Radiation Physics and Chemistry 140 (2017) 428–434

Contents lists available at ScienceDirect

Radiation Physics and Chemistry

journal homepage: www.elsevier.com/locate/radphyschem

Entrance surface dose distribution and organ dose assessment for cone-beam computed tomography using measurements and Monte Carlo simulations with voxel phantoms

M. Baptista[a,*], S. Di Maria[a], S. Vieira[b], P. Vaz[a]

[a] Centro de Ciências e Tecnologias Nucleares, Instituto Superior Técnico, Campus Tecnológico e Nuclear, Estrada Nacional 10, km 139,7, 2695-066 Bobadela LRS, Portugal

[b] Fundação Champalimaud, Centro Clínico Champalimaud, Avenida de Brasília, 1400-038 Lisboa, Portugal

ARTICLE INFO

Keywords:
Monte Carlo simulations
Cone-beam computed tomography
CTDI measurements
Organ doses

ABSTRACT

Cone-Beam Computed Tomography (CBCT) enables high-resolution volumetric scanning of the bone and soft tissue anatomy under investigation at the treatment accelerator. This technique is extensively used in Image Guided Radiation Therapy (IGRT) for pre-treatment verification of patient position and target volume localization. When employed daily and several times per patient, CBCT imaging may lead to high cumulative imaging doses to the healthy tissues surrounding the exposed organs.

This work aims at (1) evaluating the dose distribution during a CBCT scan and (2) calculating the organ doses involved in this image guiding procedure for clinically available scanning protocols. Both Monte Carlo (MC) simulations and measurements were performed. To model and simulate the kV imaging system mounted on a linear accelerator (Edge™, Varian Medical Systems) the state-of-the-art MC radiation transport program MCNPX 2.7.0 was used. In order to validate the simulation results, measurements of the Computed Tomography Dose Index (CTDI) were performed, using standard PMMA head and body phantoms, with 150 mm length and a standard pencil ionizing chamber (IC) 100 mm long. Measurements for head and pelvis scanning protocols, usually adopted in clinical environment were acquired, using two acquisition modes (full-fan and half fan). To calculate the organ doses, the implemented MC model of the CBCT scanner together with a male voxel phantom ("Golem") was used.

The good agreement between the MCNPX simulations and the $CTDI_w$ measurements (differences up to 17%) presented in this work reveals that the CBCT MC model was successfully validated, taking into account the several uncertainties. The adequacy of the computational model to map dose distributions during a CBCT scan is discussed in order to identify ways to reduce the total CBCT imaging dose. The organ dose assessment highlights the need to evaluate the therapeutic and the CBCT imaging doses, in a more balanced approach, and the importance of improving awareness regarding the increased risk, arising from repeated exposures.

1. Introduction

Cone-beam computed tomography (CBCT) is an emerging technology that enables high-resolution volumetric scanning of the anatomy under investigation. This computed tomography (CT)-like imaging technique uses an X-ray beam, in the form of a divergent cone or pyramid, to illuminate a two-dimensional (2D) digital flat-panel detector (FPD) array for image capture. The projection images acquired are directly reconstructed into a three-dimensional (3D) dataset (ICRP, 2015; Sykes, et al., 2013).

Although it is a relatively new modality, the use of CBCT is increasing in clinical practice due to the variety of its clinical applications (ICRP, 2015; IAEA, 2011). In radiotherapy, CBCT is extensively used in Image Guided Radiation Therapy (IGRT) for pre-treatment verification of patient position and target volume localization. CBCT imaging, especially when employed daily may lead to high cumulative imaging dose to tissues outside the exposure field (ICRP, 2015; Dixon and Boone, 2010; Murphy, et al., 2007; Nelson and Ding, 2014). For this reason, its use should be evaluated for each patient for sparing radiosensitive organs, as it is recommended by AAPM Task Group 75 report (Murphy et al., 2007).

The current method for characterizing radiation dose in CT is based on a metric called computed tomography dose index (CTDI). This is measured for a single axial rotation using a 100 mm long cylindrical

* Corresponding author.
E-mail address: marianabaptista@ctn.tecnico.ulisboa.pt (M. Baptista).

http://dx.doi.org/10.1016/j.radphyschem.2017.02.018
Received 30 September 2016; Received in revised form 4 February 2017; Accepted 7 February 2017
Available online 09 February 2017
0969-806X/

ionization chamber (IC) in cylindrical polymethylmethacrylate (PMMA) phantoms (AAPM, 2010). $CTDI_{100}$ is therefore used as an indicator for the dose received by patients undergoing CT examinations (Abuhaimed et al., 2015). However, CTDI methodology has some limitations for CBCT systems due to the cone-beam nature of the irradiated field, presenting new challenges in terms of dose management.

Since CBCT systems have X-ray beam widths sufficiently broad to image the anatomy of interest in a single rotation without table movement, $CTDI_{100}$ measurement do not capture and record all the primary beam and scattered radiation that would contribute to the patient dose (ICRP, 2015; Sykes et al., 2013; Dixon and Boone, 2010; AAPM, 2010). Boone has shown that for beam width of 150 mm, $CTDI_{100}$ decreases approximately 40%, when compared with its value for a narrow X-ray beam (≤ 40 mm) (Platten et al., 2013).

To overcome the shortcomings of CTDI concept, different methods have been proposed by the American Association of Physicists in Medicine (AAPM) task group 111 (AAPM, 2010) and the International Electronic Commission (IEC), whose approach is also recommended by the International Atomic Energy Agency (IAEA) (IAEA, 2011). The IEC methodology suggests measurements with a narrower reference beam (≤40 mm) to which a correction factor is applied, equal to the ratio between $CTDI_{100}$ measurements free in air for the wide beam of interest and the reference beam (IAEA, 2011; Platten et al., 2013). The AAPM approach is based on the cumulative dose concept, where the dose is measured with a small IC in the centre of a sufficient long phantom to obtain an equilibrium condition for measurement of scatter radiation, such that an increase in the length of the phantom will not increase the measured dose (AAPM, 2010; Abuhaimed et al., 2015).

The current recommendations for dose measurements in CBCT are divergent and there are practical difficulties in implementing both methodologies. Nevertheless, both IAEA and AAPM note that more detailed measurements and the use of Monte Carlo (MC) simulations might be required to calculate the dose values associated with this imaging technique (IAEA, 2011; Dixon and Boone, 2010; AAPM, 2010). Additionally, MC calculations allow the determination of dose distributions for a range of situations including medium and large fields of view (FOV) with offset collimation, partial arcs and offset isocentres (Dixon and Boone, 2010). Furthermore, MC radiation transport simulation codes, coupled with computerized phantoms, represent a highly versatile and effective tool to prospectively estimate patient organ doses, since the 3D spatial distribution of absorbed dose within internal organs of the human body is not directly measurable in individual patients (Lee et al., 2007).

This study aims at (1) developing a MC model of the CBCT medical equipment; (2) evaluating the Entrance Surface Dose (ESD) distribution and the organ doses involved in typical and clinically available CBCT scanning protocols: Head and Pelvis, using two acquisition modes (full-fan and half fan). To reach the aforementioned objectives, a set of $CTDI_{100}$ measurements were performed, with kV imaging system mounted on a linear accelerator at Champalimaud Centre for the Unknown (Lisboa, Portugal), to investigate a different approach to CBCT dosimetry, based on the cumulative dose concept. Additionally, MC calculations were performed, mimicking the CBCT acquisition process, for the different scan protocols. The developed MC tool was used together with a male voxel phantom ("Golem") to execute a detailed study of the organ doses in CBCT.

2. Materials and methods

In this study, measurements with CTDI phantoms and IC were carried out in the CBCT kV imaging system, mounted on Varian Edge™ linear accelerator (Varian Medical Systems, Palo Alto, CA) and MC simulations were performed.

2.1. CBCT imaging system and scanning protocols

The CBCT imaging system is mounted on the gantry of the linear accelerator at 90° to the therapeutic beam. In this mode, the system acquires several radiographic projections during the rotation of the kV source around the patient, over arcs of 360° or 200°, and then a reconstruction algorithm is applied to obtain a 3D image.

The equipment has four collimator blades, X1, X2, Y1 and Y2 that work independently and control the size of the X-ray beam, delivering a symmetrical our asymmetrical field. The X pair sets the diameter of the scan while the Y pair controls the beam width (W) along the rotation axis (z-axis). Two different acquisition modes, Full-Fan and Half-fan, can be employed taking into account the size of the scanned target region. The Full-fan is used with a full bowtie filter and is selected to image the volume of interest symmetrically with a FOV of 28 cm at the isocenter, where the collimator blades X1 and X2 are set to 14.0 cm, and Y1 and Y2 at 10.7 cm, at the isocenter. The Half-fan mode is employed with a half bowtie filter and allows larger FOVs by scanning target regions asymmetrically, where blades X1 and X2 are opened by 2.4 cm and 24.7 cm at the isocenter, whereas Y1 and Y2 are set similarly to those for the Full-fan mode. Thus, the FOV at the isocenter, for the Half-fan mode, is 49.4 cm.

Two CBCT scanning protocols, Head and Pelvis, frequently used in clinical environment, were studied and their respective acquisition parameters are listed in Table 1.

2.2. CBCT dosimetric formalism

Abuhaimed, et al. (2015) showed that one of the approaches to determine the cumulative dose for a CBCT scan is the calculation of the dose descriptor $f_{100}(150)$, which is measured as an average dose over the 100 mm length of the IC within the 150 mm long PMMA phantoms, similarly to the $CTDI_{100}$ measurements (Platten et al., 2013; Shope et al., 1981). In the present study, the dosimetric formalism proposed by Abuhaimed, et al. (2015) was followed to calculate CBCT scan doses.

2.3. CTDI measurements

In order to validate the computational model of the CBCT equipment, $CTDI_{100}$ measurements for the two clinical scanning protocols were performed and compared against the MC results. The measurements were executed for a clinical beam width (W) of 214 mm, with standard cylindrical PMMA head and body phantoms (Pro-CT dose, ProProject®), with diameters of 160 mm and 320 mm respectively, and 150 mm length. A standard pencil IC (RaySafe Xi CT, Unfors RaySafe ®) 100 mm long, previously calibrated, was used and the associated uncertainty was 5%. In Fig. 1, an example of a $CTDI_{100}$ measurement using the PMMA body phantom can be observed. The central position of both phantoms was aligned with the isocentre of the CBCT imaging system with a source-to-isocentre-distance (SID) of 100 cm.

Table 1
Acquisition parameters of the CBCT scanning protocols.

Parameters		Head	Pelvis
Tube voltage (kVp)		100	125
Exposure (mAs)		270	1080
Gantry rotation (°)		360	
Acquisition mode		Full-fan	Half-fan
Beam width (cm)		21.4	
Collimator blades	X1 and X2 (cm)	−14.0 and 14.0	−24.7 and 3.4
	Y1 and Y2 (cm)	−10.7 and 10.7	