MAGIC with formaldehyde applied to dosimetry of HDR Brachytherapy source

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Abstract. The use of polymer gel dosimeters in brachytherapy can allow the determination of three-dimensional dose distributions in large volumes and with high spatial resolution if an adequate calibration process is performed. One of the major issues in these experiments is the polymer gel response dependence on dose rate when high dose rate sources are used and the doses in the vicinity of the sources are to be determined. In this study, the response of a modified MAGIC polymer gel with formaldehyde around an Iridium-192 HDR brachytherapy source is presented. Experimental results obtained with this polymer gel were compared with ionization chamber measurements and with Monte Carlo simulation with PENELOPE. A maximum difference of 3.10% was found between gel dose measurements and Monte Carlo simulation at a radial distance of 18 mm from the source. The results obtained show that the gel’s response is strongly influenced by dose rate and that a different calibration should be used for the vicinity of the source and for regions of lower dose rates. The results obtained in this study show that, provided the proper calibration is performed, MAGIC with formaldehyde can be successfully used to accurately determine dose distributions from high dose rate brachytherapy sources.

1. Introduction

Polymer gel dosimetry offers a great potential to measure complex dose distributions in three dimensions, with the ability of measuring high dose gradients. This special characteristic of gel dosimetry can be applied on high dose rate (HDR) brachytherapy, solving some of the most important problems in this dosimetry: the lack of spatial resolution and non-tissue equivalence of conventional dosimeters used like thermoluminescent dosimeters, diodes and films [1].

The usefulness of gel dosimetry for external beam radiation therapy has been shown by several studies [2-4], but its application for HDR brachytherapy studies is conditioned to the understanding of some specific imaging and radiochemical influences that can result in significant dose errors [5]. Measurements in the vicinity of Brachytherapy sources are susceptible to oxygen permeability from the catheter wall that leads to an inhibition of polymerization and to magnetic susceptibility artefacts during imaging of the gel phantom. Another source of errors can be the diffusion of monomers during irradiation causing overshoots in regions of high dose and high dose gradients.

In this study we used MAGIC gel with formaldehyde to measure dose distributions of a 192-Iridium brachytherapy source while some simple procedures were used to avoid the above cited problems. We
have also compared our results with Monte Carlo Simulation performed using PENELOPE code with an implementation that considers the extended source geometry used and a voxel model to obtain volumetric dosimetry.

2. Materials and methods

2.1. Gel preparation
The gel preparation was described elsewhere [6]. Part of the gel was poured into six cylindrical glass tubes routinely used for blood sample collection (BD Vacutainer® with 5ml volume, 12mm diameter and 75 mm height, closed with a 20mm hermetic stopper inserted in a plastic cover) and the rest was poured into an acrylic rectangular recipient that is impervious to oxygen and is normally used to make and visualize cell cultures (CellStar® 50 ml volume).

2.2. Gel irradiation
The GammaMed Plus 232 192-Ir source used to irradiation has an active cylindrical volume of 0.6 mm diameter and 3.5 mm height encapsulated in stainless steel that is welded to a steel cable. An esophageal catheter of 1.6 mm radius was used to guide the source. The source activity was 5.43 Ci (200.91 GBq) by the time the experimental procedures were performed.

A cubic box of 30 cm height filled with water was used to accommodate the recipients containing the polymer gel during irradiation. The rectangular acrylic recipient was irradiated with the catheter held on its surface while the source was scheduled to stop at the center of the gel volume, as shown in figure 1.a. In this case, a continuous distribution of dose rates reaching the dosimeter gel is achieved, the portions of the gel closer to the source position receiving higher dose rates. The glass tubes were positioned in an acrylic fixture to keep them aligned alongside with the center of the catheter during irradiation, as shown in figure 1.b. Five tubes have been irradiated (one at a time), the first one being 16 mm away from the catheter and the next ones in 10 mm distances from each other. In this case, the polymer gel was in a region of lower dose gradient. In water measurements were also made in several radial distances from the source with a plane parallel ionization chamber, Markus type, of 0.05 cm³ volume, as shown in figure 1.c.

2.3. MRI imaging
MR images were acquired one day after the irradiation to allow enough time for gel reaction completion and achievement of thermal equilibrium with the MRI scanner room temperature. The images were acquired using a 1.5 T scanner (Siemens, Magnetom Vision) with a head coil and multi spin echo sequences with 16 echo times multiples of 22.5 ms, a repetition time of 4000 ms and a matrix size of 256 × 256 pixels. The slice thickness was 2mm and the FOV was 150 mm. Two acquisitions were averaged for each scan. The transverse relaxation rate $R_2 = 1/T_2$ was calculated by fitting the image signal intensities versus the echo time on a pixels wise base in a specific program developed by our group in MatLab® 6.5 (Mathworks Inc).
2.4. Monte Carlo simulation.
The Monte Carlo simulations were run with PENELOPE code system. A user code was written to describe faithfully the geometry of the source and simulate all anisotropic properties of the brachytherapy extended source. Beta radiation of 240, 536 and 672 keV and an average energy of 376 keV for photons were used to represent the source’s spectra. The simulated cubic water phantom dimensions (20 cm) were assumed to be sufficient for obtaining full scattering conditions for the relevant range of distances.

A 3D voxel-dosimetry routine was implemented to record the energy deposition values in the volume along the simulation.

3. Results and Discussions
The R² versus depth curves obtained with the two experimental configurations (figures 1.a and 1.b) are plotted in figure 2.

![Figure 2 – R² versus depth curves for MAGIC with formaldehyde irradiated in 192-Iridium HDR brachytherapy source: (2.a) Acrylic recipient; (2.b) Glass tubes.](image1)

Different exposure times for each of the settings were used in order to achieve a significant signal in each configuration. Exposure times of 40.2 and 1331.6 s were used in the region of high and low gradients, respectively, in order to avoid saturation due to the radiation-induced macromolecule breakings in the higher gradient region or lack of signal in the region of lower gradient.

Figures 3.a and 3.b show the fitted curves used to correlate the R² with dose for the acrylic recipient (high dose region) and for the glass tubes (lower dose regions), respectively. The calibration curve for the glass tubes using the same exposure time as used for the acrylic recipient resulted in the same calibration curve shown in figure 3.b.

![Figure 3 – Calibration curves used in high and low gradient regions to correlate MAGIC gel with formaldehyde R² MRI signal with dose: (3.a) Acrylic recipient, with corresponding fitting $D=0.00216 \cdot e^{1.03209 \cdot R^2}$; (3.b) Glass tubes, with corresponding fitting $D=0.02306 \cdot e^{0.27832 \cdot R^2}$.](image2)
Figure 4.a presents three depth dose curves relative to radial distances from the center of the source obtained with gel data (acrylic recipient and glass tubes) and the ionization chamber. In figure 4.b. the doses are normalized to the dose at 2.0 mm away from the center of the active volume of the source (point just outside the source’s capsule) to be compared with PENEOPE simulated data.

PENEOPE Monte Carlo simulation and MAGIC with formaldehyde polymer gel data has an average concordance of 99.20% in dose percentages measured with the HDR brachytherapy 192-Iridium source. A maximum difference of 3.10% between simulation and experimental dose obtained with gel appears at 18 mm from the center of the source for the acrylic recipient (at this same distance the difference between simulation and data for glass tubes is of 2.56%). The results suggest that a calibration recipient including both high and low dose rates, such as the acrylic recipient used, provides an accurate calibration curve for all therapeutic relevant distances.

R2 distributions, dose maps and dose gradient maps for the acrylic recipient and the glass tubes are shown in figure 5. The left side of this figure (5.a, 5.c, 5.e) shows results for the acrylic recipient, relative to high gradient regions, and the right side of the figure (5.b, 5.d, 5.f) shows results for the glass tubes, relative to lower gradient regions.
4. Conclusions

MAGIC with formaldehyde has suitable features for use in HDR 192-Iridium brachytherapy source three-dimensional dosimetry such as high spatial resolution. This work shows that a proper gel calibration can provide accurate dose measurements in regions of high and low dose rates, allowing it to express dose rate gradients with high dose resolution.

The comparison of depth dose data obtained with gel, ionization chamber and Monte Carlo simulation showed that simulation data can be used as reference to polymer gel studies since it provides similar spatial resolution as the gel dosimeter.

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