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Evaluation of dose recalculation *vs* dose deformation in a commercial platform for deformable image registration with a computational phantom

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A B S T R A C T

Deformable image registration (DIR) is an important tool for mapping both dose and contours of a new set of planning images when recurrent, that is, adaptive radiotherapy, or further treatment, that is, re-treatment, is required. The aim of this study was to evaluate the need for plan recalculation in deformed anatomies and to develop a reliable workflow for validating the DIR algorithm to be applied to dose warping such as dose accumulation (DA) for adaptive radiation therapy, and dose summation (DS) in the case of re-treatment. A set of 3 computational phantoms was developed to validate the application of B-Spline-based registrations for dose mapping among the various computed tomography image data sets. Two different versions were defined for each phantom to simulate clinical needs: adaptive radiotherapy and re-treatment; a DIR was performed to obtain a displacement vector field (DVF) for dose applications. Comparison of calculated and deformed doses was carried out by means of known markers inside the virtual phantoms. The differences were evaluated using a 3% dose index as acceptance criteria. A paired Wilcoxon signed-rank test was carried out to test the statistical significance of differences within the markers. Significant differences were only observed for the deformed dose in the DA test; no significant differences were observed for recalculated dose values in the DA and DS tests. The dose index is in accordance with these results. The warping dose process obtained by registering various sets of images was validated; a recalculation approach seems to be more accurate for DA purposes and image-guided adaptive radiation therapy (IGART) applications.

Introduction

Deformable image registration (DIR) is an important tool for the development and clinical implementation of both image-guided radiation therapy and image-guided adaptive radiation therapy (IGART). It is a common practice in adaptive radiotherapy to collect cone beam computed tomography (CBCT) on a daily basis throughout the course of treatment. Because of daily variations, it is essential to register daily images with planning images and to deform contours and doses to monitor the actual dose administered to the organs.[1-6]

Whenever recurrent or re-treatment is required, it is particularly important, moreover, to map both doses and

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contours to a new set of planning images to evaluate the total dose administered to the patient. Much progress has recently been made in image registration algorithms, and the accuracy of DIR has been improved. Several commercially available systems with a black-box DIR algorithm have been validated by means of clinical landmark tracking[7-9] and phantoms with known deformations are mapped by carrying out contour or structure comparisons.[5,6,10-12] Differences in accuracy between algorithms were observed depending on the image region.[7,8,13-16] Structure correspondence is quantified with metrics such as average surface distance error, Hausdorff distance, and dice similarity coefficient (DSC).

Further studies on "dose warping"[17-29] have been carried out. It is possible to deform the dose distributions just as one can deform the images by applying the same registration matrix. In contrast to contour propagation, dose-mapping accuracy cannot be visually verified. Some studies concerning the effectiveness of this technique were carried out with homogenous 2D and 3D gel dosimeters[17-19] modified by physical compression and manipulation. Lack of high-contrast regions and dosimetric accuracy limits these DIR validation methods; however, only these 3D dosimeters are available for this purpose. Other authors have used point dose measurements, but only in homogeneous phantoms.[21] Hardcastle *et al.*[29] used landmarks to identify dose accumulation (DA) accuracy. Many studies have focused on using virtual phantoms to find an appropriate metric for estimating the uncertainty of dose warping due to uncertainties in DIR,[22] and currently there is much controversy concerning the most useful metric,[30] bearing in mind both density and dose gradients.

To make accurate estimates of the total dose delivered to the various organs of the patient, it is essential to establish a relationship between dissimilar volumes in different scan sets. Two dissimilar image sets can be matched with DIR.

Some issues limiting the application of dose warping such as tumor shrinking, enlarged lymph nodes, or patient weight loss represent some of the instances where tissue appears or disappears. In these cases, it is impossible to take into account biologic and biomechanical properties between 2 different image sets. It is therefore impossible to make a correct evaluation of the deformed doses either by means of contours/structures or dose-volume histograms.[23-25]

Moreover, the process of deforming doses by geometric (elastic) evaluation conceals the physical interaction between radiation and matter. Therefore, one must evaluate the estimation of dose deformation by means of an elastic process.[23]

The work aim is based on the same attempt from Yeo *et al.*, Janssens *et al.*, Salguero *et al.*, and Hardcastle *et al.*[17-19,21,28,29] to demonstrate the accuracy of dose warping. We want to compare the usefulness of dose recalculation in modified anatomies to improve the accuracy of DIR application in dose warping applications, using a computational approach with simplified but representative geometries. So the purpose of this study is to provide quality assurance to some basic clinical requirements regarding the accuracy of dose tracking during the course of treatment and dose summation (DS) for various treatment courses planned on various computed tomography (CT) sets using commercial DIR software.

Materials and Method

Deformable registration

Commercial software was tested with the method proposed. The VelocityAI software package (V2.7; Varian Medical Systems, Palo Alto, CA) has 3 options for 3D deformable registration algorithms: "Deformable Demons" (Demons), "Deformable Single-Pass" (DSP), and "Deformable Multi-Pass" (DMP). The DIR uses mutual information as similarity metrics. A multiresolution modified basis Spline (B-Spline) algorithm is used to iteratively modify a free parameter until the transformed source image optimally matches the target image. A couple of options are available to operators who want to optimize the settings of the registration parameters: grid size and limiting the registration space to a region of interest. Registration is also multimodal; for this study we only used x-ray CT images[31-34] to compare our results with those of other studies on registration accuracy within this imaging modality. Daily CBCT was not taken into account as we were analyzing the accuracy of the "recalculation" method in deformed anatomies instead of a simple deformation, bearing in mind that CT to CBCT registrations have been thoroughly reviewed in other studies.[35-37] Moreover, the daily dose is usually calculated on CBCT images for DA. Hounsfield unit inaccuracy in CBCT images might affect dose calculation accuracy (especially for inhomogeneous cases such as the lung) resulting in errors in DA with the recalculation approach.

Only the DMP algorithm has been evaluated for various scenarios of volume deformation. The registration space was optimized to obtain acceptable registrations for all scenarios under study.

In 2 cases, the warping dose process obtained by registering 2 sets of images was applied according to clinical needs. Anatomy variation during radiotherapy treatment is a well-known issue; therefore, many authors have suggested using a dose tracking/accumulation strategy.[2-6] A test for DA accuracy is presented in this study.

A common problem for many patients is to undergo recurrent and second treatments; therefore, a test of DS of various radiotherapy treatments is presented.

These 2 approaches are available in the software by means of semiautomated macros.