Reproducibility assessment of dynamically deforming DEFGEL in a respiratory motion phantom

R D Franich¹, J R Supple¹, B Lindsay¹, U J Yeo¹, P Lonski¹,², R L Smith¹,³, M L Taylor¹, L Dunn¹ and T Kron¹,²
¹School of Applied Sciences and Health Innovations Research Institute, RMIT University, Melbourne, VIC, Australia
²Physical Sciences, Peter MacCallum Cancer Centre, Melbourne, VIC, Australia
³William Buckland Radiotherapy Centre, The Alfred Hospital, Melbourne, VIC, Australia

E-mail: rick.franich@rmit.edu.au

Abstract. Conducting four-dimensional deforming dosimetry with a deformable gel dosimeter presents several challenges for implementation and interpretation of results. In this work, we describe a modification to a respiratory motion phantom to accommodate the DEFGEL dosimeter, and an evaluation of the reproducibility of the setup and deformation cycle. Setup errors are sub-mm while deformation reproducibility is typically less than half the CT voxel size (1 mm AP and LR; 3 mm SI). 4DCT confirms the absence of hysteresis.

1. Introduction
We have previously introduced the deformable gel dosimeter, DEFGEL, and demonstrated its use for direct measurement of dose accumulation in different states of deformation [1]. This has been shown to be an invaluable tool for the experimental validation of mathematical deformable dose accumulation approaches such as DIR–based dose warping [2].

To extend this to a range of situations involving more complex geometries and motions, we have adapted a QUASAR respiratory motion phantom (Modus Medical Devices Inc.) to accommodate the DEFGEL dosimetry element. The phantom was originally designed to sinusoidally oscillate a wooden lung-like component in a torso analogue. Our group has designed and implemented an upgrade to the phantom to enable more complicated motion profiles including actual patient breathing profiles recorded with Varian’s RPM system at the time of 4DCT [3].

In this work, we have created a custom module to allow the phantom to accommodate a DEFGEL in a piston-driven deformation component. We describe the modifications to the phantom and its drive motor, and the evaluation of its suitability for performing dynamically deforming dose integration.

The application of dynamic deformation to a 3D dosimeter [4] presents several complications for both implementation and interpretation of measurements. In common with, for example, in vivo dosimetry in the presence of movement, the measurement is critically dependent on the reproducibility of the geometry with respect to the dosimeter, source and phantom/patient. In the special case of a 3D dosimeter used to experimentally validate dose accumulation over multiple motion cycles, two factors must be verifiably reproducible:

(i) the position of the dosimeter in the phantom, and
(ii) the location and shape of the dosimeter as it is deformed over multiple cycles.
In this study, we describe the use of a DEFGEL phantom with embedded fiducial markers, combined with CT scanning, to quantify the reproducibility of sample positioning and cyclic deformation.

2. Method

2.1. Phantom modification
The QUASAR normally drives a wooden cylinder back and forth through a cylindrical hollow through the torso phantom. To deform a DEFGEL, a cylindrical insert, closed at one end, was locked in place with a clamp and a piston was made to be driven by the stepper motor to apply pressure to the DEFGEL. The closed-end cylinder liner, piston and clamp are shown in figure 1(a).

A DEFGEL, approximately cylindrical as shown in figure 1(c), is supported in the deformation chamber by two end-cups, indented to support the gel in place (see figure 1) and featuring air escape holes. The assembled QUASAR with the deformation chamber installed, and the cylinder liner clamped in place, is shown in figure 1(b).

Initial trials of the system identified a weakness of the QUASAR drive system that was not able to exert enough pressure on the DEFGEL to deform it significantly without the adjustable amplitude drive screw slipping. Thus a new drive screw coupling was fashioned (also included in figure 1(a)).

![Figure 1](image1.png)

2.2. DEFGEL with markers
To assess the position of the DEFGEL when installed in the chamber inside the QUASAR, and also later when being driven, a DEFGEL was made with 13 small aluminium fiducial markers (FM) embedded at the time of gel pouring. These markers, visible in CT imaging, have previously been used for motion and deformation assessment for the evaluation of deformable image registration algorithms applied to DEFGEL deformations [5]. The DEFGEL with fiducial markers is shown in figure 2.

![Figure 2](image2.png)
2.3. Reproducibility of sample positioning
The ability to reproducibly locate the sample inside the phantom is important for consistency especially in studies where pre-irradiation CT imaging of the phantom will be performed for the purpose of treatment planning system calculations to be compared to the measurements.

To assess this reproducibility and effectively assess any setup errors, the DEFGEL with markers was installed in the phantom and then CT scanned. The whole assembly was dismantled, re-assembled and re-imaged 4 times (for a total of 5 scans). The position coordinates of the markers were extracted using ImageJ and the mean error and standard deviation were recorded.

2.4. Reproducibility of deformation
The DEFGEL was deformed with driving amplitude of 20 mm, giving the individual markers various movement amplitudes between 0 and 20 mm (as the distal end of the DEFGEL from the piston is a stationary point). Computed tomography imaging was performed before and after 30 cycles. The marker coordinates were determined at the extrema of the motion and at the mid-point, with the phantom stationary to avoid motion artefacts confusing the marker positions.

2.5. Analysis of hysteresis of dynamic deformation
A 4DCT image set was acquired while the QUASAR dynamically deformed a DEFGEL by applying a 20 mm peak-to-peak sinusoidal piston motion. Marker coordinates were compared in complementary phases of the deformation to ascertain whether any hysteresis was present (i.e. compare the 10 % phase image to the 90 % phase image, 20 % to 80 %, etc.).

3. Results and Discussion

3.1. Reproducibility of sample positioning
The distribution of errors of the FM positions relative to the mean position is shown in Table 1, for each of the 3 coordinate directions. The sample could usually be positioned with sub-mm reproducibility with few exceptions. Coarse resolution of the CT imaging in the SI direction (slice thickness of 3 mm) resulted in a one-voxel error occurring.

|                           | AP  | LR  | SI  |
|---------------------------|-----|-----|-----|
| Mean absolute error (mm)  | 0.53| 0.44| 0.15|
| Standard deviation (mm)   | 0.23| 0.36| 0.89|
| Min. (mm)                 | 0.02| 0.01| 0.00|
| Max. (mm)                 | 2.21| 1.69| 3.00|
| Voxel dimension (mm)      | 1.17| 1.17| 3.00|

3.2. Reproducibility of deformation
Table 2 describes the displacement of all markers after 30 cycles of sinusoidal deformation in each of 3 positions: at each extremum of the motion (piston position +/- 10 mm) and half way between (0 mm). The reproducibility is consistent with the setup accuracy. The larger of the errors observed are a consequence of coarse resolution in the SI direction (slice thickness = 3 mm) and partial volume averaging of the markers in the CT images.
3.3. Analysis of hysteresis of dynamic deformation

Table 3 describes the displacement of all markers between phase images acquired at the same piston position but with opposite piston trajectories. No obvious hysteresis effects can be observed as the differences are consistent with setup accuracy and CT resolution.

Table 3. Marker displacements associated with hysteresis during deformation of the DEFGEL within the phantom. All measurements are in millimetres.

| Image phases compared (%) | AP | LR | SI |
|---------------------------|----|----|----|
|                          | Abs. mean | St. Dev. | Abs. mean | St. Dev. | Abs. mean | St. Dev. |
| 10 - 90                   | 0.29 | 0.42 | 0.25 | 0.18 | 0.21 | 0.20 |
| 20 - 80                   | 0.03 | 0.24 | 0.10 | 0.14 | 0.13 | 0.48 |
| 30 - 70                   | 0.42 | 0.04 | 0.24 | 0.11 | 0.22 | 0.27 |
| 40 - 60                   | 0.35 | 0.22 | 0.32 | 0.29 | 0.23 | 0.23 |
| Voxel dimension          | 1.17 | 1.17 | 3.00 |

4. Conclusions

It is imperative to quantify setup uncertainties and reproducibility of dosimeter position when using 3D dosimetry to evaluate dose redistribution arising from deformation. We have demonstrated a respiratory phantom modification that establishes sub-mm sample positioning, and deformation reproducibility typically within +/- 0.5 mm (AP & LR) and 2 mm (SI) over multiple cycles for measuring dose redistribution with DEFGEL.

5. References

[1] Yeo U J et al 2012 Med. Phys. 39 2203-13
[2] Yeo U J et al Med. Phys. 39 5065-72
[3] Dunn L et al 2012 Australas. Phys. Eng. Sci. Med. 35 93-100
[4] Baldock C et al 2010 Phys. Med. Biol. 55 R1-63
[5] Yeo U J et al 2013 Med. Phys. 40 101701