3D-MR-based Polymer Gel Dosimetry of Proton Needle Beams

A. G. Berg[1,2], C. Bayreder[1], and J. Heufelder[3,4]

[1]Center for Biomedical Engineering and Physics, Medical University of Vienna, Vienna, Austria, [2]MR-Centre of Excellence, Medical University of Vienna, Vienna, Austria, [3]Augentumortherapie (SF4/ATT), Hahn-Meitner-Institut, Berlin, Germany, [4]Division of Radiation Medicine, Paul Scherrer Institut, Switzerland

Introduction/Purpose

Magnetic Resonance supported dosimetric imaging is relying on the sensitivity of the transverse relaxation time T2 to the immobilization of polymer and water protons. The change in mobility is correlated to the polymerization process induced by irradiation. The application to the dosimetry of Hadrons (i.e. high-energy heavy ions or protons) for radiation therapy represents a challenge due to the strong lateral and depth confinement (Bragg-peak) of dose in very small planning target volumes achievable with this new most modern radiation therapy concept. Moreover it has been shown that the polymerization dose response in polymer gels might be suppressed in regions of high linear energy transfer (LET) present in the Bragg-peak regime, when Hadrons reach their penetration depth. New Hadron radiation concepts for radiation therapy are relying on the spot scanning technique using very narrow (i.e. mm) pencil beams. The 3D-dose verification of such pencil beams with ionization chambers with minimum size of a few mm is problematic due to partial volume detection and the demands on measurement time. We here investigate the applicability of parameter selective MR-micro-imaging for the 3D-dose visualization of proton pencil beams at about 1-2 mm diameter. We use voxel volumes 3 orders of magnitude (10^3) smaller than those reported on 3D-arrangements of small sized ionization chambers. The unexpected results on the depth dose profile are explained by a model of increased scattering rate at penetration depth; this model is strongly supported by new experimental data on the beam width and Monte-Carlo-simulations on the dose deposited by the protons.

Materials and methods

The polymer gel is containing methacrylic acid as monomer part (6% w/w), gelatin (14% w/w) as matrix and de-ionized water. The normoxic polymer gel is manufactured in our laboratory at normal oxygen levels present in the air using ascorbic acid as oxygen scavenger (c_{AscA} = 2 mM) and copper-sulfate (c_{CuSO4} = 10 µM) to avoid polymerization suppression by oxygen (Methacrylic and Ascorbic Acid in Gelatin Initiated by Copper: MAGIC. The irradiation of the polymer gel dosimeter with 68 MeV protons is performed at the eye tumor therapy department of the Ion Beam Laboratory (ISL) at Hahn-Meitner-Institut Berlin (HMI). For calibration dose levels of D =0,2,4,8,16 Gy are directed to the polymer gel samples. The narrow proton beams at small diameter are achieved by collimation using a cylindrical slab of lead (th = 10mm), in which 3 bores of different diameter d1= 2.1 mm, d2 = 1.5 mm and d3 = 0.86 mm are drilled. The necessary high spatial resolution (VS: 199 x199 x 2000 µm^3) in R2=1/T2 imaging is achieved on a high-field 3T human scanner using a customized strong gradient insert (G = 200mT/m) and a sensitive small sized volume resonator (d=35 mm). A multi-slice multi-echo CPMG-sequence was used for parameter (R2=1/T2)-mapping (nr of echoes: 20, TE = 20 ms, TR =6.9 s, nr. of slices: 16, Mtx: 128x128x16).

Results

The calibration data for the polymer gel dosimeter exhibits a linear dose response of the relaxation rate with dose level (fig. 1). 16 dose maps rectangular to the direction of the 3 pencil proton beams can be obtained. A maximum intensity projection of the 3D-dose data set is shown in fig. 2. The sharp lateral dose gradients can be delineated at excellent SNR due to the high spatial resolution used. The data set corresponds to about 260 000 single measurements with a 0-dimensional dosimetric method (ionization chamber). Even by qualitative visual inspection no dose enhancement at the penetration depth (bottom) as usually observed for proton beams is observed. The depth dose profile is investigated on a more quantitative level in fig. 3 though systematic errors, up to about 50% due to partial volume detection and high LET, might be present in the Bragg-peak regime. The Bragg-peak dose enhancement representing the main advantage of Hadron therapy as indicated in the measurement profile of the 20 mm beam is strongly suppressed. The reason for this behavior is enlightened by a quantitative measurement of the beam width along with depth (fig. 3 bottom line). The proton beam is strongly widened when the protons reach their penetration depth due to increased lateral scattering, which results in lower energy dose dissipated per unit area to the polymer gel. Monte Carlo simulations support this interpretation.

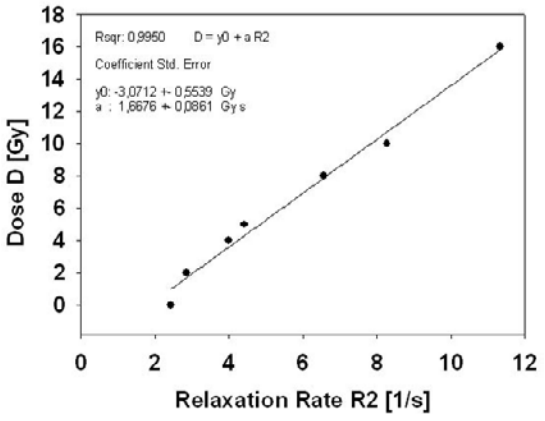

Fig. 1 *Calibration data for the assignment of dose levels to 3D-multi-slice parameter selective (T2-images) in the polymer gel. The data is obtained in the plateau regime of proton beams for eye tumor treatment at an energy of 68 MeV.*

Fig. 2 *Maximum intensity projection of the 3D-dose distribution originating from 3 pencil beams at diameter: d_1=2.1, d_3 =0.86, d_2=1.5 mm.*

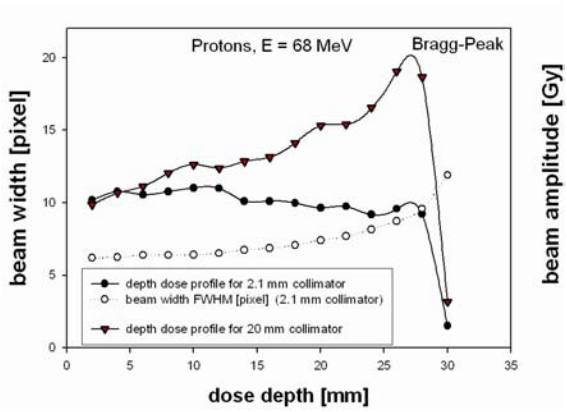

Fig. 3 *Depth dose distribution in a proton pencil beam (d_1=2.1 mm) and a wide beam of 20 mm diameter (top). The Bragg-peak present in the wide beam is suppressed.*
The beam width (open circles) is strongly increased when the protons approach their penetration depth.

Conclusion

Using customized hardware parameter selective MR-micro-imaging is capable of measuring the 3D-dose distribution of very narrow proton beams in tumor therapy in a unique way. The quantitative dose evaluation in the Bragg-peak regime is still limited by LET quenching of the dose response in the polymer gels but sufficient to detect the dose reduction due to increased proton scattering.