

New silicon microdosimetry probes for RBE and biological dose studies using stationary and movable targets in ^{12}C ion therapy

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Abstract. Due to the high LET and dense ionisation tracks associated with ions, microdosimetric approaches have been used in carbon ion therapy to assess field quality and calculate radiobiological quantities for a variety of cell lines. There is however a lack of instrumentation for simple and routine use in a clinical environment, important for determination of RBE which provides accurate treatment planning and delivery in hadron therapy. In this study, a 10 μm thick silicon microdosimeter with 3D sensitive volumes has been used to investigate the effect of motion on the RBE and field quality of a typical ^{12}C ion therapy beam. For a passively scattered 290 MeV/u ^{12}C beam with 6 cm spread-out Bragg peak (SOBP), variations in biological dose along the SOBP were observed, as well as a significant changes to particle LET when incident on a moving target.

1. Introduction

In heavy ion therapy it is of paramount importance to ensure that the biological dose calculated in the treatment plan is identical to that given to the patient. There is however a lack of instrumentation for simple and routine use in a clinical environment, important for determination of RBE which provides accurate treatment planning and delivery in hadron therapy. Whilst preliminary theoretical calculations and cell studies have been undertaken [1], the effect that patient and organ motion has on these quantities is an issue that needs further investigation, especially with advancing technology such as proton and ^{12}C pencil beam scanning systems. Microdosimetry is a useful technique for RBE determination in unknown and mixed radiation fields typical of hadron therapy, currently implemented in Japan [2, 3]. However, the gold standard microdosimeter, the tissue equivalent proportional counter (TEPC), has a sensitive volume diameter that is larger than the typical motion amplitude, rendering it ineffective at detecting motion and misalignment anomalies. Microdosimeters with high spatial resolution are required to fully understand these effects. In this study, a 10 μm thick silicon microdosimeter with 3D sensitive volumes



has been used to investigate a typical ^{12}C ion therapy beam, as well as the effect of motion on RBE and field quality.

2. Method

The detector used in this study is the Bridge Microdosimeter, designed by the Centre for Medical Radiation Physics (CMRP), University of Wollongong, Australia. The microdosimeter is an n-type silicon-on-insulator (SOI) detector based on an array of $30 \times 30 \mu\text{m}$ sensitive volumes (SVs) with a thickness of just $10 \mu\text{m}$, achieved through the use of masked ion plasma etching. Silicon “bridges” are left unetched to support the aluminium tracks between each SV. The microdosimeter is connected to an in-house designed low noise optimised preamplifier and shaping amplifier, enabling detection of lineal energies as low as $\sim 0.2 \text{ keV}/\mu\text{m}$. The charge collection in this device has been characterised previously using the ion beam induced charge collection technique at ANSTO [4]. A high resolution scanning electron microscope (SEM) image of the Bridge microdosimeter showing the parallelepiped SVs and an image of the “MicroPlus” probe are pictured in figure 1.

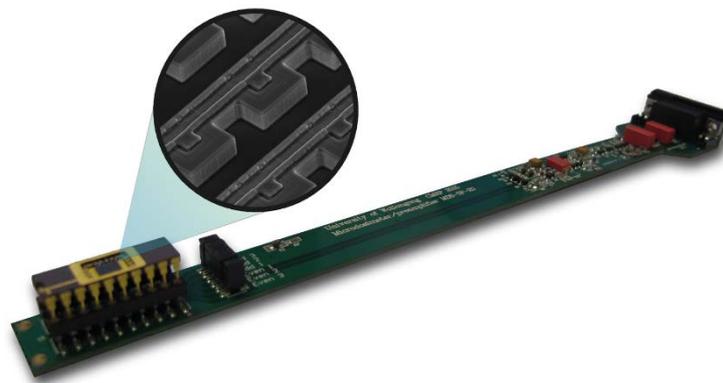


Figure 1. The MicroPlus probe with an inset SEM image of the Bridge Microdosimeter sensitive volumes.

Previous studies with the Bridge microdosimeter have used a modular PMMA phantom to adjust the detector depth [4, 5], however this setup is relatively inflexible due to the set thickness of PMMA slabs. To overcome this limitation, a relatively low-cost XY-stage was built using a MakerBot Replicator 3D-printer and PMMA water tank, controlled remotely using Arduino-driven stepper motors. Not only does such a system allow flexibility in controlling the depth and lateral position of the microdosimeter, it also facilitates custom movements, used in this study to simulate simple linear motion as well as lung motion. This is achieved by moving the depth and lateral position of the detector using predefined profiles, shown in figure 2.

Experiments were performed at the Heavy Ion Medical Accelerator in Chiba (HIMAC), NIRS, Japan, utilising a passively scattered ^{12}C ion beam to irradiate the microdosimeter. Using a ridge filter designed to modulate the beam, multiple pristine Bragg peaks of discrete energies were created with a maximum energy of $290 \text{ MeV}/u$. The resultant field had a 6 cm spread-out Bragg peak (SOBP) with the assumption of constant biological dose along its plateau. The biological dose along the SOBP was calculated using measurements taken with the microdosimeter (RBE_{10} derived from microdosimetric spectra) and a PTW pinpoint ionization chamber (physical dose). The effect of lung motion was also studied close to the end of the SOBP along the beam axis, important for cases when a critical organ may be irradiated by high LET particles.

A spherical polyethylene bolus used in passive beam treatments to produce distal conformity was then placed upstream along the central axis of the beam. The microdosimeter was placed at various off-axis positions in the tank, labelled A and B in figure 3. Microdosimetric spectra were obtained while the

microdosimeter was stationary at each position, in addition to constant motion from 20 mm to 40 mm off-axis, towards the edge of the bolus.

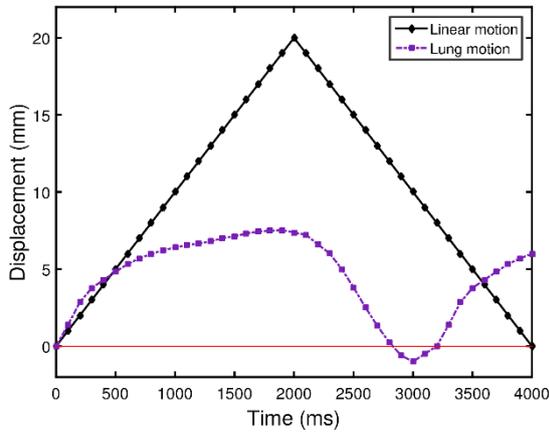


Figure 2. Linear and lung motion profiles

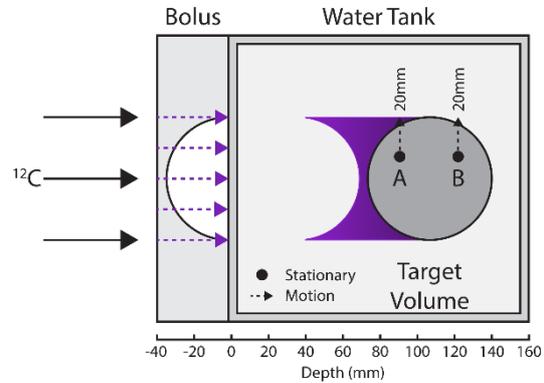


Figure 3. Schematic showing the phantom-bolus setup with acquisition points (A, B), and motion vectors.

3. Results

RBE₁₀ was derived from the microdosimetric spectra and physical dose measurements were carried out with the ionisation chamber over the depth of the phantom, shown in figure 4. These distributions were found to be typical of heavy ion SOBP fields where, in order to produce constant biological dose in the target volume, the physical dose is made to decrease with depth due to increasing RBE₁₀. However, from figure 5, convolving these quantities showed that the biological dose along the SOBP is only relatively constant up until 120 mm, after which it decreases slightly then sharply increases at the distal part of the SOBP. Due to the high spatial resolution of the microdosimeter compared to TEPCs in previous studies [3], a more detailed biological dose distribution was measured.

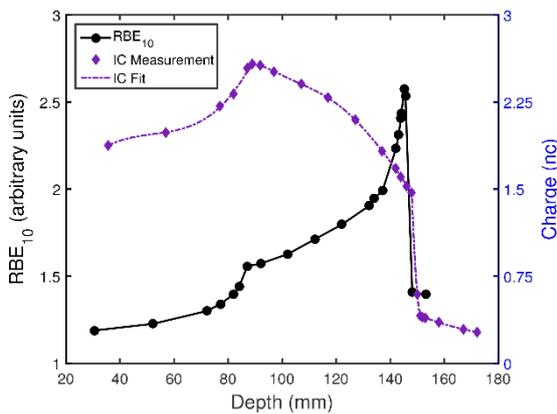


Figure 4. Charge collected from the ionisation chamber and RBE₁₀ derived from microdosimetric spectra as functions of depth in water.

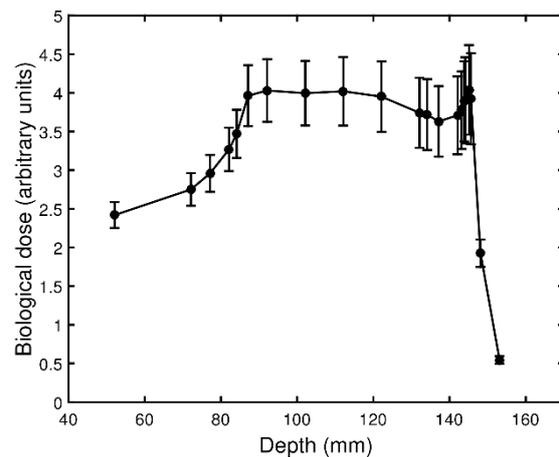


Figure 5. Biological dose distribution along the depth of the water phantom.

A significant difference was observed between the stationary spectra at a depth of 148mm and when undergoing lung motion from 141-149mm, seen in figure 6. When in motion, the microdosimeter enters the highest LET region of the field, resulting in lineal energy events from carbon ions dominating the spectra. In the stationary case, lower lineal energy events from neutron interactions dominate. From

this observable change in field quality, significantly more damage would be delivered to the non-target volume in a clinical scenario, as expected.

When undergoing motion from stationary points A and B (see figure 3), it can be seen from Fig. 7 that the spectra in both cases shifts towards higher lineal energies due to the contribution of high LET carbon ions stopping at the end of their range, towards the edge of the bolus. An increase in low lineal energy events was also observed when in motion from point B due to a higher contribution of fragments and neutrons produced from particle interactions further upstream.

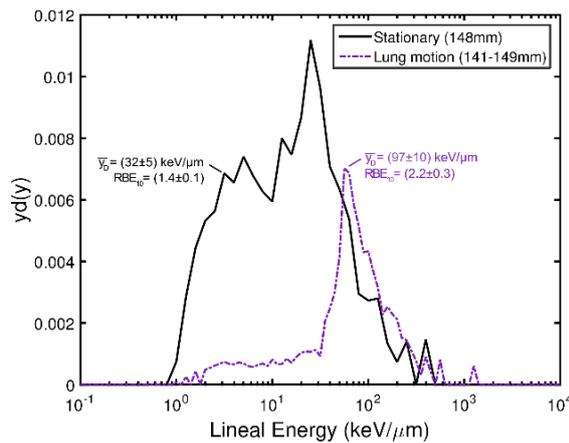


Figure 6. Microdosimetric spectra from stationary and moving acquisitions at points A and B with the bolus.

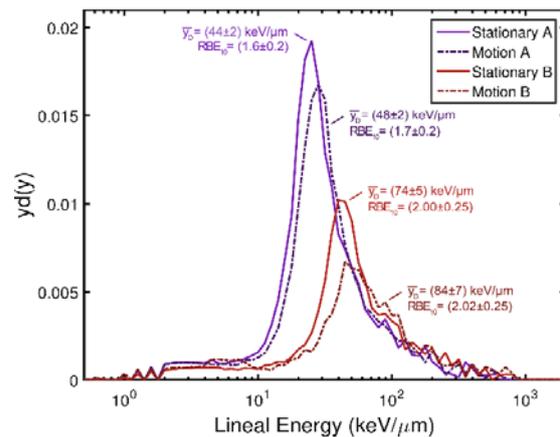


Figure 7. Microdosimetric spectra from stationary and moving acquisitions from depths 148mm, and undergoing lung motion from 141-149mm.

4. Conclusion

The CMRP has developed and implemented a new microdosimeter probe, enabling measurement of microdosimetric spectra with lineal energies as low as ~ 0.2 keV/ μm . We have demonstrated that motion can lead to significant changes in the microdosimetric spectrum, and consequently the RBE, resulting in undesirable treatment outcomes. Due to the high spatial resolution of the microdosimeter compared to gold standard tissue equivalent proportional counters, a more detailed distribution of biological dose and other quantities can be measured, paving the way for routine QA procedures using solid-state microdosimetry.

5. References

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