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Review Article

Cone Beam Computed Tomography: The Challenges and Strategies in Its Application for Dose Accumulation

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ABSTRACT

Online image guidance using cone beam computed tomography (CBCT) has greatly improved the geometric precision of radiotherapy. Changes in anatomy are common during a course of fractionated treatment, resulting in dose deviation from the planned distribution. There is increased interest in performing dose accumulation to compute the actual delivered dose and to adapt the treatment when necessary. This can be achieved by delineating the volume of interest and by generating "dose of the day" through dose computation on the CBCT. However, the image quality and the accuracy of the CT number of CBCT are deemed to be inferior to fan beam CT, which increases the uncertainty associated in this process. A review of literature was conducted to assess the reliability of and to examine strategies for overcoming the challenges in using CBCT for volume delineation and dose computation. The review demonstrates that the uncertainty varies across body sites, and different strategies have been recommended to generate comparable results to images from CT simulators. This facilitates a better understanding of the potential and the limitation of using CBCT for dose accumulation.

RÉSUMÉ

Le guidage par image en ligne au moyen de la tomodensitométrie à faisceau conique (TDMFC) a permis une grande amélioration de la précision géométrique de la radiothérapie. Les changements anatomiques sont fréquents dans le cours d'un traitement fractionné, ce qui se traduit par une déviation de la dose par rapport à la distribution planifiée. Il y a un intérêt croissant en faveur de l'utilisation de l'accumulation de la dose pour calculer la dose effectivement administrée et adapter le traitement au besoin. Ceci peut être fait en délimitant le volume d'intérêt et en produisant une « dose du jour » par calcul de la dose sur l'appareil de TDMFC. Cependant, la qualité de l'image et la précision des données TDM de la TDMFC sont réputées inférieures à la tomodensitométrie à faisceau en éventail (TDMFE), ce qui augmente l'incertitude associée à ce processus. Une recherche documentaire a été effectuée afin d'évaluer la fiabilité de la TDMFC et d'examiner des stratégies permettant de surmonter les défis liés à l'utilisation de la TDMFC pour la délimitation du volume et le calcul de la dose. L'examen a permis de constater que l'incertitude varie selon e site anatomique et différentes stratégies sont recommandées afin de produire des résultats comparables aux images des simulateurs de TDM. Ceci facilite une meilleure compréhension du potentiel et des limites de l'utilisation de la TDMFC pour l'accumulation de dose.

Keywords: Cone beam CT; dose accumulation

Introduction

Cone beam computed tomography (CBCT), which is a volumetric imaging modality, has become more commonly used in clinical settings for image guidance due to its capability of providing soft tissue information [1, 2]. This information enables better target localization and potential reduction of planning target volume (PTV) margin. Various studies have demonstrated its benefits in providing greater sparing of organs at risk (OARs) and in facilitating dose escalation to improve the therapeutic ratio [3–6].

Despite the use of CBCT for image guidance to reduce geometric uncertainty, the actual delivered dose to the target and the OARs are expected to deviate from the planned dose due to various reasons, such as interfraction motion, weight loss, organ deformation, and tumor regression and/or progression [2]. There is an increased interest in performing dose accumulation to track the actual delivered dose for better understanding of dose–response relationship [7] and in adapting the treatment to further improve the therapeutic ratio [8, 9]. There is a paradigm shift from image-guided to dose-guided radiotherapy [10].

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The use of CBCT in performing online planning has been demonstrated to be feasible for palliative radiotherapy, with acceptable dosimetric accuracy and time frame [11]. Moreover, it is much more cost-effective than a fan beam CT (FBCT) because of an increased x-ray utilization that facilitates purchase of an x-ray tube with reduced heat-load capacities [12]. Therefore, there is great interest in exploring the potential of using CBCT for radiotherapy planning in other disease sites at a lower cost and improved efficiency.

Currently our institution is developing the dose accumulation process, which entails the use of CBCT to delineate target and OARs, to calculate dose based on the anatomy of the day, to accumulate delivered dose, and to evaluate the dose–response relationship. Because the process is dependent on the quality and the information provided by CBCT, it is important to assess its reliability and to identify the uncertainty associated with various components.

The purpose of this article is to examine factors that affect CBCT image quality and its impact on volume delineation and dose computation. Strategies in improving the quality and the performance in the prostate, head and neck, and lung group are discussed to demonstrate the potential of using CBCT as an imaging modality for dose accumulation.

Methods and Materials

A literature review was conducted using PubMed and Google Scholar in March 2015. Using a combination of the following keywords, a total of 165 peer-reviewed articles that were published in English from 2005 related to CBCT image quality, volume delineation, CT number correction, and application for dose accumulation in the head and neck, lung, and prostate cancers were retrieved: cone beam, dose calculation, volume delineation, interobserver variability, dose accumulation. Articles related to imaging dose of CBCT, proton dose calculation, and application of CBCT in nonradiotherapy setting were excluded, resulting in 21 eligible articles. Additional articles were identified by hand searching the reference lists of the eligible articles and using the “cited by” function in PubMed and Google Scholar.

Information from various sources was then synthesized into the following categories:

- CBCT image quality
- CBCT for volume delineation
- CBCT for dose computation
- Current application of CBCT for adaptive planning.

CBCT Image Quality

Image quality of three-dimensional imaging is strongly dependent on the acquisition and reconstruction parameters, and it has been demonstrated that the quality of CBCT is inferior to FBCT because of the differences between the two systems [13]. First, the use of a cone-shaped beam to acquire an entire volume rather than a single slice with fan-shaped beam increases the scatter, which results in a reduced contrast-to-noise ratio and an increased scatter to primary ratio (SPR) [14, 15]. Second, although FBCT can acquire an image in seconds, the International Electromechanical Commission limits the maximum gantry rotation speed of CBCT to ∼1 revolution/min, subjecting the latter to be more sensitive to intrascanning organ motion, and hence motion artifact [14, 15]. Third, the number of projections acquired for CBCT is significantly less than FBCT (300–800 vs 1,000–2,000), resulting in less raw data for reconstructing a high-quality image. Fourth, the signal range of the detector in CBCT is narrower than FBCT. This renders CBCT to experience lag effects attributed to saturated signal, especially at the periphery of the patient, due to increased exit dose compared with the centre [16]. Along with beam hardening, there is an increase in cupping, streak, and motion artifacts associated with CBCT.

Because scatter is the primary factor in deteriorating CBCT image quality, different management methods have been applied. First is minimizing the field of view (FOV) to improve SPR. However, this is not preferred, because the lack of a complete three-dimensional dataset can compromise the accuracy of dose computation required for planning and dose tracking. An alternative is to use a beam-shaping device, such as a bowtie filter. By attenuating more primary fluence at the edge of the object to flatten the profile, Mail et al (2009) [16] observed an improved SPR from 0.645 to 0.443 at the centre and from 0.133 to 0.124 at the periphery of a phantom. Increase in dose and number of projections also demonstrate an improved contrast-to-noise ratio [17]. Antiscatter x-ray grid placed on the surface of the detector has also been shown to improve image quality by reducing cupping artifact by almost 50%; however, at the expense of decreased primary dose and flexibility in positioning the detector for acquisition of different FOVs [18, 19]. Nevertheless, it has been clinically used to achieve better image quality for planning and delineation purposes [11, 20]. Post-imaging processing algorithms have also been developed to estimate and to correct for scatter, beam hardening, and lag effect [16, 17, 21].

CBCT image quality can also be improved by applying organ motion management to reduce motion artifact. The presence of gas can significantly obscure visualization of the soft tissue boundary [20]. Dietary recommendations have been suggested to minimize the incidence [22]. Image blurring caused by respiratory motion can be reduced by various breath-hold techniques, with or without the use of active breathing control [23]. In addition, respiration-correlated or four-dimensional (4D) CBCT can be reconstructed to minimize motion artifact. Different reconstruction strategies have been proposed, which include the incorporation of a patient-specific motion model [24], the placement of radiopaque markers on skin or implanted inside the body to guide warping of the image projection data [25], and modulation of the gantry speed and the projection pulse rate [26]. The image quality of 4D CBCT is superior to CBCT, evidenced by an

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