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Evaluation of deformed image-based dose calculations for adaptive radiotherapy of nasopharyngeal carcinoma

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A B S T R A C T

The ultimate goal of adaptive radiotherapy (ART) is to deliver truly customized radiation treatments. Currently, the quality of cone-beam computed tomography (CBCT) images is still inferior to that of conventional CT images in contour delineations and dose calculations for replanning purposes. This retrospective study aims to evaluate the dosimetric accuracy of using deformed conventional CT images for dose calculations, in the hope of inferring the feasibility of ART using planning CT (PCT) images that deformed to up-to-date CBCT images for patients with nasopharyngeal carcinoma (NPC). Thirty consecutive patients with NPC who had undergone 1 replan in their radiotherapy treatments were selected. The pretreatment PCT images were deformed to match the mid-treatment PCT images by deformable image registration. The same volumetric modulated arc therapy plan was then calculated on the deformed PCT images. The resulting dose distributions and dose volume histograms of the tumors and organs at risk (OARs) were compared with the original plan. Five dose levels, $D_{98\%}$, $D_{95\%}$, $D_{50\%}$, $D_{5\%}$, and $D_{2\%}$, were recorded for 9 NPC targets. Four dose levels, D_{max}, $D_{10\%}$, $D_{50\%}$, and D_{mean}, were recorded for 15 OARs. The greatest percentage difference in observed dose for $D_{98\%}$, $D_{95\%}$, $D_{50\%}$, $D_{5\%}$, and $D_{2\%}$ of the targets were 1.71%, 1.55%, 0.64%, 0.97%, and 1.13%, respectively. The greatest percentage difference in observed dose for D_{max}, $D_{10\%}$, $D_{50\%}$, and D_{mean} of the OARs were -26.51% (left optic nerve), -17.06% (left optic nerve), 56.70% (spinal cord), and 18.97% (spinal cord), respectively. In addition, 29 of 45 (64%) dosimetric end points of the targets showed statistically significant dose differences ($p < 0.05$) between the original plan and the plan calculated on deformed images. Forty-nine of 60 (82%) dosimetric end points of the OARs also showed statistically significant dose differences ($p < 0.05$). Dose calculations using deformed PCT images could result in significant dose uncertainties in target volumes and OARs. Larger dose deviations were found in OARs in comparison with target volumes. The spinal cord and optic nerve showed the greatest percentage dose differences and the clinical significance has yet to be determined. Deformable registration error was believed to be the problem causing the dose deviations. Owing to unknown clinical significance

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of dose deviation results obtained from this study, a conventional CT scan is still required for replanning in patients with NPC who are experiencing significant anatomical changes during the course of radiation treatment.

Introduction

Modern radiotherapy treatment techniques such as intensity modulated radiotherapy, volumetric modulated arc therapy, or helical tomotherapy can deliver highly conformal radiation doses to the target volume while sparing the surrounding critical organs. Any changes in the size and location of the tumor or normal tissues may lead to significant underdosage of the target volume or overdosage of critical organs. Adaptive radiotherapy (ART) is a novel approach to correct for these tumor and normal tissue variations at any point during the course of treatment to maintain optimal target dose coverage and critical organs sparing. Xerostomia, sore mouth, and difficulty swallowing are common side effects for patients with nasopharyngeal carcinoma (NPC) undergoing radiotherapy treatments, and these side effects can contribute to weight loss. ART is, therefore, particularly important for patients with NPC as these anatomical variations can be large during a 6- to 7-week course of treatment because of fluctuations in body weight or disease response. Barker *et al.* quantified the geometric and volumetric changes of the target and critical structures in 14 patients with head and neck cancer undergoing definitive radiotherapy. Their results showed that significant changes were observed after 3 to 4 weeks of treatment in which the rate of volume regression of target was 1.8% per day and the rate of volume reduction of parotid was 0.6% per day.[1] As a result, it is anticipated that ART could frequently be applied on these patients to maximize the therapeutic ratio of the treatment. A replanning approach, however, will require additional computed tomography (CT) acquisition, which will increase workloads to the radiotherapy and extra radiation dose to the patient.

Several previous studies have proven the dosimetric benefits for patients with head and neck cancer undergoing 1 or more replans throughout the course of treatment.[2-4] The anticipated benefits of ART are desirable; however, ART is also a complicated process that is still in its early stage of development in terms of the method, workflow, implementation, and clinical significance. These factors vary by center,[2,5,6] and there are still many problems that need to be resolved at present. For example, daily new intensity modulated radiotherapy plan is basically impractical because it is time-consuming and labor-intensive, which requires reimaging, recontouring, replanning, and new quality assurance measurements. Faster replanning methods are needed if personalized planning is to be implemented. More research needs to be carried out to optimize the benefits of ART to the patients without increasing the workload to the radiotherapy.

One method that is being widely investigated to replace the need of acquiring new planning CT (PCT) is to use the on-board kilovoltage cone-beam CT (CBCT) images for dose calculation.[7-11] Yang *et al.* and Yadav *et al.* both studied the accuracy of CBCT-based dose calculation to determine the feasibility of using these images for the purpose of dosimetric checks.[7,8] Their results showed that it is acceptable to use CBCT images for dose calculation. Two studies, 1 by Ding *et al.* and the other by Hu *et al.*, further investigated the feasibility of using CBCT for treatment planning in ART.[9,10] Their results were also in good agreement that CBCT-based treatment plans were dosimetrically comparable with CT-based treatment plans. Although the results sounded promising, the authors of both studies suggested that CBCT images should be used only for dosimetric validation at the moment. An additional PCT will still be necessary to perform replanning because of the suboptimal image quality of CBCT. The inferior image quality of CBCT because of scattered radiation may hinder the oncologist's ability to accurately delineate the tumor and critical organs. In addition, the slow gantry rotation speed of the linac makes the CBCT more prone to motion artifacts.[7] Another limitation of CBCT is the limited field of view (especially in the longitudinal direction), which renders the resultant images nonusable for treatment planning.[10] Given these limitations, our study explored the possibility of using a deformed CT image for dose calculations in order that up-to-date tumor and normal tissue information can be used for treatment planning without acquiring a new PCT while maintaining acceptable image quality for accurate delineation.

In this study, Phase 1 (Ph 1) PCT images were deformably registered to match the anatomy at Phase 2 (Ph 2) PCT images. The rationale for not using CBCT images to perform the deformable image registration (DIR) was that the PCT-CBCT registration error could be a potential confounding variable. A CT-CBCT registration is known as a quasi-intermodality case, and Zhen *et al.* acknowledged that there are uncertainties and errors existing in such DIR.[12] Although the underlying physical acquisition process for the CT and CBCT images is identical, the acquisition geometry is different, which causes the CBCT to be corrupted by noise and artifacts.[13] The purpose of this study was to first evaluate the accuracy of using a CT-CT DIR (*i.e.*, images of the same modality) for dose calculations so that the result could