Diode Arrays and QA of Advanced Techniques

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Abstract. Dosimetric verification of delivery for intensity-modulated radiotherapy (IMRT) treatment plans is critical to ensure accurate and safe patient treatments. Commonly, a point dose measurement using a calibrated ion chamber as well as a planar dose measurement using film was traditionally implemented for dosimetric quality assurance (QA) of treatment plans. However, new products have become commercially available in which both an absolute and coarse planar dose measurements can be acquired simultaneously by the use of an array of detectors—either ion chamber- or diode-based. Currently, two devices, MapCHECK and Delta4, utilize diode technology for planar dose measurements with Delta4 implementing an orthogonal biplanar arrangement versus the common singular plane. Both devices have been thoroughly clinically characterized with more published experience in the literature available for the MapCHECK due to the novelty of Delta4. In this review, an overview of basic diode dosimetry and both diode array systems is presented with an emphasis on our research and clinical experience of the Delta4.

1. Introduction
The delivery verification of patient specific intensity-modulated radiotherapy (IMRT) plans is critical in order to ensure accurate and safe delivery of precise patient treatment plans. While multiple means exist to accomplish such verification, common clinical practice has established a need for an absolute point dose measurement along with a method of measuring a planar dose distribution as standard. Traditionally, a calibrated ion chamber along with radiochromic or radiographic film has been used to validate treatment deliveries. However, new electronic arrays of ion chambers and diode detectors have become commercially available and have facilitated and shortened the time required for delivery verification due to their ease of setup and instantaneous absolute dose readout.

Two array devices currently on the market employ diodes as means of radiation measurement. Diode detectors have a role in radiation dosimetry due to their high sensitivity, high spatial resolution, and quick response time when compared to ionization chambers. Their small detector size (<1 mm) makes them ideal for measuring complex IMRT planar dose distributions with minimal volume averaging effect. Even though diodes exhibit excellent reproducibility and good mechanical stability, diodes do show slight dose-rate, temperature, direction and energy dependence—all of which must be accurately characterized prior to use as an absolute dosimeter.

The basic structure in a silicon diode is a p-n junction. This junction is typically manufactured by lightly doping a pure silicon substrate to establish either an n-type or p-type diode. The diode is termed n-type when the substrate is doped with phosphorous and p-type when the substrate is doped with boron. A surface region is then heavily doped with impurities of the opposite
type to form a p-n junction. By doing so, a region, known as a depletion region, with steep charge gradient and strong electric field is formed at the p-n junction. Because of this strong electric field, charge collection is possible without the need of an external bias. The incident ionizing radiation generates electron-hole pairs throughout the diode. The electrons on the p side and holes on the n side diffuse toward the p-n junction and are swept across the junction by the strong electric field. The total current measured is a sum of the radiation induced current and the leakage current of the diode and is proportional to the dose. [1]

2. Diode Arrays

2.1. MapCHECK

The MapCHECK diode array (SunNuclear Corp. Melbourne FL) contains 445 n-type solid-state diode detectors. The inner 221 detectors cover the central 10.0 x 10.0cm$^2$ area and are arranged in a zig-zag pattern so that the diagonal spacing between any given two detectors is 0.707cm. The remaining 224 detectors are arranged in a similar pattern with double the diagonal spacing between detectors, namely 1.414cm. A total area of 22.0 x 22.0cm$^2$ is covered by 445 diodes of 0.8 x 0.8mm$^2$ active area.

The response of the MapCHECK has been thoroughly characterized and evaluated. Jursinic and Nelms [2] and Létourneau et al. [3] examined the linearity and temperature dependence of the MapCHECK detectors and found that the diode response was linear within the range of the radiation dose delivered—up to 2.95Gy. All diodes were calibrated to within 1.0% response of each other with excellent reproducibility—standard deviation of 0.15%. A temperature dependence of 0.57%/°C was noted and was necessary to correct for absolute dosimetric measurement.

A clinical evaluation and comparison of the MapCHECK unit to an ion chamber array performed by Li et al. shows that no field size or SSD dependence was observed within the range of the field sizes and SSDs used in the study at both 6 MV and 18MV photon energies. The MapCHECK showed negligible errors (<1%) when measuring doses of more than ~8cGy, but exhibited errors of ~3% when measuring doses on the order of 1cGy. [4] Moreover, the MapCHECK showed a less than 1% discrepancy and more than 90% of the detectors within 0.5% response variation. Excellent gamma passing rates were obtained when compared with the planar dose distributions from the treatment planning system for IMRT fields.

2.2. Delta$^4$

The Delta$^4$ system (ScandiDos AB, Uppsala, Sweden) consists of 1069 p-type silicone diodes arranged on two orthogonal arrays placed in a 22.0cm diameter cylindrical polymethyl methacrylate (PMMA) phantom. The arrays lie orthogonal with respect to each other however are rotated with respect to the treatment couch—essentially forming an “X.” The diode active area is 1.0mm in diameter and the diodes are placed on a varying square grid with 0.5cm spacing for the central 6.0 x 6.0cm$^2$ region and 1.0cm spacing in the remaining 20.0 x 20.0cm$^2$ measurement area.

The Delta$^4$ system is a bit more advanced than the MapCHECK in terms of radiation acquisition, for it measures the dose per pulse as oppose to a continuous sampling. This is accomplished by synchronizing the sampling of the Delta$^4$ to the linear accelerator through a coaxial cable attached to the synch output. Doing so, the measurements in the electrometer are only acquired shortly before, during, and after the radiation pulse providing excellent dose resolution. Additionally, corrections are applied to the raw diode readings to account for rotational sensitivity, depth, and field size dependence since the beam parameters are known from the treatment planning system.

In a recent study, Feygelman et al. evaluated the Delta$^4$ and its performance in conjunction with the helical tomotherapy system for patient specific delivery QA. [5] It was shown that the short-term reproducibility of the Delta$^4$ was 0.1%, dose linearity was <0.1%, dose-rate dependence was 0.4% and absolute calibration accuracy was 0.4%. Additionally, the Delta$^4$ response to rotational
irradiation changed by no more than 0.2%. Their clinical validation of nine IMRT plans showed a mean \( \gamma(3%/3mm) \) passing rate of 97.0 ± 2.7%.

2.2.1. 3D Dose Model Validation

The Delta\(^4\) system uses the calculated dose distribution from the treatment planning system to generate a semi-measured 3D dose volume. The 3D semi-measured dose calculation methodology utilizes the response detected for a given radiation ray and scales the calculated dose along the path based on the response of the two diode detectors. Due to the detector geometry of the phantom, any given ray will intersect both detector planes.

In order to validate the semi-measured 3D dose calculation algorithm, measurements were performed using a Tomotherapy\(^\text{TM}\) HiArt\(^\text{TM}\) and a calibrated pinpoint PTW N31006 chamber with a sensitive volume of 0.016cc for point dose measurements. A section of the Delta\(^4\) PMMA slab was modified to accept the ion chamber. Eight (\(n=8\)) quality assurance plans were created and scaled to span a range of doses from 20% to 100% (20% steps) and 200% of the prescribed dose from the tomotherapy TPS. At each delivery, a point dose measurement was recorded. Point dose measurements and semi-measured point doses were compared against the calculated point doses of tomotherapy.

Good agreement was noted among all measurements. Tomotherapy delivery results showed a mean point dose difference between the tomotherapy TPS and ion chamber of 1.3% and a mean point dose difference between the tomotherapy TPS and semi-measured dose of 2.1%. The Delta\(^4\) semi-measured point dose showed good agreement (<1.0%) with the pinpoint chamber for the majority of measurements.

2.2.2. SBRT TomoTherapy Validation

Implementation of the Delta\(^4\) for delivery verification of coarsely hypofractionated treatments, particularly stereotactic body radiotherapy (SBRT), using helical tomotherapy overcomes the current necessity of scaling the delivery quality assurance (DQA) procedure in order to ensure that the maximum dose delivered is within the dynamic range of the film being utilized. By using the Delta\(^4\), scaling errors, possibly due to MLC leaf latency, would be minimized or eliminated, and the un-scaled treatment plan would be verified.

Five patients (\(n=5\)) with single or multiple small lesions in either the lung or liver were treated with SBRT techniques using the tomotherapy unit. Their five different DQA plans were delivered—3 liver patients and 2 lung patients—over the course of 4 months. Treatment plans delivered doses per fraction ranging from 10.0-20.0Gy. Corresponding DQA plans were generated and delivered on the Delta\(^4\).

Excellent agreement was found to exist for all patients between measured and calculated dose distributions. The mean \( \gamma(3%/3mm) \) for all plans was 99.3% [98.7-100%]. Our preliminary results indicate that the Delta\(^4\) is an effective and efficient method for delivery quality assurance of high dose per fraction treatment plans.

2.2.3. UTHSCSA Delta\(^4\) Experience

The Delta\(^4\) system has been commissioned for delivery verification of all tomotherapy treatment plans delivered at the University of Texas Health Science Center San Antonio since January of 2009. During this time period, over 200 patient delivery validations have been performed. Pass criteria for the dose validations were defined as a \( \gamma \) index of 90% or greater. Gamma parameter tolerances were set to 3% or 3mm for detectors with measured doses between 20 to 500% of the reference dose. The reference dose was defined as the maximum measured dose. Based on all DQA measurements, a mean \( \gamma(3%/3mm) \) value of 96.5 ± 2.8% was computed with values ranging from 86.5 to 100%.

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3. Conclusion

The availability of diode arrays for patient specific quality assurance has provided another established method of accurately validating precise, measured dose distributions. The ability of current diode technology to provide stable and reproducible results as shown in multiple published literature validates the future role of diode arrays as a robust dosimeter. Current diode array systems such as the MapCHECK and Delta4 eliminate the need of film and ion chamber-based dose validation and further shorten the time associated with dose validation due to their ability of instantaneously reading, processing and analyzing the data.

References

[1] Zhu TC, Saini AS. Diode Dosimetry for Megavoltage Electron and Photon Beams. Clinical Dosimetry Measurements in Radiotherapy. Med Phys Publishing. 2009.

[2] Jursinic PA, Nelms BA. A 2-D diode array and analysis software for verification of intensity modulated radiation therapy delivery. Med Phys. 2003;70(2);199-206.

[3] Letourneau D, Gulam M Yan D, et al. Evaluation of a 2D diode array for IMRT quality assurance. Radiother Oncol. 2004;70(2);199-206.

[4] Li CG, Yan G, Liu C. Comparison of two commerical detector arrays for IMRT quality assurance. J Appl Clin Med Phys. 2009;10(2);62-74.

[5] Feygelman V, Opp D, Javedan K, et al. Evaluation of a 3D Diode Array Dosimeter for Helical TomoTherapy Delivery QA. Med Dos. 2010. (In Press)

[6] Low D, Harms WB, Mutic S, et. al. A technique for the quantitative evaluation of dose distributions. Med Phys. 1998;25(5):656-61.