

Filmless methods for quality assurance of Tomotherapy using ArcCHECK

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Purpose: Tomotherapy delivers an intensity-modulated radiation therapy (IMRT) treatment by the synchronization of gantry rotation, multileaf collimator (MLC), and couch movement. This dynamic nature makes the quality assurance (QA) important and challenging. The purpose of this study is to develop some methodologies using an ArcCHECK for accurate QA measurements of the gantry angle and speed, MLC synchronization and leaf open time, couch translation per gantry rotation, couch speed and uniformity, and constancy of longitudinal beam profile for a Tomotherapy unit.

Methods: Four test plans recommended by AAPM Task Group 148 (TG148) and the manufacturer were chosen for this study. Helical and static star shot tests are used for checking the leaves opened at the expected gantry angles. Another helical test is to verify the couch traveled the expected distance per gantry rotation. The final test is for checking the couch speed constancy with a static gantry. ArcCHECK can record the detector signal every 50 ms as a movie file, and has a virtual inclinometer for gantry angle measurement. These features made the measurement of gantry angle and speed, MLC synchronization and leaf open time, and longitudinal beam profile possible. A shaping parameter was defined for facilitating the location of the beam center during the plan delivery, which was thereafter used to calculate the couch translation per gantry rotation and couch speed. The full width at half maximum (FWHM) was calculated for each measured longitudinal beam profile and then used to evaluate the couch speed uniformity. Furthermore, a mean longitudinal profile was obtained for constancy check of field width. The machine trajectory log data were also collected for comparison. Inhouse programs were developed in MATLAB to process both the ArcCHECK and machine log data.

Results: The deviation of our measurement results from the log data for gantry angle was calculated to be less than 0.4° . The percentage differences between measured and planned leaf open time were found to be within 0.5% in all the tests. Our results showed mean values of MLC synchronization of 0.982, 0.983, and 0.995 at static gantry angle 0° , 45° , and 135° , respectively. The mean value of measured couch translation and couch speed by ArcCHECK had less than 0.1% deviation from the planned values. The variation in the value of FWHM suggested the couch speed uniformity was better than 1%. The mean of measured longitudinal profiles was suitable for constancy check of field width.

Conclusion: Precise and efficient methods for measuring the gantry angle and speed, leaf open time, couch translation per gantry rotation, couch speed and uniformity, and constancy of longitudinal beam profile of Tomotherapy using ArcCHECK have been developed and proven to be accurate compared with machine log data. Estimation of the Tomotherapy binary MLC leaf open time is proven to be precise enough to verify the leaf open time as small as 277.8 ms. Our method also makes the observation and quantification of the synchronization of leaves possible. © 2016 American Association of Physicists in Medicine [<https://doi.org/10.1002/mp.12009>]

Key words: ArcCHECK, quality assurance, Tomotherapy

1. INTRODUCTION

As the development of rotation radiotherapy has grown rapidly in the past decade, many advanced techniques such as intensity modulated radiation therapy (IMRT), helical Tomotherapy, and volumetric arc therapy (VMAT) have been widely used in radiotherapy.^{1–7} Tomotherapy delivers IMRT technique using a rotating linear accelerator which is capable of radiating a 6-MV photon beam continuously while the couch moves into

the gantry.⁸ A compressed air-driven binary multileaf collimator (MLC) is used in Tomotherapy for intensity modulation by controlling the open time for each leaf. Therefore, the performance of MLC is crucial to the final outcome of a Tomotherapy treatment. Moreover, due to the helical delivery pattern, Tomotherapy is much more complex compared to the conventional Linac, hence the dosimetry verification and machine quality assurance (QA) are particularly important to assure the treatment safety and accuracy.^{9–13}

Ion chamber and film measurements with a manufacturer-supplied Virtual Water cylinder phantom were widely used for dosimetry verification of patient treatment plans in helical Tomotherapy.^{12,14} However, film QA using EDR2 has been reported to be easily affected by the development process which introduces uncertainty to the calibration curve.^{15,16} Devices with 2D arrays also have successful applications in helical Tomotherapy QA^{17,18} despite the possible limitation due to its directional dependency.^{19,20} The ArcCHECK (Sun Nuclear, Melbourne, FL, Australia), a cylindrical acrylic phantom with an array of spirally arranged diode detectors, has been found to be well suited for QA of VMAT, IMRT, and Tomotherapy,^{21–27} since the cylindrical design of ArcCHECK removes rotational dependence of the detectors.

Regarding machine QA, as mentioned by AAPM Task Group 148 (TG148), the treatment accuracy of Tomotherapy system would be compromised if any inaccuracy or drift in parameters of gantry rotation and table movement occurs during a treatment.¹¹ Thus, the accuracy of the gantry angle of the system, the synchronization between couch translation per gantry rotation and the ability of the system to correctly synchronize the couch position with the beam delivery should be tested periodically.¹¹ TG148 recommended several couch/gantry tests in quarterly QA, which were originally raised by Fenwick et al.⁹ Although TG148 did not cover the TomoDirect™ feature, it was strongly recommended by the manufacturer to perform a star shot test with a nonrotating gantry, since a separate gantry positioning system was used for static procedures in Tomotherapy.¹² The details of these film-based synchrony tests are briefly introduced below:

1.A. Helical and static star shot tests

The helical and static star shot tests were designed to verify that the leaves open at the intended gantry angles for a helical and static delivery, respectively. The helical star shot test which had a total of 40 gantry rotations while the couch moved continuously and the central leaves No. 32 and 33 opened simultaneously for 277.8 ms at projections centered at 0°, 120°, and 240°. The plan set a gantry start angle of −2.5° to ensure the projections were centered at the expected angles.

The static star shot test was used to check the gantry positions at the expected static angles 0°, 45°, 90°, and 135°, respectively, without any couch movement and leaves No. 32 and 33 opened sequentially for a total of 20 seconds.

The angles could be directly measured on the irradiated films using protractor. However, no information about gantry speed could be provided by the film-based test.

1.B. Couch speed uniformity

A plan with a static gantry at 0°, 1-cm field width and constant couch movement speed of 0.5 mm/s for a distance of 20 cm was designed to verify that the couch speed was constant for a clinically typical speed. A profile along the Y-axis was taken for analyzing the uniformity and no exact value of couch speed was calculated. Note that the test requires a

constant dose rate or a reference signal would be needed for normalization.

1.C. Couch translation per gantry rotation

A helical plan with a 1-cm field width and a pitch of 1 opened the leaves for 180 degrees at the 2nd, 7th, and 12th of the 13 total rotations. It was used to verify if the couch traveled the expected distance per gantry rotation. The resulting exposures on the film should be separated by 5 cm in the Y-axis profile.

The machine QA methods recommended in TG148 are mainly film-based with different setup involving solid water slabs.¹¹ Although some QA methods based on a step wedge phantom and on-board MVCT detector were developed by Mikołajczyk and Althof et al.,^{28,29} which was further embedded in the Tomotherapy Quality Assurance (TQA): a software package for monitoring the machine status,³⁰ there is little literature discussing about machine QA for Tomotherapy using an independent or third-party tool. The ArcCHECK provides some built-in functions for control point dose analysis and MLC QA per control point for conventional Linac.³¹ The feasibility of using ArcCHECK for machine QA for VMAT was also studied by utilizing its cylindrical geometry and spiral pattern of diodes distribution.³² In this study, we aim to develop some novel methods based on ArcCHECK for machine QA measurements of a Tomotherapy unit.

2. MATERIALS AND METHODS

The film-based QA plans recommended by TG148 were delivered without any modification in our studies. All measurements were performed using ArcCHECK on a Tomotherapy unit, which consists of 60 binary leaf pairs of 6.25-mm width at isocenter and is equipped with the Dose Control System (DCS). The ArcCHECK consists of 1386 diode detectors which are arranged in a spiral pattern with a length of 21 cm and a diameter of 21 cm. The distance between adjacent diodes in each column is 1 cm. The ArcCHECK is also capable of saving a movie file which takes a snapshot of the detector signals every 50 ms. The feature of virtual inclinometer has also been utilized to record the gantry angle during the plan delivery.

The ArcCHECK was adjusted for couch sag and isocentrically set up for 1.A. For covering the whole irradiated area in 1.B and 1.C, the ArcCHECK was moved 10 cm out of bore relative to the isocenter.

MATLAB programs were developed to process these measured movie files. Every test was repeated 10 times in different days for observing the stability and feasibility of our proposed methods.

2.A. Gantry angle

When delivering the helical star shot test, the virtual inclinometer tool of the ArcCHECK was used to measure the gantry angle at each snapshot, it would record multiple angle values for each 5° projection with leaves opened. A mean

value and the corresponding time for each projection were calculated. The gantry speed could then be calculated simultaneously. The machine trajectory log data were also collected and analyzed for comparison.

For the static star shot test, due to the detector distribution of the ArcCHECK, one detector picking up the signal was located on the beam entry side while the other one was located at the beam exit side for gantry angles except 0° . Since the detector is either close to the edge or out of radiation field at gantry angle 90° , which may cause larger uncertainty, we decide not to analyze the measurement data for 90° .

2.B. MLC synchronization and leaf open time

For the static star shot test, since the gantry and couch were stationary, the open time for leaves No. 32 and 33 could be easily obtained by calculating the full width at half maximum (FWHM) of the corresponding detector signal versus time curve, respectively. However, in helical star shot test, for each 5° projection with leaves opened, the detector signal versus time data would be collected from two adjacent detectors closest to the beam central line. To reduce the influence from the beam transverse profile and relative change in the distance between the detector and the x-ray source caused by the gantry rotation, the start time of leaf open was decided by the ramp-up of the detector which was closer to the leaf open position, while the stop time of leaf open was calculated from the ramp-down of the other detector. The whole process is illustrated in Fig. 1, which also shows a typical detector signal plots for two adjacent detectors in helical test.

2.C. Couch translation per rotation

Due to the spiral pattern of the diodes' distribution, when one of the diodes of the ArcCHECK located at the beam

center, the dose profile as measured by the row of diodes which surrounded the center diode should have a symmetrical pattern if the Tomotherapy unit and all diodes were in good condition.

For quantitatively evaluating the symmetry of a profile normalized to its maximum, we divided the profile measured by one row of 67 detectors: $(D_1, D_2, \dots, D_{67})$ into left half **A**: $(D_1, D_2, \dots, D_{33})$ and right half **B**: $(D_{35}, D_{36}, \dots, D_{67})$, while D_{34} was the maximum point. Then, we defined a shape parameter as:

$$S = \frac{\sum |A - B|}{\sum |A + B|}$$

By searching the local minimum of the S parameter, the beam center at different times could be located, which made the calculation of the couch translation possible by assuming a constant couch speed. An illustration of the measurement principle and a typical detector signal plot at the beam center are shown in Fig. 2.

2.D. Couch speed and uniformity

Since the test of couch speed uniformity is a plan with static gantry at 0° , the location of the beam center is between two adjacent detectors by using the same method mentioned in 2.C. With the location of beam centers and the corresponding time, the couch speed could be easily calculated.

Furthermore, it is obvious that the detectors under irradiation are capable of measuring a beam profile while the couch is moving along the longitudinal direction. Two columns of detectors, which are located on top of the ArcCHECK almost symmetrically, were chosen for analysis in this study. A total of 34 profiles were collected and a five-order one-dimensional median filter was applied to remove the spike noise. According to TG148, the method of measuring the beam

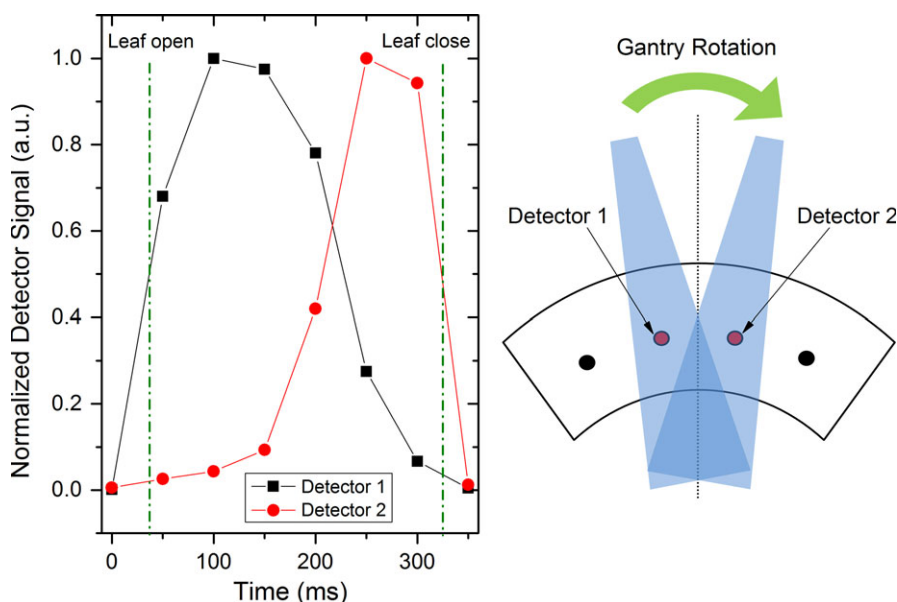


FIG. 1. Illustration of the principle described in 2.B. for the measurement of leaf open and close time in helical star shot test. [Color figure can be viewed at wileyonlinelibrary.com]

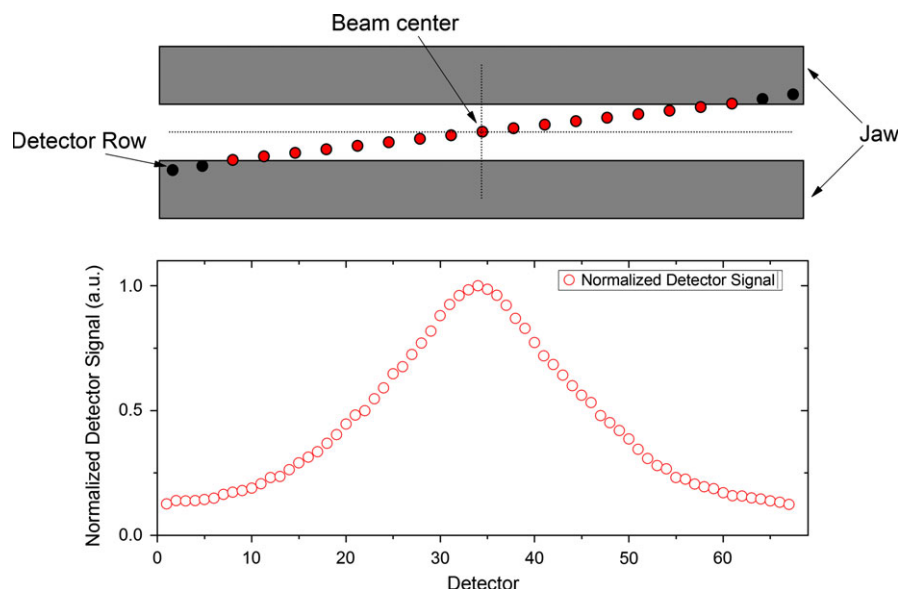


Fig. 2. Illustration of the principle described in 2.C for locating the beam center. [Color figure can be viewed at wileyonlinelibrary.com]

profile relies on uniform couch motion.¹¹ The drift of couch speed would lead to a change in the measured beam profile. Therefore, after the FWHM was calculated for each profile, the variation in FWHM could be used to evaluate the couch speed uniformity.

2.E. Constancy of longitudinal beam profile

All 34 profiles measured as described in 2.D were used to calculate a mean which represented the beam profile for single measurement. The mean profile and its FWHM measured on the first day were chosen to be the benchmark. All measurements conducted on different days were compared with the benchmark using gamma analysis with a 2%/0.1 mm criterion. Since TG148 also suggest an alternative way of using film dosimetry to monitor the longitudinal beam profile for consistency,¹¹ we also irradiated films with a setup simulating the location of the detectors in ArcCHECK measuring the profile.

We should emphasize that our measured longitudinal beam profiles were different from those measured using ionization chamber under the standard topographic plan setup in TG148 and could not be directly compared with the reference data provided by the manufacturer.

3. RESULTS

Although ten measurements were taken, for elucidating the performance of our proposed methods, only a typical measurement result is presented for 3.A, 3.B, and 3.D.

3.A. Gantry angle

Table I shows the mean and standard deviation (SD) of measured gantry angles by ArcCHECK for both helical and static star shot tests. For helical test, the difference between the mean measured angle and the expected value was less

TABLE I. Results of gantry angle measured by ArcCHECK for both helical and static star shot tests.

	Expected angle (°)	ArcCHECK result		
		Mean (°)	SD (°)	Difference (°)
Helical	0	359.9	0.3	−0.1
	120	119.9	0.2	−0.1
	240	239.8	0.2	−0.2
Static	0	0.0	0.5	0.0
	45	44.8	0.5	−0.2
	135	134.6	0.5	−0.4

than 0.2°, which was comparable to the *gantry phase angle difference* in TQA helical step wedge test. The mean measured angle for static test had a deviation as large as 0.4° which should be caused by the location of those irradiated detectors in the ArcCHECK as mentioned in 2.A. Furthermore, the SD was also extended to be 0.5°. For further studying the accuracy of our method, we extracted the machine trajectory log data of a delivered plan. After synchronization with the log data, the plots of both our measured and machine-recorded gantry angle versus time are shown in Fig. 3(a). The mean deviation of our measurement results from the log data for the total 40 rotations was calculated to be less than 0.25°. Figure 3(b) shows how the gantry speed varies with time. The mean measured gantry speed was 18.02°/sec with an uncertainty $\pm 0.07^\circ/\text{sec}$, which was very close to the plan setting of 18.00°/sec and the mean value of 18.02°/sec calculated from log data.

3.B. MLC synchronization and leaf open time

The machine-recorded leaf open time which was obtained from the post-treatment data of MV detector confirmed the

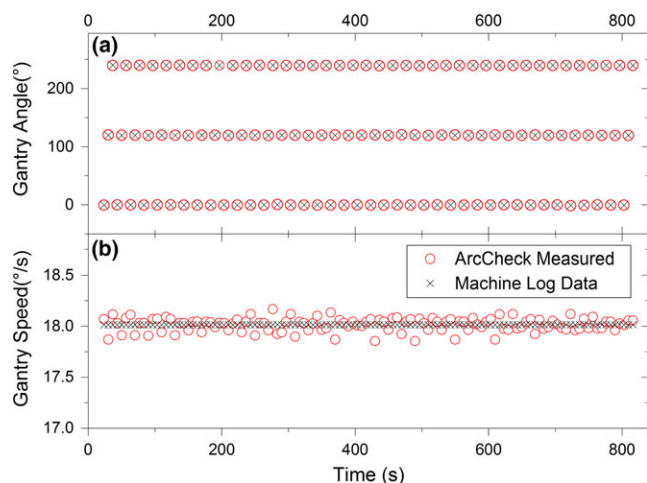


FIG. 3. (a) Plots of gantry speed versus time for measured results by ArcCheck and data extracted from machine log file. (b) Plots of gantry angle versus time for measured results by ArcCheck and data extracted from machine log file. [Color figure can be viewed at wileyonlinelibrary.com]

plan setting of leaf open time. The mean measured leaf open time with its SD by ArcCHECK for both helical and static plans are shown in Table II. The percentage differences between measured and expected values were calculated to be within 0.5% in all the tests. Figure 4 shows the plots of measured leaf open time versus plan delivery time for helical plan at gantry angle 0°, 120°, and 240°, respectively. The maximum deviation of measured open time was as large as 14 ms. For the static test, Fig. 5 shows how the measured signals from detectors vary with time at static gantry angle 0°, 45°, and 135°. Since the detector that is located at the beam exit would produce low signal to noise ratio due to beam attenuation by the ArcCHECK, this caused a relatively higher standard deviation on the result as shown in the Table II and Fig. 5. The moment when one leaf was closed and the other was opened could be clearly observed in the plots, that is, the region in the rectangle in Fig. 5. If leaves are synchronized perfectly, the sum of the two detectors' response should be one when the leaf state is “in transition”. Our results show

TABLE II. Results of leaf open time measured by ArcCheck for both helical and static star shot tests.

	Gantry angle (°)	Measured leaf open time (ms)		Expected leaf open time (ms)	% Difference
		Leaf no. 32	Leaf no. 33		
Helical	0	278.9 ± 6.8		277.8	0.4
	120	278.0 ± 6.5		277.8	0.1
	240	277.6 ± 6.4		277.8	-0.1
Static		Leaf no. 32	Leaf no. 33	Leaf no. 32	Leaf no. 33
	0	1996.2 ± 1.8	1999.1 ± 0.8	2000.0	-0.2
	45	1998.5 ± 0.9	1996.6 ± 7.1	2000.0	-0.1
	135	1991.2 ± 2.9	1991.5 ± 4.3	2000.0	-0.4

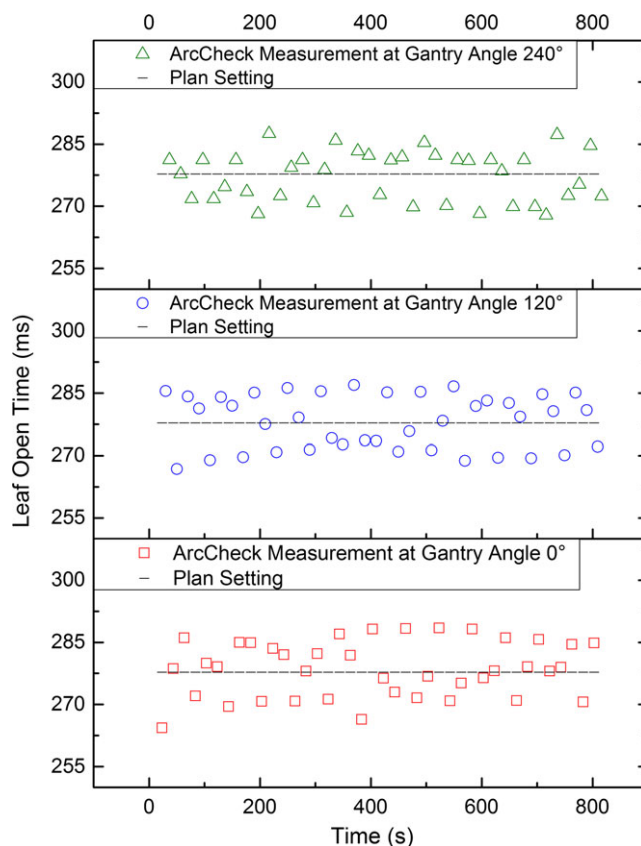


FIG. 4. Plots of leaf open time versus plan delivery time for measured results by ArcCheck at gantry angle 0°, 120°, and 240°, respectively. [Color figure can be viewed at wileyonlinelibrary.com]

mean values of 0.982, 0.983, and 0.995 at static gantry angle 0°, 45°, and 135°, respectively.

Since current methods for measuring the leaf open time were mostly based on the sinogram collected from MV detector,^{30,33} our proposed method succeeds to provide an independent check for the timing accuracy of the machine.

3.C. Couch translation per rotation

The measured couch translation agrees well with the plan setting. The mean separation of all measurements was calculated to be 49.970 with an uncertainty of ± 0.033 mm. The precision of our method is comparable or even better than film. The shaping parameters of all located beam centers were less than 0.01. A small displacement of 0.152 mm in longitudinal direction which was the longitudinal resolution of ArcCHECK could change the shaping parameter from 0.009 to 0.08. Therefore, the shaping parameter was proved to be sensitive enough for our purpose even when the setup error was included.

3.D. Couch speed and uniformity

Figure 6(a) shows the plot of ArcCHECK-measured couch speed versus time. The calculated speed based on data retrieved from machine log file is also presented for comparison. Our result shows a mean value of

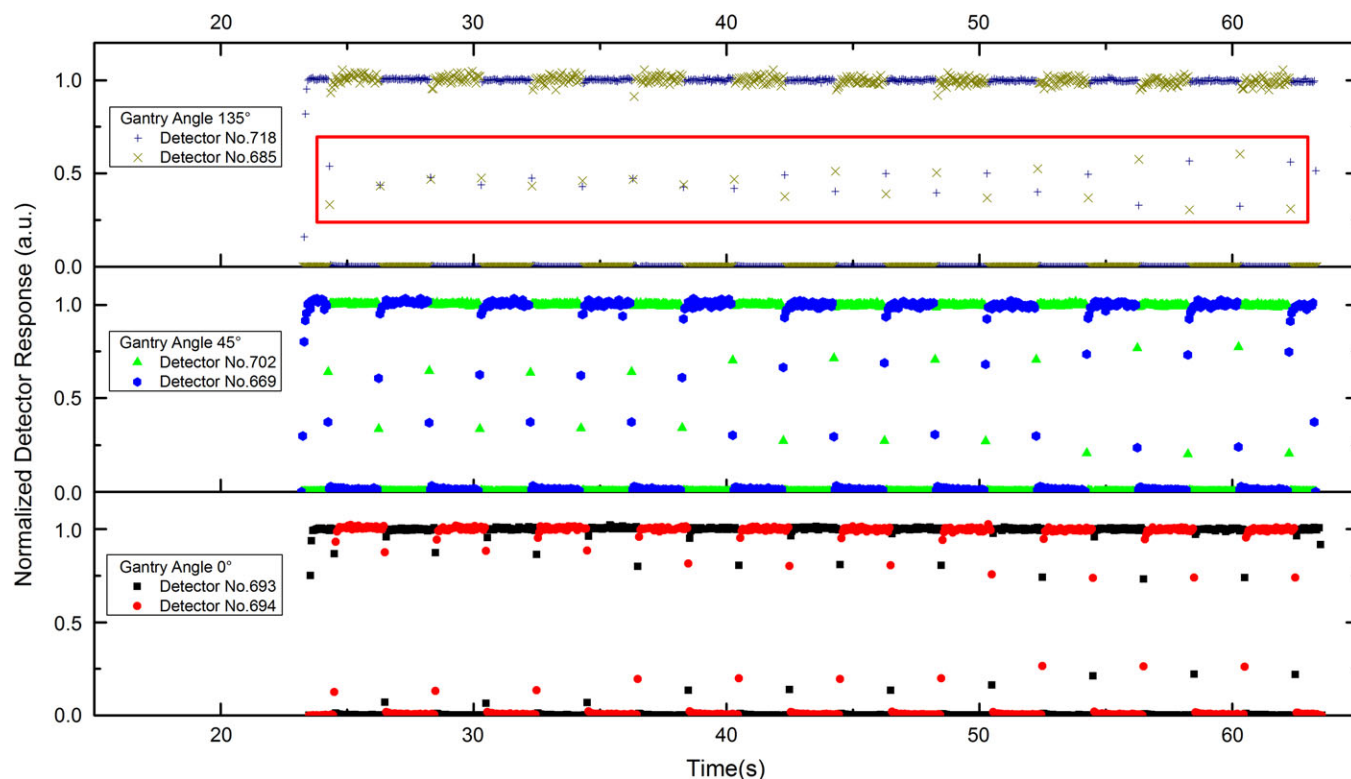


FIG. 5. Plots of normalized measured detector signal versus time at static gantry angle 0° , 45° , and 135° , respectively. The region marked by a rectangle shows an example of MLC synchronization. [Color figure can be viewed at wileyonlinelibrary.com]

0.5002 mm/s with an uncertainty ± 0.0025 mm/s, which agrees very well with both the plan setting of 0.5 mm/s and the machine log data of 0.5005 mm/s. The total ten consecutive measurements of the mean couch speed with its SD are also shown in Fig. 6(b), which proves the

stability of our method. Furthermore, if we focused on the mean couch speed during the plan delivery, only the first and last located beam centers would be used for calculation, which would certainly give a smaller uncertainty less than 0.1%.

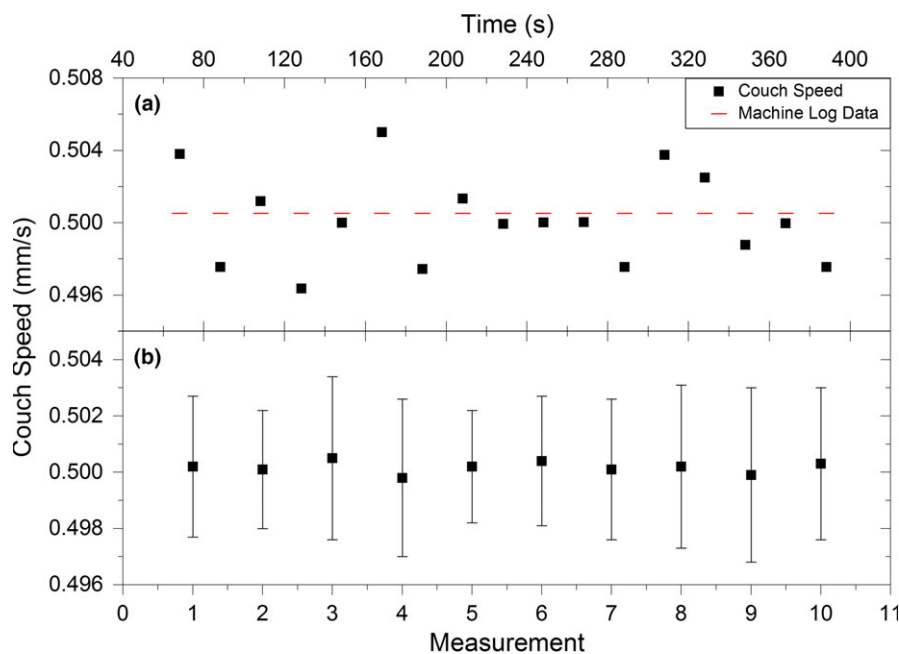


FIG. 6. (a) Plots of couch speed versus time for measured results by ArcCheck in single measurement. (b) Mean couch speed with its standard deviation for ten consecutive measurements. [Color figure can be viewed at wileyonlinelibrary.com]

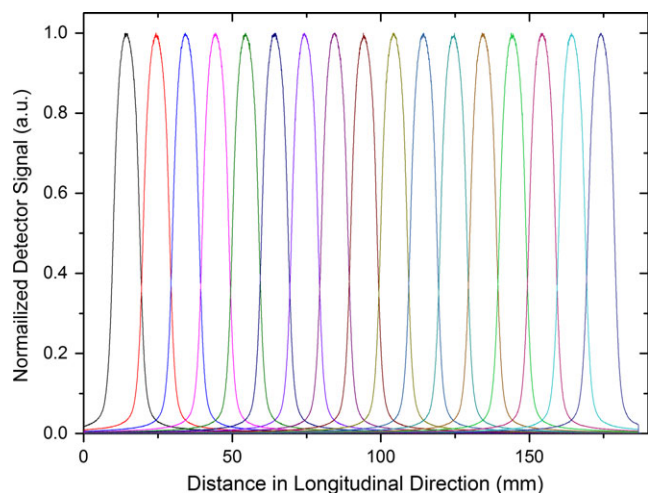


FIG. 7. Measured longitudinal beam profiles by 17 detectors in the same column. [Color figure can be viewed at wileyonlinelibrary.com]

The measured beam profiles by one column of detectors are shown in Fig. 7. The distance indicated in the figure was calculated by multiplying a couch speed of 0.5 mm/s. The mean of FWHM for all profiles was calculated to be 8.950 mm, with an uncertainty of ± 0.014 mm. The maximum deviation of FWHM was found to be less than 0.6%, which indicated a stable couch speed during the plan delivery. After analyzing all of the ten measurements, the maximum deviation and the maximum SD of FWHM, which were less than 1% and 0.5%, respectively, proved that the tolerance of 2% from TG148 is still applicable in our test. Our proposed method combined the advantages of both film and TQA step wedge and was able to measure the couch speed and uniformity at the same time.

3.E. Constancy of longitudinal beam profile

Figure 8 shows the measured profiles by different detectors and the gamma analyses when comparing their measured

profiles with the calculated mean profile. For a clear illustration, only 6 of the total 34 profiles were selected. A mean value of gamma indexes less than 0.1 suggests that the calculated mean profile is a good representation of longitudinal beam profile.

Day-one benchmark and the film-measured profile are shown in Fig. 9(a), while [Fig. 9(b)–9 (j)] show the gamma analyses for measurements conducted on nine different days. The FWHM of film measurement was calculated to be 9.002 mm, which was close to our benchmark 8.960 mm. Gamma analysis was not performed for the film since the result would be affected by the film calibration curve and the detector response at the penumbra region. The mean and maximum gamma index and FWHM for measurements from day 2 to day 10 were also shown in Table III. The maximum of gamma indexes were all less than 0.5, which proved the feasibility of constancy check for longitudinal beam profile using ArcCHECK.

4. DISCUSSION

In the gantry angle measurement for helical star shot test, compared with the film-based method recommended by TG148 which shows an averaged result of several rotations, our proposed method was capable of measuring the gantry angle for each projection in all 40 rotations and make the gantry speed measurement possible. However, in the static angle measurement, our proposed method showed no additional advantage over film due to the design and detector arrangement of ArcCHECK. Although our measured static angle was obtained by calculating the mean of the inclinometer reading from beam entry and beam exit detectors, the additional uncertainty coming from the error propagation was compromised by such algorithm. Thus, the intrinsic uncertainty of virtual inclinometer, which is $\pm 0.5^\circ$ according to Ref. 31, turns out to be determinate.

Fortunately, the static star shot test provided us more information about the status of MLC during plan delivery. Our

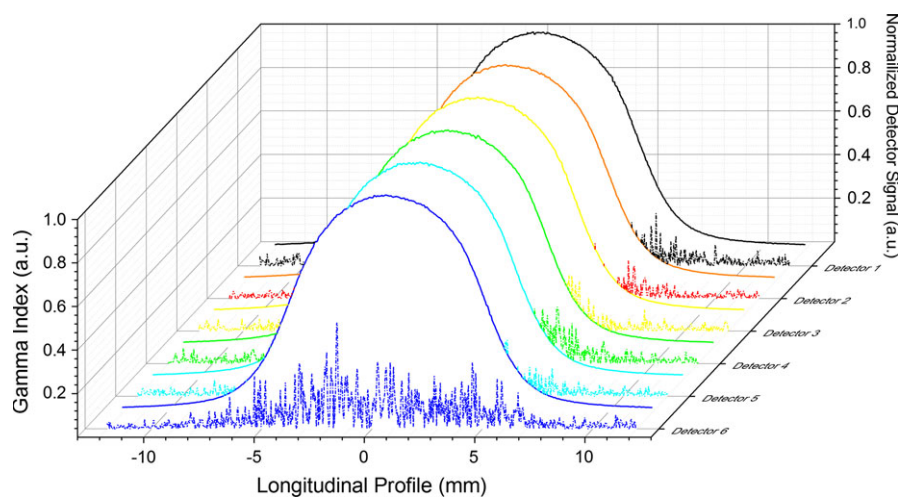


FIG. 8. Measured profiles by six detectors and the corresponding gamma analyses. [Color figure can be viewed at wileyonlinelibrary.com]

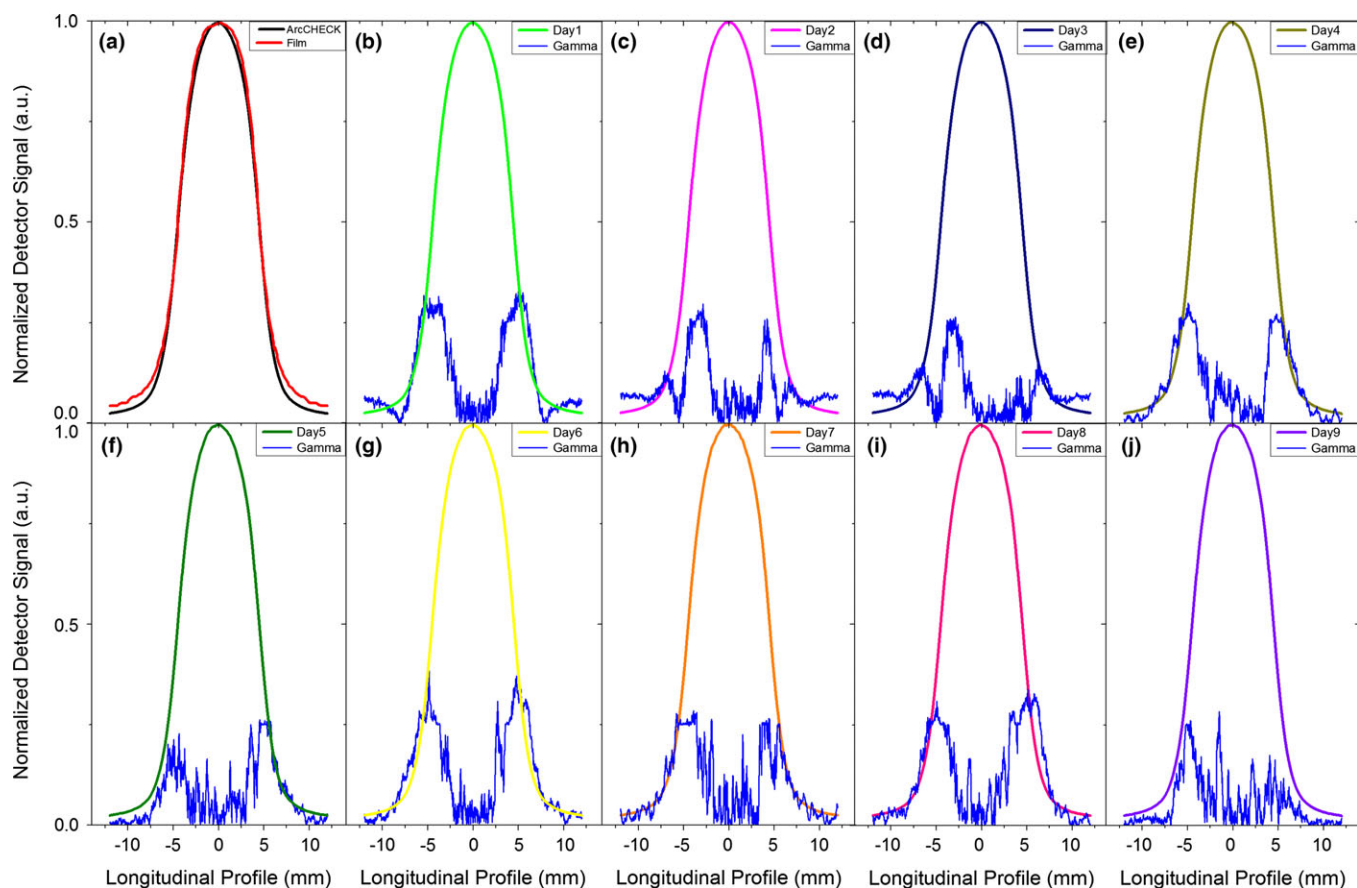


FIG. 9. (a) Day-one benchmark and film-measured profile. (b)–(j) Gamma analyses by comparing measurements conducted on different days with benchmark. [Color figure can be viewed at wileyonlinelibrary.com]

method made the observation and quantification of the synchronization of leaves possible. We also believe that multiple deliveries of the plan at a single static angle will reduce the uncertainty by increasing the signal to noise ratio. The ArcCHECK measures continuously when the gantry was rotating in MLC open time measurement for the helical plan. Therefore, we may need to consider the change in the distance between the detector and the beam central line, which affects the response of the detector in consequence. The gantry speed of helical start shot plan was set to be $18.00^\circ/\text{sec}$, which caused a $\sim 1.65\text{-mm}$ shift of the detector's position relative to the beam central line between 50-ms snapshots of the ArcCHECK measurement. According to the transverse beam profile of our measured beam data, the induced dose difference for a 1-cm central region at 3.3-cm depth, which is the water equivalent depth for the detectors, is less than 0.3%. As a result, the uncertainty caused by this effect is negligible. The ability of our method to discover leaf errors was as small

as ± 18.5 ms with 99% confidence interval, which was larger compared with ± 8.31 ms from Chen et al.³³ The reason is believed to be due to the limited updating rate of movie data, which was 20 Hz in our case while it was 300 Hz in the study by Chen et al.

It should be noted that the plan for couch translation per gantry rotation was not originally designed for our purpose. It was a coincidence that we succeeded in locating the beam center during the leaf open time and confirmed this specific plan was also usable in our method. Careful calculation should be conducted to find a suitable pitch if a user-defined helical plan is created for applying our method. Although the uncertainty of detector location might be compromised due to the large amount of detectors used, we should emphasize that our method depends on an accurate array calibration of the diodes of ArcCHECK. Any substantial drift of the detector response may lead to a wrong location of the beam center. Therefore, a regular calibration of ArcCHECK may be needed.

TABLE III. Mean and maximum gamma index and FWHM for measured longitudinal beam profile from day 2 to day 10 compared with day 1 benchmark.

	Day 2	Day 3	Day 4	Day 5	Day 6	Day 7	Day 8	Day 9	Day 10
FWHM	8.921	8.933	8.956	8.947	8.938	9.002	8.991	8.955	8.921
Mean γ	0.115	0.086	0.077	0.088	0.072	0.118	0.097	0.114	0.056
Max. γ	0.333	0.296	0.264	0.291	0.262	0.385	0.284	0.338	0.283

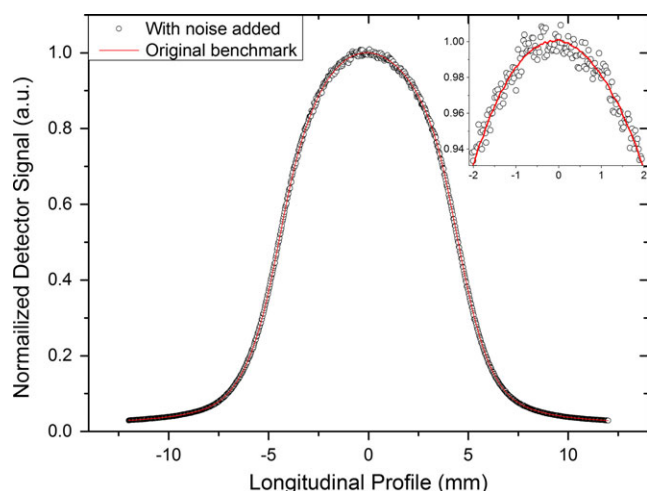


FIG. 10. Benchmark profile with and without 0.6% noise added. The inner graph shows the enlarged details around the peak. [Color figure can be viewed at wileyonlinelibrary.com]

It might be noticed that, after the beam centers for the longitudinal profiles were located, the couch speed could also be calculated. However, this method would be greatly affected by the uncertainty from the location of detector. According to the manufacturer, the distance from spiral band to spiral band and distance between detectors along the length of the spiral were 10 ± 0.25 mm.³¹ In the worst scenario, it could lead to an additional error of 0.025 mm/s to a single value calculated from two adjacent beam centers. Besides, compared with our proposed method using shaping parameter, this method also suffered from the stability of beam output.

Although the measurement of the mean couch speed was convenient and accurate, it would be inappropriate to directly evaluate the uniformity from [Fig. 6(a)], due to the uncertainty of detector location and drift of array calibration which were difficult to be quantified. The uncertainty of the FWHM measured from a longitudinal profile should mainly come from detector response, machine output, and couch speed. The uncertainty coming from detector consistency and machine output could be evaluated from (Fig. 5), which gave a value of 0.6%. For studying the impact on FWHM measurement, we added a 0.6% noise to the benchmark profile as shown in Fig. 10 and recalculated the FWHM. We repeated 100 times to obtain a SD of 0.16% for the FWHM. Thus, we were able to conclude that the uncertainty coming from the couch speed solely should be less than 0.47%. Tomotherapy claims that the position accuracy of translation is better than 1.0 mm. For a treatment length of 20 cm, the induced uncertainty for couch speed should be less than 0.5%. This was comparable to our observation.

Our measured result for longitudinal profile was the mean of 34 profiles, which made it less vulnerable to machine output variation and setup error. The accurate results suggest our method could be an alternative to the current QA procedure involving ionization chamber and electrometer. It is reasonable to believe that our method should also work for 2.5 cm and 5.0 cm field width. More results of profile measurements including all three clinical field widths and comparison with

the method using ionization chamber will be discussed in our future studies.

Unlike the gantry-related tests in TQA helical step wedge procedure which achieved indirect results by comparing the measurements with the reference data, our method measured the real-time gantry angle. However, TQA step wedge tests did have an obvious advantage in timing accuracy due to the repetition rate of 300 Hz. Thus, the results related to timing would certainly have better accuracy, for example, in gantry period difference and MLC open time. Besides, the result for couch speed measurement had an uncertainty of 0.2%,²⁹ which was also slightly better than our 0.5%. While the so called “MLC flash center difference” was used to represent the MLC synchrony, it was actually an averaged result of all leaves under all-open and all-close status. Our proposed method for MLC synchrony tested one-open-one-close status which was not studied in TQA and one diode corresponding to one specific leaf made the diagnosis for single leaf possible.

5. CONCLUSION

This study has proposed several novel methods for measuring the gantry angle and speed, MLC synchronization and leaf open time, couch translation, couch speed and uniformity, and constancy check for longitudinal beam profile of Tomotherapy using ArcCHECK. The results have been proven to be accurate compared with machine log data and can provide much more information than film-based methods. The experimental setup is easy and convenient, which makes it possible to create an all-in-one workflow for routine QA of Tomotherapy.

CONFLICT OF INTEREST

The authors have no relevant conflicts of interest to disclose.

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REFERENCES

1. Dobler B, Groeger C, Treutwein M, et al. Commissioning of volumetric modulated arc therapy (VMAT) in a dual-vendor environment. *Radiother Oncol.* 2011;99:86–89.
2. Otto K. Volumetric modulated arc therapy: IMRT in a single gantry arc. *Med Phys.* 2008;35:310–317.
3. Palma DA, Verbakel WFAR, Otto K, Senan S. New developments in arc radiation therapy: a review. *Cancer Treat Rev.* 2010;36:393–399.
4. Van Esch A, Huyskens DP, Behrens CF, et al. Implementing RapidArc into clinical routine: a comprehensive program from machine QA to TPS validation and patient QA. *Med Phys.* 2011;38:5146–5166.
5. Yu CX. Intensity-modulated arc therapy with dynamic multileaf collimation: an alternative to tomotherapy. *Phys Med Biol.* 1995;40:1435–1449.
6. Ezzell GA, Galvin JM, Low D, et al. Guidance document on delivery, treatment planning, and clinical implementation of IMRT: report of the IMRT Subcommittee of the AAPM radiation therapy committee. *Med Phys.* 2003;30:2089–2115.

7. Mackie TR, Balog J, Ruchala K, et al. Tomotherapy. *Semin Radiat Oncol*. 1999;9:108–117.
8. Mackie TR, Holmes T, Swerdloff S, et al. Tomotherapy: A New Concept for the Delivery of Conformal Radiotherapy. *Med Phys*. 1993;20:1709–1719.
9. Fenwick JD, Tomé WA, Jaradat HA, et al. Quality assurance of a helical tomotherapy machine. *Phys Med Biol*. 2004;49:2933–2953.
10. Thomas SD, Mackenzie M, Field GC, Syme AM, Fallone BG. Patient specific treatment verifications for Helical Tomotherapy treatment plans. *Med Phys*. 2005;32:3793–3800.
11. Langen KM, Papanikolaou N, Balog J, et al. QA for Helical Tomotherapy: report of the AAPM Task GROUP 148. *Med Phys*. 2010;37:4817–4853.
12. Accuray Corporation. *Tomotherapy Physics Training Course*. Madison, WI: Accuray Corporation; 2012.
13. Balog J, Holmes T, Vaden R. A helical tomotherapy dynamic quality assurance. *Med Phys*. 2006;33:3939–3950.
14. Yan Y, Papanikolaou N, Weng X, Penagaricano J, Ratanatharathorn V. Fast radiographic film calibration procedure for helical tomotherapy intensity modulated radiation therapy dose verification. *Med Phys*. 2005;32:1566–1570.
15. Zhu XR, Jursinic PA, Grimm DF, Lopez F, Rownd JJ, Ratanatharathorn V. Evaluation of Kodak EDR2 film for dose verification of intensity modulated radiation therapy delivered by a static multileaf collimator. *Med Phys*. 2002;29:1687–1692.
16. Shi C, Papanikolaou N, Yan Y, Weng X, Jiang H. Analysis of the sources of uncertainty for EDR2 film-based IMRT quality assurance. *J Appl Clin Med Phys*. 2006;25:1–8.
17. Myers P, Stathakis S, Gutiérrez AN, Esquivel C, Mavroidis P, Papanikolaou N. Evaluation of PTW seven29 for tomotherapy patient-specific quality assurance and comparison with ScandiDos Delta⁴. *J Med Phys*. 2012;37:72–80.
18. Xu S, Xie C, Ju Z, et al. Dose verification of helical tomotherapy intensity modulated radiation therapy planning using 2D-array ion chambers. *Biomed Imaging Interv J*. 2010;6:e24.
19. Li JG, Yan G, Liu C. Comparison of two commercial detector arrays for IMRT quality assurance. *J Appl Clin Med Phys*. 2009;29:2942.
20. Kong CW, Yu SK, Cheung KY, et al. Quality assurance of TomoDirect treatment plans using I²mRT MatriXX. *Biomed Imaging Interv J*. 2012;8:e14.
21. Handsfield LL, Jones R, Wilson DD, Siebers JV, Read PW, Chen Q. Phantomless patient-specific TomoTherapy QA via delivery performance monitoring and a secondary Monte Carlo dose calculation. *Med Phys*. 2014;41:101703.
22. Létourneau D, Publicover J, Kozelka J, Moseley DJ, Jaffray DA. Novel dosimetric phantom for quality assurance of volumetric modulated arc therapy. *Med Phys*. 2009;36:1813–1821.
23. Li G, Zhang Y, Jiang X, et al. Evaluation of the ArcCHECK QA system for IMRT and VMAT verification. *Phys Med*. 2013;29:295–303.
24. Chapman D, Barnett R, Yartsev S. Helical tomotherapy quality assurance with ArcCHECK. *Med Dosim*. 2014;39:159–162.
25. Bresciani S, Di Dia A, Maggio A, et al. Tomotherapy treatment plan quality assurance: the impact of applied criteria on passing rate in gamma index method. *Med Phys*. 2013;40:121711.
26. Stambaugh C, Nelms B, Wolf T, et al. Measurement-guided volumetric dose reconstruction for helical tomotherapy. *J Appl Clin Med Phys*. 2015;16:5298.
27. Yue Q, Duan J, Li R, Yang J. Systematic analysis of the arccheck diode arrays for tomotherapy delivery. *Int J Med Phys Clin Eng Radiat Oncol*. 2014;3:218–225.
28. Mikołajczyk K, Piotrowski T. Development of cylindrical stepwedge phantom for routine quality controls of a helical tomotherapy machine. *Phys Med*. 2013;29:91–98.
29. Althof V, van Haaren P, Westendorp R, et al. A quality assurance tool for helical tomotherapy using a step-wedge phantom and the on-board MVCT detector. *J Appl Clin Med Phys*. 2012;13:148–163.
30. Coevoet M, Denis JM, Cravens B, et al. Tomotherapy quality assurance (TQA): a fast and comprehensive software tool. *IFMBE Proceedings*. 2009;25:678.
31. Sun Nuclear Corporation. *ArcCHECK[®] Reference Guide*. Melbourne, FL: Sun Nuclear Corporation; 2014.
32. Wang Q, Dai JR, Zhang K. A novel method for routine quality assurance of volumetric-modulated arc therapy. *Med Phys*. 2013;40:101712.
33. Chen Q, Westerly D, Fang Z, Sheng K, Chen Y. TomoTherapy MLC verification using exit detector data. *Med Phys*. 2012;39:143–151.