Development of quality assurance dosimetry systems for MRI brachytherapy and MRI-Linac technology

Poster No.: R-0280  
Congress: 2014 CSM  
Type: Scientific Exhibit  
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Keywords: MR physics, Radiation physics, MR, Brachytherapy, Radiation therapy / Oncology, Dosimetric comparison, Radiotherapy techniques, Image guided radiotherapy  
DOI: 10.1594/ranzcr2014/R-0280

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Aim

To observe the effect of a 1 tesla magnetic field upon the function of silicon semiconductor radiation dosimeters using the MOSkin dosimeter and the epitaxial diode dosimeter for application in MRI guided radiotherapy modalities

Background

Image guided radiotherapy is a modality of radiation therapy that combines traditional methods of radiotherapy with real time imaging of the treatment volume. By utilising imaging modalities, clinicians can track the treatment volume in real time. This allows clinicians to perform a treatment that better conforms to the actual tumour volume, resulting in better dose homogeneity delivery to the tumour and a lower dose delivered to the patient's healthy tissue. Image guided radiotherapy can improve a treatment's probability of success while minimising the probability of complications occurring in healthy tissue.

While beneficial, the majority of image guided radiotherapy procedures are performed using cone beam computer tomography and fluoroscopic imaging techniques. These imaging techniques utilise an ionising radiation source and as such they impart additional radiation dose to the patient and reduce the overall dose sparing capabilities of image guided radiotherapy.

A growing interest in image guided radiotherapy is the potential use of magnetic resonance imaging techniques in order to guide treatments. Magnetic resonance imaging has undergone advances over the past few decades that have improved availability, accessibility and overall image quality of the machines. MR imaging has many features that could be advantageous to radiotherapy. These features include:

- Real time imaging of the treatment volume
- Improved treatment conformity and dose homogeneity
- High soft tissue contrast
- Potential for simultaneous acquisition of physiological imaging
- No need for fiducial markers
- No additional radiation dose delivered to the patient
While MRI guided therapy does offer many advantages, the magnetic field produced during magnetic resonance imaging can potentially interfere with treatment and dosimetry systems. If these challenges were to be overcome, MRI guided therapy may become the new gold standard of imaging guided radiation therapy.

Research has been conducted into the feasibility of MRI-Linear accelerators for use in therapy. There are currently four MRI-Linear accelerators in production worldwide, Viewray (Washington), Cross Cancer Institute (Alberta), University Medical Centre (Utrecht) and the Australian MRI-Linac Project (Sydney). The Australian MRI-Linac Project features a 1 tesla split bore magnet that will be paired with a portable linatron system. The linatron is intended to be used in either an in line or transverse mode of operation. The University of Wollongong is developing the dosimetry systems to be used within the Australian MRI-Linac. The key dosimeters being used for these dosimetry systems are the MOSkin dosimeter, primarily used for gauging skin dose to the patient, the Dose Magnifying Glass (DMG) and the Magic Plate (MP) dosimeters. The Dose Magnifying Glass and Magic Plate are array detectors based upon epitaxial diode technology [1]. As a preliminary study, the MOSkin and a singular epitaxial diode dosimeters were characterised. The dosimeters' operational characteristics and dose response were observed within various orientations of a magnetic field. For the purposes of the preliminary study, brachytherapy seeds were used as an ionising radiation source.

In brachytherapy, dosimetry can be performed through the use of in vivo dosimeters [2, 3, 4]. Brachytherapy is a modality of radiotherapy where a sealed source is placed near or inside the treatment volume. The sources used in brachytherapy deliver their dose over a short range which can produce a lower radiation dose to healthy tissue than observed in other treatment modalities. Brachytherapy can be used as a stand-alone treatment or in combination with other treatment modalities (e.g. surgery, radiotherapy). Brachytherapy is often performed in one of three different modalities:

- Low Dose Rate Brachytherapy (LDR)
- High Dose Rate Brachytherapy (HDR)
- Pulsed Dose Rate Brachytherapy (PDR)

Traditionally, brachytherapy is performed on tumours in relatively static positions such as in the prostate and in the head and neck regions. Treatment planning is primarily performed through the use of CT-scans while treatment is guided using fiducial markers and fluoroscopic or ultrasonic imaging techniques.
Dosimetry is important in both low dose rate brachytherapy and in high dose rate brachytherapy. In low dose rate brachytherapy, the seed delivers dose to the target volume over a long period of time, during which the seed position may shift within the organ due to cellular growth, decay or transport mechanisms. In high dose rate Brachytherapy, positioning of the source is incredibly important and any error in source position may result in insufficient dose to the treatment area or overexposure to healthy tissues. Intraoperative probes can be placed near the treatment volume to ensure that the seed is positioned correctly and delivering the intended radiation dose to the treatment volume [2]. Dosimeters can also be placed near treatment boundaries or organ surfaces to ensure that healthy tissue does not receive unintentionally high doses. In prostate therapy, dose verification can be performed with dosimeters inserted against the surface of the colon [3] or within the urinary system via urethral catheterisation [4]. Real time dosimetry in MRI guided brachytherapy can lead to precise localisation, positioning and control of a source, leading to contained and effective dose distributions at the treatment site.

The aim of this study will be to test the MOSkin and epitaxial diode dosimeters within a magnetic field and assess their feasibility for use in MRI guided radiotherapy procedures. Measurements will focus on the effect a magnetic field has on the dosimeters' dose response through their I(V) characteristics, the epitaxial diodes sensitive volume through their C(V) characteristics, and the dosimeters' readout process through irradiation using both a laser light and a brachytherapy irradiation source.
Fig. 1: Illustration of the Australian MRI Linear Accelerator with visualisation of the effect MRGT could have on treatment volumes

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Methods and materials

Epitaxial Diode:

The epitaxial diode dosimeter is a silicon diode type dosimeter. The epitaxial diode features a high quality crystalline epitaxial film that is grown over the diode's heavily doped p-substrate wafer. The epitaxial layer results in an improved radiation hardness, allowing for reductions in diode thickness. Incident radiation causes ionisation to occur within the dosimeter's depletion region. Ionisation causes a current across the device which is collected by the readout device. For the purposes of this study the epitaxial diode was connected to a 30cm kapton pigtail, as shown in figure 2. Readout of the dosimeter was performed using the TERA acquisition system [5]. The TERA chip is a Very Large Scale Integration (VLSI) device designed by the Istituto Nazionale di Fisia Nucleare (INFN) for readout procedures of pixilated detectors. Readout is performed by counting the charge and discharge cycles of a capacitor that receives current from the connected dosimeter.

MOSkin:

The MOSkin dosimeter is a silicon semiconductor MOSFET type dosimeter. For the purposes of this study, the MOSkin dosimeter was connected to a 30cm kapton pigtail, as shown in figure 3. Readout of the dosimeter was performed using the CMRP Clinical Dosimetry Readout System. Radiation incident upon the MOSkin dosimeter causes ionisation and produces charges within the dosimeter's sensitive volume. The MOSkin is able to trap these charges within its sensitive volume. The accumulation of these trapped charges causes a shift in the MOSkins' operational characteristics. Dose delivery can be monitored by measuring the shift in threshold voltage experienced by the dosimeter over the course of irradiation. The MOSkin dosimeter features a unique, compact and waterproof encapsulation and measures radiation dose delivered at an effective depth of 0.07mm, a depth recommended by ICRP as the basal cell level depth and the first important boundary for radiation dosimetry in skin dosimetry [6].

CMRP Permanent Magnet Device:

The Center of Medical Radiation Physics (CMRP) Permanent Magnet Device is a magnet design developed for by CMRP for research purposes. In its current configuration, the magnet features a pole gap of 1cm width. This pole gap width corresponds to a magnetic field strength of 1 tesla present between the magnets poles.
Iodine-125 Irradiation Source:

Irradiation of the dosimeters was performed using an Iodine-125 source. Iodine-125 seeds are sources used in low dose rate brachytherapy. The Iodine seed is contained in a silver capsule encapsulated by a thin external titanium shell. Iodine-125 seeds are gamma emitters that emit gamma rays with average photon energies of 27 keV.

Rotational Dosimeter Jig:

The dosimeter was fixed at a point central to the magnetic field using the apparatus shown in figure.5. The dosimeter pigtail was positioned using a hollow solid water rod. The solid water rod can be rotated upon its central axis, allowing the dosimeter to be oriented at different angles to the magnetic field.

Method

Dosimeter characterisation was performed on both the MOSkin and epitaxial diode dosimeter. The MOSkin dosimeter underwent I(V) characterisation while the epitaxial diode dosimeter underwent I(V) characterisation and C(V) characterisation. If the dosimeters' I(V) characteristics are affected by the introduction of a magnetic field, the dosimeters dose response could be affected. If the epitaxial diode's C(V) characteristics are affected by the introduction of a magnetic field, the dosimeters sensitivity could be affected.

The MOSkin I(V) characterisation was performed by applying a bias to the MOSkin gate. The gate was biased over a range of 0 volts to 30 volts and the current induced across the dosimeter was recorded. The epitaxial diode I(V) characterisation was performed by applying bias across the p-n junction of the diode. The diode was biased over a range of 0 volts to 50 volts while the current induced across the diode was recorded. The epitaxial diode C(V) characterisation was performed using a capacitance bridge. The diodes were biased over a voltage range of 0 volts to 50 volts.

Characterisation was performed both in the absence of the magnetic field and in the presence of a magnetic field. Magnetic field characterisation was performed using the rotational jig, as shown in figure.6. The jig was positioned in two different orientations; parallel to the magnetic field and perpendicular to the magnetic field. The parallel orientation was defined as the angle where the dosimeters' surface was facing the magnetic cones.
Irradiation of the dosimeters was performed using an iodine-125 seed. The seed was fixed to the surface of the dosimeter and the dosimeter was positioned using the rotational jig. Measurements with the epitaxial diode were performed at the parallel and perpendicular to the magnetic field orientations. Epitaxial diode irradiation was also performed in the absence of the magnetic field. Measurements with the MOSkin dosimeter in the magnetic field were performed over an angular range of 0 degrees to 360 degrees with measurements being performed at 45 degree increments.

The epitaxial diode was also exposed to a 660µm laser light. The laser light was mounted 50cm from the epitaxial diode and the light was focused upon the surface of the dosimeter. Ambient light was minimised to reduce the background counts experienced by the epitaxial diodes. Acquisition was performed using the TERA system over 30 second intervals. Measurements were performed in 45 degree increments across an angular range of 0 to 180 degrees. For each orientation, measurements were performed in the presence of the magnetic field and in the absence of the magnetic field. This was achieved by mounting the magnet upon rails and manually sliding the magnet away from the dosimeter.
Fig. 1: Illustration of the Australian MRI Linear Accelerator with visualisation of the effect MRGT could have on treatment volumes

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Fig. 2: Illustration of epitaxial diode mounted to pigtail and technical schematic of diode structure

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Fig. 3: Illustration of MOSkin mounted to pigtail and technical schematic of MOSkin structure

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Fig. 4: Center of Medical Radiation Physics Permanent Magnet Device

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Fig. 5: Rotational Dosimeter Jig Apparatus

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Fig. 6: Illustration of dosimeter orientation with respect to the magnetic field

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Results

The MOSkin I(V) characteristics are shown in figure .7. There was no significant change in the I(V) characteristics between the different magnet setups and orientations. As there was no change to the I(V) characteristics, the MOSkin threshold voltage dose response should not be affected by the introduction of a magnetic field.

The epitaxial diode I(V) characteristics are shown in figure.8. Introduction of the magnetic field caused mild divergence of the epitaxial I(V) characteristics. This effect was observed to be greatest in the perpendicular orientation. Exposure to the magnetic field also appears to have caused a higher susceptibility to noise in the epitaxial diode. As the I(V) characteristics maintained a consistent trend, the dose response of the dosimeter should not be affected significantly by the introduction of the magnetic field.

The epitaxial diode C(V) characteristics, as shown in figure.9, The epitaxial diodes' C(V) characteristics were observed to be unaffected by the introduction of the magnetic field when oriented perpendicular to the magnetic field. When oriented parallel to the magnetic field, the epitaxial diode C(V) characteristics experienced an offset in capacitance. This offset was observed to reach a maximum value of 2 picoFarads. This offset is insufficient to affect the epitaxial diodes' sensitive volume and as such, the epitaxial diodes' sensitivity to radiation should not be affected by the introduction of the magnetic field.

The MOSkin dose response when exposed to the brachytherapy seed while in a magnetic field is shown in figure 10. During irradiation, the MOSkin response varied with respect to the orientation of the dosimeter in the magnetic field. The MOSkin dose response variations were within 15% of the average dose response for all orientations. The variation in dose response was observed to be sinusoidal and as such is clearly an effect clearly caused by orientation to the magnetic field. MOSkin measurements were performed over long intervals in order to provide good statistics. Because of this, the MOSkin results were scaled to correct for any loss of activity that the seeds may have experienced during measurement.

The epitaxial diode response to the brachytherapy seed is shown in figure 11. When comparing the epitaxial diode response with no magnetic field, the dosimeter appears to have underestimated dose delivery in the parallel orientation while over estimating dose delivery in the perpendicular orientation.

The epitaxial diode relative response to the laser, as shown in figure.12, presented a consistent response for all measured angles. The average ratio of response was
observed as 1.04 and results varied at maximum by 3% from parity. The magnetic field
did not significantly affect the photon collection process of the epitaxial diode.

Dose response to the brachytherapy seeds was affected by the orientation of the
dosimeter with respect to the magnetic field for both dosimeters. The dosimeters dose
response was affected similarly with the dosimeters both under responding at 0 degrees
and over responding at the 90 degree angle. Despite this common effect, the dose
response of the epitaxial diode with the laser was consistent for all orientations. The
lack of effect induced by the magnetic field in the characteristic tests and the epitaxial
diode laser test suggest that charge collection within the dosimeter is unaffected by the
magnetic field. This indicates that there is potentially an effect on the dose delivered to
the dosimeters in the brachytherapy seed tests. It is possible that there is some electron
contribution from the brachytherapy seeds which is affected by the magnetic field. It is
also possible that the magnetic field may affect the brachytherapy seeds' position. If
this were the case, the brachytherapy seeds would produce a higher response in the
dosimeters when the seed is closer to the surface of the dosimeter and it would explain
the geometric pattern in dose response.
Fig. 7: MOSkin I(V) characteristics in the presence and absence of a 1 tesla magnetic field

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Fig. 8: Epitaxial diode I(V) characteristics in the presence and absence of a 1 tesla magnetic field

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Fig. 9: Epitaxial diode C(V) characteristics in the presence and absence of a 1 tesla magnetic field

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**Fig. 10:** MOSkin dose response with angulation to a 1 tesla magnetic field (average presented in red)

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Fig. 11: Epitaxial diode dose response to iodine-125 source at different orientations to the magnetic field

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Fig. 12: Epitaxial diode response to 660µm laser light at different orientations to the magnetic field (average presented in red)

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Conclusion

• The results suggest that silicon semiconductors placed within a 1 tesla magnetic field are a promising option for use as dosimeters in MRI guided radiotherapy procedures.
• The characterisation results suggest that the readout process of the dosimeters should not be significantly affected by the magnetic field and the epitaxial diodes' sensitivity should not be significantly affected by the magnetic field.
• The laser test results suggest that the magnetic field does not affect photon collection within the epitaxial diode dosimeter regardless of dosimeter orientation
• The dose response from the brachytherapy seeds was observed to vary with orientation to the magnetic field for both dosimeters
• When considered with the laser test results, the brachytherapy seed results suggest that care should be taken when introducing a source within a magnetic field.
Personal information

Nathan Thorpe is a post graduate student studying for a PhD in Medical Physics at the University of Wollongong. His studies focus on skin dosimetry and the applications of semiconductor dosimeters developed at the University of Wollongong by the Center of Medical Radiation Physics.
References


