Dosimetric verification of breathing adapted radiotherapy using polymer gel

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1. Introduction
In radiation therapy patient movement caused by respiration can be a major challenge to the ambition to deliver a high absorbed dose to the target volume while minimizing the dose to normal tissues. Large respiratory motion requires increased margins, which implies an increased risk of morbidity from late toxicity. It is therefore important to take respiratory motion into account when treating targets in the thorax region. Studies show that breathing adapted radiotherapy (BART) of breast and lung cancers reduces the dose to organ at risks, without compromising target coverage [1,5]. Respiratory gating is a BART method that allows radiation beam-on only during a certain pre-specified phase of the respiratory cycle. Depending on the length of the duty cycle, however, a certain dose smearing of the field edges due to movement during the beam-on time will remain [2]. Other factors, such as for instance accelerator output stability during switching on and off the beam, may also contribute to the uncertainty of the delivered dose [4]. In previous studies, ionization chambers, film and diode arrays have been used for dosimetric verification of gated dose delivery in 1D or 2D [2,3]. However, there is no experimental 3D data on the dosimetric benefit of respiratory gating. The aim of this study was to investigate the feasibility of using a 3D gel dosimeter for dose verification of breathing adapted radiotherapy.

2. Methods and materials
In this study a moving gel phantom, simulating small and large respiratory motions of the thorax region, was used. Two identical gel phantoms were irradiated. One was irradiated in a static position, and the other gel was irradiated repeatedly in a specific phase of its motion, representing gated radiotherapy. Since the moving device had both vertical and horizontal motion both a small and a large gating window could be investigated at the same time. The resulting data from the static and dynamic measurements was compared and analyzed. A gated CT-scan of another identical gel phantom was obtained, and the irradiation was reconstructed in a treatment planning system for comparison.
2.1. Gel preparation.
The gel was prepared under normal levels of oxygen using gelatine (8% w/w swine skin, 300 bloom, Sigma Aldrich), ultra pure deionized water (90% w/w), methacrylic acid (2% w/w, purity grade approx. 99%, Sigma Aldrich) and Tetrakis(hydroxymethyl)-phosphonium (2 mM, techn. 80% in water, Sigma Aldrich). The mixing procedure has been described elsewhere [7]. The gel was poured into 2 cylindrical glass bottles (gel phantom, Ø 10 cm, volume 1.2 l), 12 glass vials (calibration, Ø 1.5 cm, length 6 cm) and 4 test tubes (depth dose, Ø 1.6 cm, length 13 cm). Another identical cylindrical glass bottle, containing only water and gelatine, was used for gated CT scan and dose planning.

2.2. Moving gel phantom.
To simulate respiratory motion, the gel bottles were mounted on an in-house designed and constructed motion device (figure 1). The cyclic motion of the device had a total vertical motion extent of 7 mm and a total horizontal motion extent of 37 mm. The Varian Real-time Position Management (RPM) system was used to monitor the moving gel phantom, to gate the CT-scanner and to gate the treatment machine. The real-time position of the gel was obtained using an infrared camera system viewing the RPM marker box placed on the moving phantom. The RPM system allowed beam-on only in the pre-specified phase of the phantom motion cycle, which was set around the maximum of the motion extent. The duty cycle was set to 26% and both small (2 mm vertical motion) and large (10 mm horizontal motion) gating windows were investigated (figure 2).

2.3. Gated treatment planning and gated irradiation.
A single slice Siemens CT scanner was used together with the Varian RPM system to acquire images of the moving gel phantom during the phase that represented maximum extension. The dataset was input into the Eclipse treatment planning system (Varian Medical Systems) to plan two 6 MV, 6 x 6

![Vertical motion](image1)

**Figure 1.** Black bar indicates motion of the gel phantom, where the green fraction denotes beam-on and the red denotes beam-off. Not to scale.

![Horizontal motion](image2)

**Figure 2.** The Varian RPM system shows the horizontal and vertical motion of the gel phantom. Please note that the scale of the y-axes differs (10 mm/unit in both cases).
cm² beams with gantry angles 109° and 285°. The linac was set to deliver 600 MU/min. A dose of 2 Gy at the isocentre was chosen to minimize dose rate effects, cf. De Deene et al 2006 [8]. Two identical treatment plans were delivered; one for the uninterrupted beam treatment with the gel phantom in a static position, and one for the gated treatment with a moving gel phantom. During irradiation the first gel received 112 MU/beam in one uninterrupted fraction, while the gated treated gel received 10 beam-on segments with 11 MU each, plus one with the remaining 2 MU.

2.4. Magnetic resonance imaging and evaluation.
Magnetic resonance imaging was carried out using a 1.5 T Siemens Symphony scanner (Siemens Medical Systems, Erlangen, Germany). The images were acquired using a 32-echo multi spin echo sequence with inter-echo spacing equal to 10.6 ms. The repetition time was 4000 ms and the voxel size was 1 x 1 x 3 mm³. In-house developed software was used for image processing [6]. The measured dose profiles were normalized at the isocentre. To focus on the smearing effect the vertical profiles were matched at the beam edges, i.e. at 50% relative dose.

3. Results and discussion
Dosimetric measurements were undertaken to verify whether gel is a useful dosimeter for dose verification of breathing adapted radiotherapy. The dose-smearing effect around field edges for small and large gating windows was compared for the gated and static uninterrupted beam treatment. For the small gating window (2 mm) no smearing effect was detected (figure 3a). For the large gating window (10 mm), however, there was a significant smearing effect (figure 3b).

The static non-gated profiles satisfyingly agreed with the TPS-profiles. A difference between the vertical profiles of the static non-gated and gated data close to the surface of the gel phantom (inset in figure 3a) was not fully understood. The gated and non-gated gels were from the same batch, which suggests that this deviation was not caused by gel malfunction. Output stability and set-up deviations are parameters that could have an effect on the result. However, a study shows that for a 6 MV gated photon beam from a Varian linear accelerator, maximum deviations in output, flatness and symmetry are only a small fraction of the actual measured difference in the resulting data [4]. The differences between the vertical profiles will be further investigated, for example using other detector systems. A more realistic gel phantom, containing for instance a low-density gel insert [9] simulating lung tissue, could also be developed.

Figure 3. (a) Vertical dose profiles through iso centre in the isocentre slice. (b) Horizontal dose profiles through the gel phantom at the isocentre.
4. Conclusion
This study shows that it is feasible to use a 3D gel dosimeter for dose verification of breathing adapted radiotherapy. As long as the gating window can be kept small the smearing effect is negligible according to our measurements.

5. References
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