Physica Medica 31 (2015) 219–223

Contents lists available at ScienceDirect

Physica Medica

journal homepage: http://www.physicamedica.com

Original paper

Validation of a deformable image registration produced by a commercial treatment planning system in head and neck

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ARTICLE INFO

Article history:
Received 29 July 2014
Received in revised form
14 January 2015
Accepted 16 January 2015
Available online 7 February 2015

Keywords:
Deformable image registration
Adaptive radiotherapy
IMRT

ABSTRACT

In recent years one of the areas of interest in radiotherapy has been adaptive radiation therapy (ART), with the most efficient way of performing ART being the use of deformable image registration (DIR). In this paper we use the distances between points of interest (POIs) in the computed tomography (CT) and the cone beam computed tomography (CBCT) acquisition images and the inverse consistence (IC) property to validate the RayStation treatment planning system (TPS) DIR algorithm. This study was divided into two parts: Firstly the distance-accuracy of the TPS DIR algorithm was ascertained by placing POIs on anatomical features in the CT and CBCT images from five head and neck cancer patients. Secondly, a method was developed for studying the implication of these distances on the dose by using the IC. This method compared the dose received by the structures in the CT, and the structures that were quadruply-deformed. The accuracy of the TPS was 1.7 ± 0.8 mm, and the distance obtained with the quadruply-deformed IC method was 1.7 ± 0.9 mm, i.e. the difference between the IC method multiplied by two, and that of the TPS validation method, was negligible. Moreover, the IC method shows very little variation in the dose-volume histograms when comparing the original and quadruply-deformed structures. This indicates that this algorithm is useful for planning adaptive radiation treatments using CBCT in head and neck cancer patients, although these variations must be taken into account when making a clinical decision to adapt a treatment plan.

Introduction

One of the areas of greatest interest in radiotherapy is adaptive radiation therapy (ART), with deformable image registration (DIR) being the most efficient way of performing ART [1]. In order to clinically adapt a treatment plan the DIR must be validated, and so researchers and users must determine whether any dose changes observed are due to poor DIR algorithm accuracy or due to anatomical changes in the patient.

There are different methods to test DIR algorithms, including the use of: (a) landmarks or/and contours in two separate acquisition images from a patient's computed tomography (CT) scan or cone beam computed tomography (CBCT) [2,3], (b) physical and/or deformable dosimetric phantoms [4–7], or (c) dedicated software applications. [8–10], and each method has specific limitations. For instance, specific quality assurance (QA) software does not take image acquisition into account and the problem when using contours or landmarks is that point selection or structure creation is uncertain. Additionally, it must be added that only a few voxels are studied [2]. One of the general limitations of these methods is that all of them, except for dose deformable phantoms, give results in terms of distances whereas absorbed dose quantity is of most interest in radiotherapy [11]. Moreover, many hospitals do not have access to physical phantoms.

The distance between landmarks is widely used to calculate the accuracy of DIR algorithms [2,3], and the use of the inverse consistency (IC) property as a validation method has also been previously studied [12–14]. The IC property is very desirable in DIR algorithms, and validation studies using IC properties have shown that their value greatly depends on the specific DIR algorithm used [13,14]. For instance, suppose that image A is first deformed into image B and then B is deformed into A by an algorithm with an IC property. Consequently, this algorithm would have the same deformation vector fields (DVF) but these would be inverse to each

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http://dx.doi.org/10.1016/j.ejmp.2015.01.007
1120-1797/

other. In this case, if the structures/regions of interest (ROIs) are mapped from image A to image B using the first DVF (DVF_1) and later mapped back from B to A with the second DVF (DVF_2), both the original and the doubly-deformed structures should theoretically be equal.

In this study, we use the distances between points of interest (POIs) in the CT and CBCT acquisition images and the IC property to validate a the RayStation's treatment planning system (TPS) DIR algorithm (v.4.0.1.4, RaySearch Laboratories AB, Stockholm, Sweden) [12]. This study was divided into two parts: firstly, the distance-accuracy of the TPS hybrid DIR algorithm was ascertained by placing POIs on anatomical features in CT and CBCT acquisition images obtained for head and neck cancer patients, and the distances from these POIs mapped from the CBCT to CT were measured. Secondly, a new method was developed for studying the implication these distances have on the absorbed dose in distinct anatomical regions, by using the IC property of the DIR algorithm to compare the absorbed dose received by the structures contoured in the CT by the physician, and the structures which were quadruply-deformed by the hybrid DIR algorithm.

Materials and methods

DIR algorithms

The RayStation TPS has two DIR algorithms: the first one is the hybrid DIR which is based on a mathematical formula in which the registration is a non-linear optimization problem. The objective function is composed of four terms: 1) to maintain image similarity, 2) to keep the image grid smooth and invertible, 3) to keep the deformation anatomically reasonable when structures are present, and 4) a penalty term when structures are used. The second algorithm is the structure-based DIR that is based entirely on controlling the ROI and POI regions which are created within the planning CT (pCT) and CBCT. This study is focussed on validating the hybrid DIR algorithm because our aim was to validate the use of adaptive radiation using CBCT in an efficient way. It should be noted that although the invertibility condition of the vector field is assured with the hybrid RayStation algorithm (term 2 of the objective function), this does not mean that the IC property is met.

Patient anatomic data

For this study we selected five head and neck cancer patients. These patients were treated with step and shoot intensity-modulated radiation therapy (IMRT) and were positioned using an Elekta Synergy™ XVI image-guided radiotherapy-capable linear accelerator kV-CBCT imaging system (Crawley, UK; release 4.2.1). For each patient, pCT and three CBCT images were used to validate the DIR. The CBCT images were taken in the first and last weeks and during a week in the middle of the treatment to take into account the influence of possible anatomical changes in the patients on the accuracy of the DIR. The pCT images were acquired with a Siemens SOMATOM Sensation 16 CT scanner (Siemens AG, Erlangen, Germany), with a slice thickness of 3 mm and a pixel size of 1 mm, and were acquired using the previously mentioned XVI CBCT imager with a slice thickness and pixel size of 1 mm.

The deformable image registration process

The process of comparing planned dose vs. delivered accumulated absorbed dose with the TPS RayStation consists of three stages: 1) A rigid registration is performed with pCT and CBCT images; the DIR is then performed and thus the ROIs/POIs in the two registered images can be mapped in either direction (the CBCT to pCT or vice versa). 2) After the doses are calculated for different CBCT images, they are projected to the pCT by the DVF. 3) The plan is then adapted by comparing this information with the planned pCT dosimetry and the DIR dosimetry accumulated from the CBCTs.

Distance validation

To estimate the accuracy of the DIR distances, a radiation oncologist selected ten anatomically recognizable features in the pCT acquisition image (reference POIs) from the five head and neck cancer patients with the POI tool (Fig. 1), and selected them again in the same areas in the three CBCTs which were acquired. Half of the POIs were selected in soft areas and the other half were in rigid areas. Table 1 shows the areas where the POIs were placed. To reduce potential variation in operator POI position selection and to assess the observer variability, three different observers selected the same points on each of the CBCT and pCT images, using hard copies of pCT images as a reference. The accuracy of the hybrid DIR algorithm was quantified using the distance between the POIs mapped from CBCT to pCT and the POIs of the pCT. DIRs were performed using a grid size of 2.5 mm as recommended by the manufacturer and the contour from a skin patient was used as a control ROI. This external contour was used as a controlling ROI to force the deformable registration to focus more on matching the outer contour of the patient. The observer variability was quantified using the distance between the POIs of the radiation oncologist and the average POIs of the observers.

The four points per location (created by the three observers and radiation oncologists in pCT and in each of the CBCTs) were averaged to reduce inter-observer point placement variation and the average POI was mapped from the CBCT to the pCT using the DVF_1. The difference in the distances between the each POI projected from the CBCT and its corresponding reference POI determined the DIR distance accuracy. The TPS gave the coordinates of the POIs with a resolution of 0.1 mm. Six hundred (600) POIs were placed on the CBCT images to validate the DIR algorithm, and two hundred (200) were placed on the pCT images of the five patients to evaluate the observer variability.

To discard any suspected outliers in the observer data (the POI selected by the observer), suspicious results are discarded when the standard deviation of this value is at least four times the average standard deviation of the other results. Four times the average standard deviation is an arbitrary value which is commonly used for detecting outliers and is very unlikely to exclude any valid information.

Inverse consistency method validation

The purpose of the IC method is to determine the accuracy in dose values of the algorithm. As the hybrid algorithm does not have a perfect IC, the original and deformed structures (projected from the pCT to the CBCT followed by projection from the CBCT back to the pCT) do not coincide on the pCT image and therefore a difference is observed in the HDV. In this way, we can take advantage of the lack of IC to determine the dose accuracy of the hybrid algorithm in terms of doses rather than distances. In order to validate this method, we must ensure that the distances obtained using the IC method coincides with those obtained in the previous section since we assume that this distance represents the accuracy of the algorithm.

The process used to determine the accuracy of the IC in distances is as follows: the pCT POIs are projected from the pCT to the CBCT by DVF_2 and then back from CBCT to the pCT by DVF_1. To obtain distances comparable to the IC method and the accuracy of the algorithm, the process was performed twice, meaning that the