Innovative detectors for quality assurance dosimetry in SBRT of stationary and movable targets

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Abstract: The high spatial and temporal resolution 2D monolithic silicon detector arrays M512 and DUO for quality assurance (QA) in real time motion adaptive radiotherapy (ART) have been developed. The DUO array possesses a spatial resolution of 0.2 mm and has demonstrated agreement within 5% with EBT3 film measurements of 6MV linac beam profiles for field sizes 1×1 cm^2 and SRS cone diameter 0.5 cm. Dynamic characterisation of the M512 for QA in real time ART evaluated the performance of M512 for small fields while the detector experiences periodic motion. It was demonstrated with M512 that MLC tracking with Calypso electromagnetic array compensates for the periodic motion and improves the agreement between static and dynamic beam profiles for field size 1×1 cm^2 from within 75% in the penumbra to within 11% agreement. The dynamic profile is returned to a similar distribution as the static case.

1. Introduction

Stereotactic Radiotherapy (SRT) describes a form of external beam radiotherapy (EBRT) treatment delivering a hypo-fractionated high dose regimen using highly conformal photon beams. Stereotactic Body Radiation Therapy (SBRT) is the application of this methodology to extracranial tumour sites with tumour diameters less than 5 cm [1]. Treatment sites may include: lung, liver and kidneys within the abdominal and thoracic cavities [2]. SBRT requires accurate delineation of the target structure and minimisation of treatment margins associated with physical, biological and physiological tumour processes and motions, to spare surrounding healthy tissue and nearby critical organs [3]. Accurate delineation is achieved through pre-treatment imaging protocols and improved over the course of treatment using a combination of image guidance and motion management strategies.

The treatment of small volume tumours in the vicinity of critical organs within the abdomen requires conformal small area radiation beams [4, 5]. Challenges in small field dosimetry are well known [6, 7] and require that an ideal dosimeter for small area radiation beams exhibits properties including: dose-rate, energy and directional independence, near water equivalence, minimal beam perturbation and small sensitive volume [8, 9].

The radiobiological advantages associated with adopting highly conformal, hypo-fractionated, high dose treatments, are compromised by the impact of tumour motion (both inter and intra-fraction). Lung tumours may move up to 20-30 mm (superior-inferior plane) during the respiratory cycle [10]. In general, to account for tumour motion, the treatment margins must be enlarged to encompass the full

range of motion of the intended target, however, this sacrifices the conformal delivery of the treatment and increases dose delivery to surrounding healthy tissue.

Adaptive radiotherapy (ART) which minimises the need for large treatment margins based on the motion management strategies designed to minimise the effects of organ motion upon treatments include: gating [11], patient breath-hold and real-time tumour tracking with Multi-Leaf Collimator (MLC) adaptation [12].

The quality assurance (QA) in real time motion ART requires the dosimetry system possess both high spatial and high temporal resolution to accurately and simultaneously evaluate the delivered dose distribution and the consequences of the interplay effects attributable to the motion and tracking.

2. Materials and Methods

1.1. Detectors

The Centre for Medical Radiation Physics (CMRP), University of Wollongong, has developed novel pixelated silicon detectors, for use in the QA of modern EBRT. The MagicPlate 512 (M512) is a monolithic two-dimensional square array consisting of 512 silicon diodes with 2 mm pitch and 0.5×0.5 mm^2 sensitive area, figure 1(a). DUO is comprised of 505 silicon diodes arranged in intersecting orthogonal linear arrays with sensitive area 0.02×1 mm^2 and pitch 0.2 mm, figure 1(b).
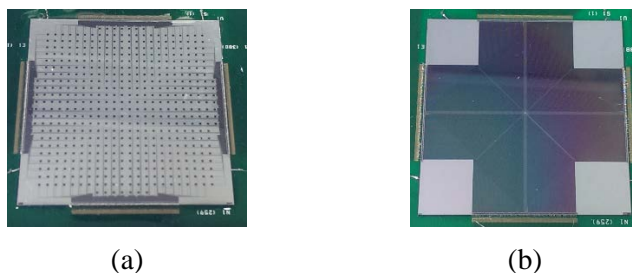

(a)   (b)

Figure 1. The silicon diode arrays mounted and wire bonded to printed circuit board carries. (a) MagicPlate 512. (b) DUO.

1.2. Characterization for small static fields

Beam profiles of a small area radiation field of size 1×1 cm^2 defined by the collimation jaws, with the MLC retracted and a SRS cone with diameter 0.5 cm, were measured. DUO was placed at a depth of 10 cm in a solid water phantom with 10 cm of backscattering material. The system was irradiated at 90 cm SSD using a 6 MV photon beam from a linac for 100 monitor units (MU) at 600 MU min^{-1}. The measurements were repeated under identical conditions with Gafchromic EBT3 film (ASHLAND, Wayne, NJ) for comparison.

1.3. Calypso Motion Tracking Array and MLC Tracking

MLC tracking utilising a Calypso (Varian Medical Systems) electromagnetic array and radiofrequency beacons implanted within the target, presents an attractive motion management solution [13]. The changing spatial coordinates of the target (or a surrogate) are provided to the MLC controller to alter the leaf positions in real time.

1.4. Characterization for dynamic target

Dynamic characterisation of the M512 for QA in real time ART evaluated the performance of M512 for small fields while the detector experiences periodic motion. M512 is placed upon a HexaMotion platform (ScandiDos, Uppsala, Sweden) on the treatment couch of a linac, figure 2 (a). The M512 is irradiated by square MLC defined fields of size 1×1 cm^2 at 1.5 cm water-equivalent depth and 100 cm SAD for 1000 MU at 600 MU/min, with the gantry at 0° rotation [14]. Three cases were investigated; static platform without MLC tracking, dynamic platform (lung motion) without MLC tracking and dynamic platform with MLC tracking (MLC compensates for motion of the target).
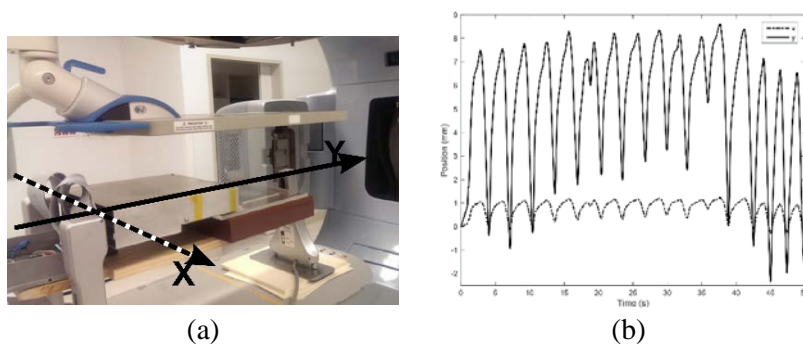
Figure 2. (a) M512 detector positioned upon HexaMotion platform. (b) The temporal motion pattern provided to the platform. The platform mimics the lung motion during the irradiation across the two axis of motion provided *X* and *Y*.

(a)   (b)

3. Results

1.5. Characterization of small static fields

The EBT3 film response is normalised to the pixel values within a 1 mm window surrounding the central axis (CAX) of the profile. The DUO profiles are normalised to the response of the central detector pixel. The beam profiles acquired from both detectors are aligned such that the origin lies at the coordinate corresponding to 50% response for DUO and the EBT3 film.
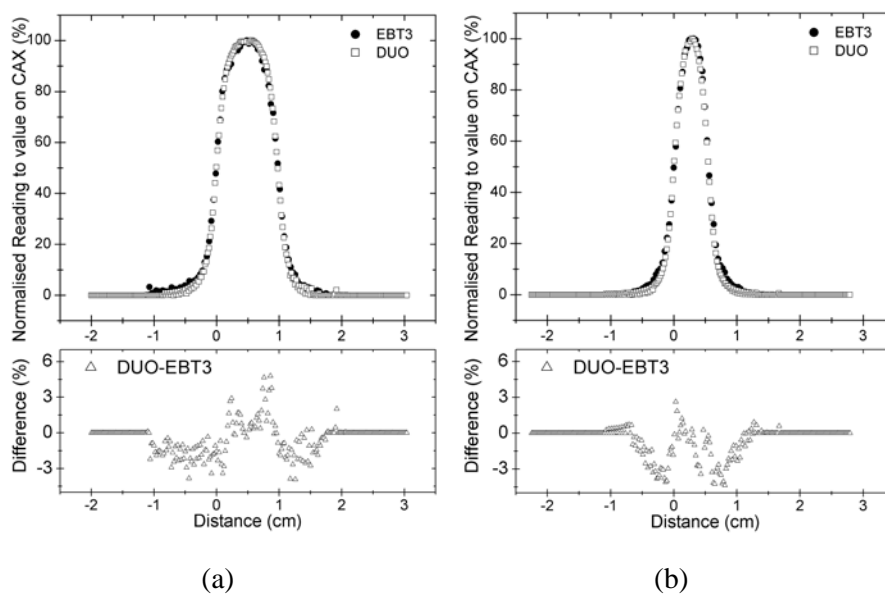

Figure 3. Comparison of response of DUO detector and EBT3 film for small field sizes. (a) Field size 1×1 cm^2. Lower panel shows agreement between EBT3 and DUO. (b) SRS cone collimator 0.5 cm diameter. Lower panel shows agreement between EBT3 and DUO.

(a)   (b)

In Figure 3, DUO has demonstrated good agreement with EBT3 film measurements to within 5% in the penumbra of 6MV linac beam profiles for field sizes 1×1 cm^2 and SRS cone diameter 0.5 cm, figure 3(a), 3(b).

1.6. Characterization of dynamic target

The beam profiles of the M512 detector for the separate motion cases are compared, the line profiles are extracted along the identical column of channels within the array. The result shown in figure 4 illustrates the beam profiles along the *Y* direction of motion, figure 2 (a). M512 has been shown to agree with EBT3 film to within 0.4 mm for penumbral width measurements and 3% for FWHM measurements [14].

The profiles acquired with M512 for the motion cases along the *Y* axis is shown in figure 4. The dynamic platform without MLC tracking case demonstrates a shift in the delivered dose distribution. The motion introduces this displacement and smears the dose out in the penumbra leading to disagreement between the cases. The dynamic platform with MLC tracking case highlights the

capability of the MLC tracking system to compensate for the periodic motion and return the profile to a similar distribution as the static platform case. The agreement within the penumbra of the profiles acquired with M512 for the no motion and motion cases is improved from within 75% without MLC tracking to within 11% with MLC tracking, figure 4.
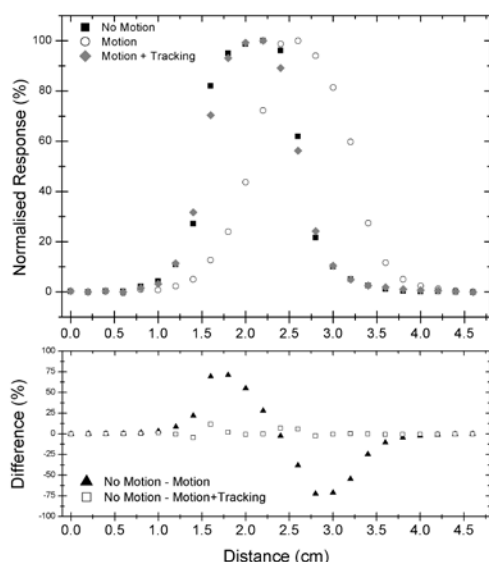

Figure 4. Comparison between responses from M512 for measurements of 1×1 cm^2 MLC defined field along the *Y* axis. M512 is irradiated in identical position for cases: i) static platform without MLC tracking – no motion case. ii) Dynamic platform without MLC tracking – with motion case. iii) Dynamic platform with MLC tracking – motion and tracking case. The lower panel shows the agreement between the no motion and motion case and the no motion and motion and tracking case, presenting the percentage differences between the opposing cases across the profiles.

4. Conclusion

M512 has been demonstrated as an attractive alternative to both radiochromic films and two-dimensional ionisation chamber arrays for the quality assurance of motion adaptive RT and SBRT [14]. The high spatial resolution of DUO presents valuable benefits for QA of real-time ART treatments. The increasing complexity of modern EBRT treatments and the further implementation of motion management strategies necessitates both high temporal resolution and real-time response in QA dosimetry systems to identify possible inaccuracy or failure in critical time-dependent effects.

5. References

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