Imaging of dose distributions using polymer gels based on radiation induced changes in stiffness

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Abstract. Previously, dose determination based on radiation induced stiffness difference measurements has received no or very little attention. Here, a preliminary evaluation of a combined system for dosimetry based on radiation sensitive gels, ultrasonic elastography and a plane strain inverse algorithm is presented. A block of gel was irradiated along one of its axes producing stiff rod-like regions. The dose distribution found with quantitative ultrasound elastography was compared with a reference dose distribution measured with magnetic resonance imaging. In these early results, the high dose areas were clearly detected, while noise in the ultrasound measurement and strong regularisation in the inverse computing introduced shape distortions, noise in the dose estimates and problems estimating the correct dose contrast. Improvements in the experimental setup and inverse computing are possible, for example by acquisition of transversal ultrasound data, which could essentially reduce the noise and restrict direct influence of the experimental boundary condition on the dose estimation by providing additional information for inverse computing. Based on the preliminary results and the potential for improvement it is concluded that further investigations should follow to establish the potential of the rapidly developing field of elastography for measuring radiation dose based on radiation induced changes in stiffness.

1. Motivation and background

In radiation sensitive polymer gels, monomers polymerize and the molecular structure changes [1]. To date, for dose determination, predominantly irradiation-induced changes of the magnetic properties have been investigated, but this requires magnetic resonance imaging (MRI) [e.g. 2], which is expensive. A quick, cheap and easy-to-use alternative for measuring a dose-dependent property of these gels would be appreciated. Optical imaging may stand as an alternative, if it is used in combination with radiation sensitive plastics [3]. Indeed, optical transmission tomography systems are commercially available, but at considerable cost. With many ultrasound systems already in daily use in clinics, ultrasound methods could provide the benefits of an easy-to-use low cost alternative to MRI. One method that can take advantage of widely available ultrasound equipment is quantitative elastography, which combines the detection of strain distribution within a deformed object with an inverse problem solving algorithm to convert the measurement of displacement or strain into an estimated stiffness distribution. This is potentially useful in gel
dosimetry because the elastic properties of polymer gels change under irradiation [4]. This paper describes a preliminary evaluation of the potential of quantitative elastography for dose imaging. For simplicity, a plane strain inverse experimental setup and algorithm were employed, estimating dose only in a plane.

2. Material and methods
A deliberately tall (y-axis) and narrow (x-axis) block of radiation sensitive polymer gel (4 × 10 × 10 cm³ along x, y and z-axis, respectively) was produced by adding ultrasonic scatterers to the recipe by Fong et al [5]. It was then irradiated with a linear accelerator (Elekta SL series with RT desktop software) applying three small 10 × 8 mm² fields to produce a stiffness distribution that was complex in the x-y-plane but uniform along the z-axis, forming three rod-shaped regions along the z-axis. The output factor of the linear accelerator to calculate the radiation dose was not known for such small fields but was estimated to be approximately 18 Gy from measurements with diamond detectors. The block of gel was placed in a mechanical frame (figure 1), which allowed expansion in the x-direction but prevented z-direction motion. The block was compressed in the y-direction at a strain rate of 1 % per s up to a maximum strain of 6 %, while radiofrequency (RF) ultrasonic echo data were acquired at 14 Hz (Z.one™ with an L10-5 linear array, Zonare Medical Systems Inc.) in repeated compressions in the x-y-plane at three different z-positions. This was accomplished with the sample and the mechanical frame sitting in an oil bath. The oil decreased ultrasonic reflections from the boundaries of the gel, attenuated sound outside the sample and provided slippery boundaries between the gel and the compressor plates. Cross-correlation was applied to track the movement of the echo pattern in a small region within a reference RF-frame to its new position in the RF-frame that was acquired at a later time-point, and the process repeated for other reference regions to build up a local displacement map for a region of interest (ROI) in the centre of the scanned plane. An average was then taken of such displacement maps from the different planes. From the average displacement map, the stiffness distribution was determined using an iterative inverse algorithm [6] using the finite element method, in which the material in the ROI was modelled as an incompressible, linear elastic solid.

![Figure 1](image_url)

**Figure 1:** The radiosensitive gel was positioned in a frame that only allowed movement (compression or expansion) in the x-y-plane. The gel had been irradiated with three small fields through the x-y-face to create three rod-like, stiff, high dose regions along the z-axis.
Zero traction boundaries were chosen, as the tall and narrow shape of the sample was designed so that friction at the physical top or bottom boundary would not introduce additional stress in the ROI. For coping with the measurement noise and for turning this ill-posed inverse mathematical problem into a well conditioned problem, total variation diminishing (TVD) regularization was used; the regularization parameters were adjusted so that the algorithm produced an estimation with an homogeneously stiff background (an ‘a priori’ assumption, as it was not irradiated). For simplification, only the two-dimensional reconstruction described above has been accomplished. The plane strain experimental setup described in Figure 1 (uniform stiffness distribution along z and compression and expansion only in the x-y-plane) was chosen for such computation.

As a reference dose distribution and because the dose to the gel was only estimated,  magnetic resonance imaging (MRI) of the same x-y-planes was employed using a 1.5 T scanner (Philips Medical Systems, Best, The Netherlands). Also with MRI, it was established that the dose distribution was indeed uniform in z-direction and that there was no major oxygen contamination that had inhibited the radiation induced polymerisation. T2-weighted multiple-spin-echo sequences with 8 echo times from 20 to 160 ms, and a repetition time of 2 s were used to acquire data with a $1 \times 1$ mm$^2$ in-plane resolution and 5 mm slice thickness.

Independent calibration was performed for both MRI and quantitative elastography, each with four smaller cylindrical samples of gel, to relate Young’s modulus and the transversal relaxation rate ($R_2$) with dose, using MRI and a standard mechanical testing device (Instron™). For this purpose, two samples were homogeneously irradiated to 20.8 Gy and two were left non-irradiated.

Between production, irradiation, MRI and elastography measurement, the gels were stored in a fridge at approximately 9 °C. For each experiment, all gels were warmed to room temperature in a water bath for a sufficiently long time to reach temperature equilibrium.

3. Results

Figures 2 and 3 show the calibration results for the compression experiment and the MRI-measurement, respectively. For both modalities, the standard deviation from a series of compressions or $R_2$ measurements was computed. However such error bars are smaller than the symbols in the figure. The derived dose images are given in figures 4 and 5, again for both

![Figure 2: Young’s modulus versus dose relationship from mechanical measurements of the four homogeneously irradiated gels.](image1)

![Figure 3: Transversal relaxation rate versus dose relationship from MRI measurements of the four homogeneously irradiated gels.](image2)
imaging modalities. For the inverse computation, the regularization parameter was adjusted to best filter the noise in the measurement while conserving real stiffness contrast and edge sharpness.

4. Discussion
All three high dose areas were detected with good spatial accuracy (figure 4), however with strong shape distortions. The reason for the shape distortions is not known, but is thought to be associated with the combined effect of the TVD regularization and measurement noise due to ultrasound beam attenuation and reflection from the sides of the sample that was just 2 mm wider than the ultrasound transducer. Both effects decreased the signal to noise ratio in the ultrasound measurement. The smoothing characteristics of the regularization probably also caused the incorrect estimation of the dose contrast in the high dose areas, whilst the measurement noise also influenced the dose estimation in the background, especially at the sides. However, the top and bottom boundary regions were artefact-free, which indicates (as expected) that friction, if present at the gel-compressor plate boundary, did not introduce lateral (x-direction) stress in the region of interest.

Improvement of the experiment is possible, and is indeed planned for future work, for example by changing the sample geometry to minimise the reflections from the edges or by acquisition of ultrasound data from more than one direction to estimate lateral as well as axial displacement. Also the inverse algorithm is to be adapted to incorporate the additional lateral information, which will allow estimates for boundary conditions to be computed, rather than assuming that they are traction free. It is expected that such improvements will produce data with better signal-to-noise ratio while preserving real stiffness and hence dose gradients, and reduce or eliminate the influence of the boundary conditions.

Overall the technique shows potential if further improvement can resolve the difficulties described above. Although the method is currently being studied using experiments with controlled two-dimensional dose distributions it could be expanded to three dimensions (3D) by

![Figure 4: Dose distribution (in Gy) from ultrasound elastography and inverse algorithm.](image4)

![Figure 5: Dose distribution (in Gy) from MRI.](image5)
using a 3D model and by acquiring 3D image data with, for example, two-dimensional ultrasonic transducers. Such technology is currently under development and should enable arbitrary three-dimensional dose distributions to be determined.

5. Conclusion
We have visualized irradiation-induced changes of the elasticity in a polymer gel using ultrasound elastography and a plane strain inverse algorithm. Based on these preliminary results, and the known potential of further improvement, it can be anticipated that accurate determination of 3D dose distributions may eventually be possible.

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