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2009 J. Phys.: Conf. Ser. 164 012055

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## Carbon beam dosimetry using VIP polymer gel and MRI

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**Abstract.** VIP polymer gel dosimeter was used for Carbon ion beam dosimetry using a 150 MeV/n beam with 10 Gy plateau dose and a SOBP irradiation scheme with 5 Gy Bragg peak dose. The results show a decrease by 8 mm in the expected from Monte Carlo simulation range in water, suggesting that the dosimeter is non water equivalent. However VIP shows efficiency close to 1 in the plateau region and significantly reduced efficiency in the peak. On the other hand the SOBP results yield an efficiency close to 1 in the SOBP implying that the dose response of the VIP dosimeter may not be solely related to LET.

### 1. Introduction

To date, at least three ion-beam radiotherapy facilities worldwide are in clinical use. The main advantage that heavy ion beam irradiation presents in comparison to conventional (using photon or electron radiation) radiotherapeutic methods is the refinement of dose deposition with depth due to the Bragg peak, which spares healthy tissue before and after the target, as well as the extremely higher biological effectiveness of ion radiation in comparison to photon radiation.

However, the dosimetry of such modalities presents a scientific and practical challenge, mainly due to the higher LET which changes with energy and depth.

In this work, preliminary results of VIP polymer gel dosimeter's response to Carbon ion irradiation are presented along with corresponding Monte Carlo simulation data in order to investigate the dosimeter's properties in high LET radiation beams.

### 2. Materials and methods

### 2.1. Polymer gel

For this study's purposes the VIP polymer gel dosimeter, a normoxic formulation recently introduced by our group [1, 2], was used. It consists of 4% (w/v) *N,N'*-methylenebisacrylamide, 8% (w/v) *N*-Vinylpyrrolidone and 7.5% (w/v) gelatin, while 0.0008% (w/v) Copper Sulfate and 0.007% (w/v) Ascorbic Acid were added to act as oxygen scavengers. Hyper pure water (resistivity > 18 MΩ·cm) was used to prepare the solution in normal atmospheric conditions. The manufacturing process is described in detail in previous works [1, 2, 3]. The VIP's elemental composition and density are presented in table 1.

Table 1: Elemental composition and density of the VIP formulation

Density (1.0313g/cm <sup>3</sup> )	
Elements	w/w (%)
Carbon	11.6534
Hydrogen	10.4521
Oxygen	74.9725
Nitrogen	2.9215
Copper	3.06E-04
Sulphur	1.54E-04

Two 100 ml borosilicate glass bottles were completely filled up with the prepared gel solution and subsequently were tightly sealed using Parafilm and Teflon tape, to ensure non penetration of oxygen. The bottles were left overnight in room temperature for the gel to solidify and subsequently were shipped to the GSI (Darmstadt, Germany) installation for irradiation.

### 2.2. Irradiation

The GSI Carbon ion radiotherapy unit was used for irradiation purposes. A 150 MeV/n monoenergetic beam was employed for the first bottle's irradiation, using a square field of (2x2)cm<sup>2</sup> size, through the bottle's cap, so as to avoid interactions and secondary particles generation in the borosilicate glass walls. The irradiation of the first bottle (first irradiation) was planned to deliver 10 Gy physical plateau dose in water using the 150 MeV/n monoenergetic beam, with the central beam axis parallel to the bottle's main axis.

The second bottle was irradiated using a multi-energetic spectrum beam, along the bottle's longitudinal axis, with a (1x1) cm<sup>2</sup> square field, planned to deliver 5 Gy in a spread out Bragg peak (SOBP) residing between 3 cm and 6 cm depth in water (second irradiation).

### 2.3. Magnetic Resonance Imaging

Following irradiation, the bottles were immediately shipped to the MRI facility. They were scanned using a 1.5 T magnet and a quadrature RF receiver coil, five days post irradiation. Both bottles were placed in the receiver coil's centre to ensure minimal RF field inhomogeneities and were scanned using a three dimensional multiple spin-echo CPMG (Carr-Purcell-Meiboom-Gill) imaging pulse sequence (32 equidistant echoes, TE<sub>1</sub>=40 ms, TR=2000ms). Coronal slices were reconstructed with a (0.73864 x 0.73864) mm<sup>2</sup> pixel size and a slice thickness of 0.75 mm.

The three dimensional data were fitted on a voxel by voxel basis using a least squares mono-exponential fitting routine of signal intensity versus echo time, for all the acquired echo base images, thus obtaining a three dimensional relaxation time (T<sub>2</sub>) matrix, out of which a relaxation rate (R<sub>2</sub>=1/T<sub>2</sub>) matrix was calculated, a quantity known to be proportional to the polymer gel recorded dose for photon beam irradiation.

### 2.4. Monte Carlo simulation

The FLUKA [4, 5] general purpose Monte Carlo code was employed to simulate the carbon ion beam incident to the VIP gel dosimeter, also serving as a phantom. The monoenergetic beam's field size and

energy as well as the VIP's elemental composition and density, presented in Table 1, were used to exactly simulate the experimental setup of the first irradiation. An additional simulation was performed in water, for reasons of comparison, since the planned dose distributions (10 Gy in the plateau region) were performed assuming the gel as water.

For optimum dose calculations, the option HADROTHE was used in the DEFAULT card in order to take advantage of the low particle transport threshold and small fraction of kinetic energy lost in each step. The dose was firstly scored via USRBIN card in a 3-D matrix with a voxel  $(0.74 \times 0.74 \times 0.75) \text{ mm}^3$  similar to the spatial resolution of the MR scanning. Due to the small voxel the uncertainty in dose is high ( $\sim 10\%$ ), thus a second detector was also defined via USRBIN. This detector is consisted of cylindrical voxels with 0.5 mm height, along the incident beam's axis and 1 cm radius so as to acquire an acceptable statistical uncertainty ( $< 1\%$ ) in a short time frame ( $< 20\text{h}$ ).

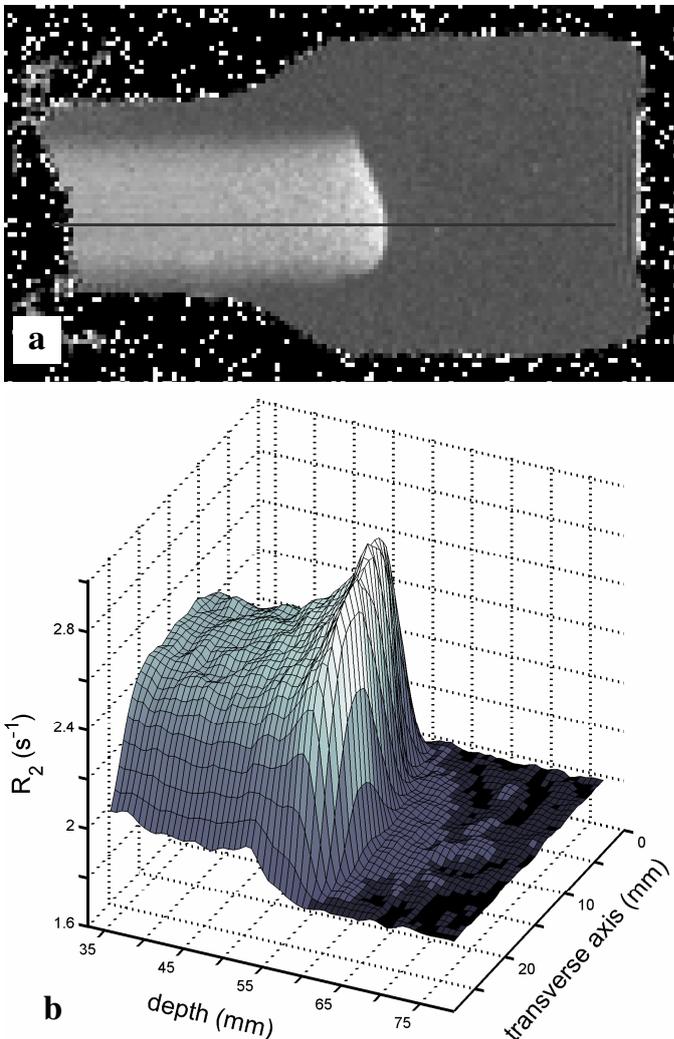


Figure 1: A coronal  $R_2$  map of the gel of the first irradiation, residing in the centre of the Carbon-ions beam on top (a). A surface plot of VIP's response along this plane on bottom (b). The height of the plotted surface in each point represents the corresponding  $R_2$  value. The surface of the irradiated gel is obviously malformed; however the well recorded Bragg peak region follows closely the surface shape.

### 3. Results and discussion

In Figure 1(a) the central coronal  $R_2$  map of the gel of the first irradiation, which corresponds to the 150 MeV/n monoenergetic beam, is presented. As it can be clearly observed by the  $R_2$  map, gel's surface is malformed. This can be attributed to the fact that the VIP substance was not completely solidified prior to shipment. A small gap appeared below the bottle's cap during solidification and gel shrinkage and since the package could have been left with the side down, the surface of the gel solidified in such a non flat fashion. However this non-flatness is accurately recorded in the  $R_2$  map thus revealing the ability of the gel to accurately record the Bragg peak distance of the carbon ion beam.

The general characteristics of measured  $R_2$  distribution on the coronal plane of figure 1(a), can also be observed in figure 1(b). Although the surface of the irradiated gel is malformed the recorded Bragg peak region follows closely the surface shape.

In figure 2(a) an axial  $R_2$  map, in the depth of 37 mm, is presented. The rectangular shape of the incident beam is well depicted. The beam's Full Width at Half Maximum, shown in figure 2(b) and measured across a transverse to the central beam axis profile, was found to be 20 mm, in excellent agreement with corresponding Monte Carlo calculations. Moreover, the shape and size of the recorded field were found to be the same at various depths and similar to those expected and verified by the Monte Carlo simulation.

Figure 3(a) presents the response of the dosimeter with depth along the line drawn on the coronal  $R_2$  map of figure 1(a). The shape of this response is similar to the one expected with the plateau, the Bragg peak found at a depth of 51 mm from the gel surface and the tail region directly after the Bragg peak. However, according to Monte Carlo simulations in water, the Bragg peak was expected to be at a depth of 59 mm. As pointed out in figure 3(b), the observed difference is due to the different energy deposition process with depth between the gel substance and water. Thus carbon ions beam imparts the maximum energy in a lower depth in the VIP volume compared to water. Monte Carlo calculations revealed that the above differences are mainly due to differences in the elemental composition between the VIP gel and water (6 of the 8mm difference in the Bragg peak depth between polymer gel and water are due to differences in composition) and secondly due to differences in density (2 of the 8mm difference in the Bragg peak depth between polymer gel and water are due to differences in density). Thus VIP polymer gel dosimeter, and polymer gels in general, is not water equivalent phantom material for carbon ion beam dosimetry. However, results presented in Figure 3 suggest that the polymer gel method can provide relative accurate dosimetric measurements for the plateau region and the depth of the Bragg peak (taking into account its density and composition) and moreover, can record the expected tail after the Bragg peak (figures 1b, 3a) which is attributed to beam's and target's fragmentation due to nuclear reactions. The plateau value recorded by VIP, as seen in figure 3a is

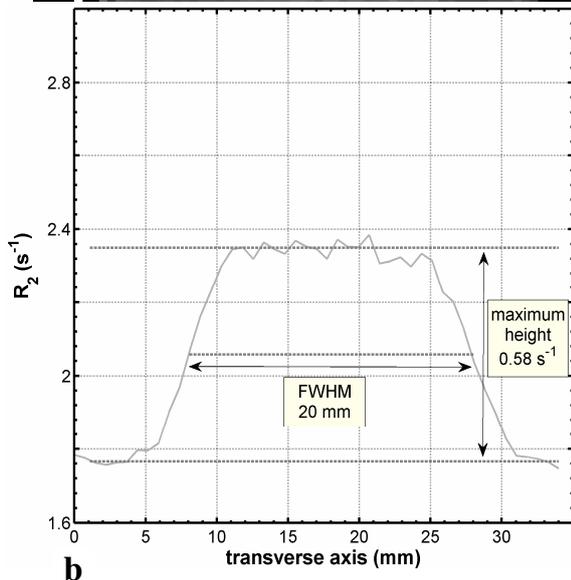
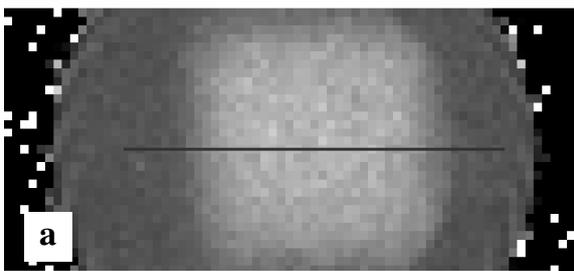


Figure 2: An axial  $R_2$  map, transverse to the beam's central axis at 37 mm depth, measuring from the gel surface, is presented (a). The response profile presented on b is along the black line on the axial  $R_2$  map. The "background" and "maximum" signal are clearly marked so as to figure out the beam's FWHM, which is found to be 20 mm.

about  $2.23 \text{ s}^{-1}$ . Taking into account the typical dose-response characteristics of the VIP polymer gel [2] with photon beams, the dosimeter presents a linear response from  $\sim 3 \text{ Gy}$  up to  $\sim 38 \text{ Gy}$ . In this dose region the typical linear response function for photons is:

$$R_2 = 1.4(\text{s}^{-1}) + 0.08(\text{Gy}\cdot\text{s})^{-1}\cdot D \quad (1)$$

while the unirradiated gel signal exhibits  $R_2(0) = 1.6 \text{ s}^{-1}$ .

According to this response curve for photons, the recorded plateau signal corresponds to a 10.38 Gy dose value, in good agreement with corresponding Monte Carlo calculations (10.83 Gy). This indicates that the VIP gel dosimeter presents a response similar to photons in the plateau region of the Carbon ions beam (relative to photons response efficiency close to 1) where the LET is of the order of  $50 \text{ keV}/\mu\text{m}$ . Comparing this value with an efficiency around 0.4 reported by Ramm et al for BANG-3 dosimeters and around 0.63 for BANG-1 dosimeters [6], the VIP gel seems to present an improved relative to photons efficiency in the plateau region. However the recorded value in the Bragg peak is about  $2.92 \text{ s}^{-1}$ , a value which corresponds to a dose of 19 Gy by using the dose-response curve for photons. This yields a relative to photon response efficiency of about 0.29 which is mainly attributed to the high LET (over  $150 \text{ keV}/\mu\text{m}$ ) of the Carbon beam in the Bragg peak. It is also noted that the recorded value at Bragg peak may be significantly affected from volume averaging effects because of the extremely low width of the peak.

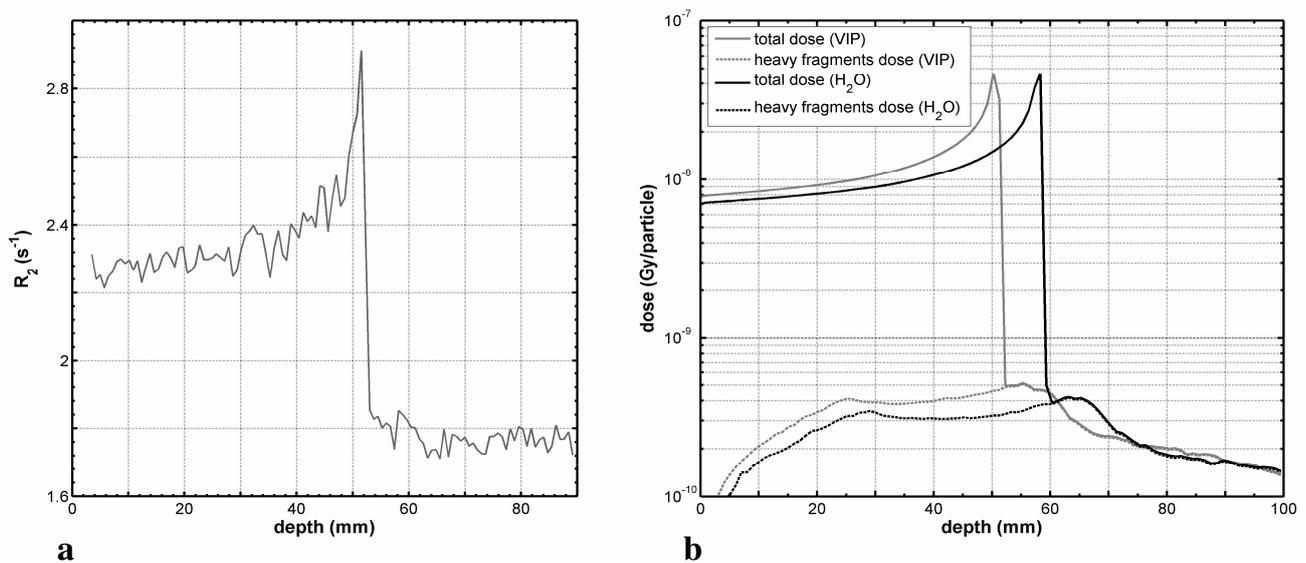


Figure 3: The dose-depth curve as calculated by Monte Carlo simulation, both for water and VIP polymer gel. The figure is presented in logarithmic dose scale so as to show the non-primary heavy particles contribution.

The second bottle irradiation scheme involved doses ( $\sim 5\text{Gy}$ ) just over the detection limit of VIP for photons ( $\sim 3\text{Gy}$ ). However an average signal of  $1.87\text{ s}^{-1}$  for the SOBP was recorded between 3 cm and 6 cm depth from gel surface, while the  $R_2(0)$  value for the bottle was found  $1.76\text{ s}^{-1}$ . According to the photon response curve of equation (1) the SOBP response value corresponds to  $5.88\text{ Gy}$ , thus obtaining a relative to photon response efficiency close to 1, within experimental uncertainties. Although this dose recorded in the SOBP is close to the VIP's dose detection limit, the aforementioned finding suggests that the low efficiency of the VIP dosimeter in high LET – high dose regions (Bragg peak of figure 3a) may be also related to the specific dose characteristics of the gel dosimeter (i.e. dose range, dose response and in general the specific monomers used which determine these characteristics).

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