Evaluating analytical ionization quenching correction models for 3D liquid organic scintillator detector

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Abstract. Proton therapy offers dosimetric advantage over conventional photon therapy due to the finite range of the proton beam, which improves dose conformity. However, one of the main challenges of proton beam therapy is verification of the complex treatment plans delivered to a patient. Thus, 3D measurements are needed to verify the complex dose distribution. A 3D organic scintillator detector is capable of such measurements. However, organic scintillators exhibit a non-linear relation to the ionization density called ionization quenching. The ionization quenching phenomenon in organic scintillators must be accounted for to obtain accurate dose measurements. We investigated the energy deposition by secondary electrons (EDSE) model to explain ionization quenching in 3D liquid organic scintillator when exposed to proton beams. The EDSE model was applied to volumetric scintillation measurement of proton pencil beam with energies of 85.6, 100.9, 144.9 and 161.9 MeV. The quenching parameter in EDSE model ρ_q was determined by plotting the total light output vs the initial energy of the ion. The results were compared to the Birks semi-empirical formula of scintillation light emission.

1. Introduction

Proton therapy, in particular spot scanning proton therapy, introduced complex treatment plans with conformal dose distribution. This required 3D detectors that are capable of recording the dose deposition in 3D for quality assurance and dose verification [1]. Volumetric organic scintillators are detectors that convert the dose deposited in the scintillator to light, which is captured using CCD cameras [2-4]. Multiple views of the detector are used to reconstruct the 3D dose distribution [5]. However, organic scintillators exhibit a nonlinear response to the ionization density, called the ionization quenching, when exposed to heavy charged particles [6]. Ionization quenching is problematic in proton beams; where the linear energy transfer (LET) changes as a function of depth and increases rapidly at the Bragg peak region. Therefore, a quenching correction factor is needed to obtain accurate dose distribution. The Birks model is a popular and widely used semi-analytical model that can correct for ionization quenching [6]. Others tried to explain the ionization quenching phenomenon by accounting for the difference in the incident charged particle atomic number and not relying on the average LET values [7, 8]. We investigated the EDSE model by Michaelian and Menchaca-Rocha for use in correcting ionization quenching in 3D liquid organic scintillator detectors [7].

2. Methodology

2.1. EDSE Model

The energy deposition by secondary electrons (EDSE) model relates the ionization quenching to the deposition of energy by the secondary electrons along the track of the ion beam. The realization of the EDSE model is based on the difference in the spectrum of secondary electrons produced by ions of different atomic number. The electron energy density as a function of radial distance is given as [7]:

$$\rho(r) = N\ \frac{e^4}{nm_e}\ \frac{z^{*2}}{V^2}\ \frac{1}{r^2}\ \left[1 - \frac{r}{R_{\max}}\right]^{d+\frac{1}{n}} \tag{1}$$

where N is the number of electrons per unit volume in the medium, m_e and e are the electron mass and charge, n is the exponent for approximating the electron range, z^* and V are the effective ion charge and velocity, R_{max} is maximum range of the secondary electron, and $d=0.045Z_{eff}$, where Z_{eff} is the effective atomic number of the medium. The energy carrier density per unit path length of the ion is then given by [7]:

$$\frac{dN_e}{dx} = K\left[\int_{b_{min}}^{R_{max}} \frac{\rho(r)}{1+\rho(r)/\rho_q}\,dr\right] \tag{2}$$

where K is a constant relating the energy deposited to the number of energy carriers. Later, K is absorbed in C, a constant incorporating the scintillators efficiency. The term b_{min} is the minimum impact parameter of the electron, and ρ_q is the quenching parameter that is specific to the scintillator detector. Finally the luminescence in a given region is given by: $\frac{dS}{dx} = C\frac{dN_e}{dx}$.

The EDSE model parameters ρ_q and C are experimentally determined by plotting the total light output vs the energy of the ion.

2.2. Birks Model

The Birks model assumes that the scintillator light emission due to ionizing radiation is dependent on the stopping power (dE/dx) of the medium. Therefore, the scintillation light is expressed as [6]:

$$\frac{dS}{dx} = \frac{A\frac{dE}{dx}}{\left(1+kB\frac{dE}{dx}\right)} \tag{3}$$

where dS/dx is the luminescence yield per unit length, A is the light production efficiency, and kB is the quenching factor. The term (BdE/dx) is the quantity of damaged molecules and k is the probability that a damaged molecule will capture an exciton. The values A and kB are determined experimentally for the type of the scintillator and ion beam used.

2.3. Experimental data

We used previously published data of a volumetric liquid organic scintillator tank exposed to proton beams [3]. The light scintillation was collected using a CCD camera. The liquid scintillator used was BC-531 (Saint Gobain), which consisted of fluorescing molecules in linear alkyl benzene solvent (density 0.87 g cm^{-3}). We also used the accompanied validated Monte Carlo simulation (MCNPX, version2.7d [9]) of the dose, fluence, and track averaged LET [3].

2.4. Quenching parameter determination

A least square fitting of the EDSE model to the CCD data was used to extract the quenching parameter ρ_q for pristine proton beams with energies of 85.6, 100.9, 144.9 and 161.9 MeV that spans the range of energies used clinically. Pixels along the central axis of the depth dose curve were fitted individually. We used a Monte Carlo tabulated stopping powers of the liquid scintillator to determine the incident ions energy and the energy loss as a function of depth. Then, we plotted the ratio between the calculated

light (S_{EDSE}) to measured light (S_{CCD}). We compared the EDSE model fit to the published results that used the Birks model [3].

3. Results and Discussion

In Figure 1, we show the secondary electron deposited energy density as a function of the radial distance (equation 1) for a single 98.6 MeV proton. Also plotted in figure 1, is the electron deposited energy density for the quenched part of the scintillator (equation 2). The principal assumption in the EDSE model is that the ionization quenching in a scintillator happens at regions very close to the ion's track.
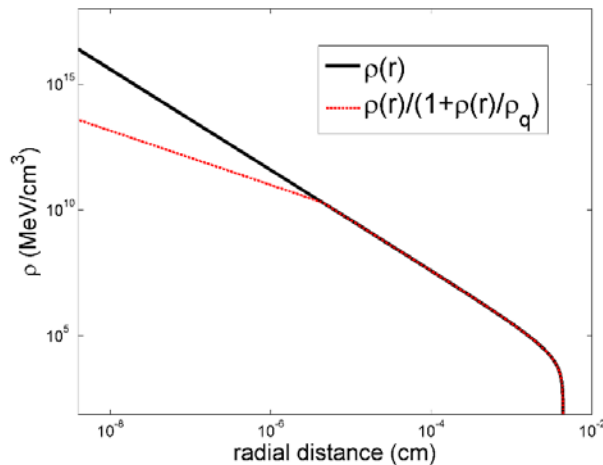

Figure 1. Electron energy deposition density per unit path length of the incident ion beam (proton 98.6 MeV) as a function of the radial distance from the ion's track (solid line). The EDSE model assumes a region close to the ion's track where the scintillator quenches (red dotted line).

We assumed a mono-energetic proton beam to calculate the residual energy of the beam, which caused unrealistic sharp distal edges. Thus, the fit, in particular at the distal edge beyond the Bragg peak, does not match very well. However, the percent difference between calculated and measured light at the Bragg peak was 0.42% as shown in Figure 2. The percent difference between calculated and measured light at the proximal region of the proton beam was within less than ±5%. This is demonstrated in figure 2, which also plots the Monte Carlo depth dose curve relative to the entrance. The EDSE quenching parameter ρ_q was equal to 3.85×10^{13} MeV/cm^3.
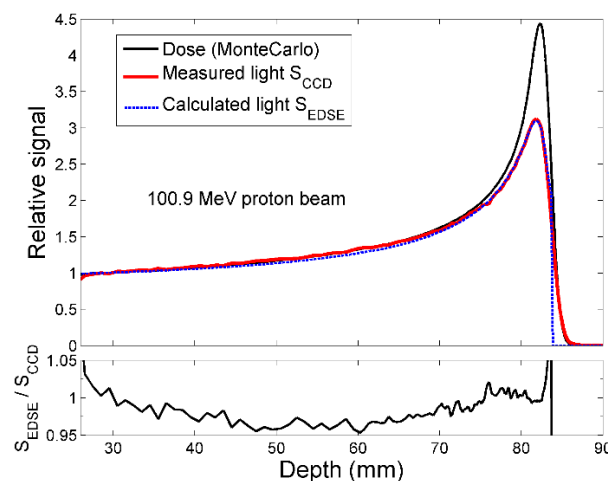

Figure 2. Illustrated is the results for the 100.9 MeV proton pencil beam as an example for one of the 4 energies (Top) Central axis depth-dose profile: Black line is the validated Monte Carlo dose simulation. Red line is the measured light emitted in a liquid organic scintillator by a CCD camera. Blue dashed line is the calculated light by the EDSE model. (Bottom) The ratio between the calculated light and measured light.

The usefulness of the EDSE model over the Birks model for calibrating 3D detectors needs further investigations, which are currently being implemented by including other parameters that account for the energy spectrum and range straggling of the proton beam. Therefore, the EDSE model could be applied to single spot proton beams and passive scatter proton beams. Once these parametrizations are determined, a quenching correction factor can be calculated using the ratio of the deposited energy to the emitted light per voxel. Robertson et al used one energy to determine the quenching factor in Birks model [3]. Then they applied it to the four different beam energies. The corrected light compared to the Monte Carlo dose was within ±3% for all energies except for the lowest energy (±10%) [3]. These results could be due the shape of the beam (sharper Bragg peak curve for low proton beam energies). Accounting for the spectrum of energies per unit path length of the proton beam (i.e. not relying on an average LET value) should result in better fits for both Birks and EDSE quenching models.

4. Conclusion

We have explored the ionization quenching phenomenon in organic scintillators by using semi-analytical models like the Birks and EDSE model to correct for ionization quenching. The EDSE model was formulated to calibrate detectors for energy and particle detection. An advantage of the EDSE model is that it will account for the difference of the ion beam's atomic number. The EDSE model can accurately predict the light emission at the Bragg peak, however further parametrization is needed to account for the energy spectrum and generate better fits for the distal edge region.

5. Acknowledgments

6. References

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