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Analysis of Dosimetric Impacts of Cone Beam Computed Tomography–Based Volumetric Modulated Arc Therapy Planning

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ABSTRACT

Objective: To quantify the Hounsfield unit (HU) variations between computed tomography (CT) and cone beam CT (CBCT) and study its impact on volumetric modulated arc therapy (VMAT) plans.

Methods: HU number variations in CT and CBCT images were evaluated using the Catphan-504 phantom, and changes in seven different materials within the phantom (air, polymethylpentene, low-density polyethylene, polystyrene, acrylic, Delrin, and Teflon) were studied. The HU variations in half-fan and full-fan modes of CBCT were evaluated. The effect of variations in the shape of the body cross sections was assessed by reducing the body of the Catphan by 0.5 cm and 1.0 cm. CBCT-based VMAT plans in 27 patients (10 prostate, 10 brain, and 7 head and neck (HN)) were compared with corresponding CT-based plans. The dosimetric variations were assessed referring to different points on the dose volume histogram ($D_{5\%}$, $D_{50\%}$, and $D_{95\%}$ for PTVs and $D_{1\%}$, D_{max}, and D_{mean} for organs at risk). The relative percentage of difference (ΔD (%)) between CT- and CBCT-based VMAT plans were examined on these points. To evaluate the dosimetric accuracy, dose distributions were compared using Omnipro-I'mRT software. The VMAT plans were evaluated based on 3 mm-3%, 2 mm-2%, and 1 mm-1% gamma criteria.

Results: The HU difference in CT and CBCT was highest for air, Delrin, and Teflon, whereas the difference was less than 20 HU for the other materials. The dose volume histograms of both CT- and CBCT-based plans were in excellent agreement in both phantom and patients, except in HN cases where the difference was 7%. The average 3 mm-3% gamma pass points in brain, prostate, and HN patients were 97 ± 0.2%, 96 ± 0.06%, and 93.3 ± 1.1%, respectively. The gamma pass rates reduced to 88.8 ± 0.06%, 91 ± 0.04%, and 79 ± 6% in 2 mm-2%, and further declined to 76.6 ± 0.09%, 75.2 ± 0.5%, and 60 ± 6% using the stringent 1 mm-1% gamma criteria for brain, prostate, and HN cases, respectively.

Conclusion: Based on the results of this study, it is our belief that CBCT images can be used as a tool for evaluating the dosimetric variation in patient VMAT plans.

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RÉSUMÉ

Objectif : Quantifier les variations d'unités Hounsfield (HU) entre la tomodensitométrie (TDM) et la tomodensitométrie à faisceau conique (dans les imagesTDMFC) et en étudier l'incidence sur les plans d'arcthérapie par modulation de volume (VMAT).

Méthodologie : les variations du nombre d'UH dans les images TDM et TDMFC ont été évaluées à l'aide du fantôme Catphan-504 et les changements dans les sept matériaux différents du fantôme (Air, PMP, LDPE, Polystyrène, Acrylique, Delrin et Teflon) ont été étudiés. Les variations d'unités Hounsfield en mode demi-faisceau et plein faisceau deTDMFC ont été évalués. L'effet des variations dans la forme des coupes transversales du corps a été évalué en réduisant le corps du Catphan de 0,5 cm et 1,0 cm. Les plans de VMAT en base TDMFC de 27 patients [10 cancers de la prostate, 10 cancers du cerveau et 7 cancers de la tête et du cou (TC)] ont été comparés avec les plans correspondants en base TDM. Les variations dosimétriques dans les structures ont été évaluées par rapport à différents points sur l'histogramme dose-volume(HDV) ($D_{5\%}$, $D_{50\%}$ and $D_{95\%}$ pour les PTV et $D_{1\%}$, D_{max} et D_{moy} pour les OAR). Le pourcentage relatif de différence (ΔD (%)) entre les plans de VMAT en base TDM et TDMFC a été examiné sur ces points. Afin d'évaluer l'exactitude dosimétrique, les distributions de dose ont été comparées à l'aide du logiciel Omnipro-I'mRT. Les plans de VMAT ont été évalués selon le critère the 3 mm-3 %, 2 mm-2 % et 1 mm-1 % gamma.

Résultats : L'écart en UH entre la TDM et la TDMFC était le plus élevé pour l'air, le Delrin et le Teflon, alors que la différence était inférieure à 20 UH pour tous les autres matériaux. Les HDV des plans basés sur la TDM et la TDMFC présentaient un excellent accord entre le fantôme et les patients, sauf dans le cas des cancers

TC où l'écart était de 7 %. Les points de contrôle moyens à 3 mm-3 % gamma pour les patients ayant un cancer du cerveau, de la prostate et TC étaient respectivement à 97 % ± 0,2 %, 96 % ± 0,06 % et 93,3 % ± 1,1 %. Les points de contrôle gamma diminuaient à 88,8 % ± 0,06 %, 91 % ± 0,04 % et 79 % ± 6 % en 2 mm-2 % et à 76,6 % ± 0,09 %, 75,2 % ± 0,5 % et 60 % ± 6 % en appliquant le critère strict 1 mm-1 % gamma respectivement pour le cancer du cerveau, de la prostate et TC.

Conclusion : Sur la foi des résultats de cette étude, nous croyons que les images TDMFC peuvent être utilisées comme outils pour évaluer la variation dosimétrique dans les plans de VMAT des patients.

Keywords: VMAT; Cone beam computed tomography; Hounsfield unit; DVH

Introduction

In the new era of radiotherapy, kilovoltage cone beam computed tomography (CBCT) has become a potential tool for evaluating deviations in positioning set up and changes in organ dimensions during the course of treatment. These images provide the necessary anatomic information needed for correcting set up deviations [1–5]. The CBCT images offer a better picture of soft tissues by providing sufficient soft tissue contrast; thus enabling visualization of the target on a daily basis, compared with the traditional method of using megavoltage (MV) portal images. Positioning of the patient is confirmed after matching the soft tissues and bony structures in CBCT images to those in planning CT, which is not possible in MV imaging systems. Furthermore, it helps to assess the anatomic changes in patients due to weight loss, tumour shrinkage, and soft tissue changes [6, 7]. Changes in anatomy and organ motion can lead to variations in the dose distributions calculated based on planning CT. These changes may end up with a daily dose, which does not match the prescribed dose. Therefore, the CBCT data acquired before treatment can be used as a potential tool for recalculating daily treatment plans based on daily patient anatomy [8–16]. This adaptive planning allows us to modify the radiation therapy course based on the delivered dose. However, because of scattering artifacts and limitation in the reconstruction of CBCT images, it shows deviations in the Hounsfield unit (HU) from that of the planning CT [9, 11, 12, 15, 17].

There are several methods described in the literature for correcting HU variations in CBCT images. The simplest method is creating a HU-relative electron density curve specific to CBCT [13]. Another common method is correcting the CBCT by mapping it with the planning CT information [9]. In addition, there is a projection scatter correction method, which reduces the scatter before CBCT image reconstruction [18–20]. However, studies by Yoo and Yin and Lee et al concluded that HU variation in CBCT images acquired using Varian On-board Imager (OBI) system (Varian Medical Systems, Palo Alto, CA) showed only a small variation (less than 10 HU) [8, 14]. Therefore, they tried to recalculate the CT-based plan directly on the CBCT, without any correction. Their investigations revealed that intensity-modulated radiotherapy dose variation between the CT- and CBCT-based dose calculations are within 3%. There was positive correlation between the CT- and CBCT-based IMRT plans. In contrast, the Elekta Synergy (Elekta limited, Crawley, UK) CBCT x-ray volume imaging (XVI) system showed larger deviations in HU, which makes correction strategy necessary [11, 15].

Most of the studies dealing with dose reconstruction on CT and CBCT images are done on three-dimensional conformal radiotherapy and IMRT [9, 11–14, 16]. There are other techniques, like volumetric modulated arc therapy (VMAT), which need to be evaluated on the CT- and CBCT-based dose calculations. RapidArc (Varian, Palo Alto, CA) is a VMAT technique based on the simultaneous optimisation of multileaf collimator shapes, dose rate, and gantry rotation speed [21]. The VMAT plan relates to delivery of a single or double arc, which moves around the patient's body. In this work, the effect of the dosimetric difference between CT-based and CBCT-based VMAT planning in three different patient scenarios, namely brain, prostate (pelvic region), and head and neck (HN), were studied.

Materials and Methods

HU Comparison Between CT and CBCT Images

For the comparison of HU between CT and CBCT images, a Catphan 504 phantom (The Phantom Laboratory, Salem, NY) was used. The Catphan contains seven different materials: air (0 gm/cm^3), polymethylpentene (0.83 gm/cm^3), low-density polyethylene (0.92 gm/cm^3), polystyrene (1.05 gm/cm^3), acrylic (1.18 gm/cm^3), Delrin (1.41 gm/cm^3), and Teflon (2.16 gm/cm^3) [22]. The HU values of these materials range from approximately −1,000 HU to +1,000 HU. CT images of the Catphan were acquired using a GE Light-speed CT simulator (GE Medical Systems, Milwaukee, WI). These images were imported to Eclipse (Varian Medical Systems, Palo Alto, CA, version 10) treatment planning system. CBCT images for this study were generated using a kV x-ray tube and an amorphous silicon detector (aSi500, PortalVi-sion, Varian Medical Systems) mounted on Varian Clinac iX linear accelerator, called OBI. The system is attached to the machine through a robotically controlled arm. Using this system, CBCT can be acquired in two modes: full-fan mode and half-fan mode. As per the manufacturer's suggestion, an additional filter called "Bow-Tie" filter is used to increase the image quality. There are two filters, namely full Bow-Tie and half Bow-Tie, used for the full-fan mode and half-fan mode, respectively. CBCT images of the Catphan were acquired for half-fan mode