation therapy (IG-IMRT) [1,2]. The system uses a large number of beam projections to achieve an exceptionally conformal dose distribution. Several studies have shown that tomotherapy treatment plans provide favorable dose distribution compared to conventional IMRT [3-7]. After a clinic acquires a second TomoTherapy system, it would be logical to generate cross-backup plans for both machines. These backup plans ensure that patients receive consistent treatment plan quality, and eliminate the need for re-simulation. More importantly, the calculation of compound dose across treatment planning systems (from one Hi-Art to another) is easily achievable.

However, creating backup plans between TomoTherapy systems using current methods and resources, is time-consuming and requires significant personnel and computing resources. Based on our experience, with an average of one new start per day per TomoTherapy machine, given that each tomotherapy plan requires about 8.5 hours to complete, including patient QA on the planning system, and since each TomoTherapy machine can be serviced with only one planning system, generating duplicate tomotherapy plans would require extending working hours to 17 hours per day. In order to address some of the above-stated issues, we

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developed a procedure that enables one to verify that two TomoTherapy machines are identical in terms of delivering radiation beams with identical characteristics within acceptable tolerances. This procedure allows the transfer of treatment plans from one machine to another without the need for a lengthy optimization process and enables one to verify that the transferred plan can be delivered with acceptable accuracy [8,9].

2. Materials and Methods

Two TomoTherapy Hi-ART machines were used: TomoTherapy I running TomoTherapy software version 2.1.0.2 on both the operator and planning stations and TomoTherapy II running version 2.2.1.2 on both stations. The differences between the two planning software versions, 2.1.0.2 and 2.2.1.2, include minor changes in the user interfaces of the operator and planning stations, along with additional software fixes in the operator station.

A tomotherapy treatment machine delivers a given MLC sinogram, synchronized with the couch speed and gantry rotation period. The MLC sinogram is a two-dimensional array (64 leaves by the number of projections), where each entry is either 0 (closed leaf) or 1 (open leaf). The couch speed is a real number, while the gantry rotational period is an integer between 15 and 60 seconds. The MLC file format, as well as the couch speed and the gantry rotational period, are consistent across both software versions. The TomoTherapy planning system has been previously detailed [10-12].

A tomotherapy beam scanning system was used to check the beams on both machines. This system consists of a two-dimensional water tank, two A1SL ion chambers, a TomoElectrometer (Standard Imaging, Middleton, WI.), and beam analysis software (TomoTherapy Inc. Madison, WI). Additionally, the TomoTherapy planning system was used for comparing treatment plans. The delivery quality assurance (DQA) module of the TomoTherapy planning software was used to compare the delivered dose (measured with film in the Tomo phantom) to the calculated dose from the plans [13].

The matching of two TomoTherapy machines was accomplished through the following procedure:

i. Three commissioned field widths (1.05, 2.5, and 5.02 cm) were verified to match on both machines.
ii. Beam matching between the two machines was performed by comparing the longitudinal and transverse profiles and the percent depth dose of the beams.
iii. The MLC tongue-and-groove and MLC leakage were verified to be identical within measurement uncertainties.
iv. Gantry rotational speed was confirmed to be within acceptable tolerances at different planned speeds on both machines.
v. Couch drive speed was verified to be within acceptable tolerances at different planned speeds on both machines.

2.1 The Beam Model

Once the beams on the two TomoTherapy machines had been verified to be identical, the beam model on TomoTherapy I was changed to the beam model used on TomoTherapy II. This step was essential since the planning system uses the field widths specified in the beam model to calculate the couch speed during delivery and the total couch translation while the MLC is in active delivery status. Since the pitch controls the couch drive during MLC delivery, and therefore the field width, any mismatch in the field widths would result in either shorter or longer treatment lengths.

2.2 Patient Plan Transfer

The TomoTherapy planning system does not allow any modifications to a treatment plan after final acceptance. If changes to a patient's treatment plan are required post-acceptance, a new plan and a full re-optimization must be conducted. It is not unusual for clinicians to request prescription changes after treatment has already begun. These changes may be as simple as adding a fraction or combining the last two fractions into one biologically equivalent fraction. To accommodate such modifications without the need for replanning, we routinely archive all treatment plans just before the final acceptance step. At this stage, most treatment plan adjustments can be made quickly without re-optimization. When transferring a treatment plan from one TomoTherapy unit to another, we transfer these archived plans to the second machine. Once the archived plan is restored on the second TomoTherapy planning system, it can be finally accepted on that machine, making it

available for treatment. This archive transfer and final acceptance process takes between 5 and 10 minutes.

Once the treatment plan has been transferred and accepted by the second machine, it can be delivered as if it were originally planned on that system. Delivery quality assurance for the plan can also be performed on the second system as usual. Delivery quality assurance setup on the planning system, treatment delivery on the machine onto a phantom with films and ion chamber measurements, and film analysis on the planning system are used to verify the dose distribution agreement between the plan and delivery.

The DQA analysis is used to validate the process of transferring patient plans from TomoTherapy I to TomoTherapy II. The validation process is done by completing the following steps [13-15]:

I. Transferring an existing pre-final accepted patient archive from TomoTherapy I to TomoTherapy II and finalizing the plan for TomoTherapy II.

II. Setting up the DQA on TomoTherapy II using the same cheese phantom and setup as used on TomoTherapy I.

III. Delivering the DQA plan on TomoTherapy II using extended dose range (EDR) film in the phantom's central coronal plane and placing three ion chambers in the phantom's central sagittal plane.

IV. Delivering the DQA plan on TomoTherapy II using extended dose range (EDR) film in the phantom's central sagittal and three ion chambers in the phantom-central coronal plane.

V. Processing the films using a Kodak processor and digitizing the scan using a Vidar scanner and TomoTherapy scanning software.

VI. Transferring the digitized film files to the TomoTherapy II planning system for analysis.

VII. Performing the DQA analysis on the TomoTherapy II planning system by comparing the delivered dose distribution to the planned dose distribution on both the coronal and sagittal film planes. The ion chamber measurements are used to obtain the absolute dose distribution on the films and to compare with the point dose from the planning system.

To validate the reverse transfer process (i.e., transferring from TomoTherapy II to TomoTherapy I) the same steps are followed, swapping TomoTherapy I and TomoTherapy II.

2.3 Intra-Fraction Patient Transfer

Although small, but still finite, there remains a possibility that a patient may need to be transferred between machines during the delivery of the same fraction. This could occur, for example, during a mid-fraction interruption of stereotactic body radiation therapy (SBRT) or stereotactic radiosurgery (SRS), where the timely completion of the entire treatment is essential. To accommodate this possibility, the validation process outlined above was followed with no modifications to step IV. In this case, the DQA treatment delivery on TomoTherapy II was intentionally interrupted mid-treatment. The phantom, ion chambers, and films were transferred to TomoTherapy I, where the treatment resumed from the point where it had stopped on TomoTherapy II. By doing this, we delivered the same plan onto the same film on both machines. This was done for sagittal and coronal films. Any mismatch between the two machines or any issue in continuing the treatment delivery after the transfer would be easily detected on one or more of the films.

3. Results and Discussion

3.1 Verifying the Beams

The tomotherapy beam scanning system was used to measure the longitudinal, transverse, and percent depth dose profiles on both machines. Figure 1 shows the longitudinal beam profiles for the 1.05 cm field, with dotted points representing TomoTherapy I and solid lines representing TomoTherapy II. The profiles are taken at depths of 15, 50, 100, 150, and 200 mm. Figure 2 displays the longitudinal beam profiles for the 2.5 cm field. Again, the dotted points represent TomoTherapy I and solid lines represent TomoTherapy II, with the same depth measurements. Figure 3 shows the longitudinal beam profiles for the 5.02 cm field. The dotted points are from TomoTherapy I and the solid lines are from TomoTherapy II, measured at the same depths (15, 50, 100, 150, and 200 mm). Figure 4 presents the normalized percent depth

doses for the three fields: the 1.05 cm field (blue points for TomoTherapy I and solid blue line for TomoTherapy II), the 2.5 cm field (yellow points for TomoTherapy I and solid yellow line for TomoTherapy II), and the 5.02 cm field (red points for TomoTherapy I and solid red line for TomoTherapy II.

3.2 Longitudinal Beam Profile Match

The longitudinal beam profiles for the three commissioned fields (1.05, 2.5, and 5.02 cm, shown in Figs. 1-3, respectively) demonstrated a very good match between the two machines (discrete points from TomoTherapy I and solid lines from TomoTherapy II). Despite intrinsic differences in components and design between the two machines, the final beam profiles can be matched since they depend on the geometry of the jaws and source, as well as the energy of the photons produced. The apparent mismatch at the center of the field at different depths (Figs. 1-3) is an artifact of the tomotherapy beam scanning system. The scanning software assumes that the ion chamber used for scanning the beam always runs at the same speed, even though it starts from rest and ends at rest for each segment of the beam profile. The ion chamber travels in the opposite direction through consecutive depths which is why the center of the field seems to move back and forth for different depth profiles. Different tests are used for field alignment with the gantry rotation plane. These tests are done during routine machine quality assurance. What is relevant here is that the profiles at different depths for the three commissioned fields match for both machines. The field width at half maximum was also calculated and verified to be within acceptable tolerances for both machines.

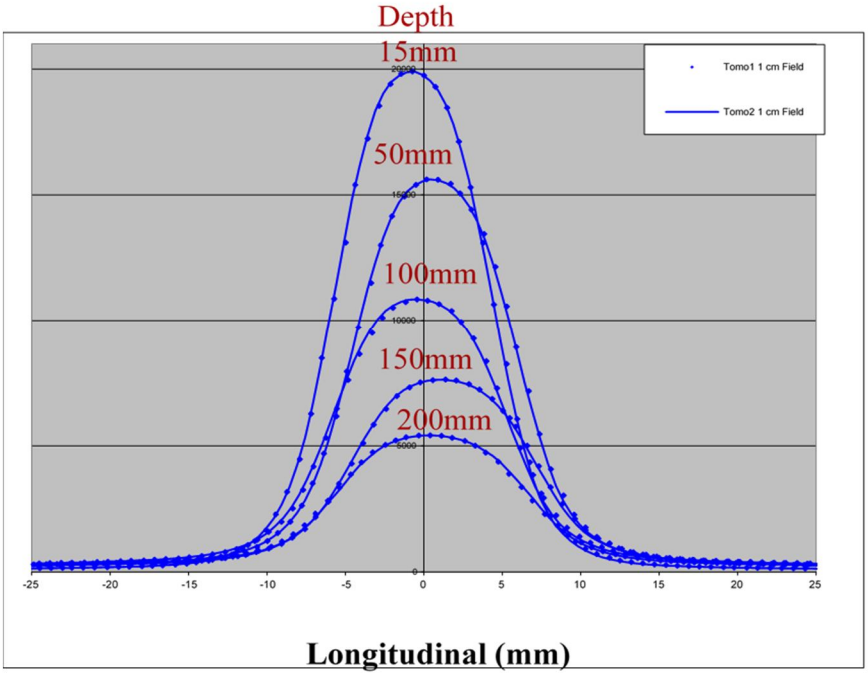

FIG. 1. Longitudinal profiles at five different depths for TomoTherapy I (discrete points) and TomoTherapy II (solid lines) for the 1.02 cm field.

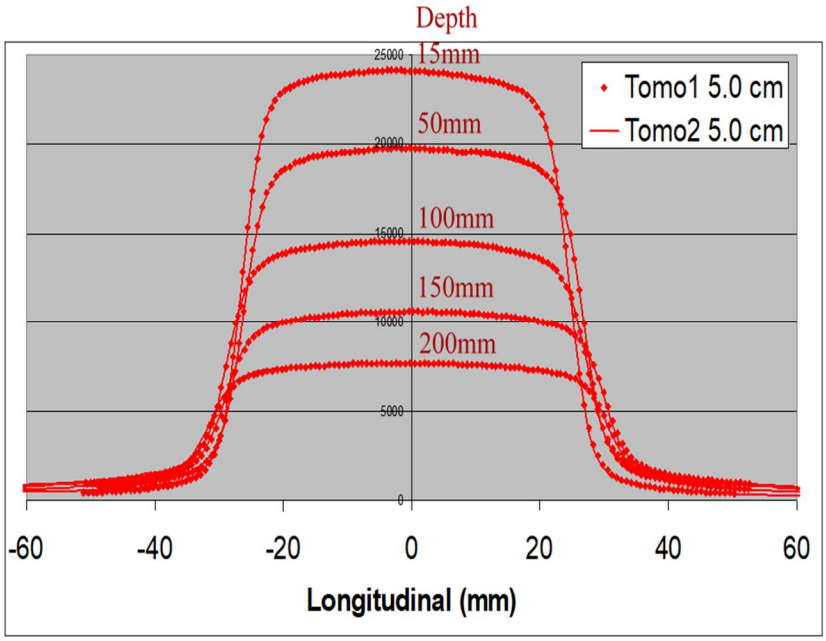

FIG. 2. Longitudinal profiles at five different depths for TomoTherapy I (discrete points) and TomoTherapy II (solid lines) for the 2.5 cm field.

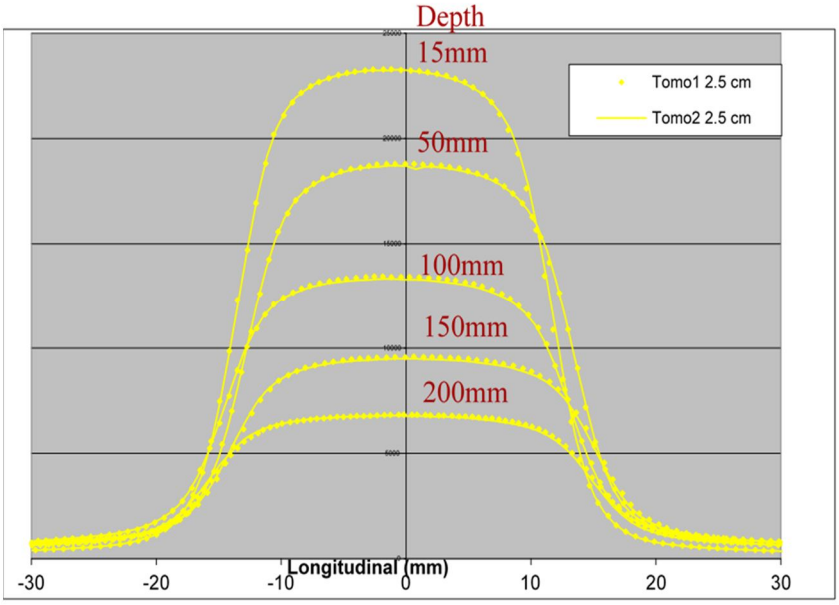

FIG. 3. Longitudinal profiles at five different depths for TomoTherapy I (discrete points) and TomoTherapy II (solid lines) for the 5.02 cm field.

3.3 Transverse Beam Profile Match

Figures 4 through 6 show the transverse beam profiles for the three commissioned fields (1.05, 2.5, and 5.02 cm, respectively), with the yellow solid line representing TomoTherapy I and the blue solid line representing TomoTherapy II. The agreement between the curves shows a very good match between the two machines.

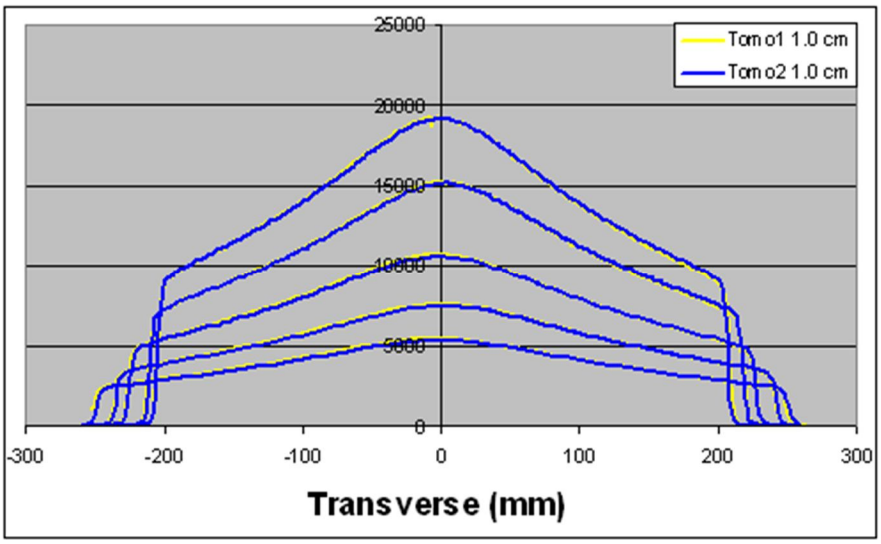

FIG. 4. Transverse profiles at five different depths for TomoTherapy I (yellow lines) and TomoTherapy II (blue lines) for the 1.05 cm field.

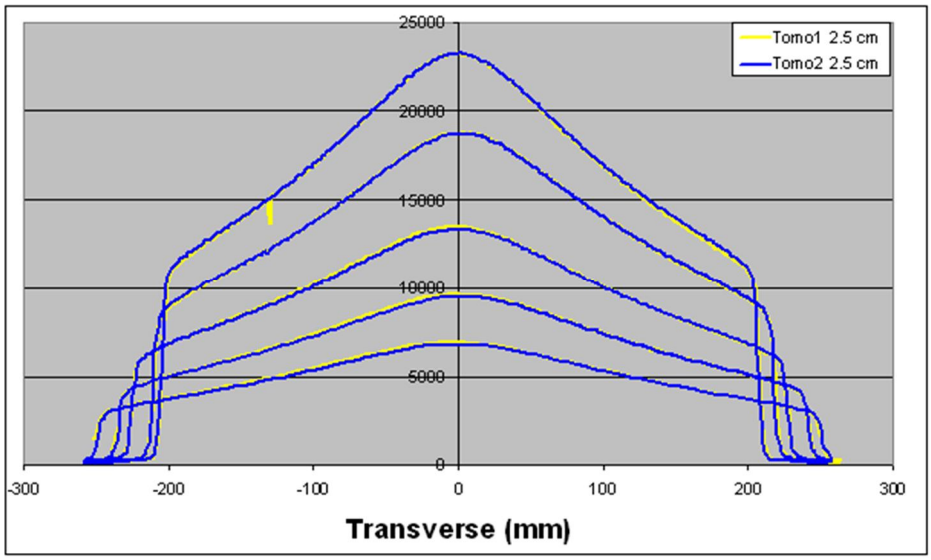

FIG. 5. Transverse profiles at five different depths for TomoTherapy I (yellow lines) and TomoTherapy II (blue lines) for the 2.5 cm field.

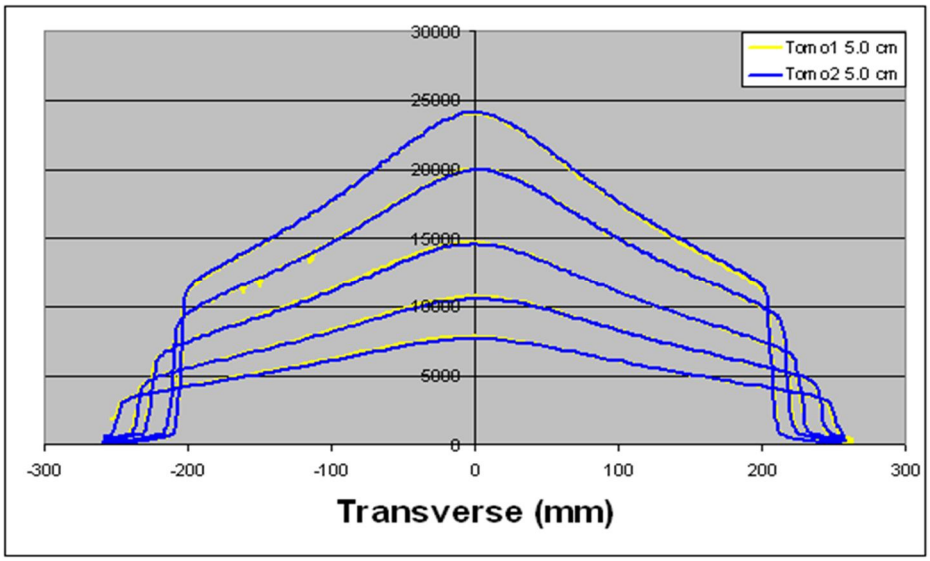

FIG. 6. Transverse profiles at five different depths for TomoTherapy I (yellow lines) and TomoTherapy II (blue lines) for the 5.02 cm field.

3.4 Percent Depth Dose

The TomoTherapy Hi-ART treatment machines use a single 6 MV energy, typically normalized at a depth of 1.6 cm. The normalized percent depth dose curves for the three commissioned fields on both machines, shown in Fig. 7 (discrete points representing TomoTherapy I and solid lines representing TomoTherapy II), are in good agreement. This agreement is expected since both machines produce the same energy photons and have identical field widths. The small differences between the TomoTherapy I and TomoTherapy II normalized percent depth dose are within acceptable measurement errors and are actually a result of expected uncertainties when measuring a 1 cm field with the A1Sl ion chamber. Therefore, treatment plan transfer can be accomplished regardless of the software version.

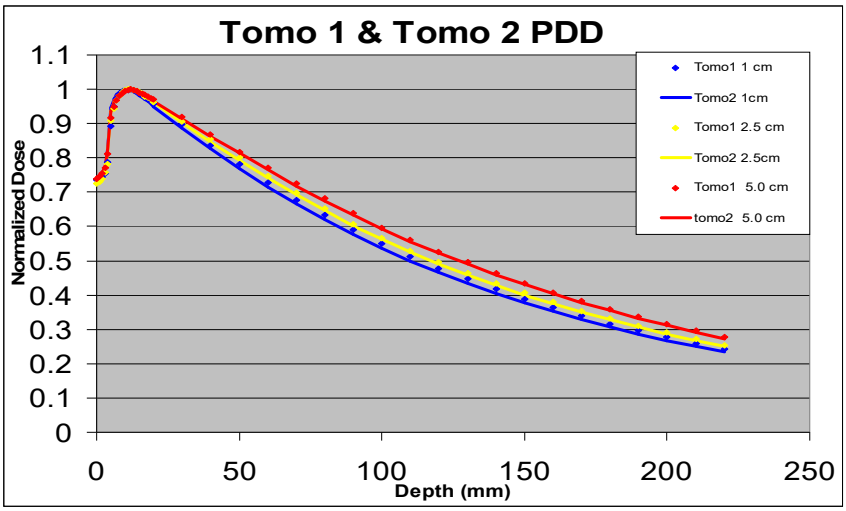

FIG. 7. Normalized percent depth dose for the two TomoTherapy machines: TomoTherapy I (points) and TomoTherapy II (solid lines).

3.5 Validation

Multiple patient DQA procedures were performed across the two TomoTherapy machines to validate the process of matching the machines. In this section, only three cases are discussed in detail: a prostate case, a stereotactic body radiotherapy (SBRT) case for the lung, and a pelvis case.

3.5.1 Example: Prostate Cancer

The first case presented here is a prostate case where 98% of the PTV volume was prescribed to receive 70.0 Gy in 28 fractions, while minimizing the dose to the rectal wall, bladder, femoral heads, and penile bulb. A typical prostate planning protocol was used, with a field width of 2.5 cm, a pitch of 0.215, and a final modulation factor of 1.81. The plan was computed on TomoTherapy II and transferred to TomoTherapy I where it was verified for plan matching between the two planning systems and for plan and delivery matching.

To verify that the transferred plan matched the original, the dose volume histogram (DVH) curves were first visually compared between the two planning systems. Then, for an accurate quantitative comparison, DVH statistics, including maximum, minimum, median, average dose, standard deviation, and physical volume, were compared between the two planning systems for the PTV and all critical structures, as reported in the plan. These statistics showed complete agreement between the planning systems, with the maximum difference being 0.06%.

To verify that the delivered dose matched the transferred plan, the dose delivered to a phantom was verified using the DQA procedure. The DQA analysis is shown in Fig. 8. Figures 8(a)-8(d) show good agreement between the planned dose distribution and the delivered dose distribution. Figure 8(a) displays the gamma map superimposed on a coronal film passing through the PTV within the cylindrical phantom. The white background corresponds to the high-dose region. The gamma index, introduced by Low *et al* [16], uses a combined ellipsoidal test of dose difference and distance-to-agreement (DTA). A gamma value of one for any pixel means that the measured pixel value matches the planned pixel value within an ellipsoid with radii of 3mm and

3% of the planned dose. The profile in Fig. 8(b), corresponding to the horizontal line in Fig. 8(a) and lateral measured and planned profiles on the film, shows a good agreement between the measured delivered and planned doses. Figure 8(c) shows good isodose line agreement between the planned and delivered doses on the coronal plane going through the center of the target. The longitudinal measured and planned profiles in the coronal plane going through the center of the target are shown in Fig. 8(d), which shows a good agreement.

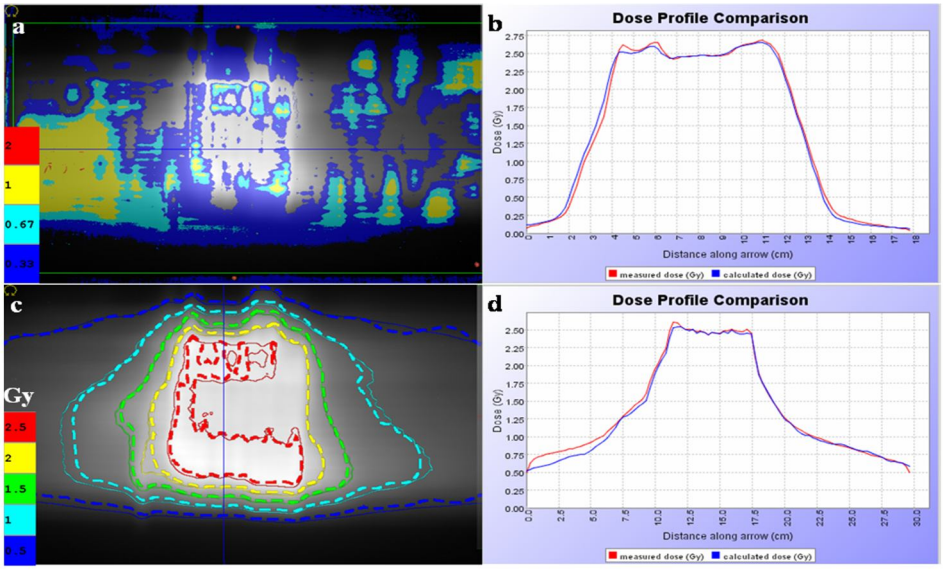

FIG. 8. (a) Gamma map superimposed on a coronal film passing through the PTV within the cylindrical phantom. The white background correlates to the high-dose region. (b) Lateral profile going through the PTV along the horizontal line in Fig. 8(a). (c) Film isodose lines (dashed lines) and plan isodose lines (solid lines) superimposed on a coronal film passing through the PTV. (d) Longitudinal profile going through the PTV along the vertical line in Fig. 8(c).

Figures 9(a)-9(d) show the analysis of a sagittal film placed at the center of the prostate PTV within the cylindrical phantom. The gamma distribution, AP profile, isodose lines, and longitudinal profile all support the good agreement between the planned and delivered dose distribution for the transferred plan between the two TomoTherapy machines.

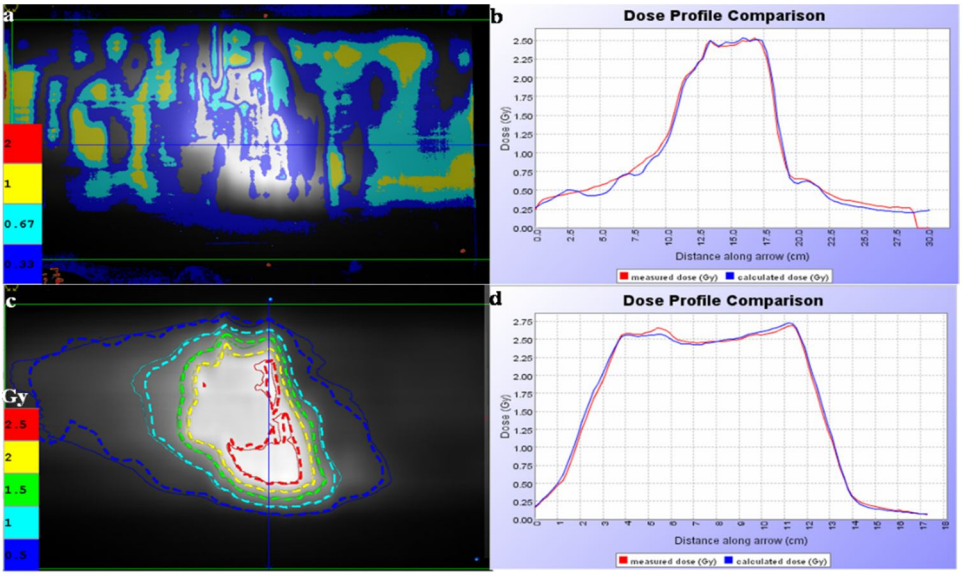

FIG. 9. (a) Gamma map superimposed on a sagittal film passing through the prostate PTV within the cylindrical phantom. The white background correlates to the high-dose region. (b) AP profile going through the PTV along the horizontal. (c) Film isodose lines (dashed lines) and plan isodose lines (solid lines) superimposed on a sagittal film passing through the PTV. (d) Longitudinal profile going through the PTV along the vertical line in Fig. 9(c).

3.5.2 Stereotactic Body Radiotherapy (SBRT) for Lung Cancer

The second case presented is a lung SBRT case, where 98% of the PTV volume was prescribed to receive 60.0 Gy in 5 fractions, while minimizing the dose to the residual lung, spinal cord, heart, esophagus, bronchus, and brachial plexus. A typical lung SBRT planning protocol was followed, with a field width of 2.5 cm, a pitch of 0.123, and a final modulation factor of 1.31. The plan was computed on TomoTherapy I and transferred to TomoTherapy II, where it was verified for plan matching between the two planning systems and plan and delivery matching.

The transferred plan was verified to match the original plan using the same method described above. When comparing all statistics for all ROIs between the original and transferred plans, there was no difference between the two plans. The DQA analysis is shown in Fig. 10. Figures 10(a)-10(d) show good agreement between the planned dose distribution and the delivered dose distribution. Figure 10(a) shows the gamma map superimposed on a coronal film passing through the SBRT PTV. The white background correlates to the high-dose region. The profile shown in Fig. 10(b) corresponds to the horizontal line in Fig. 10(a), displaying the lateral measured and planned profiles on the film. Figure 10(c) shows good isodose line agreement between the planned and delivered doses in the coronal plane going through the center of the target. The longitudinal measured and planned profiles in the coronal plane through the center of the target are shown in Fig. 10(d).

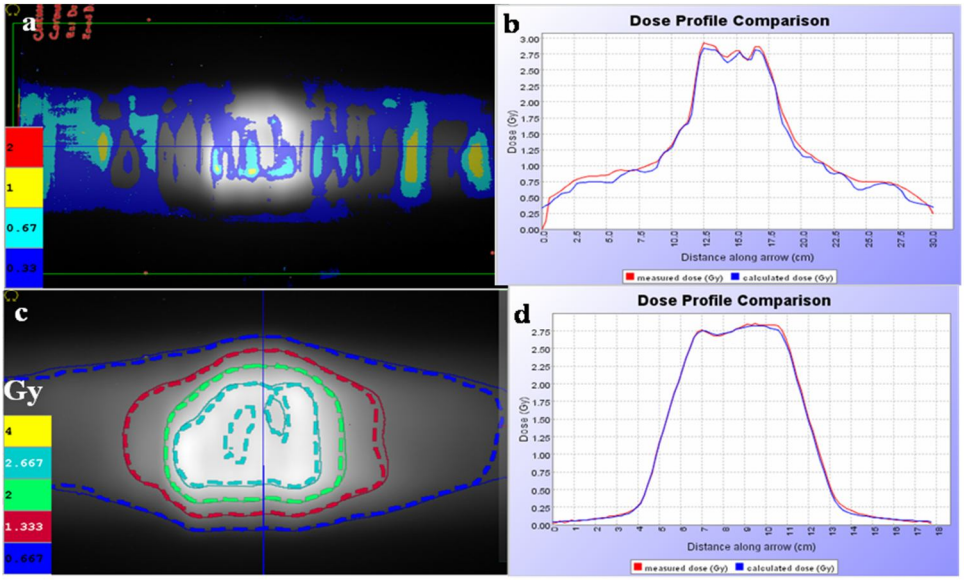

FIG. 10. (a) Gamma map superimposed on a coronal film passing through the SBRT PTV within the cylindrical phantom. The white background correlates to the high-dose region. (b) The lateral profile going through the PTV along the horizontal line in Fig. 10(a). (c) Film isodose lines (dashed lines) and plan isodose lines (solid lines) superimposed on the coronal film. (d) Longitudinal profile going through the PTV along the vertical line in Fig. 10(c).

Figures 11(a)-11(d) show good agreement between the planned dose distribution and the delivered dose distribution. Figure 11(a) shows the gamma map superimposed on a sagittal film passing through the SBRT PTV. The white background correlates to the high-dose region. The profile in Fig. 11(b) corresponds to the horizontal line in Fig. 11(a), showing the lateral measured and planned profiles on the film. Figure 11(c) illustrates good isodose line agreement between the planned and delivered doses in the sagittal plane going through the center of the target. The longitudinal measured and planned profiles in the sagittal plane going through the center of the target are shown in Fig. 11(d).

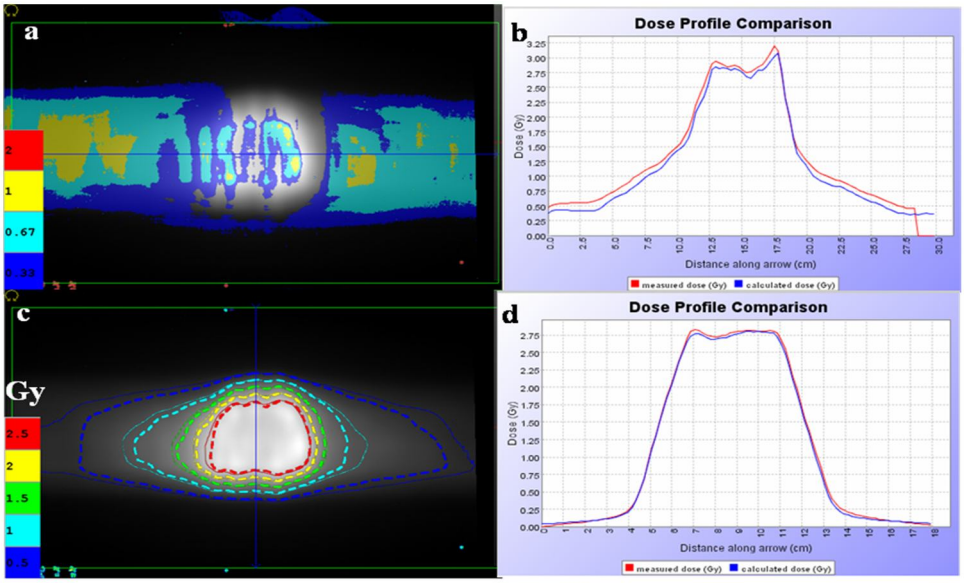

FIG. 11. (a) Gamma map superimposed on a sagittal film passing through the SBRT PTV within the cylindrical phantom. The white background correlates to the high-dose region. (b) AP profile going through the PTV along the horizontal line in Fig. 11(a). (c) Film isodose lines (dashed lines) and plan isodose lines (solid lines) superimposed on the sagittal film. (d) Longitudinal profile going through the PTV along the vertical line in Fig. 11(c).

3.5.3 Head and Neck Cancer

The third case presented is a head and neck case where 98% of the PTV volume was prescribed to receive 60.0 Gy, while the nodal PTV received 50.0 Gy in 30 fractions. Critical structures to avoid included the residual parotid, spinal cord, brainstem, larynx, and oral cavity. A typical head and neck planning protocol was used, with a field width of 2.5 cm, a pitch of 0.172, and a final modulation factor of 2.421. The plan was computed on TomoTherapy II and transferred to TomoTherapy I where it was verified for plan matching between the two planning systems. To test delivery matching in scenarios where a patient may need to switch machines mid-treatment (for example, to complete a fraction that was started on one machine and finished on the other), the DQA procedure was manually interrupted mid-treatment and completed on the second machine. This process verified the accuracy of interrupted treatments between machines.

The transferred plan was verified to match the original plan using the same method described above. When comparing all statistics for all ROIs between the original and transferred plans, we didn't find any differences. The DQA analysis, shown in Figs. 12 and 13, were designed to demonstrate that an interrupted treatment on one machine can be safely completed on the other machine. The top half of the film in Fig. 12(a) was delivered on TomoTherapy II. The treatment was manually interrupted after the first half. The phantom and film were transferred to TomoTherapy I where the second half of the treatment was delivered. Figure 12 shows the film dose compared to the planned dose on TomoTherapy I. The gamma distribution within the reliable region of the film (green rectangle) in Fig. 12(a) is well within the acceptable limits of 3% of the prescribed dose and 3 mm distance to agreement. The direction of treatment progression is along the vertical line (top to bottom) in Fig. 12(a). The measured and planned profiles along this line are shown in Fig. 12(b). Any mismatch between the two machines during treatment would be presented as a discontinuity (a peak or a dip) in the measured profile. The lack of such discontinuity shows that an interrupted treatment on one machine can be safely completed on the other machine. Isodose lines and AP profiles for the same sagittal film are shown in Figs. 12(c) and 12(d).

The same film analyzed on TomoTherapy II is shown in Fig. 13. The good agreement between the planned and delivered dose distributions, as shown by the gamma map, isodose lines, and profile agreement, assures that the transferred plan and the deliveries are identical across the two machines.

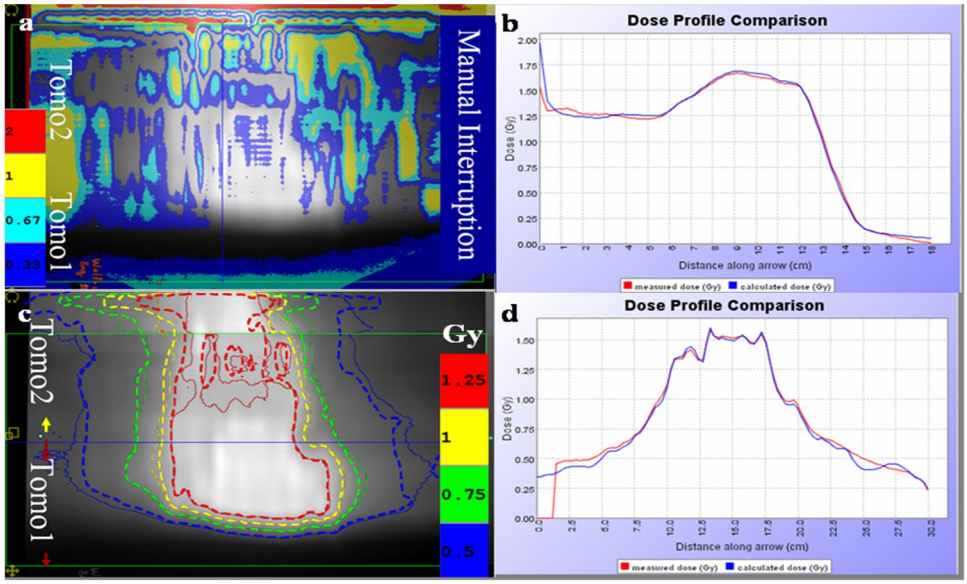

FIG. 12. The dose on the film was delivered on both TomoTherapy machines and analyzed on TomoTherapy I. (a) Gamma map superimposed on a sagittal film passing through the H& N PTV. The film was delivered on both TomoTherapy machines. (b) Longitudinal profile going through the PTV along the vertical line in Fig. 12(a). (c) Film isodose lines (dashed lines) and plan isodose lines (solid lines) superimposed on the sagittal film. (d) AP profile going through the PTV along the horizontal line in Fig. 12(c).

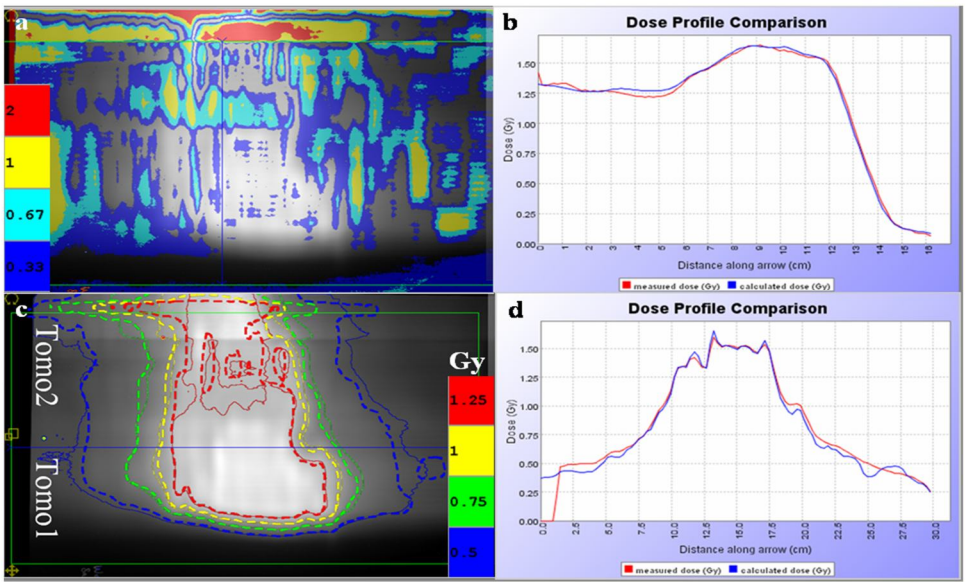

FIG. 13. The dose on the film was delivered on both TomoTherapy machines and analyzed on TomoTherapy II. (a) Gamma map superimposed on a sagittal film passing through the H& N PTV. The film was delivered on both TomoTherapy machines. (b) Longitudinal profile going through the PTV along the vertical line in Fig. 13(a). (c) Film isodose lines (dashed lines) and plan isodose lines (solid lines) superimposed on the sagittal film. (d) AP profile going through the PTV along the horizontal line in Fig. 13(c).

The beams from the two TomoTherapy machines were checked and verified to be identical within measurement uncertainties. No physical modifications on either of these two tomotherapy delivery machines resulted from this study. Both machines still have their original gold standard files. The beam model on the TomoTherapy I planning system was replaced with the beam model from TomoTherapy II. This adjustment was necessary to deliver identical plans and does not have any effect on treatment planning since the two beams were verified to be the same. Comprehensive tests using film and ion chamber dosimetry show that both beam models are correct models for both machines within the limits of measurement uncertainty.

4. Conclusion

A comprehensive methodology to check the similarities between two TomoTherapy machines — TomoTherapy I and TomoTherapy II (TomoTherapy Inc. Madison, WI) — has been described. A strategy was developed to match the two machines, facilitating patient transfers between them. Using this approach, the two UW TomoTherapy machines were found to be similar and capable of delivering the same treatment plans within the tolerances acceptable for IMRT treatments. On several occasions, tomotherapy treatment plans were transferred between the two TomoTherapy machines to avoid treatment cancellations. Tomotherapy treatment plan transfers were accomplished within a reasonable time frame (5-10 minutes per plan) without changing the outcome of the plans.

Interrupted treatments on one machine can be safely completed on the second machine within 10 to 15 minutes. This can be useful in SRS or SBRT cases where the delivery of the treatment or fraction within a short time is essential.

The procedure of matching the two TomoTherapy machines can be applied to more machines within the same clinic or across clinics. When having two TomoTherapy machines, this procedure eliminates the need for backup planning which requires additional planning clusters and additional dosimetry staff time.

Disclaimer

The procedures and methods presented here were solely developed by the Institute's physics team for internal use. TomoTherapy Inc. did not participate in this study, and they neither support nor recommend the procedures presented here.

Acknowledgments

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