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Preliminary epi-diode characterization for HDR brachytherapy quality assurance

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Preliminary epi-diode characterization for HDR brachytherapy quality assurance

Abstract

High Dose Rate vaginal brachytherapy for endometrial cancer has evolved from simple single-channel (i.e. cylindrical applicator) deliveries to treatments involving several channels (i.e. multichannel applicator) for the radiotherapy source to dwell, increasing the complexity of the dose distribution, and allowing more space for potential errors. For this reason real-time treatment verification has gained a greater importance than ever before, and more methods need to be developed in order to provide assurance that the dose delivery has been carried out as intended by the hospital staff. P-type silicon epi diodes have been designed at the Centre for Medical Radiation Physics (CMRP) in Australia to suit the specific needs of HDR BT, and characterized in the clinical BT facility of the Fondazione IRCCS (INT) in Italy. They have shown great potential for BT treatment verification in real time due to their radiation hardness, dose rate independence, flexibility in physical design, and ability to monitor the treatment at a 1-kHz readout frequency. Their dynamic range has been determined as ± 17 to ± 20 mm and dwell time calculation accuracy of > 0.1 s has been shown. If placed on the same longitudinal plane of a treatment accessory, these detectors would enable coverage of about 40 mm for source position and dwell time tracking. Respective detector positioning at (0, +3, -3 mm) would extend this range to 45-50 mm, depending on the catheter location, proving to be sufficient for the majority of treatment cases. Further studies are encouraged to develop diodes with a wider dynamic range.

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Preliminary epi-diode characterization for HDR brachytherapy quality assurance

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Abstract. High Dose Rate vaginal brachytherapy for endometrial cancer has evolved from simple single-channel (i.e. cylindrical applicator) deliveries to treatments involving several channels (i.e. multichannel applicator) for the radiotherapy source to dwell, increasing the complexity of the dose distribution, and allowing more space for potential errors. For this reason real-time treatment verification has gained a greater importance than ever before, and more methods need to be developed in order to provide assurance that the dose delivery has been carried out as intended by the hospital staff. P-type silicon epi diodes have been designed at the Centre for Medical Radiation Physics (CMRP) in Australia to suit the specific needs of HDR BT, and characterized in the clinical BT facility of the Fondazione IRCCS (INT) in Italy. They have shown great potential for BT treatment verification in real time due to their radiation hardness, dose rate independence, flexibility in physical design, and ability to monitor the treatment at a 1-kHz readout frequency. Their dynamic range has been determined as ±17 to ±20 mm and dwell time calculation accuracy of > 0.1 s has been shown. If placed on the same longitudinal plane of a treatment accessory, these detectors would enable coverage of about 40 mm for source position and dwell time tracking. Respective detector positioning at (0, +3, -3 mm) would extend this range to 45-50 mm, depending on the catheter location, proving to be sufficient for the majority of treatment cases. Further studies are encouraged to develop diodes with a wider dynamic range.

1. Introduction

High dose rate (HDR) brachytherapy (BT) is a radiotherapy (RT) technique that is characterized by its ability to deliver a highly conformal dose to the target volume, and often delivers high doses per fraction that have a steep dose gradient [1]. Disease sites treated with HDR BT include, but are not limited to breast, prostate, and the gynaecological cavity. In the simplest gynaecological treatments the HDR source is administered using a cylindrical applicator with a single central channel for the source to dwell in a range of positions and dwell times, and can be customized based on the patient's needs.

The single-channel applicator has evolved into a multi-channel applicator, allowing increased flexibility in the dose distribution [2]. The multi-channel applicator contains one central channel, often with the ability of inserting an intra-uterine tube, and several equally spaced peripheral channels.

Flexibility in the treatment also leads to higher complexity and thus presents more room for error, for example transfer tube connections may be accidentally switched during treatment setup in the case of multiple applicator channels. For this reason treatment verification is desirable, especially one that is available in real-time and allows the treatment to be interrupted in case an error is detected.

A number of radiation detectors have been investigated for treatment verification [3, 4], both for *in vivo* dosimetry [5-8] and HDR source tracking purposes [9-11]. Source tracking in particular has been previously achieved using a number of imaging techniques, such as pinhole cameras [12, 13] and EPID imaging [14-17]. Our aim is to develop a system that is able to verify both positions and dwell times in real-time. A comprehensive treatment verification system that employs the tracking of the HDR source is one that is able to determine both the positions and dwell times of the source, is capable of real-time readout, and allows a high spatial and temporal resolution comparable to that of HDR afterloaders used to administer the source. Radiation detectors used in such a system must therefore comply with the aforementioned description.

The objective of this study is to evaluate the suitability of epi diodes that have been developed at the Centre for Medical Radiation Physics (CMRP), and evaluate their sensitivity with respect to measurement settings, source air-kerma strength (S_K), and source-to-detector distance, as well as to establish a method for source dwell time verification.

2. Materials & Methods

The most commonly used source for HDR BT treatments is currently Ir-192, which has a half-life of ~74 days and is used for treatment in the clinic for a period of three months. During this timeframe the source strength (S_K) normally ranges between approximately 10 and 45 $mGy.m^2.h^{-1}$. At the Fondazione IRCCS Istituto Nazionale dei Tumori (INT) in Milan, Italy, brachytherapy is administered using the microSelectron afterloader unit, while the patient-specific treatments are planned using the Oncentra Treatment Planning System (TPS).

P-type epi diodes have been developed at the CMRP in the University of Wollongong to suit the specific needs of HDR BT quality assurance. They measure 325 mm in length and contain a sensitive silicon chip of 1.5 x 1.5 x 0.038 mm^3 (fig. 1a,b). The detectors are tailored to treatment verification in the form of real-time source tracking and possess features such as radiation hardness, dose rate independence, high readout frequency, and an un-biased readout guaranteeing suitability for in-patient use. The readout system consists of three boards: the AFE (analog front end), the FPGA (field programmable array), and the power supply board. The reader has four channels, and was covered in aluminium to minimize background noise (fig. 1c). The FPGA is connected via a USB connection to a laptop with CMRP-developed readout software AFE-Histogram that displays the instantaneous and integral responses of the four available channels. Readout settings can be adjusted to suit the particular type of radiation source and measurement setup, and include the range, integration time, and frequency of readout. The range indicates the number of times the capacitor has discharged, and can be set between 0 and 7 to reflect the AFE sensitivity. Integration time is the window of the AFE signal integration, and can range between 50 and 400 μs, whereas the frequency of readout can range between 1 and 1000 Hz.

Current-voltage (I-V) characteristics of the diodes were verified at the start of the study to ensure a stable relationship between applied voltage and current within the diodes by testing them in reverse biased mode prior to connector and shielding assembly.

The detectors were then positioned inside a water equivalent phantom at a distance of approximately 3 mm from the source on the longitudinal axis, approximately in the middle of the 48 available dwell positions. The HDR source was sent to all 48 available positions with the default step size of 2.5 mm and dwell times of 2 seconds. Diode response was acquired as the charge collected in the diode sensitive volume (pC). The range, acquisition time, and frequency of readout were modified between experiments to determine the optimal setup for source tracking in real-time.

To ensure diode dose rate independence and evaluate the variability of its response with respect to source activity throughout the lifetime of the source, measurements were acquired at different Ir-

192 source strengths. Diode dynamic range was investigated in terms of dwell position distance from the centre of the sensitive volume and assumed to extend until 95% of the readout points no longer conformed to their corresponding cluster group i.e. dwell position response range (pC), within two significant figures. A method of dwell time verification was also determined.

Figure 1. (1a) Diode bonds and silicon sensitive chip (1.5 x 1.5 x 0.038 mm^3 as viewed under a microscope). The bonds were covered for protection (b), and the complete diode assembly is used in conjunction with the in-house produced reader (c).

3. Results and discussion

I-V tests have indicated good P-N junction operation of all three selected dosimeters i.e. D1, D2, D3 (fig. 2). Three-pin female connectors were then attached to the detector pigtails and aluminium thin foil shielding added above the Kapton tail to minimise noise arising from the electronics and light exposure.

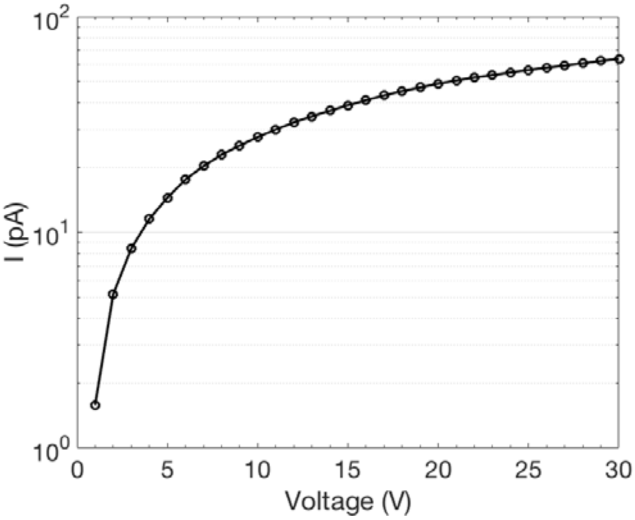

Figure 2. Typical current-voltage characteristics of the diode set.

Integration time and readout frequency were established as 400 μs and 1 kHz, respectively, to allow the diode to be read out at its maximum sensitivity. Fig. 3 shows S_K-normalised mean diode response as a function of treatment time for range (sensitivity) settings of 4, 5, and 6 and S_K of 25.4 $mGy.m^2.h^{-1}$. The response peaks while the source is closest to the diode's sensitive volume, and gradually decreases as the source moves away in either direction. At ranges 4 and 5 oversaturation occurs before the source is able to reach the closest dwell position, while a range of 6 allows the response to reach its maximum. A range setting of 6 or higher was therefore determined as optimal for measurement with the Ir-192 source to accommodate the range of dose rates throughout the lifetime of the HDR source in the hospital environment.

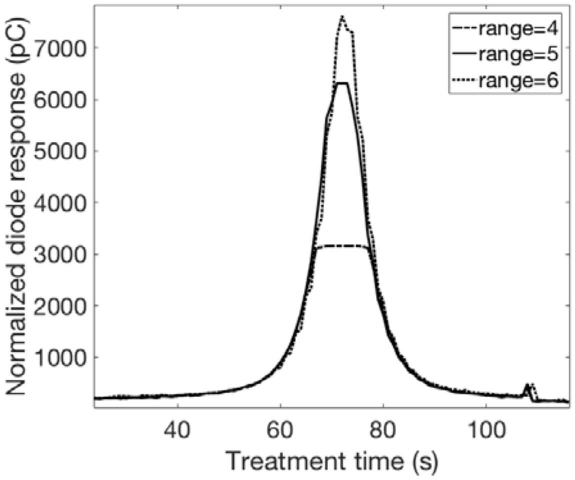

Figure 3. S_K-normalized mean diode response in each dwell position for range settings of 4, 5, and 6.

Diode response as a function of source strength, with S_K = 38.0, 34.6, 13.2 mGy.m^2.h^{-1} is shown in fig. 4a, where the highest range of measured charge plotted in black corresponds to the highest S_K value of 38.0 mGy.m^2.h^{-1}. The same three curves normalized for S_K demonstrate some dependence on the source dose rate (fig. 4b), especially when dealing with the maximum and minimum S_K values used in the clinic. Therefore, in order to increase the accuracy of source localisation, epi diodes should be calibrated at three different S_K strengths within the clinically relevant range, and expected diode response as a function of source position for individual catheters should be adjusted by means of interpolation, and embedded in a software look up table.

Moreover, due to a decrease of the response at lower dose rates diode dynamic range slightly decreases at lower S_K (diode response for S_K=13.23 is plotted in blue in fig. 4b), as shown by the rise in tail noise i.e. dwell positions located further away. It appears that normalised diode response is of similar magnitude for source positions of ±12.5 mm, while the signal-to-noise ratio is reduced at lower source activities and the response changes for positions located further away. The response peak at a treatment time of ~115 seconds corresponds to the source retraction into the afterloader, which is important for verification of its performance.

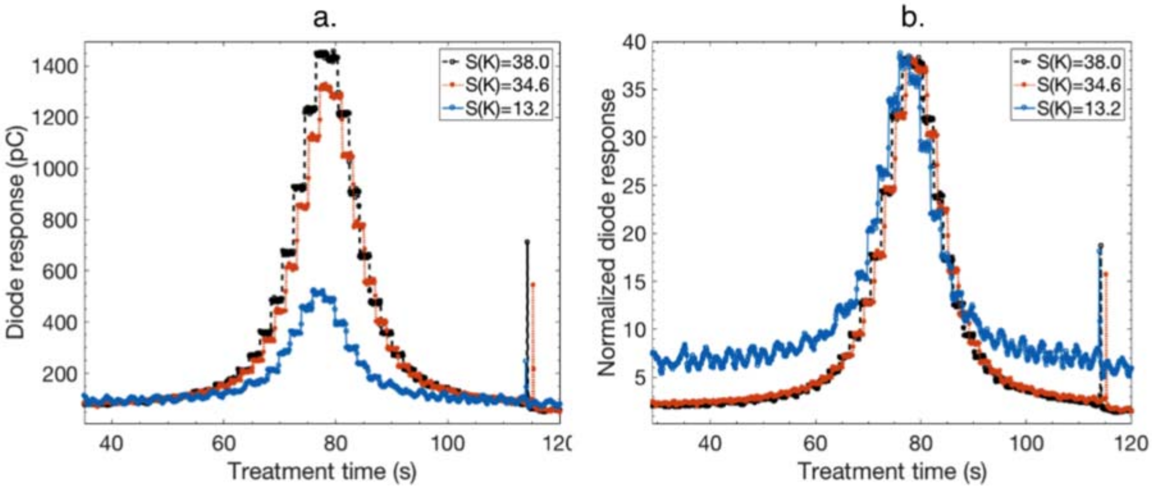

Figure 4. Diode response for various source strengths: total diode response (4a), and S_K-normalised response (4b).

Normalised mean diode response i.e. R_{DIODE} at individual dwell positions is plotted as a function of source distance from the centre of the diode's sensitive volume (mm) in fig. 5. Diode dynamic range was determined as ±20 mm, ±18 mm, and ±17 mm for diodes 1, 2, and 3, respectively. The fluctuation in diode response in a single dwell position was 0.5 - 2.6% for diode 1, 0.3 - 1.3% for diode 2, and 0.9 - 3.0% for diode 3, with higher fluctuation at increased source-to-detector distances. The diode range established in this study indicates that the combination of the three diodes would enable the coverage of approximately 40 mm of a gynaecological applicator, which may in some cases be shorter than the region of interest in HDR vaginal treatments for endometrial cancer. However if diodes are placed at (0, +3, -3 mm, where 0 is the middle position of the expected clinical range of source dwelling) of one another, then a coverage of the top 45-50 mm of the applicator would be possible, and would prove sufficient for the majority of treatment cases.

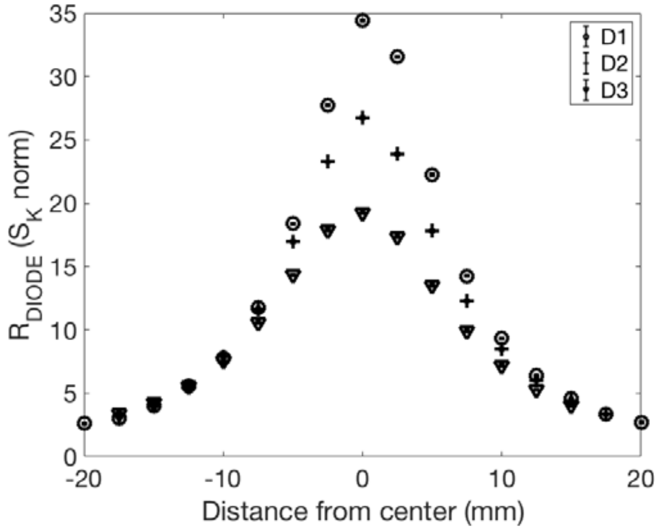

Figure 5. Normalised mean diode response in each dwell position as a function of the dynamic range of each diode.

Dwell time was determined from the time of constancy of diode response, and is represented by the signal plateaus in fig. 6. Dwell time is calculated as the product of the number of measurements in each plateau and the readout time interval, while readout signal values are constant. Measured dwell time was verified against the nominal dwell time with an accuracy of ± 0.3 s averaged over all dwelling positions. As the readout frequency was set below 10 ms, source transit time can in some cases be observed in fig. 6 as the single points between the plateaus.

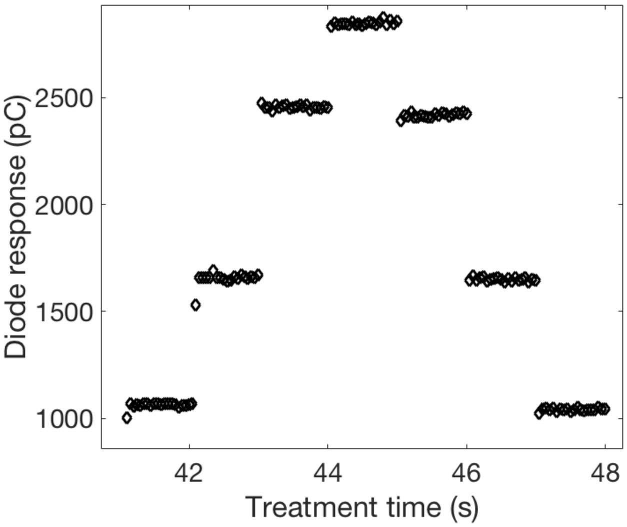

Figure 6. Diode response as a function of treatment time, where each response plateaus corresponds to individual dwell positions of 2 seconds in duration.

Source transit is visualised in fig. 7 before and after the source reaches a stable dwell position, traveling past the diode in both directions. The source transit time was calculated as 0.3 s both as it travelled from the afterloader to the planned dwell position and as it retracted back (shown in red), for a total of 0.6 s.

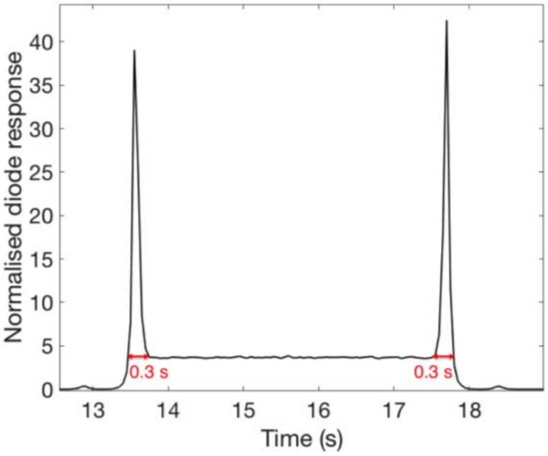

Figure 7. Diode response peaks corresponding to the source transit.

At the 0.001 s readout frequency the diodes have thus shown the ability to verify source dwell time with a better than 0.1 s accuracy in each position. The higher discrepancies in measured dwelling time determined in comparison to the TPS are attributed to source transit, equating to ~0.6 seconds per dwell position. This is taken into account in the TPS dose calculation and leads to lower physical dwell times than indicated by the TPS or measured experimentally, as above, which explains the ± 0.3 s accuracy.

4. Conclusions

The characteristics and suitability of epi diodes developed for HDR source tracking has been studied. Diode response to the HDR BT Ir-192 source has been evaluated with respect to measurement settings, source-to-detector distance, and source air kerma strength. Optimal readout settings allow a balance between minimal noise and maximum diode sensitivity to Ir-192, and are especially important in the clinical environment due to the wide range of S_K of an individual source; the dynamic range of diodes has been defined and determined adequate for use in HDR BT full treatment verification, if three detectors are placed approximately 3 mm apart. A method for dwell time calculation has been developed and tested to provide a better than 0.1 s accuracy, and a ±0.3 s mean accuracy as compared to the TPS. Although time resolution is appropriate for clinical needs, the dynamic range may in some cases be shorter than the relevant region in HDR vaginal treatments for endometrial cancer. The diode system has shown great potential, and further studies are encouraged to develop more sensitive diodes capable of detecting the source position over a wider dynamic range.

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