ANALYSIS OF PROPAGATED EFFECTS IN PROTON DEPTH-DOSE DISTRIBUTION CURVES DUE TO INITIAL BEAM ENERGY SPREAD

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Abstract

Proton therapy treatment planning uses depth-dose distribution curves of single initial beam energies to create Spread spread Out Bragg Peaks (SOBP). These are used to target specific regions in the body. However, the initial energy spread of the beams leads to an uncertainty in beam energy, affecting the dose distribution. In this paper, previous work (M. Aslaninejad et al., 2011: 189–196) on the depth-dose distribution of proton beams using inelastic-collision cross sections of liquid water is extended into use with chromatic beams. The effect of the initial energy spread on depth-dose distribution curves, the distal dose and the SOBP are discussed. Limits on beam energy spread are suggested.

INTRODUCTION

Proton therapy is advantageous over conventional radiation therapy as particles lose most of their energy at a particular location, depending on their initial energy. This effect is usually represented by means of depth-dose distribution curves. These are characterised by the Bragg Peak (BP) where the relative dose reaches a sharp maximum. As the range and shape of the BP depends on initial beam energy, the energy spread of protons within a beam distorts the theoretical BP and potentially compromises the effectiveness of the treatment. In this paper we extend previous work to account for the energy spread within a therapeutic proton beam.

Depth-dose distribution curves are a useful tool indicating which region will be most affected by incoming radiation. In the code developed in [1] depth-dose distribution curves in water are created by modelling proton beams using a combination of semi-empirical models and the Bethe-Bloch theory. At energies below 1 MeV the cross section is defined by a combination of semi-empirical models, such as the model of ionization processes by Rudd et al.. The stopping cross section gives information on the energy transferred per unit length as a function of particle energy. The total stopping cross section is the sum of the stopping cross sections of all interactions contributing to energy. Nuclear processes are disregarded.

The Bethe-Bloch formula is a good approximation for calculating energy lost per distance travelled for fast charged particles (i.e. with energies higher than 1MeV). Equation 1 shows the Bethe-Bloch formula according to Groom and Klein [2]:

$$\frac{1}{\rho}\frac{dE}{dx} = Kz^2\frac{Z}{A}\frac{1}{\beta^2}\left[\frac{1}{2}\ln\frac{2m_ec^2\beta^2\gamma^2T_{max}}{I^2} - \beta^2 - \frac{\delta(\beta\gamma)}{2}\right], \quad (1)$$

where z it the charge of the incident particle, Z and A are the atomic number and the atomic mass of the absorber, respectively. I is the mean excitation energy, $\delta(\beta\gamma)$ is the density effect correction to ionisation energy loss and β and c are the usual relativistic factors. T_{max} is the maximum kinetic energy which can be imparted to a free electron in a single collision.

Other considerations that were taken into account in the code are:

- Straggling model: range travelled by individual protons is governed by a Gaussian distribution.
- Fragmentation: effectively reduced fluence attributed to proton decay.

These lead to the broad-beam depth-dose curve characterised by increased peak width and reduced peak height. Multiple scattering was also considered; this changes the shape of the depth-distribution by changing the ratio of peak to entrance dose.

EXTENSION TO CHROMATIC BEAMS

In the discussion above proton beams of single defined energies are used. However, real beams are characterised by an energy spread. This is due to individual characteristics of the accelerator, beam transport, and collimation system [3]. The width of the initial energy spectrum is expressed as a percentage error in the initial beam energy and is estimated in the order of magnitude of ±1% [4]. In this paper a superposition of Gaussian probability weighted monochromatic beams was used to simulate chromatic depth-dose distribution curves and values of up to 2% sigma have been used for several initial beam energies. This analytical method is a good approximation for the peak itself, however the shape of the tail is affected largely by other factors and may vary further from the model used [3].

The Effect of Energy Spread on the Bragg Peak

The depth dose distributions curves created for single proton Bragg peaks as function of the initial beam energy spread were used to study the effect of the chromatic beam on the treatment. The depth dose distributions of the proton beams were modelled along a 1-D axis being the path of the proton. Effects of 3-D scattering were not included.

Depth-dose distribution curves of varying initial energy spreads were produced for 70, 100, 150, 200 and 250 MeV to cover the entire range of energies used for treatment, with energy spreads of 0.1%, 0.2%, 0.5%, 1% and 2% sigma.

Figure 1 shows the effects of increasing energy spread on the BP for a 200 MeV proton beam. Due to the

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superposition of the BPs of different energy and therefore slightly different range, we can observe that:

- The peak's height decreases,
- The peak's depth decreases and
- The peak's width increases.

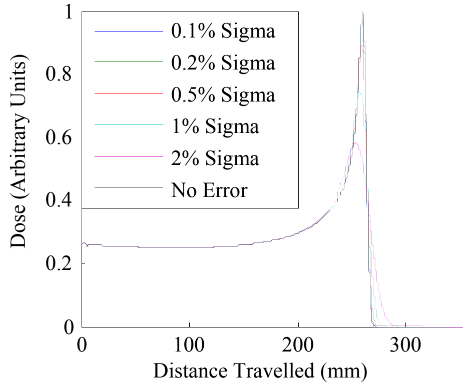

Figure 1: BPs (200 MeV) for different initial energy spread. Each BP has the same dose integral.

As the width of the Bragg Peak is of particular interest for the treatment, it was studied quantitatively. The peak width was defined as the distance from the peak's top to the distal point of a chosen percentage of peak's dose. Distal points of 95%, 50% and 5% of peak dose were used. Figure 2 shows the trend of 95% peak width for increasing energy spreads. As anticipated above, the distributed dose decreases less sharply for beams with a wider energy spread, meaning higher distal dose and more healthy irradiated tissue. While there is less of an effect in using lower energies, higher energy beams have a larger increase in peak width with increasing energy spread.

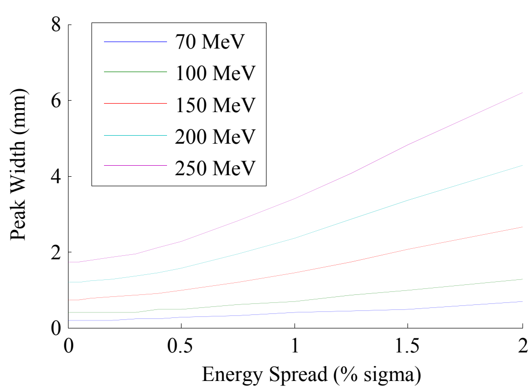

Figure 2: Peak width as distance between peak dose and distal 95%.

Investigations at all distal points found that the peak width is barely affected at energy spreads lower that 0.3% sigma. This is also the threshold point after which the distal dose rises significantly with energy spread. The distal dose encounters a 50% increase around 1% energy spread.

The Effect of Energy Spread on SOBPs

In clinical use, proton beams of initial energy between 70 to 250 MeV are superposed to create a plateau of uniform dose with the required width in order to treat a tumour effectively, depending on its shape, size and location. This is the Spread Out Bragg Peak (SOBP). The code was extended to produce this. As shown in Figure 3, the width of the plateau is called modulation width (from 90% proximal peak to 90% distal peak). The range is here defined as the distance from the entrance into the medium (zero distance travelled) to 90% distal peak.

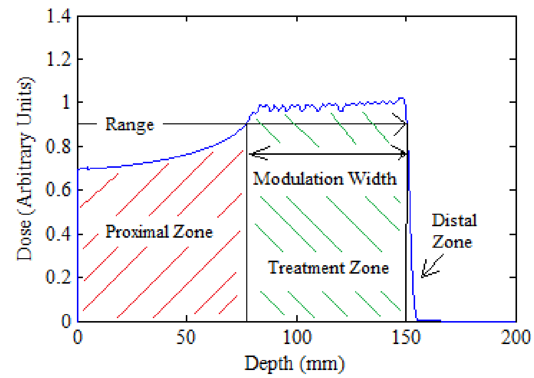

Figure 3: Sketch illustrating the different elements that were used to analyse the SOBP; proximal zone, treatment zone, modulation width, distal fall-off and range.

The shape (and uniformity) of the SOBP depends on the number of single peaks and their intensity. A common method in the literature [2, 4] uses a high intensity BP near the distal peak position and adding lower intensity peaks at regular intervals moving towards the proximal peak position. This creates a plateau characterised by a small peak at distal position and a sharp distal fall. Another method using different peak weighting produces a more uniform plateau but with a less sharp distal fall. The balance between the methods to create a smooth plateau with sharp distal fall is called distal-end optimization. Figure 4 shows an example of how to create a SOBP from its components: the most intense BP involved has most of the effect on the distal end.

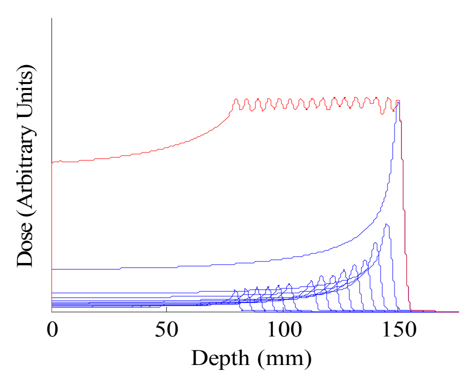

Figure 4: SOBP (80-150mm) using 15 BPs.

The chromatic beams were then used and their effect studied to learn to which extent the energy spread should be narrowed. The effect on the smoothness and uniformity of the peak were also studied.

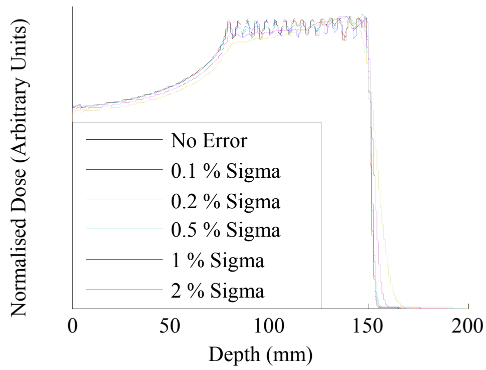

Figure 5: Same SOBP algorithm when using BPs of different initial energy spread (80-150 mm, 15 BPs).

Qualitatively, from investigating Figure 5 and similar SOBPs for different depths and widths, it was found that fewer single energy BPs were needed to create a smooth SOBP plateau when a higher energy spread was applied. Therefore a systematic study on the uniformity of the SOBP as function of the Energy Spread was launched varying the number of peaks for a SOBP 5 cm wide. The results plotted in Figure 6 show that above 0.5% sigma the reduction in the number of peaks needed for a given standard deviation is substantial. The drawback is that the distal falloff is less sharp, producing a higher distal dose.

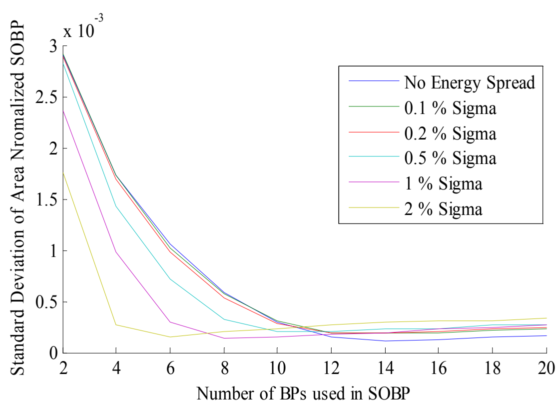

Figure 6: Standard deviation of the treatment zone as a function of BPs being used to create the SOBP. In this instance an SOBP between 10 and 15 cm was used.

Distal dose measurements were made at various modulation widths and depths. Figure 7 represents the results concisely. The distal dose is smaller for shallower and wider SOBPs because:

- For larger depths higher initial energies are needed making the distal BP wider (as shown previously in Figure 2).
- For smaller widths fewer BPs are needed and the contribution to the SOBP of the distal BP is higher, as there are a fewer components of lower energy BPs distal dose.

Below 0.5% sigma the energy spread has little influence (few percent) on the dose evaluated at 5 mm from the distal edge of the SOBP for low energy beams, whereas for higher energies the effect is significant.

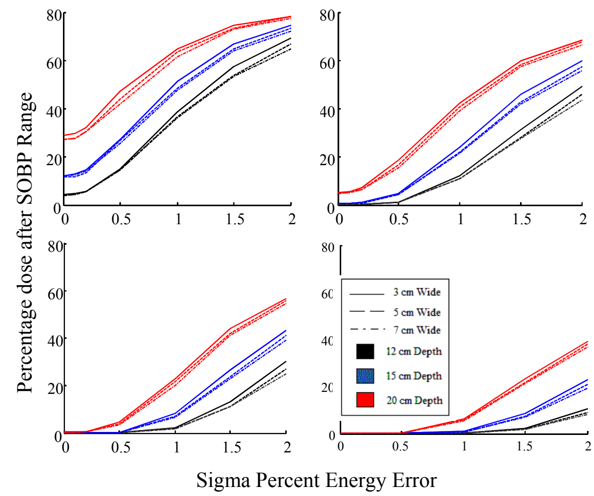

Figure 7: Graph showing the increasing distal dose at 3 mm, 5 mm, 7 mm and 10 mm (left to right, top to bottom) after the SOBP range. Different lines represent varying modulation widths while colours refer to differing ranges.

CONCLUSION

The energy spread of a proton beam causes a significant modification in shape of the Bragg Peak. This needs to be monitored and controlled in order to ensure the SOBP used in oncological treatments is modelled correctly so as to treat tumour efficiently and minimise damage to healthy tissue behind the tumour. Upper and lower limits on the beam energy spread are affected by considerations in the distal dose, the modulation width, the ratio between the zones and the shape of the resulting SOBP.

Taking into account the trade-off between the number of Bragg Peaks needed to ensure a uniform SOBP and the residual distal dose, from this work we can conclude that for beam energies:

- Lower than 100 MeV an energy spread greater than 0.5% sigma can be accepted.
- Greater than 150 MeV an energy spread lower than 0.5% sigma must be employed.

However, these considerations come from an over simplified 1-D geometry, where only water equivalent tissue is present, no interfaces between different tissues are simulated and a single-field treatment is applied. More work is needed to fill the gap between this study and the complex level of present-day treatment, however generalized, at a proton therapy centre.

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