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Deformable gel dosimetry II: experimental validation of DIR-based dose-warping

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Abstract. Algorithms exist for the deformation of radiotherapy doses based on patient image sets, though these are sometimes contentious because not all such image calculations are constrained by appropriate physical laws. By use of a deformable dosimetric gel phantom, 'DEFGEL', we demonstrate a full 3D experimental validation of a range of dose deformation algorithms publicly available. Spatial accuracy in low contrast areas was assessed using "ghost" fiducial markers (digitally removed from CT images prior to registration) implanted in the phantom. The accuracy with which the different algorithms deform dose was evaluated by comparing doses measured with the deformable phantom to warped planned doses, *via* 3D g-analysis. Mean spatial errors ranged from 1.9 mm with a g_{3D} passing ratio of 95.8 % for the *original Horn and Schunck* algorithm to 3.9 mm with a g_{3D} passing ratio of 39.9 % for the *modified demons* algorithm.

1. Introduction

There is an increasing clinical awareness of and interest in anatomic deformation and the dosimetric consequences thereof. Understanding the cumulative dose distribution in deforming anatomy may be accomplished by deformable image registration (DIR) based 'dose-warping' [1], whereby the dose distribution is morphed according to the geometric changes of anatomy evident in the patient images. The warped distribution can then be added to previous fractions in order to interpret the accumulated dose [2, 3]. What is *not* well known is the degree to which this approach is acceptable. This work quantitatively evaluates the accuracy of DIR and presents an experimental validation of dose-warping, achieved using a fully three-dimensional, deformable, integrating dosimeter.

2. Materials and Methods

We previously reported on a deformable, tissue-equivalent, dose-sensitive gel phantom dubbed 'DEFGEL' [4] based on normoxic polyacrylamide gel [5]. The gel was poured into a thin latex membrane and moulded into a cylindrical shape of 46 mm diameter. To investigate displacement of the internal structure after deformation, sixteen Aluminium fiducial markers (FMs) were implanted into the DEFGEL during the gel setting phase. The DEFGEL was then deformed – in this case, by applying a bilateral compression of equal displacement from both sides.

Eleven different DIR algorithms available in the open source MATLAB toolkit DIRART [6] were assessed in terms of spatial accuracy by taking CT images of the DEFGEL in both the deformed (compressed) and undeformed states. The high contrast FMs were digitally removed from the images prior to performing DIR so as not to contribute to the calculation and lead to a biased accuracy assessment, and later used to evaluate accuracy in uniform intensity regions. The resultant deformation vector field (DVF) was then applied to the original image of the deformed DEFGEL (containing the FMs). The locations of the FMs in this *calculated* image were then compared to the known locations from the original image of the DEFGEL in its undeformed state.

To investigate the validity of DIR-based dose-warping, a four dynamic-arc stereotactic treatment adapted from a patient plan was delivered to the DEFGEL in the deformed state. The DEFGEL returned to its undeformed state and then the measured dose was read out *via* optical CT imaging [7-9]. The planned dose distribution (from TPS) was warped by applying the DVF obtained from DIR. The measured and warped doses were then quantitatively compared *via* 3D γ-analysis using criteria of 3 % dose difference and 3 mm distance to agreement (DTA).

3. Results and Discussion

The first assessment of the 11 DIR algorithms was to test whether the general shape of the boundary or contour of the DEFGEL phantom could reasonably be calculated. As shown in figure 1, not all algorithms tested were able to replicate the DEFGEL contour. With the exception of the *double force demons*, it was observed that the *optical flow* category and *demons* category algorithms performed reasonably well. Algorithms A-G are represented by a single calculated image as these results were visually indistinguishable. Only these seven algorithms able to reasonably register the DEFGEL contour were assessed further for accuracy within the uniform intensity region (i.e. A-G).

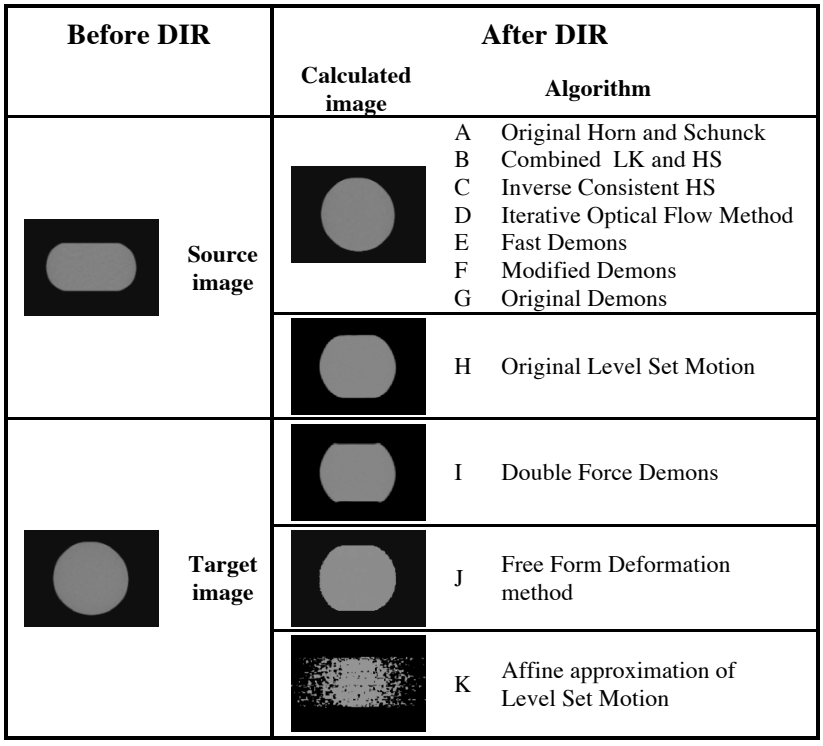

Figure 1: The calculated non-rigid registration of the source image to the target image for 11 DIR algorithms. The seven successful algorithms (A-G) are represented by a single calculated image.

Table 1: The mean error, $\bar{\Delta}$, standard deviation, σ_Δ and maximum error, Δ_{max} (values in parentheses are the maximum error as a percentage of the maximum deformation), of calculated FM positions.

Algorithm	$\bar{\Delta}$ (mm)	σ_Δ (mm)	Δ_{Max} (mm)
Original Horn and Schunck	1.9	0.9	4.3 (38%)
Modified Demons	3.9	1.1	5.6 (50%)

Table 1 shows the mean error, $\bar{\Delta}$, standard deviation, σ_Δ, and maximum error, Δ_{max}, of the 16 calculated FM positions for the best performing algorithm, *original Horn and Schunck*, and the worst performing algorithm, *modified demons*. The error is defined as the magnitude of the vector pointing from the actual position (determined from the original CT image) to the calculated position.

Figure 2 shows a comparison of calculated and measured doses delivered to undeformed and deformed DEFGELs. Transverse plane gamma maps (at D_{max}) are shown with 3 % / 3 mm criteria. The gamma map for the undeformed case i.e. comparison of planned and measured dose distributions in the absence of deformation, indicates the achievable agreement.

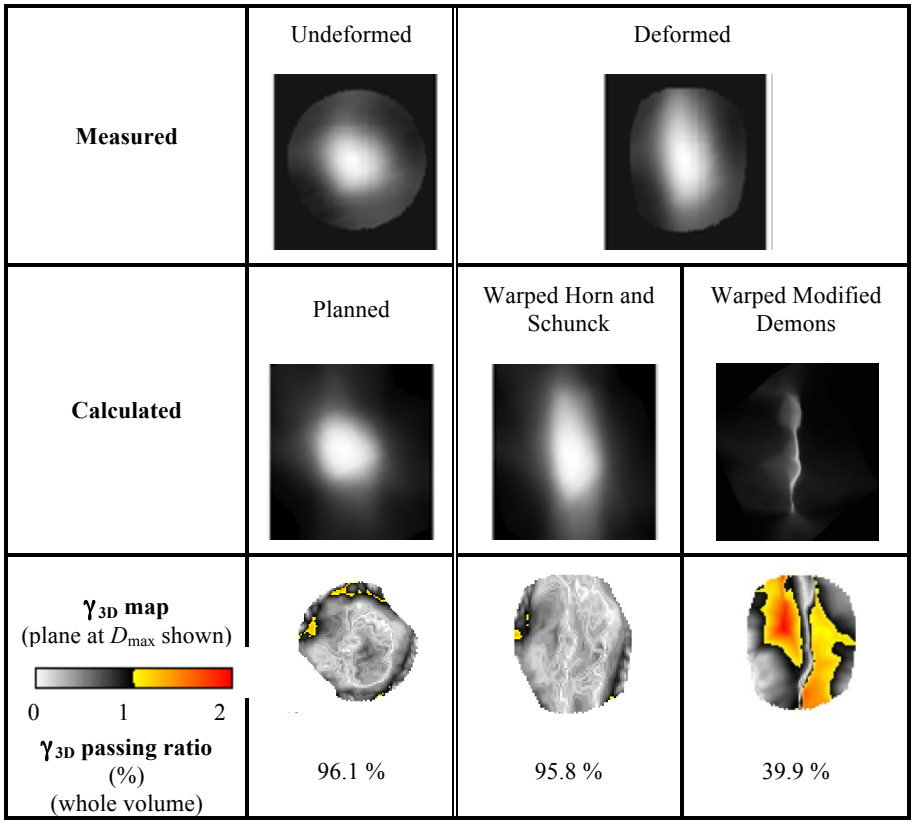

Figure 2: A comparison of calculated and measured doses delivered to undeformed and deformed DEFGELs. Transverse plane gamma maps (at D_{max}) are shown with 3 % / 3 mm criteria.

It is clear from the results for the *modified demons* algorithm that although a given algorithm may be able to accurately register the *contour* of an object, the accuracy *within* the uniform intensity region of such an object may be quite poor.

While the mean errors are small for both algorithms, the relatively large standard deviations and maximum errors indicate varying accuracy throughout the phantom. Although the maximum errors for both algorithms are larger than the DTA criterion, this does not necessarily mean those regions

would fail the γ-analysis. If these large errors were in an area of uniform dose they would likely pass as the dose at the reference point would still closely match that of the evaluated point. This is supported by the fact that most voxels failing are in high dose gradient regions. The γ_{3D} passing ratio of 95.8 % for the *original Horn and Schunck* algorithm is exceptionally good, being just 0.3 % less than the achievable accuracy indicated by the undeformed case (γ_{3D} = 96.1 %). While the maximum error for the *modified demons* algorithm was only slightly larger than that for the *original Horn and Schunck*, the mean error was larger than the DTA criterion, leading to a much lower γ_{3D} passing ratio of 39.9 %.

4. Conclusions

Using a tissue equivalent, mass and density preserving deformable gel (DEFGEL) phantom implanted with high contrast fiducial markers, we were able to demonstrate a quantitative evaluation process to systematically investigate the accuracy of DIR algorithms. Using a method of mathematically erasing the markers prior to registration, we were able to assess the accuracy of algorithms within areas of near-uniform intensity, rather than only at known landmarks. This eliminates bias introduced when using intensity-based algorithms. We have also demonstrated that dose-warping using deformation vector fields obtained *via* deformable image registration can accurately represent the true (measured) dose in a deformed medium.

5. Acknowledgements

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