Dosimetric properties of MAGIC-\textit{f} polymer gel assessed to Radiotherapy clinical beams

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Abstract. Dosimetric properties of MAGIC-\textit{f} gel were studied for a wide range of beams used in Radiotherapy. The MAGIC-\textit{f} tissue-equivalence was theoretically verified using PENELOPE Monte Carlo code and experimentally by percentage depth dose curves for water and gel (maximum differences of 2.0\% and 0.5\% for 6MV and 10MV, respectively). Energy and dose-rate dependency were evaluated in a range from 60 kV to 10 MV and 0.44 Gy/min to 10 Gy/min respectively. MAGIC-\textit{f} presents linearity to all energies studied and its sensitivity presents maximum and average variation of 8.6\% and 7.7\% respectively in the range of energy considered. The study of dose rate dependency evidence that MAGIC-\textit{f} presents no significant variation of response in clinical intervals of dose rate: lower than 0.7\% when x-ray are considered and lower than 1.9\% when all beams are considered. Its dosimetric characteristics indicate that MAGIC-\textit{f} is a very suitable dosimeter for Radiotherapy.

1. Introduction
Gel dosimetry has been extensively investigated aiming to provide accurate tri-dimensional (3D) information of dose to complex Radiotherapy treatment plans. The idea of using gelatin matrix simulating soft tissue to record dose deposition historically underlies the scenario of dose verifications and, nowadays, is the flagship of 3D dosimetry [1]. Matrix integrity is directly proportional to the ability of precisely record dose depositions and spatial resolution and the capability of absorbing the same dose as biological tissue directly reflects gel’s applicability in Radiotherapy dosimetry [2].

Mass attenuation coefficient is possibly one of the more complete dosimetric quantities to indicate radiological tissue-equivalence of a dosimeter. The stability of polymer chains inside gelatin matrix implies in its dosimetric reproducibility [1-2]. From the radiation physics point of view, free radicals are created inside matter in a spatial range proportional to the electron energies in the initial beam or of those created after photon interactions. This may indicate that polymer chains can be structured and created in different sizes, directions and rates depending on the energy and dose rate of the initial beam.

Formaldehyde was added to MAGIC gel (\textit{Methacrylic Ascorbic acid in Gelatin Initiated by Copper added formaldehyde}) aiming to increase matrix stability due to the large number of hydrogen bonds formed between gelatin and formaldehyde chemical sites. Melting point of MAGIC-\textit{f} gel has its value doubled when 1\% of formaldehyde is used [3-5]. In this work, MAGIC-\textit{f} gel (\textit{Methacrylic Ascorbic acid in Gelatin Initiated by Copper with added formaldehyde}) is investigated to determine its dosimetric characteristics of matrix integrity, tissue-equivalence, dose rate and energy dependency.
2. Material and Methods

2.1. MAGIC gel with formaldehyde

The polymer gel investigated in this work is MAGIC-f. This gel has an excellent stability of response due to gelatin integrity preservation during long time after irradiation [3-4]. Temperature stability is also reported in terms of its melting point of 69 °C [5]. Gel composition is presented in table 1. Effective atomic number of 7.53 and density of 1.0 g/cm³ indicate gel equivalence with tissue.

Table 1 – MAGIC-f gel composition

| Component         | Concentration (w/w) | Atomic component | Mass fraction (w/w) |
|-------------------|---------------------|------------------|---------------------|
| Mili-q water      | 82.7 %              | H                | 10.33 %             |
| Gelatin           | 8.4 %               | O                | 62.68 %             |
| Copper            | 0.02 %              | C                | 23.21 %             |
| Ascorbic acid     | 0.03 %              | N                | 2.52 %              |
| Methacrylic acid  | 5.9 %               | Others           | 0.81 %              |
| Formaldehyde      | 1.0 %               | (Concentrations lower than 1% were omitted in table) |

Abbreviations: Concentrations of chemical components and atomic compositions are expressed in terms of mass fraction (w/w).

2.1.1. Gel manufacture.

Gelatine is added to water at 45°C and mixed without interruption. Temperature is kept until gelatine is completely dissolved and then heating is stopped. Other components are added when temperature reach 30°C in the same order presented in table 1. Gel’s PH was mapped during manufacture process to identify free radicals presence. It was possible to observe that gelatine itself provides radicals to solution (PH changes from 6.04 to 5.43). Hydroquinone was not used to consume these radicals given the decrease in sensitivity previously reported for its use [6]. After gel solution homogenization, it was stored in 5mL glass tubes, in a vacuum condition. Glass surrounding the samples has a thickness of 1mm that was considered in the irradiation procedures. Samples were kept in 10°C during 24 hours before irradiation and 12 hours inside MRI tomography room before NMR readings aiming thermal equilibrium.

2.1.2. Irradiation procedures in high-energy beams

Radiotherapy clinical photon beams were used in this study. Varian® 2100C linear accelerators from Hospital do Câncer de Barretos (HCB) were used to produce photon beams of 6MV and 10MV. A Gammatron ⁶⁰Co unit from Hospital das Clínicas de Ribeirão Preto (HCFMRP) was used to study high energy γ-rays. Irradiations were made in a 10x10 cm² beam size with source-skin distance of 100 cm and 80 cm to x-rays and ⁶⁰Co, respectively. Samples were positioned at corresponding build-up depth of each beam in a water phantom of 50x50x50 cm³. Doses were delivered homogeneously to all samples. The range of dose rate investigated was from 0.8 Gy/min to 10 Gy/min.

2.1.3. Irradiation procedures in low-energy beams

Siemens Stabillipan ortovoltage clinical beams from HCFMRP were studied. Beams of nominal potential equal to 60kV, 100kV, 120kV and 250kV were investigated. Samples were positioned outside a water box 20cm high and 40cm length to guarantee backscattering conditions. Dose rate ranged from 0.5 Gy/min to 1.68 Gy/min. Irradiations with Iridium-192 (Varian GammaMed plus HDR source) were performed at HCFMRP, similar as previously described [7]. Dose-rate range considered...
in Iridium irradiations varies from 0.44 Gy/min to 10 Gy/min. Ionization chamber measures were made in each distance studied from the source to assurance dose values.

2.1.4. **NMR reading.**

Gel samples were read by relaxometry in a Philips 3.0 T MRI tomograph at HCFMRP. A head coil and a multi-spin echo sequence of 5 echoes, with echo-time of 20 ms and repetition-time of 4000 ms, were used. Total scan-time was 4.6 minutes for each set of two slices. Pixel size and slice thickness were 0.5 mm and 2.0 mm respectively. Three acquisitions were averaged to each scan aiming to increase reading accuracy. Transversal relaxation rates (R2) correlated to doses were calculated by Philips MRI software, normally used to medical diagnostic analysis. An acrylic box containing manganese chloride (0.04%) and sodium chloride (0.6%) solution was used to avoid abrupt differences in magnetic susceptibility. All NMR readings were made 12 hours after irradiation assuring thermal equilibrium. Data were analyzed using relaxometry process [8].

2.2. **Monte Carlo simulations**

Radiation transport in matter using Monte Carlo method as described in PENELOPE – 2008 code [9] was used to determine photoelectric, Compton, pair-creation and Rayleigh cross-sections of MAGIC-f polymer gel. Electronic transition probabilities of nine levels, from K to M5 atomic edges are considered in PENELOPE – 2008 code. Mass attenuation coefficients were also calculated and compared to water. Relative depth dose curves (PDD) were obtained experimentally and by simulation using the cross-sections determined in PENELOPE code to both 6 MV and 10 MV clinical beams.

3. **Results and Discussion**

MAGIC-f presented R2 equal to 0.47 s⁻¹ with a standard deviation of 0.06 s⁻¹ when not irradiated. This result indicates low levels of polymerization in non-irradiated gel 12 hours after being in MRI room temperature. Tissue equivalence of MAGIC-f gel was investigated theoretically comparing mass attenuation coefficient (μ/ρ) of gel and water and experimentally comparing PDD curves obtained to 6 MV and 10 MV beams, as shown in figure 1.

![Figure 1](image-url)

**Figure 1** – (A) Mass attenuation coefficients of MAGIC-f gel and water determined by PENELOPE code. Cross-sections to Compton, photoelectric, pair-production and Rayleigh scattering are referred by σ\_Compton, τ\_photoelectric, π\_pair and ρ\_Rayleigh symbols respectively; (B) Relative depth dose curves experimentally obtained for 6 MV and 10 MV beams compared to PENELOPE Monte Carlo simulations.
Sensitivity of gel ($\Delta R_2 / \Delta D$) varies on average 7.7% with energy, being 1.31 s⁻¹/Gy to the lower energy beam (60kV) and 1.42 s⁻¹/Gy to the higher energy beam studied (10MV). However, linearity with dose is present to all energies as can be seen in figure 2.a. Figure 2.b presents MAGIC-f sensitivity dependency with energy to all clinical beam studies. It is possible to observe that the standard deviation is significant greater to low energies than to high energies. This effect appears because the homogeneous area analyzed inside the tubes is different to each energy; grows with the energy. This methodology was adopted to guarantee that all average values of R2 were obtained in regions of gel that received doses between 99% and 100%. The corresponding regions were determined either by observing PDD curves simulated by Monte Carlo to each beam. Simulations consider monoenergetic beams with effective energy of each spectrum and attenuation caused by 1mm of glass positioned before gel.

Dose rate dependency (DRD) was investigated in all clinical beams studied using 2 Gy as reference dose. DRD was evaluated quantifying the mean signal variation corresponding to the same dose applied in gel with different dose rates. Figures 2.c and 2.d shows the DRD obtained to all beams studied. In a range from 0.44 Gy/min to 1.68 Gy/min MAGIC-f presents no significant variation between x-ray beams measurements (< 0.7% around 1.38 s⁻¹). In the range from 0.8 Gy/min to 10 Gy/min studied with energies between Iridium source and the 10 MV linear accelerator, gel presents mean variation of 1.8% around 1.40 s⁻¹.

Figure 2 – (A) Linearity of response evaluated to photon clinical beams of nominal energies of 60kV, 100kV, 120kV, 250kV, 6MV, 10MV and clinical sources of Ir-192 (HDR) and Co-60; (B) MAGIC-f sensitivity variation with energy; (C) and (D) Dose rate dependency assessed in a range from 0.44 Gy/min to 10 Gy/min.
Analyzing the linear behavior of gel and sensitivity variation with energy, it is possible to observe that proper calibration curves must be previously defined to each clinical beam. Gel response varies a maximum of 8.6% in the energy range studied and a maximum of 1.9% with the dose rate between 0.44 Gy/min and 10 Gy/min. These dosimetric dependencies evidence MAGIC-f as a suitable gel dosimeter to megavoltage Radiotherapy clinical beams. Applications in dosimetry of clinical kilovoltage beams and brachytherapy sources requires more careful, being viable when calibration curves were previously defined under the same irradiation conditions of the desired 3D dosimetric study.

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