Evaluation of a 3D diode array dosimeter for helical tomotherapy delivery QA

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Abstract: The Delta4 biplanar diode array dosimeter was validated for helical tomotherapy delivery QA. The basic detector characteristics were found satisfactory in terms of short-term reproducibility (0.1%), linearity (<0.1%), dose rate dependence (0.4%), and absolute calibration accuracy (0.4% in the center of the phantom compared to the independently calibrated diode). Relative calibration of the arrays was verified by comparison with film and by rotating the detector 180°. The dosimeter response to rotational irradiation changed by no more than 0.2% when one of the detector boards was replaced by the homogeneous phantom material. The daily output correction factor can be derived from a Delta4 measurement in a uniform cylindrical field. The γ(3%,3mm) passing rate (absolute dose) was above 90% for all nine evaluated clinical plans, and above 96% for all but one. The mean passing rate was 97±2.7%. The plans varied in modulation factor, pitch, and calculation grid size. For best results, the phantom needs to be aligned carefully, preferably by MVCT imaging**.**

Key words: Helical Tomotherapy, Delivery Quality Assurance, Diode Array Dosimeter, Detector Validation

I. Introduction

Ion chamber and film were traditionally used for dosimetric QA of the patient plans in helical tomotherapy (called Delivery QA, or DQA). As with other IMRT techniques, there is substantial interest in using electronic array dosimeters because they provide almost instantaneous readout in terms of absolute dose distribution. Out of the three commercially available 2D array dosimeters, one is diode-based (MapCHECK™, Sun Nuclear, Melbourne, FL) [1] and the other two utilize ionization chamber arrays (MatriXX, IBA Dosimetry GmbH, Schwarzenbrook, Germany [2], and 2D Array Seven29™, PTW, Freiburg, Germany [3]). When measuring DQAs, the diode-based MapCHECK™ performed adequately [4], while the ion chamber-based MatriXX exhibited significant differences with film measurements [5]. Another ion chamber array, Seven29™, was successfully placed in an octagonal shaped phantom with a cavity to improve the rotational response uniformity [6]. However the fundamental problem remains with using single-plane array to verify composite rotational dose distributions. The two-dimensional dose-distribution information available when the beam direction is perpendicular to the detector plane is gradually reduced to one-dimensional as the incidence angle approaches 90°.

A recently introduced bi-planar diode array dosimeter (Delta4, ScandiDos AB, Uppsala, Sweden)[7] preserves the dose distribution information regardless of the beam incidence angle. We have also independently validated this device for use with step-and-shoot IMRT. However the mode of operation of the dosimeter in a tomotherapy beam is substantially different from the conventional linacs. Therefore, the fundamental characteristics of the detector were studied in this paper, as well as its application to the tomotherapy DQA.

II. Methods

A. Device description

The Delta4 dosimeter consists of 1069 p-type silicone diodes arranged on two orthogonal boards in a 22 cm diameter cylindrical PMMA phantom. The diode active area is 1 mm in diameter. The diodes are spaced at 0.5 cm in the central 6x6 cm^2 region and at 1 cm elsewhere in the 20x20 cm^2 measurement area. The measurement triggering mechanism with tomotherapy is very different from the conventional linacs. For the conventional linacs, a measurement event is triggered by an electronic synchronization pulse obtained from the accelerator console test point connected to the Delta4 by a coaxial cable. The electrometers are in the measurement mode only shortly before, during, and after the actual radiation pulse. No such pulse synchronization signal is available from the Tomotherapy unit, and the measurement cycle is triggered by the radiation pulse itself. The unit is initially operating in the pulse search mode. Once any diode detects a radiation pulse, the electrometers switch to the measurement mode and remain in that condition as long as the next pulse arrives within the time interval corresponding to the pulse repetition frequency (PRF) of 300±10 Hz (Tomotherapy units are expected to operate with the PRF of 300 Hz). If no such pulse is forthcoming, the system reverts back to the search mode.

Another major difference from the conventional linacs is in the application of the correction factors to the raw diode readings. With the conventional treatment plan transferred to Delta4 from the treatment planning system, many beam parameters are known or can be calculated, such as the gantry angle, segment size and the depth of measurement for each diode. Therefore rotational sensitivity, depth, and field size corrections can be applied on the segment level [8]. With tomotherapy, no beam geometry information is made available to the Delta4. Subsequently only the average rotational response correction (1.010) is applied to the dose measured by each detector. For the same reason, no volumetric dose interpolation [8] is possible, and the dose distribution is only analyzed in the two orthogonal measurement planes. Delta4 has a set of typical dose comparison tools, which includes the γ analysis [9]. The latter is based on absolute dose comparison and is implemented with a global dose-difference threshold only.

B. Short-term reproducibility

The detector board was irradiated for 60 sec three times with a static field on a Hi-Art helical tomotherapy unit (TomoTherapy Inc., Madison WI) in a flat PMMA calibration phantom (#3 in Figure 1). The ion chamber provided the simultaneous reference readings (Figure 2). The chamber was shifted laterally to avoid shadowing the interrogated detectors. For each of the central 81 diode detectors, the dose deviation for each run from the average of the three was calculated.

C. Linearity

The same experimental setup was used. The net irradiation time was varied from 1.88 to 60 sec, resulting in the dose range to the measurement point at 85 cm SAD and 6.9 cm water-equivalent depth of approximately 0.2 - 7.3 Gy. The Delta4 readings were plotted against the reference ion chamber readings.

D. Dose-per-pulse dependence

Source-to-detector distance (SDD) was varied from 102.7 to 68.8 cm, resulting in the approximate dose per pulse from 0.30 to 0.66 mGy. The detector board in the flat calibration PMMA phantom was exposed for 30 sec and the average reading for the central 9 diodes was used. The detector board holder was then replaced by a PMMA slab drilled for a Farmer chamber. This positioned the ion chamber at exactly the same irradiation geometry as the central diode. Chamber readings corrected for recombination at each SDD were used as the reference.

E. PRF dependence

The PRF was varied from 300 to 285 Hz with the tomotherapy unit controlled by a service computer. The ratios of the Delta4 to reference ion chamber readings (Figure 2) were recorded. Also the PRF values reported by the Delta4 were compared to the programmed ones.

F. Delta4 calibration

F.1. Absolute Calibration. Each detector board was irradiated for 60 sec with a static 5x40 cm^2 tomotherapy beam. The boards were positioned in the PMMA calibration phantom at a physical measurement depth of 4.3 cm (water-equivalent depth 4.9 cm). The reference dose was determined with a calibrated ion chamber positioned at the same SDD and water-equivalent depth in the Solid Water phantom (# 5 in Figure 1). Absolute calibration was verified by two methods. First, immediately after the calibration exposure the phantom was irradiated again and the dose recorded in the measurement mode was compared to the reference dose, after factoring out the rotational correction factor of 1.01. Second, an Isorad-3 *n*-type diode (Model 116300, Sun Nuclear, Melbourne FL, # 7 in Figure 1) was calibrated in the rotational beam against the ion chamber in the Plastic Water phantom (#4 in Figure 1). It was expected that a raw diode reading in PMMA would exceed that in water because of the excess of lower-energy scattered photons [10]. With the SDD constant, a diode reading with a static beam was first obtained at a physical depth of 12.1 cm in PMMA and then at 13.7 cm radiological equivalent depth in Plastic Water. The ratio of the readings was used to correct the raw diode reading. The main detector board was then removed from the cylindrical Delta4 phantom (#1 in Figure 1) and replaced by the two PMMA slabs. The Isorad diode was positioned in the middle of the phantom and this assembly was exposed to a helical beam producing a uniform dose distribution in an 8 cm diameter cylindrical target. The dose measured by the Isorad diode was compared to the average dose recorded by the six immediately adjacent Delta4 detectors.

F.2. Relative calibration (equalization). Relative calibration of the detector boards is performed once in a wide conventional linac field and is used for all beams at an institution. In this work, it was further validated for tomotherapy by two methods, both involving exposure to a uniform cylindrical radiation field recommended as a plan-specific reference field for tomotherapy [11]. First, either the main or wing board(s) were removed from the Delta4 phantom and replaced by the PMMA slabs. A piece of ready-pack EDR2 film (Eastman Kodak, Rochester NY) was placed next to the remaining detector and irradiated. The relative dose distribution obtained with film was analyzed against the calculated (uniform) dose in the tomotherapy software and compared to the Delta4 dose analysis. Second, the Delta4 was exposed to the same radiation field twice, with the detector rotated by 180° between the exposures. The readings were compared for the diodes in the central 6x6 cm^2 area.

G. Rotational dependence

The Delta4 was exposed to a uniform cylindrical radiation field first with both detector boards in place, and then with the wings replaced by the PMMA slabs. The resulting dose distributions on the main detector board were compared directly in the Delta4 software by using one of the measured dose matrices as the reference for the other.

H. Tomotherapy calibration

There is more than one way to define absolute calibration of the tomotherapy unit [11]. The static dose rate was determined in a flat Solid Water phantom. The TPS dose rate is stated at 85 cm SAD and depth of 1.5 cm for a 5x40 cm^2 field. We chose to compare it to the rotational dose rate defined as the static dose rate multiplied by the rotational-to-static correction factor. This factor is determined by placing an ion chamber with a buildup cap (# 6 in Figure 1) at the end of the couch, so that the beam is not obstructed at any gantry angle, and taking a ratio of rotational and static readings [12]. During the course of measurements, the ratio varied from 1.001 to 1.006, which compares favorably with the previously reported values [12]. The overall ratio of the measured to the nominal TPS dose rate varied day to day from 0.987 to 1.020.

I. Correction for the daily output variation

Delta4 has a feature where it can be exposed to a radiation field that is uniform in the central 6x6 cm^2 region, where the detector density is higher (5 mm spacing). The mean deviation of the measured dose from the reference for the diodes in that area is used to suggest the daily output variation correction factor, thus bypassing the need for the ion chamber measurement. This feature was tested for the two helical fields using different treatment slice widths (5 and 2.5 cm) and delivering a uniform 2 Gy dose to a cylindrical target 8 cm in diameter. The correction factors suggested by the Delta4 were compared to the rotational output measurement and to the DQA ion chamber measurements in the cylindrical Solid Water phantom.

J. DQA analysis

The synthetic image of the Delta4 phantom was used for DQA calculations. It was assigned the relative density of 1.14, corresponding to the relative electron density of PMMA. Even though the Tomotherapy TPS uses physical densities, scaling by electron density is more appropriate for treatment planning [13]. The nine cases selected for the DQA analysis are summarized in Table 2. The first case is the Radiological Physics Center H&N IMRT credentialing phantom, and the other eight are randomly selected clinical cases for a variety of disease sites. The plans varied in modulation factor, pitch, and calculation grid size. All cases were analyzed in terms of the γ(3%,3mm) passing rates for absolute dose by the Delta4 software. The Delta4 was positioned in an optional jig, such that the detector boards were in the sagittal and coronal orientations. This allows additional analysis in the native Tomotherapy DQA software, which can only handle cardinal planes. The γ(3%/3 mm) maps and overlaid profiles were generated for some cases with film, using this feature. It was also verified that the γ analysis results did not change when the dosimeter was returned to its default configuration, with the detector boards at oblique angles of +50° and -40° from the vertical.

III. Results and discussion

A. Short-term reproducibility

For each of the three experiments, the average of 81 diode readings did not deviate from the mean of the three runs by more than 0.1%. The standard deviation for the diode population for each individual run varied from 0.3 to 0.6%.

B. Linearity

The plot of the Delta4 reading vs. the ion chamber produces a straight line with R^2=1.0 and negligible intercept. This confirms that in the investigated range of doses and total numbers of radiation pulses, the triggering mechanism works well enough, so that no missing pulses could be experimentally detected. A plot of the chamber reading vs. net irradiation time also produced a straight line, confirming the dose rate stability with time.

C. Dose-per-pulse dependence

The ratio of the Delta4 to ion chamber readings varied by no more than 0.4% in the studied dose range.

D. PRF dependence

The unit performed as designed, triggering reliably in the PRF range from 300 to 290 Hz. The ratio of the Delta4 to ion chamber readings varied by no more than 0.8%. The internal Delta4 PRF measuring tool reported 300±0.2 and 290±0.1 Hz corresponding to the programmed values of 300 and 290 Hz, respectively. No reliable reading could be obtained with the PRF of 289 Hz and below. This makes the Delta4 unsuitable for measuring the MVCT dose, as the scans are acquired with the PRF of 80 Hz.

E. Rotational dependence

The average difference in dose on the phantom long axis with and without the wings was -0.2%. The dose with the PMMA slabs is lower because the detector board is less dense on average than PMMA. This confirms that the inhomogeneous structure of the detector board has relatively little effect on the dose measured during helical tomotherapy delivery.

F. Delta4 calibration

F.1. Absolute calibration. The reference diode reading immediately following the absolute calibration was within 0.4% of the stated calibration dose, when the average rotational correction (1.01) was appropriately factored out. The PMMA to water correction factor for the Isorad diode was 0.984 in the 5x40 cm^2 field. The ratio of the Delat4 dose to the corrected Isorad diode reading in the middle of the cylindrical PMMA phantom was 1.004.

F.2. Relative calibration. The dose comparison between the Delta4 and film, with a typical example presented in Figure 3, was satisfactory. Essentially all the points passed the gamma criterion for both Delta4 and film, when compared to the planned dose. A more stringent (2%,2mm) criterion was used for film because the dose was scaled. In the phantom rotation experiment, the mean dose differences among the diodes between the normal and reversed phantom orientations were -0.3±0.6 and -0.4±0.7% for the main board and wings, respectively.

G. Correction for daily output variation.

With the relative rotational output measured at 1.02, the ratios of measured to predicted dose for the uniform cylindrical dose distributions are presented in Table 1. For the treatment slice width of 2.5 cm, which we use almost exclusively, there is only 0.4% difference between the corrections based on the rotational ion chamber output and the daily correction factor suggested by the Delta4. The latter can be used routinely. It was also verified that the ion chamber reading in the cylindrical "Cheese" phantom (# 2 in Figure 1) differed from the predicted value by less than 1%, once corrected for the daily rotational output variation

H. DQA Analysis

The results presented in Table 2indicate very good agreement between the measured and planned dose distributions. The average γ(3%,3mm) passing rate for absolute dose was 97±2.7%. The range was 90.7 to 99.8%, with only one case below 96%. Additional validation of the results was provided by comparing Delat4 and film-based DQA results side-by-side (Figure 4). Because of the potentially high dose gradients, the phantom needs to be aligned carefully, preferably by MVCT imaging. An intentional 2 mm vertical misalignment in Case 2, for example, resulted in a 5% decrease in the gamma passing rate.

Case #7 in Table 2 was re-measured with the detector boards in their default oblique orientations (without the jig). The gamma analysis passing rate stayed essentially the same (98.8 vs. 99.0%).

IV. Conclusions

The basic dosimeter characteristics of the Delta4 diode array in the helical tomotherapy beam were found satisfactory in terms of short-term reproducibility, linearity, dose rate dependence, rotational response and calibration accuracy. A daily output variation correction can be derived from the Delta4 measurement in a standard helical beam producing a uniform cylindrical dose distribution. All nine clinical plans passed the γ(3%,3mm) test above 90%, and all but one passed above 96%. Phantom alignment by MVCT imaging is recommended. Placing the phantom into a jig to put the detector boards in the coronal and sagittal orientations allows analyzing the dose distributions in the Tomotherapy software instead of the Delta4. However this does not improve functionality, while the increased height of the phantom limits the range of the possible phantom vertical positions.

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Figure legends

Figure 1. Phantoms used in this work. 1. Delta4 cylindrical PMMA phantom. 2. Solid Water cylindrical ("Cheese") phantom. 3. Delta4 calibration phantom. 4. Plastic Water Cube for Isorad diode (7) calibration. 5. Solid Water for static tomotherapy calibration. 6. Graphite build-up cap.

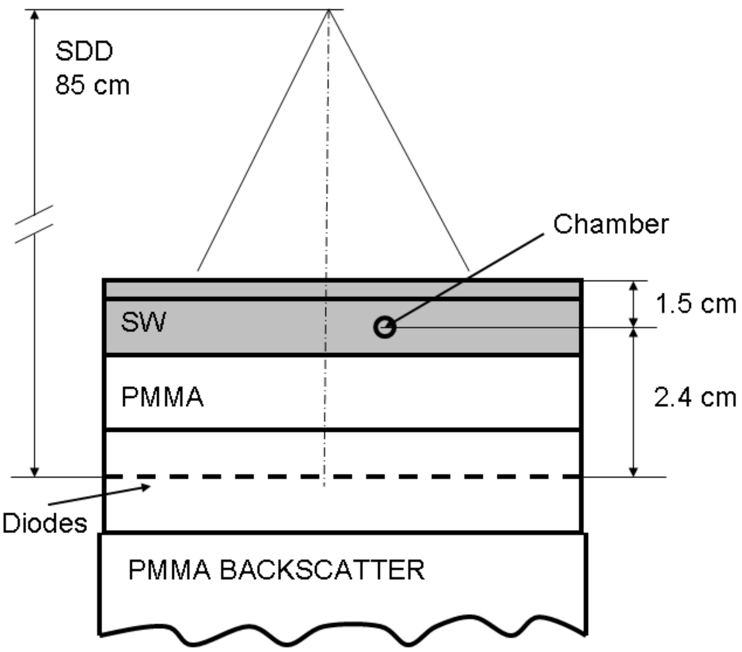

Figure 2. Experimental setup for measurements with the detector board in the calibration phantom with an ion chamber reference.

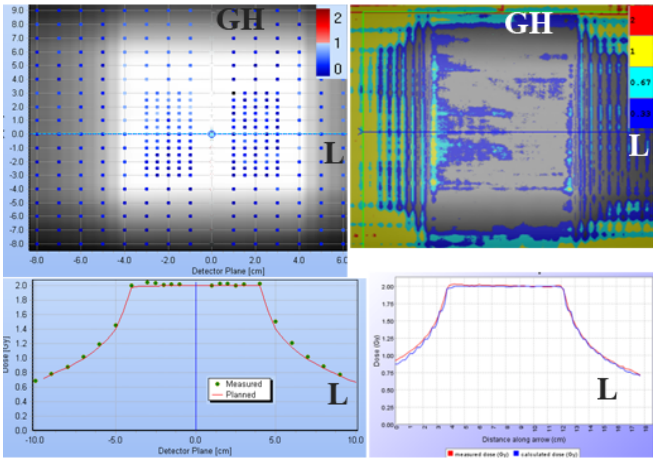

Figure 3. Gamma maps (top) and transverse dose profiles (bottom) comparing measured and calculated doses for Delta4 (left) and film (right) in the coronal plane (wings). γ(3%/3mm) is used for the absolute Delta4 dose comparison and γ(2%/2mm) for the relative film comparison.

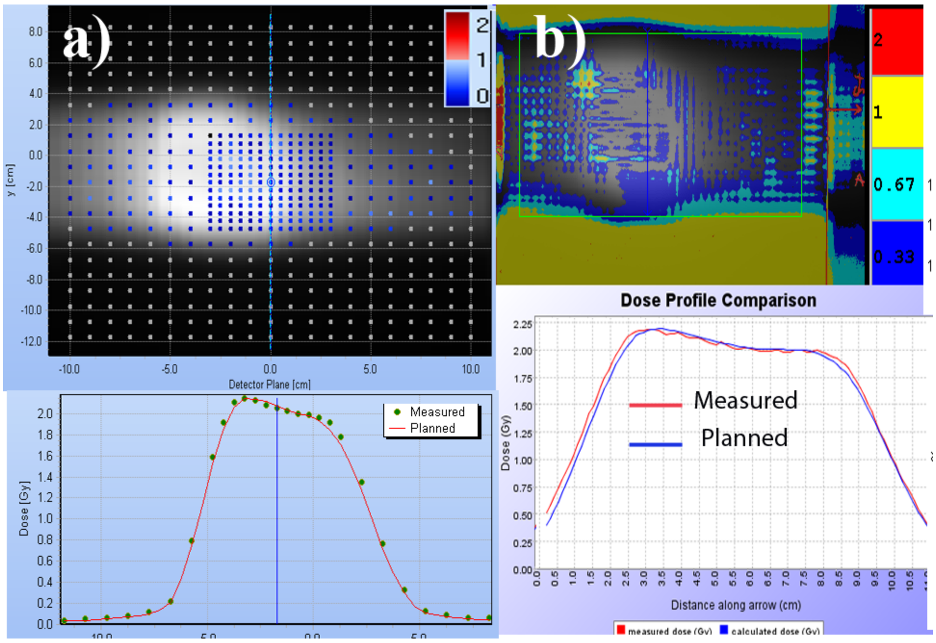

Figure 4. Dose comparison for Case 7 in the sagittal plane (main board). a) Delta4 vs. planned (absolute). b) Film vs. planned (relative). Top: γ(3%,3mm). Bottom: longitudinal dose profiles.

Tables and Captions

Table 1. Ratios of measured to planned dose for uniform cylindrical fields. IC to TPS ratio is measured in a cylindrical Solid Water ("Cheese") phantom

Tx slice width, cm	IC to TPS Ratio	Delta4 to TPS Ratio
5.0	1.013	1.003
2.5	1.028	1.016

Table 2. Delta4 DQA results for nine clinical plans and two uniform cylindrical fields

No	Case type	Tx slice width, cm	Pitch	Modulation Factor	Calc. grid, cm	γ(3%,3mm) pass rate, %
1	H&N, RPC phantom	2.5	0.3	1.803	0.231	96.5
2	Lung/Mediastinum	2.5	0.3	1.312	0.390	99.0
3	Esophagus	2.5	0.27	2.110	0.468	99.8
4	H&N (Tonsil)	2.5	0.287	2.697	0.234	96.6
5	H&N (Base of skull)	2.5	0.287	1.758	0.468	96.2
6	Bladder	2.5	0.287	2.491	0.468	96.6
7	Prostate	2.5	0.28	2.166	0.468	99.0
8	H&N (neck)	2.5	0.28	2.279	0.468	98.8
9	H&N (BOT)	2.5	0.28	2.406	0.468	90.7
10	Uniform cylinder	5.0	0.3	1.370	0.390	100

11	Uniform cylinder	2.5	0.287	1.431	0.390	99.2