Dose response of EBT2 film modeled as a bimolecular reaction

**Purpose:** Film dosimetry is a useful tool for determining two-dimensional dose distributions in clinical practice and is widely used in X-ray radiotherapy. In proton therapy, film dosimetry shows additional dependence because of changes in the linear energy transfer (LET). The first step in building a model that takes into account the LET effects in films is to accurately predict the dose response. This study proposes a new dose-response model for EBT2 film based on the chemical reactions. Such chemical models were compared against other models proposed in the literature. We also explored the LET dependence of EBT2 films through the model developed here.

**Theory:** As proposed by Candler\(^1\), the film dose response can be described as a chemical reaction where the incident particle will react with some molecules in the film. Such model can be described by the differential equation below,

\[
\frac{dn}{dD} = k(1 - n)^q D^{(p-1)},
\]

where \(n\) is the fraction of activated crystals, \(D\) is the absorbed dose, \(k\) is the reaction constant obtained experimentally, \(q\) and \(p-1\) are known as the individual chemical reaction order.\(^2\) The \(p\) value is obtained by fitting the experimental results and \(q\) is a whole positive number.

The absorbency, \(A\), of a film is usually expressed as optical density (OD), \(OD = \log(A)\). The maximum OD, \(OD_{\text{max}}\), corresponds to the total number of grains in an area of the film. Because the \(OD/OD_{\text{max}}\) is proportional to the fraction of the activated grains in a film, \(n\), the above equation can also be written as a function of \(OD/OD_{\text{max}}\).

It is a fact that to activate a crystal (make it dark); the energy delivered by the incident particle must be transferred to its molecules. Based on such assumption we formulated two hypotheses to explain the film dose response: a) the crystal activation is done by hitting one molecule where this molecule is not required to interact with any other molecule (a unimolecular reaction); b) the crystal activation is done by hitting one molecule which subsequently must interact with another molecule (a bimolecular reaction). If the film dose response is a unimolecular reaction \(q\) must be one, but if the dose response is a bimolecular reaction \(q\) must be two. The solutions for the above differential equation for \(q=1\) and \(q=2\) are shown below, equations 2 and 3.

\[
OD = OD_{\text{max}} \cdot \left(1 - e^{-\left(D/D_0\right)^p}\right), \quad \text{for } q=1 \quad \text{(2)}
\]

\[
\frac{OD}{OD_{\text{max}}-OD} = \left(\frac{D}{D_{1/2}}\right)^p, \quad \text{for } q=2, \quad \text{(3)}
\]

where \(D_0\) and \(D_{1/2}\) replaces all the integration constants and corresponds to 37% and 50% of the \(OD_{\text{max}}\), respectively. For the particular case of \(p=1\) the equation 2 turns out to be the Poisson equation.

Following the studies done by Spielberger et al.\(^3\) the LET dependence can be incorporated to the dose response functions above by adjusting the constants \(D_0\) or \(D_{1/2}\) accordingly.

**Methods:** To test our hypotheses we built a dose response curve using a set of films exposed to pristine proton beams of 161.61 MeV; each film was exposed to various dose values, ranging from 0.93 Gy to 14.82 Gy at the depth of 2 cm in water. The same procedure was followed with one film at a lower energy beam, 85.55 MeV. Each film was placed at the vertical position inside a PTW water phantom of about 50 cm × 50 cm × 50 cm. The gantry was positioned at 5° off of
the film plane in order to avoid artifacts due to protons traveling mainly through the film.

Because the chemical models predict different values for the maximum optical density of the film, we exposed another set of films to a higher dose, about 200 Gy, to determine which chemical model would better predict the film parameters. The fluence-averaged LET curves were computed by calculating the ratio of the simulated dose and the simulated fluence in water. Proton energy spectra were also computed at selected depths for both 85.55 MeV and 161.61 MeV beams. The simulations were done with the MCNPX using our validated gantry specific geometry.

Results: The unimolecular and the bimolecular models were able to accurately fit the experimental data, with both having $R^2 = 0.9996$, figure 1a. The maximum optical density values found were $0.901 \pm 0.050$ by the unimolecular model and $1.276 \pm 0.077$ by the bimolecular model. Exposing another set of EBT2 films to 200 Gy yielded an optical density of $1.360 \pm 0.070$, which indicated larger systematic uncertainties in the unimolecular model compared to the bimolecular model.

The $D_{1/2}$ values found as a function of energy spread is presented in the figure 1b and shows that such parameter depends on the local energy spread. The energy spread is defined as the ratio of the full width at half maximum by the average energy of the local spectrum.

![Figure 1. a) Dose-response curves and experimental data; b) $D_{1/2}$ parameter as a function of energy spread.](image)

Conclusions: Although both the unimolecular and the bimolecular models fit the experimental data with similar accuracy, only the bimolecular model could predict the maximum optical density of the EBT2 film. We also observed that the energy spectra at the measurement depths play a role in the LET response of the EBT2 films when described as a bimolecular reaction.

References: