Reproducibility study of normoxic polyacrylamide gel (nPAG) dosimeters

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Abstract. In this study, the overall accuracy of normoxic polyacrylamide gel (nPAG) dosimeters is considered. Different badges of nPAG are fabricated, poured in containers of glass and Barex™ and irradiated with a 6MV square photon beam. The polymer gel dosimeters were read out using MRI. The overall reproducibility and accuracy of nPAG gel dosimeters was determined by comparison with depth-dose profiles acquired with a Pin Point ionization chamber. Additionally, the effect of the container wall on the depth-dose profile and the effect of temperature changes before and after irradiation on the R2-dose response have been investigated. The average standard deviation and maximum deviation between 8 gel-measured depth-dose profiles and a depth-dose profile measured with an ionization chamber amounted to 0.543 Gy (2.5%) and 2.579 Gy (11.7%) respectively.

1. Introduction

Polymer gel dosimeters are radiation sensitive chemical dosimeters that were first proposed in 1950 by Day. In the 90s, gel dosimetry has been considered for the use of radiation dose verification in radiotherapy. Polymer gel dosimeters contain vinyl monomers dispersed in an aqueous gel matrix rendering these systems suitable for 3D dose verification. Early polymer gel dosimeters were highly sensitive to oxygen. Oxygen inhibits the radiation induced polymerization, as oxygen is as a free radical scavenger. In the first generation of polymer gel dosimeters oxygen was removed by flushing the gel with inert gases such as nitrogen and argon. In recent polymer gel dosimeters the effect of oxygen is compensated by the addition of an antioxidant. These polymer gels can be fabricated under normal atmospheric conditions and are therefore called ‘normoxic’. Studies have been performed to investigate the dosimetric properties (such as tissue equivalence, temperature dependence, energy dependence and dose-rate dependence) of different polymer gel dosimeters.

Until now polymer gel dosimeters have not been widely used in the clinic. To gain confidence in the applicability of a specific polymer gel dosimeter in the radiotherapy clinic, an overall reliability study is necessary. Such a study should not be restricted to one step in the dosimetry process (fabrication, irradiation, read out and calibration) but should encompass all steps. This study aims at providing an overall figure of reliability of an nPAG dosimeter by comparing a gel measured depth-dose curve with a corresponding depth-dose curve obtained with an ionization chamber (‘golden
standard’). Several volumetric gel dosimeters from different batches of nPAG gel are irradiated with a square field. Each experiment is accompanied by a proper calibration using a series of calibration vials irradiated in a water phantom at reference depth. Barex™ and glass have been used as cast material for the actual gel dosimeters.

2. Materials and methods

2.1. Preparation
All gel dosimeters studied in this work contained 8% (w/w) gelatin (300 bloom), 3% (w/w) acrylamide, 3% (w/w) N, N’-methylene-bisacrylamide and 3 mM tetrakis-hydroxymethylphosphonium-di-sulphate (THPS).

Gelatin is added in half of the amount of de-ionized water and is heated to 50°C until a clear solution is obtained. The monomers are added in the other half of the amount of water and the solution is heated to 60°C. After cooling down the monomers and the gelatin solution to 40°C, both solutions are mixed. The antioxidant is added when the solution is cooled down to 35°C. Subsequently the Barex™ box shaped (10 cm x 10 cm x 20 cm) and/or cylindrical (diameter = 10 cm, height = 35 cm) glass volumetric phantoms and sixteen glass test tubes (10 mm OD, 150 mm length, 1 mm thick wall) are filled with gel. After filling, all phantoms are placed in a large water basin at 35°C in order to obtain a uniform and equal cooling process in both calibration vials and volumetric gel phantom.

2.2. Irradiation
All gel phantoms are irradiated with 6MV photon beams delivered by a clinical liner accelerator (Elekta SL-18). The gel filled test tubes that serve as calibration phantoms are placed in a small water phantom at reference depth (5 cm) and are irradiated with a square beam of 10 cm-by-10 cm (SSD = 95 cm). The delivered dose in the calibration vials ranged from 0 Gy to 30 Gy in steps of 2 Gy. The volumetric phantoms were irradiated with 2000 Monitor Units (MU), with a field size of 5cm x 5cm and at an SSD of 95 cm.

2.3. MRI measurements
The volumetric gel phantom and test tubes, corresponding to the same batch were scanned together in a clinical MR scanner (Siemens, Magnetom Symphony 1.5T). A multi-echo sequence with 32 echoes and CPMG phase encoding scheme was used for the evaluation of irradiated polymer gel dosimeters. The imaging parameters are TR = 6 s, TE = 40 ms, field-of-view=220 mm for the Barex™ phantom and 240 mm for the glass phantom, matrix size=256 x 256 and slice thickness=10 mm. To eliminate errors in the determination of the R2 measurements caused by temperature changes, the irradiated gel was acclimatized in the MR scanner room prior to scanning for 24 hours. The homogeneity in the R2 maps was investigated by scanning a non-irradiated (‘blank’) volumetric gel with the same imaging parameters. The homogeneity was within 0.30%.

2.4. Ionization chamber measurements
To investigate the effect of the phantom wall material on the shape of the depth dose profile, dose measurements with a PinPoint ionization chamber were performed.

Figure 1. Set-up for measuring the influence of the phantom wall material on the depth dose profile (a). A close up of the Barex™ (b) and the glass sheet (c) are shown. The source-to-surface distance of both sheets was 80 cm.
performed. The ionization chamber was mounted on a stepper motor driven stage inside an automatic water phantom and was connected to electrometers. The source-to-surface distance was 95 cm. The initial position of the ionization chamber was at the water surface and along the beam axis. The phantom with ionization chamber was irradiated with a 5 cm-by-5 cm 6 MV photon beam corresponding to the same radiation configuration as in the gel experiment. A depth dose curve was recorded by driving the ionization chamber in the beam axis direction in the water bath with the beam on. To investigate the effect of the walls of the gel containers, a Barex™ and a glass sheet were placed between the collimator and the water phantom respectively (figure 1).

2.5. Combined ionization chamber / gel dosimetry experiment

A Barex™ phantom with two inserts for an ionization chamber was constructed (figure 2). The two Perspex inserts were constructed at 5 cm and 10 cm depth on opposite sides of the phantom so that the top of the ionization chamber was in the centre of the beam.

2.6. Temperature investigation

To investigate the effect of temperature variations in the gel after fabrication [1], three series of test tubes filled with the same batch of gel, were studied. Initially, all gel samples were stored in a water container (20 l) with the water temperature at 35 °C, the same temperature of the gel after fabrication. Temperature probes were inserted in one sample of each series. The temperature history of each of the gel samples is shown in figure 6a. The temperature of the first series of gel samples was increased to 25 °C for 4 hours before the irradiation (blue line in figure 6). The temperature of the second series was increased to 26 °C after irradiation and before the MRI acquisition (green line in figure 3). The third series was cooled normally (pink line). All gel samples were scanned together at 22 °C.

3. Results and discussion

3.1. Gel dosimeter calibration

In figure 3 the R2-dose response curve of different batches of nPAG dosimeters is shown.

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**Figure 2.** The Barex™ phantom with two inserts (a) for simultaneous dose measurement with an ionization chamber during irradiation (b).

**Figure 3.** R2 versus dose calibration plots for different gel batches (a). The colours correspond with the experiments discussed further. The slope of the R2-dose for the different experiments is shown in (b).
From figures 3a and b it can be seen that the slope of the R2-dose response of the different calibration curves does not differ significantly.

3.2. Depth dose: comparison with ionization chamber
The depth dose profile for each gel experiment is provided in figure 4a and b for gels contained in a Barex™ and glass container respectively. The black line in each of the figures corresponds to an ionization chamber measurement.

Figure 4. Comparison of gel measured (coloured lines) and ionization chamber measured (black line) depth dose curves for gels contained in a glass (a) and Barex™ container respectively. Corresponding percentage deviations of the dose calculated in the glass phantoms (c) and Barex™ phantoms (d) are also shown.

From figure 4a and b it can be seen that the depth dose response is different for the Barex™ and glass phantoms. The increase in measured dose at the top and bottom of the Barex™ phantom (figure 4b and d) may be attributed to oxygen contamination. The average standard deviation and maximum deviation of all gel-measured depth-dose profiles and a depth-dose profile measured with an ionization chamber amounted to 0.543 Gy (2.5% relative to the dose at isocenter) and 2.579 Gy (11.7% relative to the dose at isocenter) respectively in a region between 10 mm and 150 mm in the phantom.

3.3. Combined ionization chamber / gel dosimetry experiment
Average dose values at 5 cm and 10 cm depth in the phantom obtained with pin-point ionization chamber and gel dosimetry are listed in table 1.

Table 1. Average dose values recorded at 5 cm and 10 cm depth in the phantom using a Pin Point ionization chamber and gel dosimetry in the Barex™ and glass phantoms. The number between square brackets indicates the number of experiments. The values between round brackets indicate the standard deviation as calculated from the different experiments.

| Dose value | Pin Point chamber [#6] | Barex™ phantom [#4] | Glass phantom [#7] |
|------------|-------------------------|----------------------|---------------------|
| 5 cm       | 18.18 (± 0.15 Gy)       | 18.40 (± 0.72 Gy)    | 18.00 (± 0.66 Gy)   |
| 10 cm      | 13.35 (± 0.10 Gy)       | 13.47 (± 0.61 Gy)    | 13.13 (± 0.64 Gy)   |
The average dose values obtained with the nPAG gel in the Barex™ and glass phantoms correspond with the dose values measured with the ionization chamber to within 1.6 % at both depths. However larger deviations are seen amongst the different gel experiments.

3.4. Radiological influence of the container
From independent depth dose measurements with an ionization chamber no significant influence from the container material could be detected (figure 5).

3.5. Temperature investigation
The effect of temperature variations before and after irradiation of the nPAG gel dosimeter on the R2-dose response in the nPAG gel dosimeter has been investigated. R2-dose calibrations curves are shown in figure 6b. No significant effect of dose-R2 variations are found in the dose range of 0 Gy to 20 Gy. A slightly lower response is found at doses higher than 20 Gy in the gel samples that were heated to 26 °C after irradiation.

![Figure 5. Depth dose profiles recorded with an ionization chamber with different cast materials in place.](image)

Figure 6. Temperature history of three different sets of gel samples (a) and corresponding (same colors) R2-dose response curve (b).

4. Conclusions
The average standard deviation between depth dose profiles obtained with nPAG gel dosimeters and a depth dose profile recorded with an ionization chamber in the region between 10 mm and 150 mm depth in the phantom was found to amount 0.543 Gy (2.5%). The maximum dose difference amounted to 2.579 Gy (11.7%). A systematic dose deviation with ionization chamber measurements which increased with depth was found for gel dosimeters poured in a glass container. These variations could not be explained by a photon energy shift caused by the glass. Depth dose profiles in Barex™ phantoms are susceptible to large variations near the container wall which may be caused by oxygen contamination. Temperature variations in the nPAG gel dosimeter before and after irradiation were not found to have a significant effect on the R2-dose response.

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References
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