Limitations of dose-volume metrics in deformable registration: implications for organs-at-risk in sharp dose gradients

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JULY 12–16 2020 VIRTUAL JOINT AAPM | COMP MEETING
EASTERN TIME [GMT-4]

INTRODUCTION

A fundamental understanding of dose mapping for highly conformal dose distributions that are mapped between deformably registered datasets is critically important for the implementation of dose accumulation and adaptive radiotherapy into the clinic. Adaptive radiation therapy takes into account tissue deformations that occur during the course of treatment in order to potentially alter the daily doses. To realize such a workflow, the image dataset of the day (target) is registered to a reference dataset (e.g. planning dataset) and the dose distribution of the day is mapped from the target to the reference. One such method, *direct dose mapping*, effectively uses the deformation vector field as a lookup map to directly populate the voxels of the reference dataset with the dose values from the target dataset.

AIM

To investigate the behaviour of reported dose-volume metrics (such as D2cc) under direct dose mapping in a commercially available treatment planning system.

THE PROBLEM OF D2CC

In this work, we consider the clinical example of the treatment of cervix cancer with brachytherapy, with bladder and rectum as important organs at risk. One of the most clinically relevant dose metrics for such structures is D2cc, the minimum dose to a region of tissue of given volume V = 2cc containing the highest dose values. It is crucial to realize that such a dose metric relies on local volume preservation of the DIR between target and reference, such that the cells contained in the 2cc of the target ROI are *mapped to the same cells* in the reference ROI. Smooth muscle tissue, including bladder and rectum, should be considered nearly volume preserving under deformations.

METHODS: THE JACOBIAN

One important biomechanical property of a deformable vector field DVF is its Jacobian which is defined as the determinant |J| of the deformation gradient tensor. It describes a measure of local volume change as follows:

$$|\mathbf{J}| \begin{cases} < 1 & \text{for local volume shrinkage,} \\ = 1 & \text{for local volume preservation,} \\ > 1 & \text{for local volume growth.} \end{cases}$$

METHODS: DEFORMATION SCENARIOS

Several fundamental deformation scenarios (DS) were studied in a commercial treatment planning system (RayStation v. 6.1.1.2. RaySearch AB, Stockholm). In order to generate DVFs that define a "perfect" deformable registration between structures, spherical and cylindrical test objects were created in precisely known spatial relationships on target and reference frames of reference. The object dimensions were chosen in line with clinically observed data for rectal and bladder wall deformations in cervix cancer treatments. By choosing appropriate dimensions of the test objects, volume preservation could be enforced onto the resulting DVFs. As an example, for the cylindrical objects, three different scenarios were investigated:

Deformation Scenario	Controlling ROI on Reference and Target	|J| = 1
DS1	Solid cylinders, r_ref 1.5 cm, r_Target 2.5 cm	No
DS2	Cylindrical shells, iso-thick 3 mm	No
DS3	Cylindrical shells, iso-volumetric	Yes

A single brachytherapy source was placed at various distances from the outer surface of the cylinder (DS1) and cylindrical shells (DS2, DS3), and the D2cc values were recorded on the target (before dose mapping) and on the reference (after dose mapping), see Figures 1 .

RESULTS

Figures 1 and 2 show the deformable vector fields and the Jacobi maps for the deformation scenarios DS2 and DS3, respectively. The cylinder ROI is small on the reference and large on the target. The DVF points from the reference to the target (yellow arrows) and the color bar indicates the magnitude of the vector field in cm.

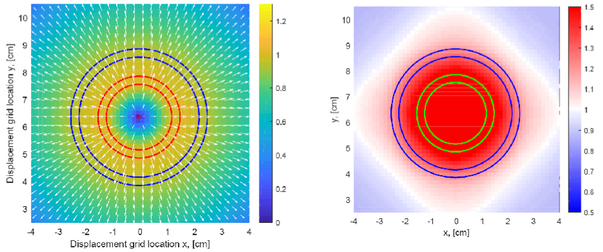

Figure 1 *(DS2): Left: DVF (yellow arrows) pointing from reference (small cylinder) to target (large cylinder). Right: map of Jacobian values in the same slice, indicating an expansion of the volume of the reference cylinder (green contours).*

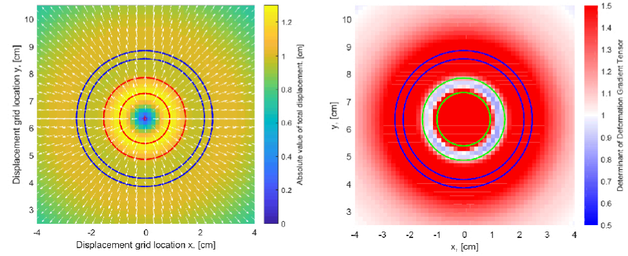

Figure 2 *(DS3): Left: DVF pointing from reference (small cylinder) to target (large cylinder). Right: map of Jacobian values, indicating local volume preservation of the reference cylinder (green contours).*

The right-hand side of the Figure 1 demonstrates that a deformation between iso-thick cylinders violates volume preservation, as expected. The DIR algorithm, however, is able to generate a nearly volume-preserving deformation between iso-volumetric cylinders (Figure 2, right).

A single Ir-192 10Ci brachytherapy source was placed at various distances from the outer surface of the cylinder (DS1) and cylindrical shells (DS2, DS3), respectively, and the D2cc values were recorded on the target (before dose mapping) and on the reference (after dose mapping), see Figure 3.

RESULTS

For DS1 and DS2 the differences in D2cc values are significant (up to between 40 and 50%), but not for DS3, as expected. The differences are due to the fact that the 2cc volume on the target is mapped to a significantly smaller volume on the reference due to the violation of local volume preservation.

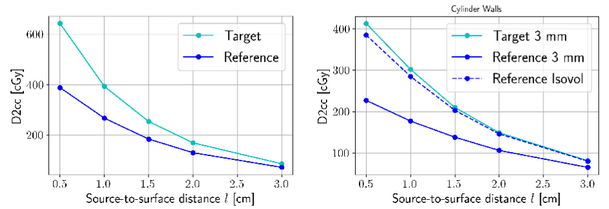

Figure 3*: D2cc values for various source to surface distances of the Ir-192 source from the target cylinder. Left: solid cylinder (DS1), right: cylinder walls (DS2, DS3).*

In addition, the differences in the maximum dose values on reference and target ROIs were significantly smaller than the differences between D2cc (not shown). Hence, it is important to realize that the differences seen in Figure 3 are not due to interpolation errors of the dose mapping algorithm, but rather the fundamental inconsistency of the dose metric D2cc in situations were volume preservation is violated.

CONCLUSIONS

DVH metrics such as D2cc rely on local volume preservation and are inconsistent for reporting dose values if this condition is violated. This is particularly prominent in high dose gradients and large deformations. DVFs must undergo careful quality control within accumulated ROIs to ensure consistent behavior with the expected biomechanics of the tissue in question.

CONTACT INFORMATION

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