Aspects of radiation beam quality and their effect on the dose response of polymer gels: photons, electrons and fast neutrons

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Abstract

Polymer gels are generally assumed to exhibit no significant dependence of the dose response on the energy or type of irradiation for clinically used beam qualities. Based on reports on differences in dose response for low energy photons and particle beams with high linear energy transfer (LET) we here investigate the dose response and energy dependence for a normoxic methacrylic acid polymer gel (MAGAT) for X-rays (100 kV), high energy photon beams (E = 1.2 MeV (⁶⁰Co), 6 MV and 15 MV) and for three different electron energies (4, 12 and 20 MeV). Due to the possible impact also the sensitivity of the dose response to the dose rate is reported. A reduction in polymer gel relaxation rate has been observed for proton and carbon beams due to the high Linear Energy Transfer (LET) of these types of radiations. We here report on the dose response of an acryl-amide polymer gel (PAG) in a fast neutron field along with collimation as proposed for Boron neutron capture therapy (BNCT).

1. Introduction

Ideal dosimeters are expected to exhibit a dose response independent of the type (electromagnetic waves vs. particles) and beam energy. The measurement result should not be influenced by the way and circumstances of application for instance time between dosimeter preparation and irradiation, temperature during scanning or dose rate. Polymer gels are generally assumed to exhibit no sensitivity to the photon energy in the range of clinical used beam qualities. Based on reports on differences in dose response for low energy photons and particle beams with high linear energy transfer (LET) we here investigate the dose response and energy dependence for a normoxic methacrylic acid polymer gel (MAGAT) for X-rays (100 kV), high energy photon beams (E = 1.2 MeV (⁶⁰Co), 6 MV and 15 MV) and for three different electron energies (4, 12 and 20 MeV). Due to the possible impact also the sensitivity of the dose response to the dose rate is reported. A reduction in polymer gel relaxation rate has been observed for proton and carbon beams due to the high Linear Energy Transfer (LET) of these types of radiations. We here report on the dose response of an acryl-amide polymer gel (PAG) in a fast neutron field along with collimation as proposed for Boron neutron capture therapy (BNCT).
carbon ions. The first polymer gel investigations on such ion particle beams revealed sensitivity to the biologically relevant Linear Energy Transfer \([6, 7]\). Polymer gel dosimetry has also been investigated for its potential use for Boron neutron capture dosimetry \([3]\). An increase in dose response with Boron content could be detected in polymer gels. However no data on the dose response to neutrons of a PAG dosimeter was offered but proposed to be useful. In the second part of our study we present data on the dose response of a PAG-type polymer gel in a fast neutron field and compare the sensitivity to that of Co60-photons.

2 Materials

We investigated two separate types of polymer gels based on:

\underline{a)} Bis-Acryl-Amide using Nitrogen flushing through the Gel: Poly-Acrylamide Gel (PAG) to remove oxygen, which suppresses polymerization. This type of polymer gel is used for comparing the dose response in a field of fast neutrons to that of a photon field (\(^{60}\)Co). The polymer gel was manufactured at the German Cancer Research Center (DKFZ/Heidelberg) from water, gelatin: 6\% w/w, monomer: acrylamide (3\%) cross-linker: BIS (3\%) using nitrogen flushing to reduce oxygen to a concentration below 0.003 mg/l (conf. table 1). We used BAREX\textsuperscript{TM} made small elliptical containers (MGS Research Inc., Madison, USA) for reasons of water equivalence and oxygen barrier characteristics.

\underline{b)} Methacrylic Acid Gel And Tetrakis-hydroxy-methyl-phosphonium-chloride (THPC) as oxygen scavenger (MAGAT). This type of polymer gel is manufactured in our laboratory at Medical Univ. of Vienna \([7, 8]\). THPC is used due to its superior oxygen scavenging capabilities.

| Components | PAG-gel | MAGAT-gel |
|------------|---------|-----------|
| Deionized water | 88\%(w/w) | 87\%(w/w), 870 g |
| Gelatin | 6\%(w/w) | 8\%(w/w), 80 g |
| Methacrylic acid | 5\%(w/w), 50 g |
| THPC | 0.3316 g (2mM) |
| Acrylamide | 3\%(w/w) |
| N,N’-methylene-bis-acrylamide | 3\%(w/w) |

Table 1 Chemical composition of the two types of polymer gels. MAGAT is used for comparing the dose response of photons and electrons in a wide energy range. PAG represents the dosimeter material for investigating differences between fast neutrons and \(^{60}\)Co-photons.

3. Methods and results

3.1 Aspects of radiation quality: photon and electron energy \([8]\)

The dose response and energy dependence for a normoxic MAGAT polymer gel was investigated for X-rays (100 kV), for higher photon energies (\(E = 1.2\) MeV (\(^{60}\)Co), 6 MV and 15 MV) and for three electron energies (4, 12 and 20 MeV). All samples were irradiated with absolute dose levels \(D = 0, 1, 2, 4, 6, 8\) and 12 Gy within about 30 hours. The MR-evaluation was completed within the next 2 days. The dose rates are determined by the specific radiation units available. DR \(\approx 0.5\) Gy/min were applied for X-rays and the \(^{60}\)Co photon field. The linear accelerators offered 5 Gy/min for the higher electron and photon energies (4-20 MeV).

3.1.1 X-ray irradiation

Irradiation with an energy of 100 kV was performed by a Gulmay D3300 orthovoltage therapy unit (Gulmay Medical Ltd., Chertsey, UK) using a tungsten target. The inherent filtration consists of 3 mm Be and the quality of the irradiation beam is determined by 2.8 mm HVL (half value layer) aluminium. A waterproof thimble Farmer-type chamber (PTW, M-30006) connected to a UNIDOS therapy dosimeter (PTW) was used for absolute dosimetry. Depth dose measurements were performed using a waterproof Roos\textsuperscript{TM} chamber (PTW, M-34001). The irradiation was adjusted such that the indicated absolute dose levels were applied to a depth of 6 cm under water level and about 2 cm distant from the bottom in the gel container.

3.1.2 \(^{60}\)Co irradiation

The irradiations were performed in a 40x40x39 cm\(^3\) water phantom using a \(^{60}\)Co source (780 Elite Theratronics, Canada, source surface distance = 80 cm) in a 15 x 15 cm\(^2\)
field. The bottom of the gel container coincides with the water surface. The polymer gel response was evaluated in about 5 mm distance at the depth dose maximum. Absolute dose levels were verified using a calibrated Farmer-type chamber (0.6 cm³, PTW type 30013, Germany). The field uniformity across the centre of 10 cm of the field is better than 2%.

3.1.3 High energy photon and electron irradiation MAGAT polymer gels were irradiated in a water phantom using a linear accelerator (Varian C linac 2100C/D). The containers were placed at a water depth, such that the dose maximum appears in the centre of the vial. Absolute dosimetry in the photon field (field size: 10x10cm²; SSD:100cm) was performed with a calibrated ionization chamber following the IAEA 398 protocol. A Markus chamber (Roos™) served for electron dosimetry. Two photon energies (6, 15MV) and three electron energies (4, 12, 20MeV) were investigated.

3.1.4 MR-evaluation Parameter selective T2 imaging with a head coil was performed on two subsets of the polymer gels comprising about 20 samples each. We used a multiple spin echo sequence (CPMG) with equidistant echoes (TE=20, 40...400 ms, TR = 10.5 s, FOV = 18 x 18 cm², Mtx: 128 x 128, 23 slices, slice thickness = 1 mm, NEX = 4).

3.1.5 Results Dose-R2-response-curves for X-rays (100 kV), ⁶⁰Co, 6 and 15 MV photons, 4, 12 and 20 MeV electrons are shown in Fig. 1. The sensitivities calculated on the basis of a linear regression analysis in between D = 0 and D = 6 Gy are plotted in fig. 2. No significant differences are observed for high energy photons and electrons provided by a linear accelerator (LINAC); only a tendency to higher sensitivities at higher beam energy is observed.

On the first view the MAGAT polymer gel appears to exhibit significant higher sensitivities for the low energy ⁶⁰Co- and X-ray photons. However these beam qualities also differ with regard to dose rate from high energy photon and electron beams provided by a LINAC radiation. We therefore investigated also the dose rate dependence for a separate batch of MAGAT gels (fig. 3). The data on the dose response clearly indicates a suppression of the relaxation rate (R2) at increasing dose rates for the MAGAT-type gel. The reduction in dose sensitivity with higher dose rates DR >2 Gy/min) is significant (fig. 3b). Thus, the observed lower sensitivities for high-energy LINAC-photons and electrons (DR≈ 5 Gy/min) with reference to ⁶⁰Co-photons and X-ray (DR≈ 0.5 Gy/min) can be explained by a reduction in the R2-response at high dose rate for the MAGAT polymer gel. For the dose range investigated, the independence of the dose response on the photon energy is in agreement with investigations on a nMAG polymer gel [4] comparing the energy response of LINAC photon fields at 6 and 25 MeV max. energy. Similar to our results a slight tendency to higher dose rates at high energy was observed in this
study. A significant energy dependence for various BANG™ gels, a VIPAR and a MAGIC gel was shown for photon energies smaller than 60 kV [1].

3.2 Aspects of radiation quality: neutron-fields [9]

3.2.1 Materials: Polymer gels (PAG). The polymer gel was manufactured at the German Cancer Research Centre (DKFZ/Heidelberg) from water, gelatin: 6% w/w, monomer: acrylamide (3%) cross-linker: BIS (3%) using nitrogen flushing to reduce oxygen to a concentration below 0.003 mg/l. We used BAREX™ made small elliptical containers (MGS Research, Inc. Madison, CT 06443 USA) for reasons of water equivalence and oxygen barrier characteristics.

3.2.2 Methods: radiation beam characteristics, reference dosimetry and MR-evaluation A radiation field (13x13 cm²) of fast neutrons (n) was generated at compact cyclotron (Scanditronic MC32 NI, 32 MeV protons) at DKFZ/Germany irradiating a Beryllium target with 16 MeV protons. The generated neutrons exhibit a broad energy spectrum with highest energy of 16 MeV and medium energy of 6-7 MeV (fast neutrons). Reference dosimetry on the neutron field for calibration of the monitor units was performed using a Boron ionization chamber in the same experimental arrangement as prepared for the polymer gel irradiations. The \( \gamma \)-contribution to the overall dose amounts to about 5%.

Magnetic resonance micro-imaging at high signal-to-noise ratio was performed on a 3T human MR scanner using sensitive birdcage-type resonators (20 echoes, \( \Delta T=20\) ms, CPMG, slice thickness: 1 mm; FOV: 5x5 cm², Mtx: 128x128). A histogram analysis over ROIs (≈300 pixel) offered mean and standard deviation for error estimation.

3.2.3 Photon versus neutron dose response: results The dose response for \(^{60}\)Co-photon may be compared to the data on the field of fast neutrons (fig. 4). The sensitivity of the acrylamide polymer to fast neutrons gel is significantly reduced with reference to \(^{60}\)Co-photon. Similarly to the procedure for determining the radiobiological efficiency of TLDs an efficiency factor can be determined as ratio of the relative sensitivities [5] to the fast neutron field.
and $^{60}$Co-photons: $\varepsilon = \frac{\Delta R_2}{\Delta D_{\text{neutron}}} = 0.37$. The reduced efficiency of the polymer gel in the neutron field is most likely related to the high linear energy transfer (LET) in neutron fields, determined by the low energy backscattered protons. The energy dissipation of neutrons is controlled by the scattering of neutrons by hydrogen. Its contribution to the KERMA of neutron fields in biological soft tissue amounts to about 90% [10] for the medium neutron energy of 6 MeV. A reduced sensitivity of polymer gels to high LET-irradiation was also reported for carbon-ions [5] and protons [6]. We interpret the reduced sensitivity for high-LET radiation by the increased presence of radicals, which results in termination of the polymerization process by two radical carrying partners. The length of polymer chains is reduced and the mobility of water molecules and multimers with reference to low LET-radiation increased.

References
[1] Pantelis E, Karlis A K, Kozicki M, Papagiannis P, Sakelliou L and Rosiak J M 2004 Polymer gel water equivalence and relative energy response with emphasis on low photon energy dosimetry in brachytherapy Phys. Med. Biol. 49 3495–3514
[2] Maryanski M J, Ibbott G S, Eastman P, Schulz R J and Gore J C 1996 Radiation therapy dosimetry using magnetic resonance imaging of polymer gels Med. Phys. 23 699-7
[3] Farajollahi A R 1999 An investigation into the applications of polymer gel dosimetry in radiotherapy Ph.D. theses Med. Phys. 26 493
[4] De Deene Y 2004 Essential characteristics of polymer gel dosimeters J. Phys. Conf. Ser. 3 34-57 [5] Ramm U, Weber U, Bock M et al. 2000 Three-dimensional BANG gel dosimetry in conformal carbon ion radiotherapy Phys. Med. Biol. 45 N95-102
[6] Gustavsson H, Bäck S, Medin J et al., 2004 Linear energy transfer dependence of a normoxic polymer gel dosimeter investigated using proton beam absorbed dose measurements Phys. Med. Biol. 49 3847-55
[7] Bayreder C, Georg D, Moser E, Berg A 2006 Basic investigations on the performance of a normoxic polymer gel with tetrakis-hydroxy-methyl-phosphonium chloride as an oxygen scavenger: Precision, accuracy, stability, and dose rate dependence Med. Phys. 33 2506-13
[8] Bayreder C submitted may 2008 High resolution resonance based dosimetry using normoxic polymer gels PhD Thesis, Medical University of Vienna, Vienna, Austria
[9] [9] Berg A, Wolber G, Bankamp A, Moser E 2003 MR-basierte Polymergel-Dosimetrie: Neutronen- und Photonen-Antwort Tagungsband (ISBN 3-925218-77-7) der 34. Jahrestagung der Deutschen Gesellschaft für Medizinische Physik (DGMP) Heidelberg/Germany 104-105
[10] Reich H (ed.) 1990 Dosimetrie ionisierender Strahlung B.G. Teubner, Stuttgart p.85