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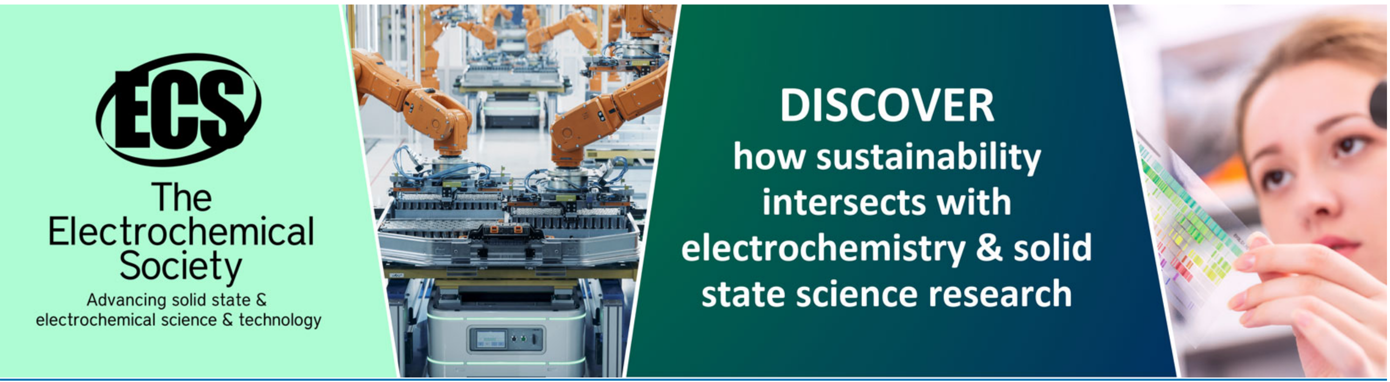

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First 3D measurements of proton beams in a deformable silicone-based dosimeter

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Abstract. 3D dosimetry provides high-resolution dose information of radiation therapy (RT), and is explored to enable and secure high-quality delivery of advanced RT modalities, including proton therapy. We present the first 3D measurements of spot-scanning proton plans in a silicone-based, radiochromic dosimeter with deformation properties. The dose information was read-out by optical CT-scanning. We found that the dosimeter signal was quenched close to the Bragg peak, and that this had a large impact on a measured spread-out Bragg peak. The dose response was linear both in the entrance region and in the Bragg peak, however, the dose response significantly reduced in the Bragg peak. Quenching was attributed to a linear-energy-transfer dependent dose response. Linear energy transfer distributions for each proton treatment plan will provide a means for calibrating the optical measurement to linear energy transfer, as well as dose. This might enable use of the silicone-dosimeter in quality assurance of proton beams.

1. Introduction
Quality assurance for proton therapy (PT) is a current challenge in modern radiotherapy (RT), due to the demanding physical beam properties. A mono-energetic proton depth-dose distribution consists of a Bragg peak; a sharp increase in dose, followed by a steep fall-off, as the protons stop in the irradiated medium. Most new centres employ spot scanning as the irradiation technique. A thin pencil beam of protons is scanned over the target, and by varying the energy, all target depths can be covered with a high dose. In conventional photon-based RT, 3D dosimetry [1, 2] has been used to obtain dose information with sub-millimetre-resolution. This technique would be highly desirable to employ in PT. Many dosimeters have been shown to be sensitive to linear energy transfer (LET), which increases sharply over the proton range [3]. In this study we have for the first time measured 3D proton dose distributions in a deformable silicone dosimeter [4-6], with special attention given to the quenching effects.

2. Material and Methods
Three 3D dosimeters were produced from a single batch, containing, in weight percentages, 5.1 % curing agent (CA) and 93.2 % silicone elastomer from a SYLGARD® 184 kit (Dow Corning) and 0.26 % leuco-malachite green (LMG) dye and 1.5 % chloroform (Sigma-Aldrich). Cone shaped, 11 cm high plastic moulds were used for curing, and could easily be removed after three days storing at room temperature

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in complete darkness. The dosimeters were fixed in the Vista 10 (Modus Medical Devices Inc.) optical-computed-tomography (CT) scanner and immersed in refractive-index-matching liquid. The highest possible number of 2D projections was used (1024). Read-outs were conducted three days prior to irradiation (pre-scan) and three days after irradiation (post-scan).

Table 1. List of 3D dosimeters irradiated with proton plans.

Name	Irradiation plan	# of deliveries	Total maximum dose
A	Single spot	3	35.22 Gy
B	SOBP	2	30.00 Gy
C	SOBP	4	60.45 Gy

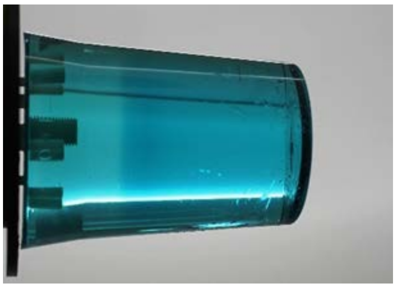

Figure 1. A photograph of a dosimeter, irradiated with an SOBP-field, entering from the right.

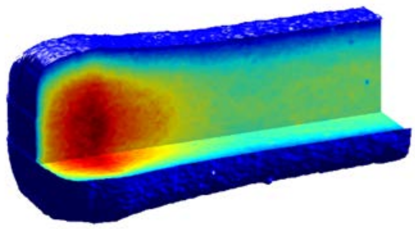

Figure 2. 3D view of the optical measurement of dosimeter C. Protons entered from the right. The optical density is scaled from 0.4 cm-1 (blue) to 0.8 cm-1 (red).

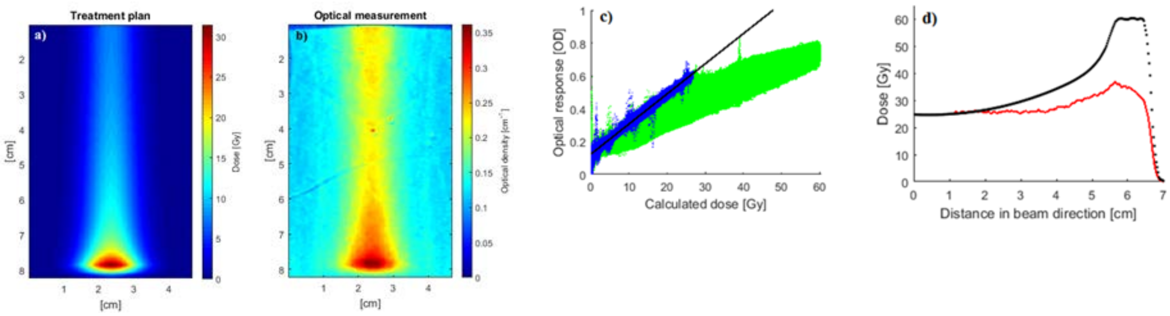

Figure 3. Interpolated planned doses (a) and optical measurement (b) for dosimeter A, irradiated with a single spot, entering from above, and delivering the maximum dose at 7.4 cm is shown. In (c), a correlation plot between individual voxels of the planned dose and the optical response is shown. The blue points correspond to a volume 1.25 cm to 2.2 cm into the entrance region with a planned dose above 1 % of the maximum dose. The black solid line is a linear fit to these points. The green points correspond to the remaining points in the plan. In (d) a projection through the central pixels of the plan (black dotted line) and the optical measurement (red solid line) is shown. The optical measurement was calibrated to the dose response in the plateau.

Dosimeters were irradiated at Institute of Nuclear Physics, Polish Academy of Sciences, six days after production, at a gantry facility with spot scanning (230 MeV cyclotron). Treatment plans were generated in Eclipse™ (Varian Medical Systems, Palo Alto, USA) using a water phantom as target, as CT-scanning was not available. Two plans were made: a single spot with 3 Gy at 2 cm depth and 8 cm range (90 % of distal dose fall-off) and a spread-out Bragg peak (SOBP) shaped field, delivered from one angle, with 15 Gy in the SOBP plateau and 6.56 cm range. Each plan was delivered several times to each dosimeter, with the number of fractions given in table 1. Dosimeters were read out at Aarhus University two days after irradiation, and were placed in a refrigerator for these two days, in order to avoid fading of the signal. The data were reconstructed using the Vista 3-D Reconstruction program (Modus Medical Devices Inc.), with a voxel resolution of 0.25 mm. Following this, an analysis similar to that described in [7] was undertaken. Spatial matching was performed by shifting the overlap between

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measurement and plan in three dimensions, and minimizing the standard deviation. The planned (i.e. calculated) and measured doses were weighted by their maximum values, in order to minimize sensitivity to quenching of the high-dose volume. Furthermore, the optical measurements were adjusted for a water-equivalent thickness of 0.93 g/cm^3 in the direction of beam entry.

3. Results

The single-spot plan (figure 3) gave a dose response in the entrance region of (12.4 ± 0.1) × 10^{-3} cm^{-1} Gy^{-1} and a background of (132.1 ± 0.5) × 10^{-3} cm^{-1} (see linear fit in figure 3 (c)). The signal in the measured Bragg peak was 41 % lower than the planned dose, when calibrated with the dose response.

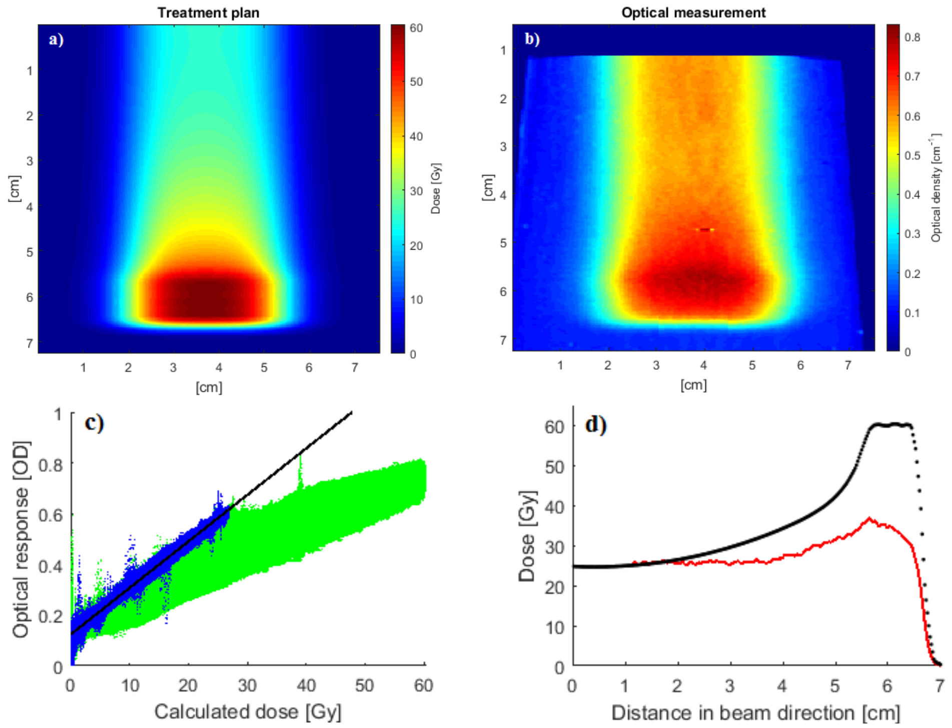

Figure 4. Interpolated planned doses (a) and optical measurement (b) for dosimeter C, irradiated with a SOBP entering from above. Correlation plot between plan and measurement is shown in (c), and (d) shows a projection through the central pixels of the plan and the measurement (see figure 3 for further details).

The SOBP plan delivered to dosimeter C had a dose response in the entrance region of (18.33 ± 0.04) × 10^{-3} cm^{-1} Gy^{-1}, with a background of (123.6 ± 0.6) × 10^{-3} cm^{-1}. The signal in the beginning of the SOBP plateau was 38 % lower than the planned dose, when calibrated with the dose response (figure 4 (d)), and this fell to 49 % at the distal end of the plateau. The same plan, but with half the dose was delivered to dosimeter B, and this gave a dose response in the entrance region of (17.94 ± 0.07) × 10^{-3} cm^{-1} Gy^{-1}, and the background was (120.3 ± 0.5) × 10^{-3} cm^{-1}.

4. Discussion

In this study, we have presented the first 3D measurements of a silicone-based, deformable, radiochromic dosimeter, irradiated with spot-scanning proton beams. Measurements of proton beams were clearly feasible, but the dose response was significantly influenced by quenching, i.e. it decreased in the high dose-volumes of the plans, compared to the entrance region. The high-dose regions are associated with a high LET, which is known to inhibit the dose response [8]. Two dosimeters (B and C) were irradiated with the same plan, but to different maximum doses. As expected, these had almost the same dose response in the entrance region. The single-spot dosimeter had a lower dose response, probably due to the different LET-distribution of the beam.

In figure 3(d), the effect of quenching is apparent as a lowering of the signal in the Bragg peak of approximately 41 %. This has a significant effect on the measured SOBP distribution in figure 4(d), where the effects seen for a single Bragg peak accumulate: the plateau region is very shallow, has a maximum value close to the beginning of the plateau, and a tilting plateau region. This is similar to what has been observed for other 3D dosimeters [9].

The correlation plots are much broader for the SOBP measurements than for the single-spot measurement. The larger physical size of the SOBP plan could affect this, but it is likely to arise from the large spread in LET that each dose level represents. The SOBP plan consists of many single spots with different energies, all with an LET that increases steeply towards the end-of-range. Thus several LET levels are found within each dose level.

The correlation plots show that low-dose regions are more sensitive to noise than the high dose regions. In general, noise arises where particles or dust block the light in the optical CT-scan, from imperfect refractive index matching, from suboptimal positioning from pre- to postscan and from artefacts created in the reconstruction.

In a recent study of cuvette size dosimeters, we have shown that the concentration of curing agent greatly affects the quenching in the dosimeter [8]. In the current study, 5 % CA was used, due to the improved temporal stability of the dose response. However, increasing the CA to 9 or even 11 % CA will give a less LET-sensitive dosimeter, albeit at the cost of dose response and temporal stability [5]. Chemical alterations in the Fricke gel dosimeter have also been shown to influence the LET dependence [10]. 5 % CA is furthermore associated with a considerable initial background colour, which limits the dynamical range available in the optical CT-scanner. This study shows that the Vista scanner was successful in reading out these dosimeters.

5. Conclusion

In this study we have performed the first 3D measurements with silicone-based, deformable, radiochromic dosimeters in proton beams. Quenching of the signal, related to an LET-dependent dose response, was observed in all dosimeters. By calculating the LET-distribution in the dosimeter, quenching can possibly be circumvented. Calculations of the expected optical response can be computed, and this can be used in quality assurance to compare with the optically measured 3D distribution.

6. Acknowledgements

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