Three dimensional radiation dosimetry in lung-equivalent regions by use of a radiation sensitive gel foam: Principles

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1. Introduction
Because of the lower electron density in lung-tissue the radiation induced interactions occur at different spatial scales as compared to water-density equivalent tissue. As a result, the dose distribution in lung can not be verified with the existing polymer gel dosimeters. In this paper, a lung-tissue equivalent gel dosimeter is proposed. The gel is basically a foamed polymer gel with a density between 0.25 and 0.35 kg/dm$^3$.

R2 images are acquired from the radiation sensitive gel foam that are subsequently converted to dose maps using calibration vials. However, it was found that the measured R2 is more susceptible to the microstructure of the gel foam due to susceptibility differences between the nitrogen bubbles and the interstitial gel phase. Magnetization transfer is another NMR contrast mechanism that is determined by the exchange of magnetization between different H-proton pools. The use of MT imaging for polymer gel dosimetry has been previously proposed [1]. In an MT experiment, part of the fast-relaxing H-proton magnetization on macromolecules is saturated. This can be achieved by use of one or more off-resonance saturation pulses. As magnetization of the H-protons on surrounding water-molecules is continuously transferred with H-protons on the polymers either by chemical exchange or by dipole-dipole interactions, this can lead to a decreased MR-signal.

![Figure 1](image1.png)

**Figure 1.** (a) Principle of magnetization transfer imaging. The polymer proton pool has a short T2 and thus covers a broader frequency lineshape than the free water proton pool. By use of off-resonance saturation RF-pulses part of the polymer protons is saturated. Because of magnetization transfer, polymer protons are exchanged with the water protons resulting in a decrease in longitudinal magnetization. (b) The observed relative signal decrease (MTR) is due to both direct saturation of the water protons ($M_{\text{dir}}$) and to magnetization transfer between the water proton pool and the polymer proton pool ($M_{\text{MT}}$).
The principle of the MT experiment is illustrated in figure 1 showing a frequency spectrum with both H-proton pool components. The observed magnetization in the MT experiment is $M_{\text{SAT}}$. The observed relative signal-decrease is called the magnetization transfer ratio (MTR). The MTR consists of two contributions: $M_{\text{dir}}$, the direct effect contribution which is due to the saturation of the water proton pool, and $M_{\text{MT}}$, the true magnetization transfer contribution due to magnetization transfer between the water proton pool and the polymer proton pool. The direct effect ($M_{\text{dir}}$) is experimentally determined from the signal intensity in a water sample ($M_{\text{H2O}}$). As a result, the true magnetization transfer ratio, $MT = M_{\text{MT}}/M_0$ is given by:

$$MT = \frac{M_{\text{MT}}}{M_0} = \text{MTR} = \frac{M_{\text{dir}}}{M_0} = \frac{M_{\text{H2O}} - M_{\text{SAT}}}{M_0}$$

(1)

2. Materials and Methods
The gel is composed of 12% (w/w) gelatin, 5% (w/w) methacrylic acid, 0.15% (w/w) sodium dodecylsulphate (SDS) and 10 mM Bis[tetrakis(hydroxymethyl)]phosphonium sulphate (THPS). The sol is fabricated along a procedure described elsewhere [2]. The sol is beaten with a household mixer until a creamy white viscous foam is obtained. Then the gel foam is poured into the final recipients and is placed in a rotating device and rotated during at least 5 hours during solidification. All gel foam dosimeters were irradiated with high energy photon beams (6 MV). Calibration test tubes were irradiated at a reference depth of 5 cm in water.

R2 images of the gel foam phantoms were obtained using a CPMG-based multiple spin-echo sequence on a 1.5 T MR scanner (Siemens, Symphony) equipped with a CP head coil. MT images were acquired using a home-written imaging sequence based on a spin-echo readout and preceded by a train of Gaussian-shaped saturation pulses of which the number and the offset frequency can be varied. The electron density and proton density were obtained by use of CT and proton-density MRI. In order to calibrate the proton density images a set of test tubes containing different concentrations of deuterium and water were used.

3. Results and discussion
The signal attenuation caused by magnetization transfer is dependent on both the number of saturation pulses and the frequency offset of the saturation pulses with a maximum dose sensitivity around 700 Hz (figure 2a).

Figure 2. (a) Magnetization transfer as a function of the offset frequency of the saturation pulses for gel foam samples irradiated to different doses. A difference curve of the 0 Gy and 20 Gy sample is also shown. A dose-MT response curve is shown in (b) obtained at a saturation pulse offset frequency of 500 Hz.
Figure 3. MT image (a) and corresponding dose image (b) of foam gel dosimeters. Upper Erlenmeyer is irradiated with a 4 cm-by-4 cm photon beam. The phantom in the lower part of the image is irradiated with 4 small photon beams (1 cm-by-10 cm) at angles of 45 degrees with respect to each other. A dose-depth profile of the upper Erlenmeyer is also shown (c).

MT images and corresponding dose images are shown in figure 3 for some gel phantoms. R2 images of the same gel foam phantoms were also obtained (not shown). It was found that the MT images were less dependent on the foam microstructure than the R2 images.

Bubble size related R2-relaxation dispersion was found in the gel foam. The relaxation dispersion is attributed to the magnetic susceptibility difference between the gel phase and the air bubbles in the foam. This difference causes microscopic magnetic field gradients that cause diffusion related attenuation of the MR signal. The diffusion weighting is proportional to the echo time spacing (TE = 2T).

Figure 4. Measured R2 as a function of the inverse echo time spacing showing relaxation dispersion in gel foam at several times after fabrication (a). Simulations are carried out to investigate the relation between the gel foam microstructure and the relaxation dispersion (b).

4. Conclusions
A gel foam is introduced as a potential three dimensional integrating dosimeter for verification of absorbed dose distributions in the lung. This study showed that magnetization transfer imaging might be preferable to R2 imaging. Diffusion-related relaxation dispersion that is characteristic for the foam microstructure has been observed in the gel foam dosimeters.

5. References
[1] Lepage M, McMahon K, Galloway G J, De Deene Y, Bäck S A J and Baldock C 2002 Magnetization transfer imaging for polymer gel dosimetry Phys. Med. Biol. 47 1881-1890
[2] De Deene Y, Vergote K, Claeys C and De Wagter C 2006 Three dimensional radiation dosimetry in lung-equivalent regions by use of a radiation sensitive gel foam: Proof of principle Med. Phys. 33 2586-96