# The quenching effect in PRESAGE® dosimetry of proton beams: Is an empirical correction feasible?

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**Abstract**. Chemical dosimeters, including PRESAGE® as used in optical CT, exhibit significant quenching effects in response to proton irradiation and this may limit their widespread uptake. This study performs careful measurements of the observed quenching of a recently developed variant of PRESAGE® in a 60 MeV proton beam and uses them to attempt an empirical correction of a simple superposition of two unmodulated beams.

## 1. Introduction

Proton therapy is an advanced radiotherapy technique with the potential for achieving dose distributions superior to those available in x-ray and electron beam therapy. Protons deposit their energy very rapidly at the end of their range in a sharp and well defined region, called the Bragg peak. Furthermore, the range of a proton beam is strongly modulated by the density of the tissue through which it passes. These properties lead to great potential benefits in terms of the conformality of delivered doses to tumours, but make proton therapy an inherently riskier technique, with the possibilities of depositing either significantly too much dose or no dose at all, potentially resulting in either serious damage to healthy tissue or treatment failure and lack of tumour control.

The recommended devices for calibration dosimetry of proton beams are ionisation chambers, but these are not suitable for the high-resolution 3-D mapping needed for whole-system commissioning and the verification of dose plans. A volumetric 3D dosimeter with comparable dose measurement accuracy to that of an ionisation chamber, and dimensions similar to those of the tumour and adjacent organs at risk, is thus highly desirable [1, 2].

But there is a problem: most chemical dosimeters (film, polyacrylamide gels (PAG), Fricke gels, PRESAGE®, alanine, etc.) *under-record dose at depths near the Bragg peak*. This is often known as signal "quenching" [3, 4]. The phenomenon is also referred to as "saturation" and, as we show below, is linked to the high-dose saturation that has long been observed in traditional low-LET measurements, particularly for PAG. Gustavsson *et al* [5] observed quenching effects in polymer gel samples and explained the findings in terms of ion-recombination, whilst Jirasek *et al* [6] interpreted similar observations using the framework of track structure theory [7]. Despite the clear challenge posed by

quenching, previous authors [8] have been optimistic that the difficulties could be overcome by appropriate calibration. The aim of this study, therefore, was to perform careful measurements to measure accurately the extent of the quenching phenomenon and to determine whether an empirical correction can be performed.
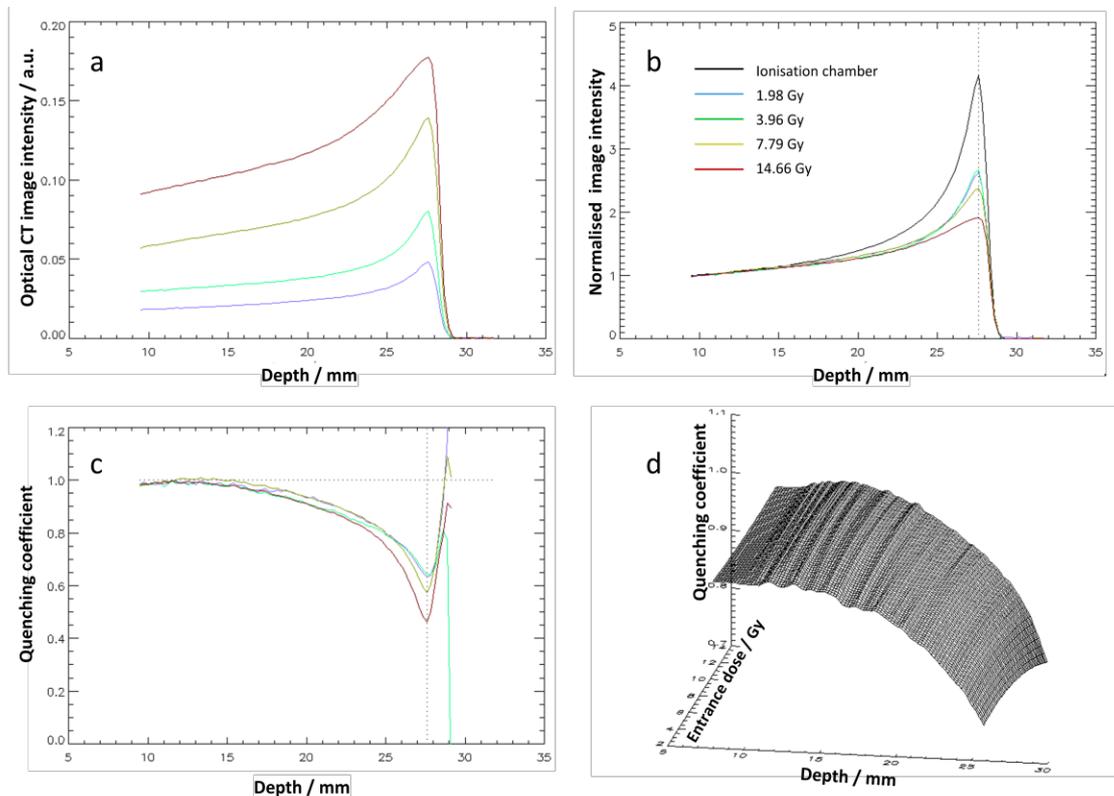


**Figure 1.** Processed data derived from proton irradiations: (a) Aligned, but un-normalised profiles demonstrate the form of the proton depth dose curve and its scaling with entrance dose, but the profile shapes change subtly with increasing dose. (b) Normalising the curves and comparing with the equivalent ionisation chamber readings demonstrates graphically how quenching is a function of dose. (c) Quenching coefficient; (d) The quenching function appears to be smooth and monotonic along both dose and depth directions and can be interpolated, thus allowing us to calculate the profile for arbitrary doses. N.B. All values plotted are measured, not simulated data.

## 2. Methods

### 2.1. Proton irradiations

Five solid cylindrical dosimeters (diameter 61 mm and length 90 mm), made from a PRESAGE® formulation (Heuris Inc, Skillman, NJ) specially designed for use with proton beams [9, 10], were irradiated using an unmodulated 60 MeV proton beam from the Douglas Cyclotron at the Clatterbridge Cancer Centre (CCC), Wirral, UK. The first four samples were each irradiated with a single beam of circular cross-section and with calculated entrance doses of 1.98, 3.96, 7.79 and 14.46 Gy respectively. The fifth sample was irradiated twice in the same place with an unmodulated beam designed to deposit $2 \times 3.97$ Gy at the entrance, but on the second occasion a 1 cm block of solid water was inserted at the proximal end of the sample to displace the position of the Bragg peak.

### 2.2. Optical CT imaging

After irradiation, dosimeters were refrigerated at 5°C for between 2 and 4 days before scanning in a CCD-based optical CT scanner [11]. For optical matching, a composition of 93.4% 2-Ethylhexyl Salicylate (Sigma-Aldrich Co. LLC.), 6.6% 4-methoxycinnamic acid 2-ethylhexyl ester (Sigma-Aldrich Co. LLC.) and a small quantity of green dye showed the most similar optical absorption and

refractive index to PRESAGE®, with a calculated refractive index of 1.505. 400 raw projection images of the dosimeter, each with 256 × 256 pixels, were recorded, and reconstructed to an isotropic spatial resolution of 0.255 mm.
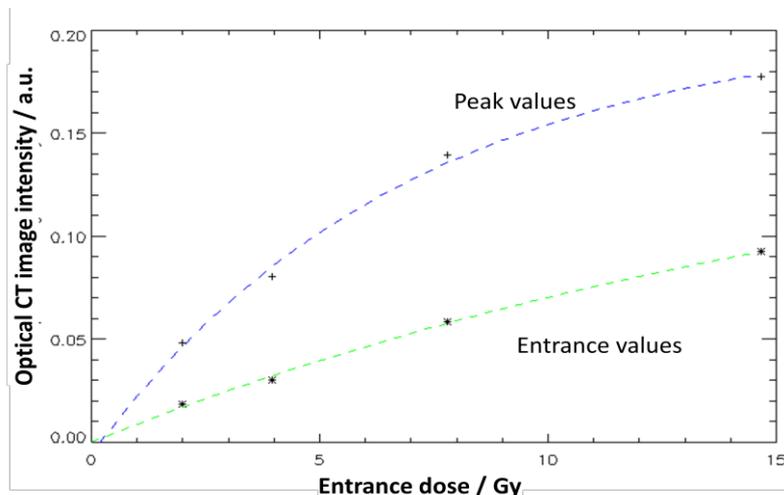


**Figure 2.** Demonstration of a significant saturation effect in peak region and slight effect in the entrance

*2.3. Data processing*

Since the Bragg peak covers only a few mm for 60 MeV protons, significant changes in signal occur over a very small number of voxels. Thus, in order to obtain a reliable estimate of the optical CT quenching effect, significant care was required in processing the data. The individual steps were:

- *Averaging over regions-of-interest*: median intensity from a circular region of radius 3.6 mm (approx. 615 pixels), inscribed within the irradiated region and excluding any penumbra;
- *Subtraction of background* using an ROI from the post-irradiation data on a slice-by-slice basis;
- *Alignment of Bragg peaks* to compensate for any inconsistency in manual positioning;
- *Truncation of entrance data*: quantitative values in the first few mm of the data are strongly affected by image artefacts caused by the interface between PRESAGE® and matching liquid;
- *Conversion of ion chamber data* (independent separate calibration of the proton beam in water supplied by AK) recalculated for the equivalent depth in PRESAGE® (see [9] for discussion);
- *Normalisation*: data were divided by the value at the first point on the truncated profile (9.4 mm depth). This point is discussed further below, but is defensible because the quenching coefficient is expected to vary only weakly with distance and dose near this point (see figure 1c).
- *Calculation of quenching coefficient*: we define the quenching coefficient $Q(d, D)$ as the ratio of the normalised dose for the PRESAGE® measurements at depth $d$ in a sample exposed to an entrance dose of $D$ to the normalized ion chamber measurement made at the same depth.
- *Surface fitting*: the variation of the quench profile is a smooth function and thus we can fit an appropriate surface allowing the estimation of the data at an arbitrary intermediate dose.

**3. Results**

Figure 1a demonstrates the excellent SNR available from the system when an entire ROI is measured. Figures 1b and 1c show the most significant result to come from this study, namely that *signal quenching is a combined function of dose and LET*. Figure 1d is a smooth fitted surface that allows quench profiles to be generated for arbitrary doses.

Figure 2 plots the data from the first point on each profile of figure 1a as a function of dose (lower line) and the Bragg peak (upper line). A significant saturation effect is observed.

Figure 3 shows the results for the sample that was irradiated twice. A clear depiction of the double-Bragg-peak structure is seen in the inset coronal image. The black curve corresponds to the experimental data, whilst the dotted green curve is the same data as in figure 1b. The dotted blue curve represents a first attempt to make an empirical model of the combined irradiation.

## 4. Discussion and conclusions

The very existence of an LET-dependent quenching phenomenon immediately tells us that we have a
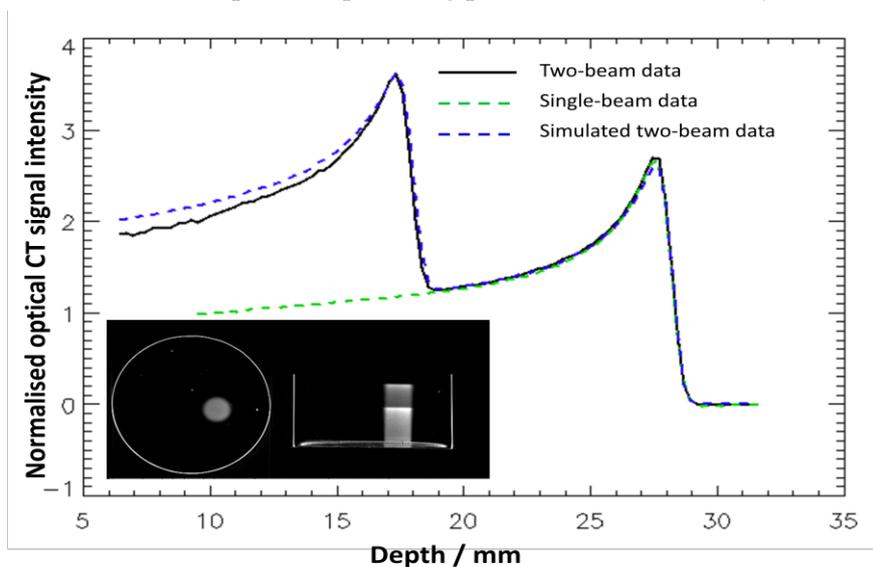


**Figure 3.** Data from a sample irradiated from one end with two proton beams, one of which has been range-modulated by 1 cm of solid water. The excellent superposition of these two curves between the first and second Bragg peaks shows that the quenching effect is reproducible between samples. The blue dotted line is simulated with a forward model using the known physical dose and the quenching factors previously calculated.

problem that is non-invertible. There is no longer a one-to-one mapping between optical attenuation coefficient (or MRI R2-value) and dose, since a given attenuation may be achieved with different total physical doses via contributions from components with different LET values. Prior to this study, however, grounds for optimism existed that, given a quenching coefficient whose functional form depended only on LET, a simple, linear *forward model* would enable optical effect to be predicted for a known dose pattern. If the quenching effect were indeed dose-independent, we would simply be able to correct each of the physical dose contributions to figure 3 by the relevant quench profile and add them together. The fact that there is a discrepancy tells us that such simple empirical corrections are deficient and further work is necessary to understand the quenching phenomenon theoretically.

## 5. Acknowledgments

## 6. References

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