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3D polymer gel dosimetry using a 3D (DESS) and a 2D MultiEcho SE (MESE) sequence

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1. Introduction
Magnetic Resonance Imaging (MRI) polymer gel dosimetry is now an established methodology with numerous applications in radiotherapy. The main characteristic of polymer gel dosimeters is that when exposed to ionising radiation they polymerise. This radiation induced polymerisation increases the spin-spin relaxation rate \( R_2 = 1/T_2 \) of the material. \( R_2 \) is linearly correlated with the absorbed dose and can be used as an index of the absorbed dose in the material. When appropriately calibrated (\( R_2 \) vs absorbed dose response curve), gel dosimeters can be utilized for direct dosimetric measurements. \( R_2 \) measurements as assessed by 2D or 3D parametric maps can be a valuable means for assessing 2D and 3D spatial distribution of absorbed doses. In order for such purpose to achieve the utilization of direct 3D or reconstructed 3D MR sequences is to be considered. The utilization of 3D techniques in MRI data acquisition and post-processing analysis is a prerequisite especially when modern radiotherapy techniques (conformal RT, IMRT, Stereotactic RT) are to be used.

The aim of this work is to compare a 3D Double Echo Steady State (DESS) and a 2D Multiple Echo Spin Echo (MESE) sequence in 3D MRI radiation dosimetry using two different MRI scanners and utilising N-VinylPyrrolidone (VIPAR) based polymer gels.

2. Materials and methods

2.1. Gel preparation and Irradiation
The polymer N-vinylpirrolidone argon (VIPAR) gels were prepared according to the guidelines of Pappas et al [1] : (a) Monomer: N-Vinylpyrrolidone (4%w/w), (+99.9%, Sigma-Aldrich), (LD50, oral rats = 1.09 g kg\(^{-1}\), Merck Index), (liquid form), (b) Cross-Linker : N, N'-methylene-bis-acrylamide (4% w/w), (GIBCOBRL, 99.5%), (LD50, oral rats=0.39 g kg\(^{-1}\), Merck Index), (powder form) and (c) Gelatin : (5%w/w), (Type A/ 300 Bloom, Sigma) (powder form), in water environment (87%w/w). After production the gel was placed in cylindrical glass vials, with 18 cm length and 1.9 mm internal diameter, that were pre-filled with argon and then they were stored at room temperature.

Prior to irradiation all gel tubes were irradiated uniformly with a boost dose of 5 Gy with a 6 MV LINAC (30 cm x 30 cm field size) to ensure a linear response throughout the delivered dose region (12 – 48 Gy). Irradiations were performed 24 h after the fabrication of the gels. The irradiations were performed using a 6 MV x-ray linear accelerator (Primus LINAC, Siemens), calibrated to deliver 0.01
Gy per monitor unit, in water, at the depth of maximum dose (d = 1.5 cm) with SSD 100 cm and a field size 10 cm x 10 cm and with a dose rate 3 Gy min$^{-1}$. Solid Water Equivalent Material (SWEM) was placed around each vial in order to ensure appropriate build up (2 cm SWEM) and scattering conditions. Each VIPAR gel vial was irradiated with two 6 MV x-ray beams (field size 4 cm x 4 cm) placed 5 cm apart from each other utilizing two different LINAC gantry angles (0° and 180°). The absorbed doses, delivered at the 95% isodose for each cylindrical irradiated volume were 12, 18, 24, 30, 36, 42 and 48 Gy respectively.

**Figure 1.** SONATA MR System, (yr 2005) (a) 5 VIPAR Gel tubes (coloured). (b) VIPAR Gels, head coil and loader phantom. (c) Gels, head coil and loader prior to position inside the MR system.

**Figure 2.** R2 vs Dose calibration: (a) Vision system (yr 2000), (b) Sonata system (yr 2005). 1/DESS vs Dose calibration (c) Vision system (yr 2000), (d) Sonata system (yr 2005).
2.2. MR imaging technique

The gel tubes were scanned using two 1.5 T whole body superconducting imagers. (Vision, Siemens and Sonata, Siemens). MR scanning procedures were repeated every 7 days for a total period of one month post-irradiation for the Vision system. Measurements were repeated after five years using a new MR imaging Sonata system for the same gels utilizing the “same” sequences. The head coil facility was used in both systems. Head coils were loaded with loader phantoms (Fig. 1b) for better RF uniformity. MR scanning consisted of: (a) a 3D Gradient Echo (GRE) DESS sequence (TR/TE/FA, 18.2 ms / 6 ms / 90°) and (b) a 2D multi-slice-Multi-Echo train (16 echoes/slice) Spin Echo (MESE) sequence (TR / TE1 / TE16 / FA: 9800 / 50-800 ms / 90°). All slices were taken parallel to the test tubes long axis. A 1 mm slice cross plane resolution was used for the 3D DESS sequence with a total coverage volume of 4 cm. A 5 mm slice cross plane resolution was used for the 2D MESE sequence with a total coverage volume of 4 cm. Correlations of T2 relaxation rate (R2) values and 1/DESS Signal Intensity values with absorbed doses (dose calibration curves) were estimated in both systems (Fig 2a-d). MR sequence intercalibration curves were calculated using the 2D MESE and the 3D DESS sequences in both systems (Fig 3a,b).

3. Results and Discussion

Parametric T2 maps were obtained using the software supplied by the scanner manufacturer for both systems R2 vs Dose and 1/DESS vs Dose calibration curves were calculated for both systems (Fig.2). R2 values showed no statistical difference (t=-0.7, p=0.5) for the period of 5 yrs despite the fact of different MR system usage. Values of 1/DESS were statistically different (t = 7.2, p < 0.0001) for the same period of time under the use of different MR systems. R2 vs dose sensitivity of the dose calibration curves for the two MRI systems (Vision-yr2000, Sonata-yr2005) were (Fig 2) : (a) Vision-yr2000 : 0.100 (s⁻¹Gy⁻¹), (r = 0.99, p < 0.000001), (b) Sonata-yr2005 : 0.116 (s⁻¹Gy⁻¹), (r = 0.98, p < 0.0001), and 1/DESS vs Dose Sensitivity were (c) Vision-yr2000 : 0.050 (s⁻¹Gy⁻¹), (r = 0.98, p < 0.0005), (d) Sonata-yr2005 : 0.110 (s⁻¹Gy⁻¹), (r = 0.98, p < 0.0001).

MR sequence intercalibration (DESS vs T2 curves) were calculated for both systems (Fig. 3). MR sequence intercalibration curves (DESS vs T2) for the two MRI systems (Vision-yr2000, Sonata-yr2005) were (Fig 3) : (a) Vision-yr2000 : 139.5 + 0.498 (ms⁻¹), (r = 0.99, p < 0.000001), (b) Sonata-yr2005 : 66.4 + 0.255 (ms⁻¹), (r = 0.99, p < 0.000001). The 2D R2 measurements showed a linear relationship with absorbed doses in both systems. R2 Sensitivity (∼ 0.100 s⁻¹Gy⁻¹) did not change for the total period of five years (Fig. 2a,b). The 3D 1/DESS signals showed a linear relationship with absorbed doses in both systems. The 1/DESS signal sensitivity increased from 0.05 up to 0.110 (s⁻¹Gy⁻¹).
for the total period of five years (Fig 2c,d). The effect could possibly due to the newly designed DESS sequence on the Sonata system. Sequence intercalibration showed excellent results in both systems (Fig 3a,b). The 3D DESS sequence could be used in reference to a 2D MESE sequence (T2 measurements) for 3D dose measurements.

4. Conclusion
Both 2D R2 and 3D 1/DESS signals are linearly correlated with radiation doses for the range of 12-48 Gy using VIPAR gels. VIPAR gels showed practically stable characteristics (same R2 values) for a period of five years. R2 measurements can serve as a more robust technique applied for polymer gel radiation dosimetry. The 3D DESS sequence can be used either standalone or in combination with the 2D MESE sequence for 3D MRI radiation dosimetry. The 3D DESS has the advantage of speed and reliability.

5. References
[1] Pappas E, Maris T, Angelopoulos A, Paparigopoulou M, Sakelliou L, Sandilos P, Voyiatzi S and Vlachos L 1999 A new polymer gel for magnetic resonance imaging (MRI) radiation dosimetry *Phys. Med. Biol.* **44** 2677-2684