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FULL PAPER

Advantage of 3D volumetric dosimeter in delivery quality assurance of dynamic arc therapy: comparison of pencil beam and Monte Carlo calculations

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Objective: To evaluate the accuracy of pencil beam calculation (PBC) and Monte Carlo calculation (MCC) for dynamic arc therapy (DAT) in a cylindrically shaped homogenous phantom, by comparing the two plans with an ion chamber, a film and a three-dimensional (3D) volumetric dosimeter.

Methods: For this study, an in-house phantom was constructed, and the PBC and MCC plans for DAT were performed using iPlan® RT (BrainLAB®, Heimstetten, Germany). The A16 micro ion chamber (Standard Imaging, Middleton, WI), Gafchromic® EBT2 film (International Specialty Products, Wayne, NJ) and ArcCHECK™ (Sun Nuclear, Melbourne, FL) were used for measurements. For comparison with each plan, two-dimensional (2D) and 3D gamma analyses were performed using 3%/3 mm and 2%/2 mm criteria.

Results: The difference between the PBC and MCC plans using 2D and 3D gamma analyses was found to be 7.85%

and 28.8%, respectively. The ion chamber and 2D dose distribution measurements did not exhibit this difference revealed by the comparison between the PBC and MCC plans. However, the 3D assessment showed a significant difference between the PBC and MCC (62.7% for PBC vs 93.4% for MCC, $p = 0.034$).

Conclusion: Evaluation using a 3D volumetric dosimeter can be clinically useful for delivery quality assurance (QA), and the MCC should be used to achieve the most reliable dose calculation for DAT.

Advances in knowledge: (1) The DAT plan calculated using the PBC has a limitation in the calculation methods, and a 3D volumetric dosimeter was found to be an adequate tool for delivery QA of DAT. (2) The MCC was superior to PBC in terms of the accuracy in dose calculation for DAT even in the homogenous condition.

Over the past few years, there has been a considerable growth in interest concerning arc therapy. This includes a range of techniques, such as dynamic arc therapy (DAT), intensity-modulated arc therapy (IMAT), helical tomotherapy and volumetric modulated arc therapy (VMAT).^{1–3} These developments have been accompanied by the improvement of dose calculation algorithms and a significant increase in treatment efficiency, thus resulting in shorter treatment times and a smaller number of monitor units (MUs) than with intensity-modulated radiotherapy (IMRT) and other conventional methods.

Existing arc therapy planning methods, such as pencil beam calculation (PBC), are based on dividing the full rotation angle by a uniform control point and then optimizing the results.^{4,5} Only the dose calculation based on a control point below a certain angle has been previously reported to be an accurate dose delivery to the target area.^{4,6–8} However, the

errors from approximating the arc with individual beams could occur in the area where adjacent beams do not overlap.⁹ This area could be wide when the phantom size is large or when the field or target size is small. Compared with PBC, Monte Carlo calculation (MCC) has made accurate dose calculations possible because the accuracy of the dose calculation using MCC depends on the number of simulation histories rather than the number of beams.^{9,10} Whether the PBC or the MCC plan is used, the radiation that is actually delivered remains the same.

Several studies on the accuracy of PBC and MCC for DAT did not show that these errors can result when dividing the arc, and only focused on the errors that occur in the inhomogeneous condition. Chow et al⁹ compared the PBC, collapsed cone convolution (CCC) and MCC for DAT using both homogenous and inhomogeneous phantoms. For homogenous phantoms, the measured dose of the PBC and

CCC agreed well (approximately 2% dose error) with predictions made using the MCC. However, in the dose distribution in the phantom with lung inhomogeneity, only MCC agreed with the measurements within 2%, whereas PBC and CCC underestimated or overestimated the dose inside the lung. Petoukhova *et al*¹⁰ also compared the PBC with MCC for homogenous and inhomogeneous phantoms using conformal radiotherapy, IMRT, and DAT. They also concluded that the PBC and MCC results agreed well with the measured dose for homogenous phantoms, but not for inhomogeneous phantoms. In these studies, they only measured the delivered dose using an ion chamber, film or two-dimensional (2D) diode array detector.

The absolute dose measurement using an ion chamber is a target-centred dose evaluation method, and the 2D dose distribution measurement is limited to the range that can be measured because the dose distribution is only assessed on one side during rotating irradiation.^{11,12} Recently, a variety of three-dimensional (3D) volumetric dosimeters have been developed and commercialized to overcome these limitations. Representative examples include the Delta⁴TM phantom (ScandiDos®, Uppsala, Sweden) and ArcCHECKTM (Sun Nuclear, Melbourne, FL) dosimetry systems. The accuracy and advantage of these new measurement instruments have already been evaluated.^{13–19}

In this study, we evaluated the accuracy of the PBC and MCC for DAT by comparing the PBC with MCC plans and by measuring the delivered dose using an ion chamber, a film and a 3D volumetric diode array detector. We used a homogenous phantom to focus on the errors in the PBC which result from dividing the arc and calculating each beam.

METHODS AND MATERIALS

In-house phantom fabrication

Figure 1a,b shows a schematic drawing and a photograph of the in-house phantom. The phantom was constructed from acrylic and was cylindrical in shape. It was perforated by a 255-mm-long hole, with an outer diameter of 150 mm and an inner diameter of 110 mm. The phantom was designed to allow for the insertion of three acrylic components into the hole. The first of these was a solid acrylic cylinder, 255 mm long with a diameter of 110 mm for CT scanning. The second part was a cylindrical structure that allowed the EBT film (Gafchromic® EBT2 film; International Specialty Products, Wayne, NJ) to be attached, which was divided in the coronal direction and had a 100 × 100 mm film holder. The position of the film holder was 132 mm from one side of the phantom to the middle of the film region (the same distance to a measurement point of a chamber holder used in the third part). The third part was a structure with a chamber holder, which allowed an Exradin A16 micro ion chamber (Standard Imaging, Middleton, WI) to be inserted. The diameter of the acrylic cylinder of the third part was also 110 mm, and the inner diameter was 30.5 mm, which was the same as the outer diameter of the chamber holder.

Treatment design, planning and delivery

CT images, consisting of 165 slices with slice thickness of 1.25 mm, were acquired for the in-house phantom using Light-Speed® RT16 CT scanner (GE Medical Systems, Waukesha, WI).

Figure 1. In-house phantom. (a) Schematic drawing of the in-house phantom. The phantom was constructed from acrylic and was fabricated to enable the replacement of three parts of the cylinder. Part 1 was a solid acrylic cylinder for CT scanning, and Part 2 was a structure allowing the film to be attached. Part 3 was a structure allowing an Exradin A16 micro ion chamber (Standard Imaging, Middleton, WI) to be inserted. (b) Photograph of the fabricated phantom. ① the phantom; ② Part 1; ③ Part 2 with Gafchromic® EBT2 film (International Specialty Products, Wayne, NJ); ④ Part 3 and chamber holder with A16 micro ion chamber.

A cylindrically shaped target with a diameter and height of 5 cm was contoured at the centre of the acquired images. The volume of the target was 100.409 cm³.

For this study, we used iPlan® RT v. 4.1.2 (BrainLAB®, Heimstetten, Germany). We prescribed a 600 cGy to cover 95% of the target with 3 mm multileaf collimator (MLC) margin. The treatment mode

used consisted of a dynamic conformal arc with a 350° angle of the gantry rotation (185–175°) in the clockwise direction.

The plan was calculated using both the PBC and the MCC algorithms (Figure 2). The PBC plans were performed with a dose resolution of 1 mm and an arc step calculation of 10°. In the present version of the iPlan RT, this parameter cannot be changed. After the plan using the PBC algorithm had been completed, this plan was recalculated by applying the MCC algorithm. The MCC plans were performed via a full MLC geometry simulation (accuracy optimized model) with a spatial resolution of 1 mm and a mean variance of 2%. The “dose to medium” option was used.

All tests were carried out using a Novalis™ (BrainLAB and Varian Medical Systems, Palo Alto, CA) linear accelerator with a 6 MV X-ray energy and a micro-MLC. The total delivered output was 758 and 766 in the PBC and MCC plans, respectively. The MU/degree was approximately 2.166 MU. All measurements were sequentially repeated three times.

Measuring equipment

The measuring equipment used in this study consisted of an ion chamber (Exradin A16 micro ion chamber) and an electrometer (SuperMAX; Standard Imaging) for one-dimensional (1D) isocenter dose measurements. The A16 micro ion chamber, which has a collection volume of 0.007 cm³, is suitable for small-field measurements.

The film used for evaluating the 2D dose distribution was Gafchromic® EBT2, and the film scanner used was the Epson Perfection™ V700 Photo scanner (Seiko Epson, Nagano, Japan).

The ArcCHECK was used for 3D dose measurements (Figure 3). It is a new piece of dosimetry equipment in which 1386 diodes are fitted at 1 cm intervals in a helical fashion within a cylinder with a diameter and length of 21 cm. The diodes are positioned 2.9 cm below the surface, and each has a volume of 0.019 mm³, and the update frequency is 50 ms. Overall, the ArcCHECK has a diameter of 27 cm and a length of 43 cm. The centre of the cylinder has a 15 cm diameter hole where two types of plugs can be inserted. For this study, the ArcCHECK was calibrated using an absolute dose of 200 cGy with a 10 × 10 cm field size at a gantry angle of 0° in accordance with the ArcCHECK reference user's guide.²⁰ There

are axial and sagittal lines at the top of the ArcCHECK and coronal lines on both sides of the ArcCHECK. Furthermore, the ArcCHECK has four inclinometer light-emitting diodes (LEDs), which indicate the rotation and tilt status of the ArcCHECK (acceptable range: $0 \pm 0.5^\circ$ for the rotation and $0 \pm 0.25^\circ$ for the tilt). With these lines and inclinometer LEDs, the integrity of the set-up was ensured in the measurements. In addition, throughout the study, the ArcCHECK was operated with the plug inside. The isocenter measurement using an ion chamber was performed simultaneously during the ArcCHECK measurement. The accuracy and validity of the ArcCHECK dose assessment have already been demonstrated by other researchers.^{13–15,17–19}

Evaluation

Before comparing each plan with the 1D, 2D, and 3D measurements, we first compared the PBC plan with the MCC plan to assess the dose difference between the two plans. The plans were also compared using both 2D and 3D gamma analyses with the aid of the OmniPro-I'mRT® v. 1.7.x (IBA, Bartlett, TN) and SNC Patient® software v. 6.1.1.x (Sun Nuclear).

For the evaluation of the absolute isocenter dose, we compared the calculated isocenter dose from the treatment plan with the measured dose using an ion chamber. The dose differences between the calculated and the measured doses in the PBC and MCC were then compared. For the evaluation of the 2D dose distribution and 3D ArcCHECK measurements, two comparison groups were evaluated: PBC plan vs PBC measurement and MCC plan vs MCC measurement. The program used for 2D analysis was OmniPro-I'mRT. For a comparison of each plan with each film measurement, the coronal plane was analysed because the film can only be mounted in the coronal plane for the in-house phantom. The 3D dose assessment with the ArcCHECK was performed using the dedicated software program SNC Patient. The relative location of the target is the isocenter in the ArcCHECK phantom. This program inserts digital imaging and communications in medicine–radiotherapy dose, structure and plan files of the treatment plan, which is recalculated on the CT images (a diameter of 265 mm and a length of 272 mm, 2-mm slice) of an ArcCHECK phantom (phantom mapping), and then unfolds like a diode map after dose distribution at the diode positions has been acquired. The dose is then assessed by obtaining a 2D dose distribution based on the correlation of the measured dose

Figure 2. Dose distribution diagrams calculated by pencil beam calculation (PBC) (a, left; b, bottom) and Monte Carlo calculation (MCC) (a, right; b, top) treatment plans.

Figure 3. The image of the ArcCHECK™ (Sun Nuclear, Melbourne, FL).

values of the diodes and comparing this with the dose distribution from the treatment plan. The 2D and 3D evaluation methods were gamma analyses with 3%/3-mm and 2%/2-mm criteria, with a threshold of 5%.

The delivery quality assurance (QA) for the dynamic arc plans of 10 real patients was also performed in the same way as this phantom study. To apply the same methods and evaluations of our phantom study, we selected only the brain lesions that had a relatively small area of air density. These 10 patients received DAT, calculated by the PBC algorithm, and the doses ranged from 14 to 24 Gy. These PBC plans were recalculated by applying the MCC algorithm. We evaluated the absolute isocenter dose and 3D ArcCHECK measurement in the same way as the above phantom study.

RESULTS

Comparison of the pencil beam calculation and Monte Carlo calculation plans

The 2D gamma analysis performed using the OmniPro-ImRT software showed that the differences between the PBC and MCC plans were 1.63% and 2.13% in the axial and coronal isocenter planes, respectively, when using the 3%/3-mm criteria, and 5.65% and 7.85% in the axial and coronal planes, respectively, when using the 2%/2-mm criteria. The 3D gamma analysis using the SNC Patient software showed that the differences between the PBC and MCC plans were 16.0% and 28.8% with the 3%/3-mm and the 2%/2-mm criteria, respectively. The differences between the two plans were more noticeable when using the 3D gamma analysis.

Evaluation of absolute isocenter dose, two-dimensional dose distribution and three-dimensional volumetric measurements

Chamber position doses of 615 and 617 cGy were calculated for the PBC and MCC plans, respectively. The mean measured doses

of the PBC and MCC plans were 608.96 ± 2.04 and 613.08 ± 0.25 cGy, respectively. Differences between the calculated doses and the measured doses were $0.98 \pm 0.33\%$ and $0.63 \pm 0.04\%$ for the PBC and MCC plans, respectively, which did not show a significant difference between the PBC and MCC ($p=0.507$) plans. Table 1 lists the calculated doses (chamber position dose), measured doses and dose differences.

Table 2 gives the results of the gamma analysis of the two comparison groups performed using a film. Using the 3%/3 mm criteria, there was no difference between the treatment plan and film measurements for both the PBC and MCC ($p = 1.000$). Using the 2%/2 mm criteria, the gamma passing rate for the PBC plan vs PBC film measurement and the MCC plan vs MCC film measurement was $99.80 \pm 0.19\%$ and $99.54 \pm 0.51\%$, respectively, which did not show a significant difference between the PBC and MCC ($p = 0.827$). When comparing each of the treatment plans and film measurements, the difference was $<1\%$.

Table 2 lists the results of the gamma analysis of the two comparison groups performed using the ArcCHECK. 767 diodes were involved in the gamma analysis for PBC, and 762 diodes were involved in the gamma analysis for MCC. When comparing each of the plans with the ArcCHECK measurements, the gamma passing rate for the PBC plan vs the PBC ArcCHECK measurement was $78.46 \pm 0.75\%$ and $62.70 \pm 0.34\%$ using the 3%/3-mm and 2%/2-mm criteria, respectively, which showed considerable difference. Conversely, the gamma passing rate for the MCC plan vs the MCC ArcCHECK measurements was $99.26 \pm 0.11\%$ and $93.40 \pm 0.01\%$ using the 3%/3-mm and 2%/2-mm criteria, respectively, which have a comparatively small difference. This difference in these gamma-passing rates between the PBC and MCC was statistically significant ($p = 0.046$ for the 3%/3-mm criteria, $p = 0.034$ for the 2%/2-mm criteria).

Table 1. Calculated and measured isocenter dose according to the pencil beam calculation (PBC) and Monte Carlo calculation (MCC)

Calculation algorithm	Prescription dose (cGy)	Chamber position dose (cGy)	Measured dose (cGy)	Dose difference (%)
PBC	600	615	608.96 ± 2.04^a	-0.98 ± 0.33^a
MCC	600	617	613.08 ± 0.25^a	-0.63 ± 0.04^a

^aMean $\pm$ standard deviation.

Figure 4 shows the 2D assessment using the film and the 3D assessment using the ArcCHECK with two different gamma criterion. A comparison of the PBC plan and 3D measurements showed a difference of at least 22%, although a comparison of the MCC plan and 3D measurements showed a difference of <7%, even with the 2%/2-mm criteria. These findings suggest that the PBC plan for DAT is less accurate than that of the MCC plan.

Delivery quality assurance for real patients

The differences in the isocenter dose for PBC and MCC were $1.67 \pm 0.49\%$ and $0.90 \pm 0.50\%$, which did not show a significant difference. The gamma passing rates for the 3-mm/3% criteria were $91.0 \pm 2.72\%$ for PBC and $98.9 \pm 0.61\%$ for MCC. Furthermore, the gamma passing rates for the 2-mm/2% criteria were $75.5 \pm 8.19\%$ for PBC and $92.4 \pm 1.86\%$ for MCC. These findings are consistent with the results of the phantom study. The results of the delivery QA for real patients are summarised in Table 3.

DISCUSSION

Arc therapy is of particular interest in the field of radiotherapy because the surrounding organs can be effectively protected, while a sufficient dose is delivered to the target.^{21–23} The PBC algorithm is a well-established and accepted method to calculate dose distribution in radiotherapy. For the calculation of the dose for DAT, the continuous arc is split into discrete fixed beams positioned at a certain interval (typically 10°) along the arc plane. On the other hand, the MCC algorithm relies on a random sampling and integration.²⁴ The treatment planning system for the MCC used in this study is iPlan RT, which is capable of both PBC- and MCC-based DAT planning. The MCC algorithm of iPlan RT was developed by Kawrakow et al²⁵ and Fippel²⁶ on

the basis of an X-ray voxel MC (XVMC) code. The XVMC algorithm consists of three main components, which are the virtual fluence model, full MC geometry simulation and patient dose computation. Gantry rotations (static and dynamic) are continuously simulated. This feature is a big advantage over other algorithms like the pencil beam because other algorithms require discrete gantry positions to model the rotation.

The evaluation of an absolute isocenter dose and 2D dose distribution are sufficient for delivery QA of a conventional radiotherapy or static IMRT. These have been verified by many researchers, and these dose evaluation methods are still in use today.^{11,27–34} In addition, the evaluation of an absolute isocenter dose and 2D dose distribution are considered to be adequate for delivery QA of arc therapy, such as IMAT or VMAT.^{35,36} Wagner and Vorwerk³⁵ reported that the use of a 2D ionization chamber (MatriXX™; IBA Dosimetry GmbH, Schwarzenbruck, Germany) for VMAT plan verification is reasonable in clinical routine use. Iftimia et al³⁶ used a 2D diode array (MapCHECK®; Sun Nuclear, Melbourne, FL) for VMAT plan verification and reported that the average agreement was 94.4% and 96.3% for the distance-to-agreement and gamma index approach, respectively.

In this study, the difference between the PBC and the MCC plans was as high as 7.85% and 28.8% in the 2D and 3D gamma analysis with the 2%/2-mm criteria, respectively. Whether the PBC or MCC plans are used, the radiation that is actually delivered is same. This shows a clear difference between the two treatment plans, making it necessary to compare the planned dose to the actual delivered dose. As given in Table 1, the comparison of the calculated and measured isocenter dose shows a good agreement for both the PBC and MCC. The dose differences are only 0.98% and 0.63% in PBC and MCC, respectively. Petoukhova et al³⁷ also

Table 2. The results of gamma analysis in the two comparison groups using a film and ArcCHECK™ (Sun Nuclear, Melbourne, FL)

Comparison group	Gamma passing rate (%)	
	3%/3 mm	2%/2 mm
Gamma analysis of two-dimensional films		
PBC plan vs PBC film	100	99.80 ± 0.19^a
MCC plan vs MCC film	100	99.54 ± 0.51^a
Gamma analysis of three-dimensional ArcCHECK		
PBC plan vs PBC ArcCHECK	78.46 ± 0.75^a	62.70 ± 0.34^a
MCC plan vs MCC ArcCHECK	99.26 ± 0.11^a	93.40 ± 0.01^a

MCC, Monte Carlo calculation; PBC, pencil beam calculation.

^aMean $\pm$ standard deviation.

Figure 4. Gamma passing rates using 3%/3-mm and 2%/2-mm criteria of the (a) two-dimensional (2D) film and (b) three-dimensional (3D) ArcCHECK™ (Sun Nuclear, Melbourne, FL), respectively, in the two comparison groups. MCC, Monte Carlo calculation; PBC, pencil beam calculation.

reported that in a comparison study between the PBC and MCC in HybridArc™ plans, the ion chamber measurements showed average differences of 1.4% and 1.8% for the MCC and PBC, respectively. Other reports also showed that the measured isocenter dose was not significantly different from the calculated dose using the PBC.^{9,10,38} As shown by the data in Table 2 and

Figure 4, the comparison between the calculated and measured 2D dose distribution showed a good agreement for both the PBC and MCC. The gamma passing rate of PBC and MCC are 99.8% and 99.5%, respectively, even with the 2%/2-mm criteria. Chow *et al*⁹ reported that PBC agreed well with the measured results (approximately 2% error) for photon arc

Table 3. The results of the delivery quality assurance for real patients

Number	Dose (Gy)	PTV (cm ³)	Dose difference (%) of isocenter		Gamma passing rate (%) using ArcCHECK™			
					3%/3 mm		2%/2 mm	
			PBC	MCC	PBC	MCC	PBC	MCC
1	14	4.48	2.01	0.23	91.8	98.1	76.1	91.8
2	18	6.26	2.12	0.88	89.5	99.1	68.8	92.7
3	20	2.84	1.65	1.20	92.5	99.3	66.5	90.9
4	15	18.39	1.90	1.20	93.7	99.0	84.3	93.0
5	24	60.62	2.15	1.37	90.2	97.6	82.6	91.0
6	13	3.28	1.69	1.49	90.6	99.6	73.5	94.3
7	15	9.66	1.49	0.47	93.5	98.7	81.0	95.2
8	23	0.77	0.44	0.50	85.3	98.9	60.5	89.0
9	15	23.06	1.64	0.22	94.2	99.5	85.0	94.2
10	15	14.44	1.57	1.47	88.8	98.8	76.3	92.3
Mean ± SD	17 ± 3.88	14.38 ± 17.81	1.67 ± 0.49	0.90 ± 0.50	91.0 ± 2.72	98.9 ± 0.61	75.5 ± 8.19	92.4 ± 1.86

MCC, Monte Carlo calculation; PBC, pencil beam calculation; SD, standard deviation. ArcCHECK is manufactured by Sun Nuclear, Melbourne, FL.

therapy, and Malatesta et al³⁸ reported that distance to agreement between the calculated and measured 90% isodoses was <2 mm. In this study, the ion chamber and 2D dose distribution measurements did not exhibit the differences revealed by the comparison between the PBC and MCC treatment plans. However, our findings were comparable to the previous studies mentioned above.

The usefulness of ArcCHECK, the 3D volumetric dosimeter used in this study, has already been validated.^{13–15,17–19} Results from the dose assessment using ArcCHECK showed that for the PBC plan vs PBC measurement, the gamma passing rate was only 62.7% using the 2%/2-mm criteria, whereas the gamma passing rate was 93.4% for the MCC plan vs MCC measurement. The ArcCHECK measurements could reveal the difference between the PBC and MCC plans. Figure 5 shows the results of each measurement in the PBC and MCC using ArcCHECK. As shown in Figure 5a, the solid line of the treatment plan dose profile has a jagged appearance. This indicates that the dose distribution for the PBC plan was sporadic in the region in which the ArcCHECK diodes were present. This means that the PBC plan and actual measurement cannot be matched. Figure 5b shows a favourable match between the solid line of the MCC plan and the dotted line of the MCC measurement values. This in turn indicates that the dose can be successfully calculated using the MCC.

Petoukhova et al³⁷ compared the PBC and MCC HybridArc plans using the ArcCHECK and concluded that the PBC significantly differed from the ArcCHECK measurement, and the MCC was superior to the PBC for the calculation of the HybridArc plans because of the dose calculation steps of 10°. The present study also revealed that the MCC is more accurate than the PBC. This difference was only revealed when a 3D volumetric detector was used and the ion chamber and 2D dose distribution measurements were not adequate to show the differences revealed by the comparison between the PBC and MCC treatment plans.

Although we did not clearly explain the reason why the dose difference between the PBC and MCC plans could be observed only using the 3D volumetric dosimeter, it could be because a substantial portion of the errors resulted from dividing the arc and calculating each beam was distributed on the peripheral area and the diodes of the ArcCHECK are located in the periphery. The isocenter dose measurement is not adequate for peripheral dose evaluation, and the 2D dose distribution measurement is also limited to the range that can be measured because the dose distribution is only measured on one side during the rotating irradiation. Therefore, only the 3D volumetric dosimeter was sensitive to detect these errors. And, our finding may imply some clinical significance. For example, if a tumour is located on the central area of the liver and the tumour is small, only MCC could accurately calculate the peripheral dose of the liver or ribs, and only the 3D volumetric dosimeter could precisely measure the dose.

CONCLUSION

In this study, the PBC and MCC plans for DAT using an ion chamber and 2D film measurement, together with a new dose measurement method using a 3D volumetric dosimeter were evaluated. Comparison between the PBC and MCC indicated that only 3D comparisons showed significant differences. When an ion chamber and 2D film measurement methods were used, the results did not reflect the dose differences shown in the two treatment plans. Therefore, the ion chamber and 2D film measurement methods are considered unsuitable for the delivery QA of DAT. On the other hand, a 3D volumetric dosimeter could reflect the differences shown in the two treatment plans. Therefore, the evaluation using a 3D volumetric dosimeter can be clinically useful for delivery QA, and the MCC should be used to achieve the most reliable dose calculation for DAT.

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Figure 5. Results of the PBC and MCC measurements using ArcCHECK™ (Sun Nuclear, Melbourne, FL). (a) PBC plan vs measurement, (b) MCC plan vs measurement. The solid line indicates plan and the dots indicate measurement.

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