

8. Application to Fast Neutron Therapy

8.1 Background to Fast Neutron Therapy

Fast neutrons, and high LET particles in general, offer therapeutic advantages in treating locally advanced or "radioresistant" tumors at certain sites. The potential advantage of neutrons rests in the high LET of the secondary particles created by neutron interactions. Densely ionizing protons, alphas and heavy ion recoil products are present that inflict a significant number of DNA double strand breaks. It is known that about 1.5 more double strand breaks (DSB) are observed after neutron irradiation than after photon irradiation of equal dose [272]. This type of radiation induced damage is generally considered lethal and unrepairable. A further advantage, evolving from the higher percentage of unrepairable DNA damage, is a reduced cell death variability across the different phases of the cell cycle. In addition, neutrons benefit from a low oxygen enhancement ratio (OER). Photon radiation causes most of its damage through the generation of free radicals and thus is dependent on the presence of oxygen in the tumor. The OER is about 3 for photons and electrons, meaning a high resistance of hypoxic cells to these low-LET particles, and only about 1.6 for neutrons [273]. Neutrons depend less on oxygen to act as a mediator and have a greater tendency to cause cell death through a direct interaction. Therefore, the hypoxic component of the tumors is spared to a lesser extent by neutron irradiation than by low-LET particle therapy.

In view of the above mentioned mechanisms the relative biological effectiveness (RBE) of neutrons used for therapy is usually in the range of 2 to 5 [111]. Note that neutrons provide no benefit over conventional therapy in terms of an improved depth-dose distribution. The depth-dose distribution for neutrons follows a similar profile to gamma photons from cobalt 60 [155]. Based on radiobiological observations, tumors with large hypoxic areas which reoxygenate slowly and well-differentiated slowly growing tumors are expected to be good candidates for neutron therapy [111].

The first use of neutron radiotherapy was performed by Stone at Berkeley in 1938 [274]. Clinical work intensified in the early 1970s starting with the fast neutron therapy programme at London's Hammersmith Hospital and the subsequent opening of several centers in Europe and the United States. There are now 14 centers in Europe alone and

approximately 15000 patients have been treated worldwide up to 1994 [272]. Unfortunately, after almost thirty years of extensive clinical trials, it appears that only a few cancer localizations benefit from the use of neutrons.

The best results have been obtained for malignant salivary gland tumors. Clinical trials have demonstrated a statistically significant improvement in loco-regional control for the neutron group (56% neutrons versus 17% photons) but with no clear improvement in overall survival [275]. This was explained by the fact that distant metastases accounted for most of the failures in the neutron group. Similar results have been seen for prostate [276] and advanced rectal cancer [277].

Various researchers (e.g. [278]) have suggested that for a meaningful evaluation of the efficacy of neutron therapy, the neutron beam should be comparable to photon beams in terms of penetration, collimation, dose rate, isocentric capabilities etc. The fast neutron therapy facility at Harper Hospital, employed in this study, has been shown to satisfy the requirements of comparability with photon therapy [279]. An additional concern in fast neutron therapy is the dosimetric challenges imposed by the variation in RBE with neutron spectrum variations. Significant variation in beam quality occurs for neutron beams of different energies and different production mechanisms [280, 281]. Fortunately, variations in radiation quality within neutron beams irradiating homogeneous water phantoms is much less pronounced.

The traditional tool for studying the variation in radiation quality of various neutron beams is the proportional gas counter. Many microdosimetric studies have been performed on various neutron therapy beams using proportional counters. Kota [154] provides a good listing of references (e.g. [106-108]). Kota [154] also notes that in several studies [104, 105] RBE values calculated from the saturation corrected dose mean lineal energy y^* are fairly well correlated with RBE data derived from radiobiological data. The definition of y^* was developed in the theory of dual radiation action (TDRA) by Kellerer and Rossi [18] (see section 2.4.1 and 2.4.2) and will be discussed later. The correlation between y^* and RBE depends upon the specific radiobiological endpoint used. Nevertheless, the observed correlation between y^* and RBE has been used to estimate variations in RBE within beams under different irradiation conditions in a water phantom.

In this study, the performance of the silicon microdosimeter exposed to a $d(48.5 \text{ MeV})+Be$ fast neutron beam is compared to results obtained by a proportional counter [154]. Both microdosimetric spectra and parameters such as $\bar{y}_d$ and y^* are compared under similar conditions. The main advantages of using a silicon microdosimeter in fast neutron therapy include ease of use (no gas system), system cost, excellent spatial resolution and the ability to operate at high clinical dose rates.

8.2 Materials and Methods

8.2.1 Description of fast neutron beam at Harper Hospital, Detroit.

The fast neutron facility at the Gershenson Radiation Oncology Center, Harper Hospital Detroit has been treating patients since 1991. Accelerated using a superconducting cyclotron, the beam is produced by the interaction 48.5 MeV deuterons with a beryllium target [279]. The neutron beam, with a maximum energy of 52.5 MeV and a mean energy of approximately 20 MeV, is shaped using a specially developed multi-rod tungsten collimator [282]. The time profile of the beam is pulsed with a pulse width of approximately 2 ms and a repetition rate of 100 Hz. Accompanying the neutron beam is a small gamma ray component originating from neutron activation within the machine and surrounding materials and from the thermal neutron capture reaction with hydrogen in the patient.

8.2.2 Description of probe assembly and phantom

The microdosimeter probe assembly used was the low noise "Probe Assembly #2" fully described previously in section 4.4. Two types of silicon microdosimeters were used in this study with SOI thickness' of 2 and 10 μm . For both devices, the small diode size ($10 \times 10 \mu\text{m}^2$ junction) array was selected since this array has the smallest overlayer and has been used most extensively in other experiments. To correctly resolve the recoil proton component of the lineal energy spectrum a measurement down to around 1-2 keV/ μm is required. The largest thickness of SOI, 10 μm , was selected to provide the highest signal to noise ratio. The smaller SOI thickness was included to gauge the effect of chord length distribution variation and sensitive volume size.

The charge collection characteristics of the devices, at the selected reverse bias voltage of 10 V, were fully described in section 6.2.4.1 and 6.2.4.2. The device bias was set to 10V so that the depletion depth is approximately 3 μm in the 10 μm device. Hence the

10 μm SOI is not fully depleted and charge collection occurs via diffusion as well as drift processes. For the 10 μm device, the charge collection efficiency was found to vary from about 0.79 in regions most distant from a diode junction to 0.86 in the center of a junction where drift collection is strongest. This relatively small variation is a result of the large minority carrier diffusion length (61 μm) in comparison to the cell dimensions (30 $\times$ 30 $\times$ 10 μm). Therefore, the collection efficiency for the 10 μm SOI device may be reasonably approximated by a constant value of 0.83. For the 2 μm SOI device, the collection efficiency is also approximately constant at 0.94. Both devices have an effective thickness that is reduced not only by the collection efficiency but also due to LOCOS silicon consumption in some regions of the device. The later effect is proportionally more influential for the 2 μm SOI device.

In summary, the diode array sensitive volume may be approximated by an infinite slab with an effective charge collection thickness (averaged over the device area) of ~ 8.2 μm for the 10 μm SOI device and ~ 1.8 μm for the 2 μm SOI device. An infinite slab geometry is a reasonable approximation since the thickness of the devices is 2-3 orders of magnitude less than the width (1.2 mm) and length (3.6 mm) of the total array. Converting to tissue equivalent geometry using a scaling factor of 1/0.63 (as described in section 5.4), we obtain TE thickness' (h) of 12.9 μm and 2.8 μm , respectively for the 10 μm and 2 μm SOI devices. The diameter of the spherical proportional counter used in this work is 2 μm . The chord length distribution assuming μ -randomness conditions (i.e. infinite range tracks and uniform isotropic particle emission) for the infinite slabs and sphere are compared in Figure 8.1. As discussed in detail in chapter 3, the sphere is favored for its minimum CLD relative variance and isotropic response.

Microdosimetric spectra require an estimate of the detectors mean chord length (MCL or $\bar{l}$). An accurate value of $\bar{l}$ may be obtained via Monte-Carlo simulation methods which transport charged particles through the experimental setup and determine the path length traversed through the device. However, usually in proportional counter microdosimetry $\bar{l}$ is calculated analytically assuming μ -randomness. Reiterating results obtained in chapter 3, for a sphere, $\bar{l} = 2/3 d$ where d is the sphere's diameter and for an infinite slab $\bar{l} = 2h$ where h is the slab thickness. In practice, the secondary particle ranges are not infinite and the radiation may not be isotropic. Therefore, the most

appropriate mean chord length for the infinite slab may lie somewhere between h (normally incident) and $2h$.

Due to uncertainty in selecting an appropriate mean chord length for the infinite slab, two alternative approaches are adopted in this work based on the motivation to compare the silicon microdosimeter to the proportional counter. The first method involves calculating the dose mean lineal energy $y_{d,cutoff}$ for the proportional counter and silicon microdosimeter measurements. The "cutoff" subscript signifies that the calculation is only performed over the lineal energy range measured by the silicon microdosimeter as indicated in the following expression:

$$y_{d,cutoff} = \frac{\int_c^\infty y^2 f(y) dy}{\int_c^\infty y f(y) dy} \quad (8.1)$$

where c is the lower lineal limit of the microdosimeter. The mean chord length for the silicon microdosimeter measurements is then iteratively adjusted to provide the same value of $y_{d,cutoff}$ as the proportional counter. The second method for estimating $\bar{l}$ simply involves adjusting $\bar{l}$ to provide the best alpha and proton peak fit between the proportional counter and silicon microdosimeter $y d(y)$ spectra. The relative merits of both methods and a comparison with the expected $\bar{l}$ range (h to $2h$) will be discussed in the results section.

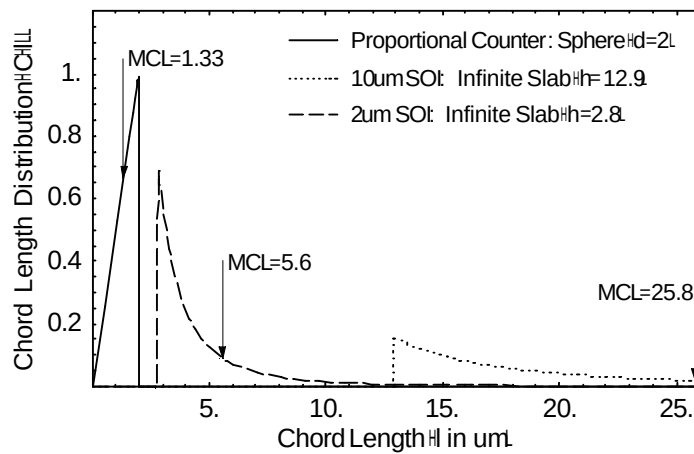


Figure 8.1. Chord length distribution for proportional counter, 10 μm SOI silicon microdosimeter and 2 μm SOI silicon microdosimeter. SOI devices are approximated by an infinite slab geometry.

8.2.3 Microdosimetric measurements

The microdosimeter probe was placed in a $30 \times 30 \times 30$ cm water phantom constructed using 8.5 mm thick Lucite walls as shown in Figure 8.2. A specially designed Lucite holder fixed the probe assembly to the phantom walls. The water phantom was placed at a source-to-surface (SSD) distance of 183 cm. Single event spectra were recorded at a field size of 10×10 cm defined at the SSD. Using the $10 \mu\text{m}$ SOI device, measurements were performed along the beam central axis at a depth in the water phantom of 2.5 cm and 10 cm. In addition, a lateral measurement was performed at a depth of 10 cm and at a position 7 cm away from the central axis. For brevity, this position will be referred to as being 7 cm off-axis in the rest of the paper. Only, a single measurement, along the central axis at 10 cm, was performed using $2 \mu\text{m}$ SOI device.

The primary objective of these measurement conditions was to facilitate comparison with previous proportional counter measurements. These measurements, performed under identical experimental and beam conditions, are described in detail by Kota [154]. The proportional counter was a commercial 1/2" spherical LET counter (Far West Technology Inc., Goleta, CA) with an internal diameter of 12.7 mm and a 2.54 mm thick A-150 tissue equivalent plastic wall. The counter was filled with a propane based TE gas (CO_2 - 40.0%, N_2 - 5.0%, C_3H_8 - 55.0%) at a pressure of 8.8 kPa to simulate a unit density tissue volume of $2 \mu\text{m}$ diameter (d). Therefore, the mean chord length for the proportional counter was $\bar{l} = 2/3d = 1.33 \mu\text{m}$

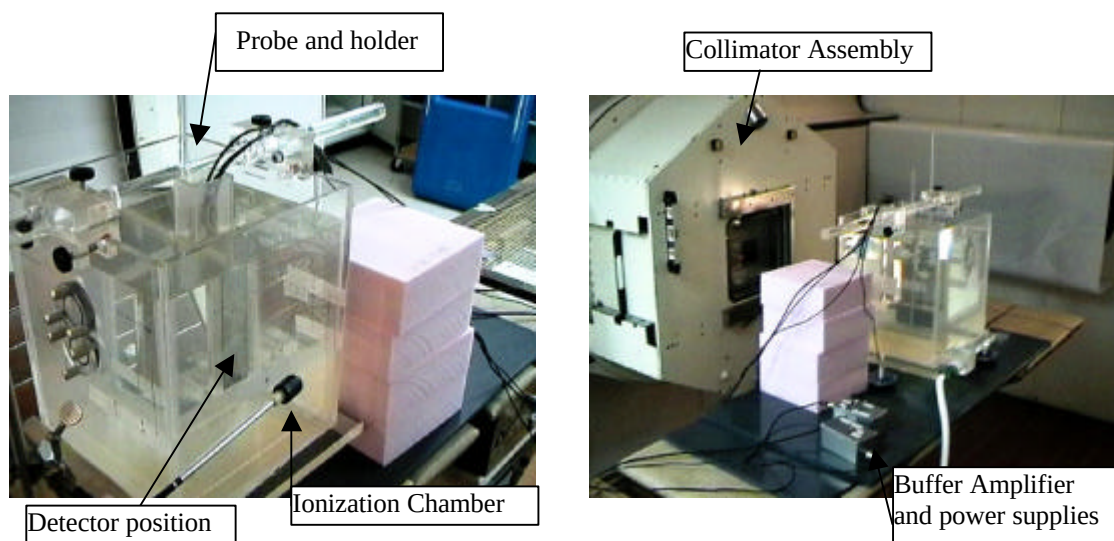


Figure 8.2. Microdosimeter probe, water phantom and collimator beam port used at Harper Hospital. The ionization chamber (Farwest Technology, 8150 TE plastic 1 cm^3) as indicated was used to monitor the total dose. Although not used in this study, the integrated charge data was collected for possible future analysis of microdosimetric spectra in terms of absolute dose.

8.3 Experimental Results and Discussion

8.3.1 Comparison of 2 μm and 10 μm SOI devices with the proportional gas counter.

The microdosimetric spectrum for the 2 μm and 10 μm SOI devices were compared with the proportional gas counter as shown in Figure 8.3. All measurements were performed at 10 cm depth on the central axis. Two presentations of the data are shown corresponding to different values of $\bar{l}$. The left side (Figure 8.3 (a)) shows the SOI diode array spectra with $\bar{l}$ set to give the same dose mean lineal energy as the proportional counter. The calculation of $\bar{y}_d$ favorably weights the data at high lineal energies, as seen by inspection of equation (8.1), resulting in the three spectra overlapping each other closely for lineal energies greater than 300 keV/ μm . The right side (Figure 8.3 (b)) has $\bar{l}$ for the SOI diode array set to provide the best peak fit to the proportional counter spectrum ($\bar{l} \sim 0.75$ times the left side values). The 2 μm SOI device is a remarkably close fit to the proportional counter despite its significantly different chord length distribution shown in Figure 8.1.

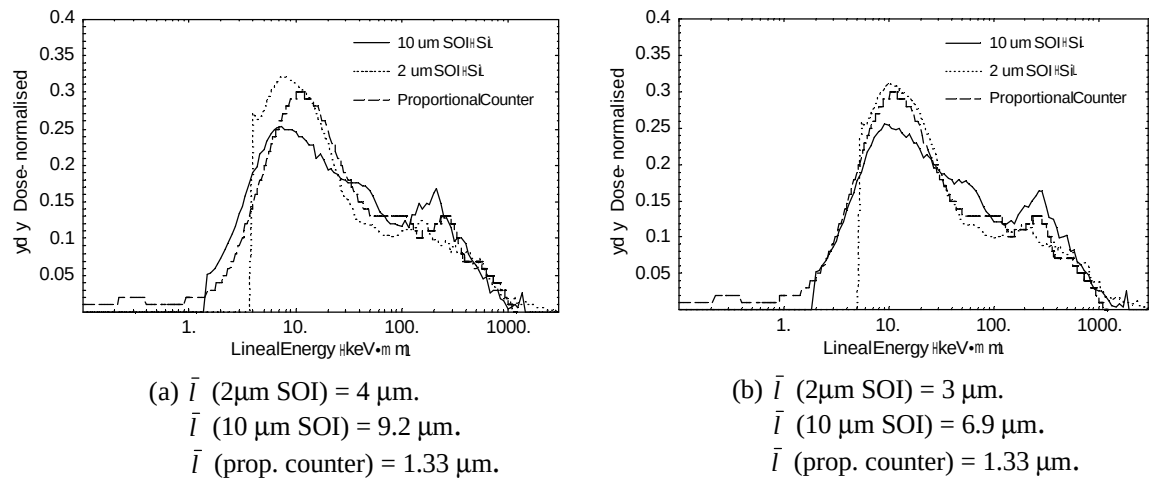


Figure 8.3. Comparison of microdosimetric spectra for 2 μm and 10 μm SOI devices with the proportional gas counter. Measurements were performed at 10 cm depth on the central axis. The left side (a) shows the SOI diode array spectra with a MCL set to give the same dose mean lineal energy as the proportional counter. The right side (b) has the MCL for the SOI diode array set to provide the best peak fit to the proportional counter spectrum ($\bar{l} \sim 0.75$ times the left side values)

Before further discussion of the spectral features, it will prove useful to review the detailed analysis of the proportional counter spectrum provided by Kota [154]. The neutron beam has a maximum energy of 52.5 MeV, resulting in a maximum recoil proton energy of 52.5 MeV. The lineal energy corresponding to such energetic protons in the T.E. gas is ~ 2 keV/ μm . Events with lineal energies lower than 2 keV/ μm are due

to secondary electrons mostly arising from the gamma rays accompanying the neutron beam. The secondary electron contribution may extend as high as 15 keV/ μm but the relative contribution above 2 keV/ μm is small in comparison to the proton component.

The prominent proton component is marked by a peak at around 10-15 keV/ μm and a proton edge at ~ 130 keV/ μm . The position of the proton peak is dependent on the mean neutron energy [283], with the peak shifting to higher lineal energies with decreasing mean neutron energy. The proton edge represents the maximum lineal energy that protons can have in a 2 μm diameter volume. This occurs at the end of the proton range in the Bragg peak. The energy of such protons with a range of ~ 2 μm in the propane based TE gas was estimated by Kota [154] from the stopping power tables in ICRU Report No. 49 [284] to be 173 keV, corresponding to a lineal energy of 130 keV/ μm . For sensitive volumes that have a well defined maximum chord length, the proton edge provides an excellent and convenient calibration technique that is independent of the mean neutron energy. Above a lineal energy of 130 keV, the proportional counter spectrum is composed of contributions from alpha particles and heavy ion recoils. In particular, the spectra displays an alpha peak at ~ 250 keV/ μm and an edge at 350 keV/ μm .

In comparing the 2 μm proportional counter and the 2 and 10 μm SOI devices, five main effects contribute to differences in the observed spectrum:

1. *Noise limitation* of SOI microdosimeter.
2. Undefined upper limit to SOI microdosimeter CLD and differing CLD => Poorly defined *proton edge*.
3. Increased *relative variance of SOI microdosimeter CLD* => Spread in spectrum and possibility of very high lineal energy events.
4. Increased *gamma contribution* due to larger sensitive volume of SOI microdosimeter => Shift in the proton peak to lower lineal energy.
5. Increased *proportion of non-crossers* due to larger sensitive volume of SOI microdosimeter => (a) Shift in heavy ion recoil contribution to lower lineal energies and (b) greater influence of nuclear reactions in silicon.

The second and third effects arise from chord length distribution differences and the last two originate from sensitive volume size differences that shift the spectrum downwards. This is compensated for by the small mean chord length used in Figure 8.3(b). Effect (3) is manifest by the increased width of the proton peak and the observed events with lineal energy >1000 keV/ μm . These influences will now be discussed in more detail:

1. *Noise Limitation:* The current noise limit of the silicon microdosimeter does not permit measurements below the lineal energies of $c \sim 1.2$ keV/ μm for the 10 μm SOI device and $c \sim 4$ keV/ μm for the 2 μm SOI device. Since the silicon microdosimeter does not measure data at the low lineal energies provided by the proportional counter, the normalization of the dose distribution spectrum $d(y)$ must be modified for a correct comparison. Normally, the dose distribution $d(y)$ is normalized to unity since by definition:

$$\int_0^{\infty} d(y) dy = 1 \quad (8.2)$$

For the silicon microdosimeter, we normalize to the proportional counter measurements as follows:

$$\begin{aligned} \int_c^{\infty} d_{si}(y) dy &= \int_c^{\infty} d_{gas}(y) dy \\ &= \begin{matrix} 0.96 & c = 1.2 \text{ keV} / \mu\text{m} \text{ (10 } \mu\text{m SOI)} \\ 0.89 & c = 4 \text{ keV} / \mu\text{m} \text{ (2 } \mu\text{m SOI)} \end{matrix} \end{aligned} \quad (8.3)$$

2. *Proton Edge:* The proton edge technique may not simply be used for calibrating the SOI microdosimeter spectra since the maximum chord length is not well defined as discussed in section 8.2.2. The maximum chord length for the diode array with side lengths of $\sim 1.2 \times 3.6 \text{ mm}$ is approximately given by the diagonal equal to 3.8 mm. In practice, this chord length will almost never be traversed. (Hence the reasonable approximation to an infinite slab) The silicon microdosimeter, with its current sensitive volume, will still display a proton edge although it will not be as sharply defined as for the spherical proportional counter due to the long upper tail of the chord length distribution. Furthermore, as the sensitive volume increases in size, the proton edge will gradually move to lower lineal energies since the average LET of the longer range proton drops. The proton edge for the silicon microdosimeters

appears at ~ 80 keV/ μm in Figure 8.3 (b) compared to ~ 130 keV/ μm for the proportional gas counter.

3. *Relative Variance of CLD*: The possibility of large chord lengths relative to the MCL in the silicon devices increases the number of very high lineal energy events (>1000 keV/ μm) for these devices as shown in Figure 8.3 (b). For Figure 8.3 (a), where the spectra have identical y_d , the main spectral features do not coincide as neatly as in Figure 8.3 (b) partly due to the increased number of high lineal energy events that leads to a shift in the silicon spectra to the left in order to satisfy $\bar{y}_d$ equivalence.
4. *Gamma Contribution*: Further distortion of the silicon microdosimetric spectra occurs due to the large sensitive volume enabling a larger gamma contribution to the spectra, particularly for the 10 μm SOI device. The effect of the larger gamma contribution is to shift the proton peak downwards and increase the prominence of the proton edge. The larger gamma contribution is a possible explanation for the relatively low $\bar{l}$ used in the spectra of Figure 8.3, particularly for the 10 μm SOI device. The $\bar{l}$ are summarised in Table 8.1. The $\bar{l}$ of the 10 μm SOI device required to match the proton peak is lower than expected since the proton peak has been shifted to lower energies due to the high gamma component.

Table 8.1. Estimated mean chord lengths for silicon microdosimeter compared with the expected range of values.

Microdosimeter	MCL (Equivalent y_d method, μm)	MCL (Peak fit method, μm)	MCL (Expected Range, h-2h) (μm)
2 μm SOI	4	3	2.8 - 5.6
10 μm SOI	9.2	6.9	12.9 - 25.8

5. *Proportion of non-crossers*: The larger sensitive volume of the silicon detector also distorts the higher lineal energies due to an increased proportion of non-crosser events such as starters, insiders and stoppers. Figure 8.4 reproduced from the work of Caswell and Coyne [285] shows the relative contribution of event types to the microdosimetric spectrum of a 1 and 32 μm spherical volume exposed to 9 MeV neutrons. The proportion of crosser events is maximized by reducing the sensitive volume dimensions relative to the range of secondary recoil products which is set by the mean neutron energy. Thus the proportion of various events in the (9 MeV

neutron, 1 μm diameter) case will be comparable to the $\sim(20\text{ MeV neutron-}2\text{ }\mu\text{m}$ diameter) configuration used in this work. The proportion of non-crosser events in the (9 MeV neutron-32 μm diameter) case will be higher than the $\sim(20\text{ MeV neutron-(}10\text{ }\mu\text{m SOI device))}$ diameter configuration due to the larger sensitive volume. Nevertheless, the general effects of large sensitive volumes on spectral characteristics shown in Figure 8.4 are illustrative.

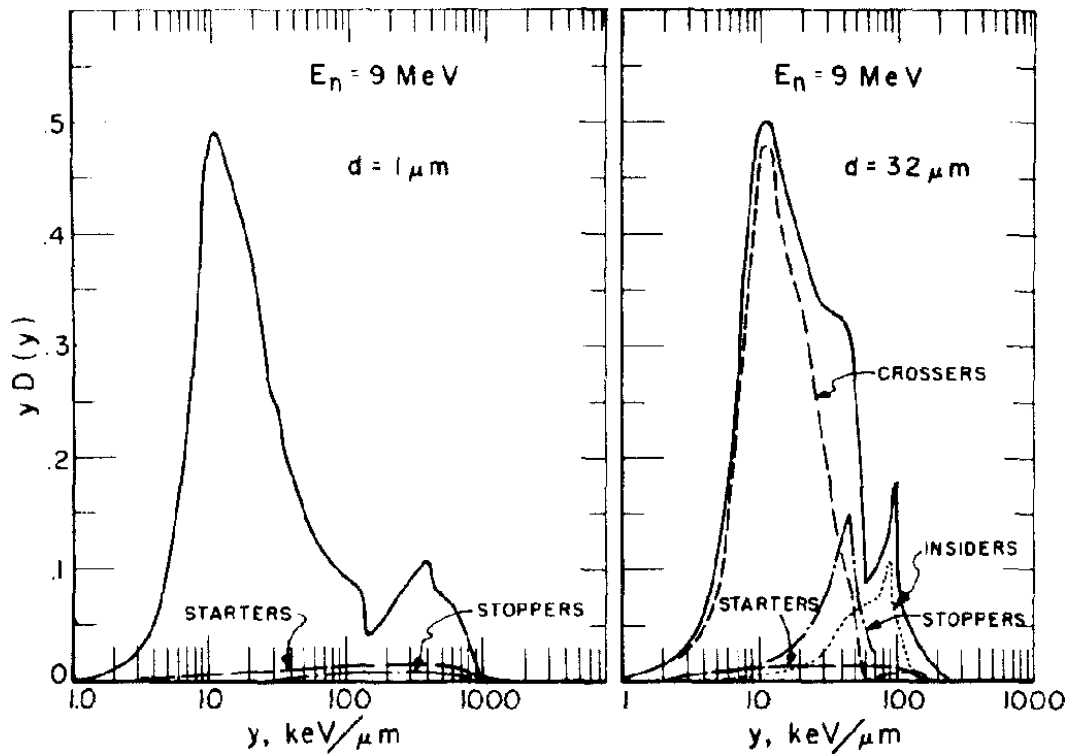


Figure 8.4. Calculated energy deposition distributions for 9 MeV neutrons in ICRU tissue for a 1 μm and a 32 μm spherical cavity, showing the contribution of insiders, starters, stoppers and crossers. For the 1 μm cavity the crossers are so close to the total, that they are not drawn on the graph, while the insiders are negligible. (Reproduced from Caswell and Coyne [285])

The effect of a high proportion of insiders and stoppers is to shift the heavy ion recoil component to lower lineal energies since the non-crosser event energy is divided by an $\bar{l}$ larger than its actual range within the sensitive volume. The 10 μm SOI device is expected to be affected by this type of spectral distortion.

The long range of proton recoils ensures that the proton peak remains at the same lineal energy despite a large variation in site size. This is an important reason for favoring the $\bar{l}$ adjustment method of maintaining a constant proton peak as shown in Figure 8.3 (b).

Another problem associated with a high proportion of non-crossers is the increasing influence of nuclear reactions with the silicon detector which will have a different

secondary recoil product spectrum than a TE material. The issue of TE is further discussed in section 8.3.3.

The difficulty in using a proton edge for calibration and the distortion of $\bar{y}_d$ by spectral changes in the prototype silicon microdosimeter are strong reasons for reducing the sensitive volume elongation and using a cubic shape. Furthermore, the cube has the minimum chord length relative variance for a RPP type volume, thus reducing chord length distribution influences on the final spectrum and providing a more clearly defined $\bar{l}$, as discussed in chapter 3. Minimization of the sensitive volume size is expected to reduce spectral deviations associated with gamma contributions and non-crosser contributions. However, to maintain an adequate signal to noise ratio with a small sensitive volume, low noise design improvements are necessary such as an on-chip pre-amplifier as discussed in section 3.5.6.

Despite the large differences in chord length distributions, the three microdosimeters display remarkably similar spectral features. A comparison of features is best performed by considering Figure 8.3 (b). The spectra have been aligned to the main proton peak. The shape of this peak is very similar for the 2 μm SOI and proportional counter since their mean chord lengths are most similar. All spectra show an alpha/ heavy ion recoil peak in the lineal energy range of 200-300 keV/ μm .

In summary, the 2 μm SOI device provides a dose distribution spectra that is similar to the proportional counter but requires improvements in low noise capability. The 10 μm SOI spectrum manifests many of the key features of the proportional counter spectrum modified somewhat by the previously discussed effects. For comparison of the proportional counter with the SOI microdosimeter, the interpretation is facilitated by selecting a MCL such that the main proton recoil peaks correspond. This presentation, as given in Figure 8.3 (b), will be used for the remainder of this study.

8.3.2 Microdosimetric characterization of neutron beam using silicon microdosimeter

Given that the silicon microdosimeter spectrum reproduces the important features of the proportional gas counter spectrum, one may study the relative spatial variation in microdosimetric qualities of the neutron beam within the water phantom. The microdosimetric dose distribution measured using the 10 μm SOI silicon microdosimeter and proportional gas counter at two depths (2.5 cm and 10cm) along the

central axis of the beam are shown in Figure 8.5. The spectra at different depths are very similar to each other, suggesting that the change in the neutron energy spectrum and RBE along the central axis, if any, is minimal as concluded by Kota [154]. Thus, although the silicon microdosimeter spectrum differs in several ways from the proportional gas counter microdosimetric radiation quality variations may still be characterized.

A similar comparison may be made at 10 cm depth and 7 cm off-axis as shown in Figure 8.6. The spectrum measured off-axis shows a significantly increased gamma fraction, an enhanced proton edge, a slight increase in the lineal energy of the recoil proton peak and a significant decrease in the heavy ion component. These effects are more strongly manifested in the 10 μm SOI device due to the larger sensitive volume invoking an increased sensitivity to gamma contributions. As noted by Kota [154], the spectral changes in the off-axis measurements reflect the decrease in the primary neutron fluence and an increase in the lower-energy scattered neutron fluence in the beam penumbra. Kota [154] also states that the measured proportional counter spectrum is an integral response to a rapidly varying neutron beam in the penumbra region, since the relevant lateral dimension of the LET gas counter is approximately 1.5 cm. In this penumbra region, of rapidly varying spectral characteristics, the silicon microdosimeter offers advantages over the proportional counter due to its smaller size and higher spatial resolution. It is recommended that future comparative studies should be performed to assess the relative spatial resolution capabilities of the microdosimeters in the penumbra region.

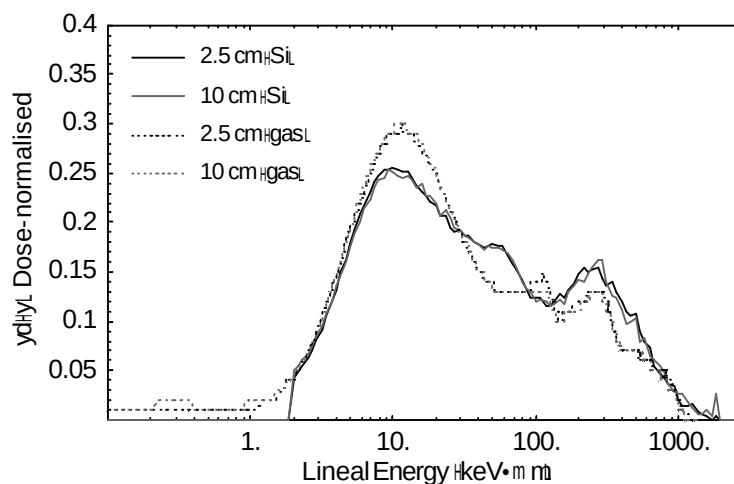


Figure 8.5. Lineal energy dose distribution measured using the 10 μm SOI silicon microdosimeter and proportional gas counter at two depths along the central axis of the beam.

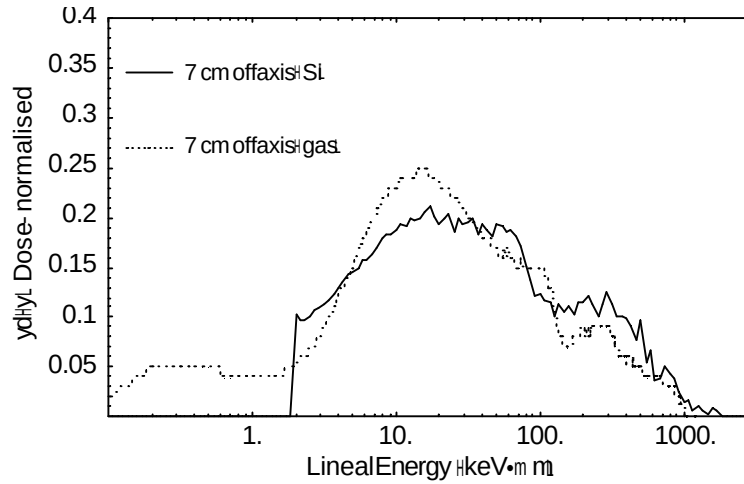


Figure 8.6. Lineal energy dose distribution measured using the 10 μm SOI silicon microdosimeter and proportional gas counter at 7 cm off-axis from the center of the beam and 10 cm depth.

The qualitative arguments presented above, in terms of the shape of the single event spectra, are quantified using $\bar{y}_d$ and y^* . Recall, that the dose mean lineal energy $\bar{y}_d$ is given by

$$\bar{y}_d = \frac{\int_0^\infty y^2 f(y) dy}{\int_0^\infty y f(y) dy} \quad (8.4)$$

In an effort to improve the relationship between $\bar{y}_d$ and observed biological effects, Kellerer and Rossi [18] proposed a saturation correction to account for the excessive ionization density of the high lineal energy particles over and above requirements for cell death. The saturation corrected dose mean lineal energy y^* is given by:

$$y^* = \frac{\int_0^\infty y_{sat} y f(y) dy}{\int_0^\infty y f(y) dy} \quad (8.5)$$

where the saturation correction function y_{sat} is given by:

$$y_{sat} = \frac{y_0^2}{y} (1 - e^{-(y/y_0)^2}) \quad (8.6)$$

with $y_0 = 125 \text{ keV}/\mu\text{m}$.

The weighting function y_{sat} is shown in Figure 8.7. The weighted spectrum $y_{sat} y f(y)$ is also shown indicating the reduced emphasis on the high lineal energy events compared

to the standard spectrum $y^2 f(y) = yd(y)$. Note that the "weighting" function for the standard case is simply y .

The calculated values of $\bar{y}_d$ and y^* for the various detector types and locations in the water phantom are shown in Table 8.2. The proportional counter shows a small (3%) decrease in $\bar{y}_d$ and y^* with depth along the central axis and a more pronounced decrease (5% for y^*) for the 7 cm off-axis measurement. The larger gamma component and decreased heavy ion component in the off-axis account for the decrease in $\bar{y}_d$ and y^* . These trends are not accurately reflected in the 10 μm SOI device calculations for two main reasons. Firstly, the SOI spectrum does not include data for lineal energies below $\sim 1.2 \text{ keV}/\mu\text{m}$. More importantly, the spectrum shape is sufficiently different due to chord length distribution and sensitive volume size differences that a match with the trends of the proportional counter is not possible.

Table 8.2. Calculated values of $\bar{y}_d$ and y^* for proportional counter and 10 μm SOI device at various locations in the water phantom

Microdosimeter	$\bar{y}_d$			y^*		
	2.5 cm central	10 cm central	7 cm off-axis	2.5 cm central	10 cm central	7 cm off-axis
2 μm Proportional Counter	84.9	81.9	64.9	27.6	26.8	25.4
10 μm SOI device ($\bar{l}=9.2 \mu\text{m}$)	81.1	84.2	74.8	29.2	29.1	28.9
10 μm SOI device ($\bar{l}=6.9 \mu\text{m}$)	108.3	112.4	100	31.1	31.0	31.45

Note: The 7 cm off-axis measurement was performed at a depth of 10 cm.

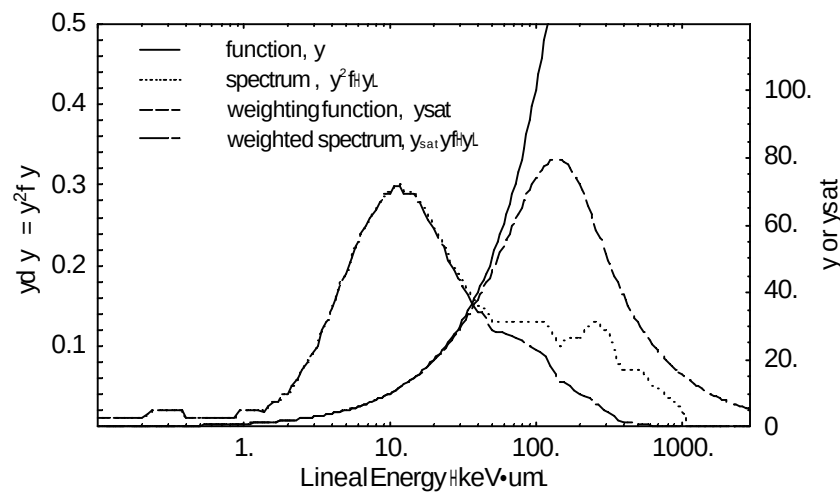


Figure 8.7. The weighting function y_{sat} used to correct the measured single event spectrum for saturation effects at lineal energies greater than 125 $\text{keV}/\mu\text{m}$. The weighted spectrum $y_{sat} y^2 f(y)$ for the 2 μm proportional counter (10 cm central axis) is shown compared to the standard spectrum $y^2 f(y) = yd(y)$. The weighting function for the standard case is simply y .

8.3.3 Tissue equivalence issues using a silicon microdosimeter in fast neutron beams

The tissue equivalence of silicon microdosimeters exposed to neutron beams was discussed in some detail in section 5.5. The main conclusions are reiterated here and applied to the specific neutron beam characteristics of the Harper hospital facility.

Given identical secondary charged particle spectra, a given volume of silicon will have the same microdosimetric energy deposition as a tissue volume of equivalent shape if the dimensions of the silicon are scaled by $1/0.63$. Differences in the spectra observed between the spherical proportional counter and the SOI microdosimeter arise not only from chord length distribution differences, following the above scaling procedure, but also from variations in the secondary charged particle spectra. Differences in secondary charged particle spectra arise from the use of silicon as the detector material compared to TE propane gas and dissimilar materials immediately surrounding the detector. For the SOI device, the materials surrounding the detector include SiO_2 , TiN and Al overlayer structures along with the 20 mm of Lucite in the probe holder. By comparison, the proportional gas counter has a 2.54 mm thick A-150 tissue equivalent plastic wall. These large differences in materials and construction are expected to account for some of the dissimilarity in high lineal energy events seen between the proportional counter and the SOI microdosimeter.

The recoil proton spectrum originating from the Lucite converter and the A-150 TE plastic should be similar. However, the secondary charged particle spectra from nuclear interactions with the detector materials will differ. The relative importance of detector material interactions depends on the proportion of "stoppers" and "crossers" to "starters" and "insiders". For sensitive volumes that are small in comparison with the secondary charged particle range, most events are due to crossers. This is the case for proportional counters with a simulated diameter of 1-2 μm as shown by Fidorra and Booz [106] (for 5.85 MeV in a site size of 1 μm diameter) and Caswell and Coyne [285] (for 9 MeV neutrons in site sizes of 1 μm and 32 μm). The 2 μm SOI device does not appear to be affected by an excessive number of starters and insiders since the spectral shape is in good comparison with the proportional counter. However, the 10 μm SOI device does have a higher heavy ion component indicative of possible nuclear interactions with the silicon.

The mean energy of the neutron beam is about 20 MeV. At this energy, the ratio of silicon to tissue kerma is ~ 0.2 as shown in Figure 5.16 compared to only 0.05 at neutron energies below 5 MeV. The probability of a nuclear interaction for 20 MeV neutrons is almost the same for equal thickness' of tissue and silicon as summarized in Table 5.9 extracted from Figure 5.19. Thus, it is not unreasonable to expect that some proportion of the heavy-ion recoil spectrum is due to silicon interactions particularly for the large volume 10 μm SOI device. The proportion at high lineal energies may be exacerbated by the higher probability for inelastic reactions in the silicon (~ 2.5 times) than tissue. The exact proportion requires more detailed calculations not performed in this work. However, one may conclude that minimizing the silicon volume is an important issue in order to reduce the proportion of silicon interactions and increase the percentage of crossers contributing to the microdosimetric spectrum. The presence of TE material surrounding the detector should also be maximized in future designs.

Table 8.3. Nuclear interaction probabilities for 20 MeV neutrons incident on silicon and muscle.

Material	Nuclear Inelastic Reactions P(interaction in 1 cm)	All Nuclear Interactions P(interaction in 1 cm)
Silicon	0.05	0.09
Muscle	0.02	0.1
Ratio(Si/Muscle)	2.5	0.9

8.4 Summary of FNT Applications

This is the first demonstration of a SOI based microdosimeter in a neutron radiation therapy beam with results sufficiently promising to confirm the feasibility of the device in this application. A detailed comparison with a proportional counter is performed. The SOI device offers several advantages in fast neutron therapy including ease of use (no gas system), system cost, the ability to operate at clinical (high) dose rates and a high spatial resolution. Shortcomings in the current design arise primarily from the large sensitive volume and the chord length distribution of the SOI device along with the need for improved low noise performance.

Despite some deficiencies in the existing design, microdosimetric radiation quality variations may still be characterized qualitatively. General trends in microdosimetric spectra as a function of position within the beam (e.g. small depth dependence, lateral variation) were in good agreement with the proportional counter. However, quantitative

analysis based on calculation of $\bar{y}_d$ and y^* is not recommended with the current design as indicated by a poor correspondence with proportional counter trends.

The study emphasizes the need for minimizing the sensitive volume of the detector to around the 1 μm region and employing a cubic shape with a smaller relative variance, well defined mean chord length and a chord length distribution more nearly approximating a sphere. Such a design will reduce the proportion of silicon interactions and increase the percentage of crossers contributing to the microdosimetric spectrum. The presence of TE material surrounding the detector should also be maximized in future designs and the design should incorporate an on-chip preamplifier to reduce noise. A more detailed analysis of neutron interactions with silicon in various sensitive volume sizes is necessary to ensure the measurement is not influenced significantly by non-TE materials.

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