Evaluation of dose from kV cone-beam computed tomography during radiotherapy: a comparison of methodologies

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Abstract. Three alternative methodologies to the Computed-Tomography Dose Index for the evaluation of Cone-Beam Computed Tomography dose are compared, the Cone-Beam Dose Index, IAEA Human Health Report No. 5 recommended methodology and the AAPM Task Group 111 recommended methodology. The protocols were evaluated for Pelvis and Thorax scan modes on Varian® On-Board Imager and Truebeam kV XI imaging systems. The weighted planar average dose was highest for the AAPM methodology across all scans, with the CBDI being the second highest overall. A 17.96% and 1.14% decrease from the TG-111 protocol to the IAEA and CBDI protocols for the Pelvis mode and 18.15% and 13.10% decrease for the Thorax mode were observed for the XI system. For the OBI system, the variation was 16.46% and 7.14% for Pelvis mode and 15.93% to the CBDI protocol in Thorax mode respectively.

1. Introduction
The introduction of kV CBCT for position verification and adaptive therapy has enabled steeper dose gradients and tighter treatment margins for improved treatment outcomes [1]. However, regular CBCT imaging during a course of radiotherapy delivers additional concomitant dose which may lead to increased risk of secondary malignancies [2-4].

The current paradigm for evaluating CT dose is the Computed Tomography Dose Index [5-7]. In its most common form, the integral dose from a single rotation of the X-Ray tube is measured with a 100mm pencil ionisation chamber and, when divided by the slice width nT gives an estimate of the central dose for a scan with multiple rotations of the X-Ray tube. Since the introduction of CTDI, CT scanning has developed to include helical CT, multi-slice CT and now wide beam Cone-Beam CT where images can be acquired in a single rotation. Hence, the relevance of the CTDI as a dose indicator for wide beam scanning has come under question due to underestimation of scatter dose lying outside the 100mm chamber length, CTDI phantoms being of insufficient length to achieve scatter equilibrium and non-uniformity along the beam [8-10].

In an attempt to better quantify the dose from wide-beam scanning, alternative methodologies have been developed which attempt to counter the limitations of the CTDI methodology. This work presents a comparison of three alternative methods, the Cone-Beam Dose Index, IAEA Report 5 Recommended Methodology and the AAPM Task Group 111 protocol [11-13].
2. Materials and Methods
The methodologies were compared on Varian© On Board Imager (OBI) and XI kV imaging systems. Both systems consist of a kV X-Ray tube mounted on a LINAC gantry 90 degrees to the treatment beam, with a flat panel detector 180 degrees to the X-Ray tube from which 3D images can be reconstructed.

2.1 Cone Beam Dose Index (CBDI)
The CBDI was evaluated with a 100mm ionisation chamber for a single rotation of the X-Ray tube. The dose was measured in-air at the centre of a Polymethyl-Methacrylate cylindrical phantom, 32 cm in diameter and 16 cm in length.

Unlike the CTDI, the integral dose $D(z)$ was not divided by the slice thickness, which for CBCT is wider than the chamber itself, but by the chambers 100mm length. That is, the 100mm chamber records a point-dose measurement as shown in equation (1).

$$CBCT = \frac{1}{100\text{mm}} \int_{-50\text{mm}}^{+50\text{mm}} D(z)$$

(1)

The weighted average dose across the phantom plane was determined by weighting the central dose and the average peripheral dose shown in equation (2), as per CTDIw in the CTDI. The CTDIw was evaluated for Pelvis and Thorax modes on both the OBI and XI systems.

$$CTDI_{w} = \frac{1}{3} CTDI_{c} + \frac{2}{3} CTDI_{p}$$

(2)

2.2 IAEA Report 5 Recommended Methodology
The IAEA protocol was carried out following the recommendations of the International Electrotechnical Commission -60601-2-44 document. The weighted average dose was determined for a reference beam width of $nT = 20$mm for the Pelvis and Thorax modes on the OBI and XI systems.

The weighted average dose was determined free-in-air following the guidelines of the IAEA for the reference and Pelvis/Thorax protocol beam widths. A single measurement was taken for the reference width with the chamber in the central position, while for the wide protocol beam width the dose was measured in three sequential steps of the chamber through the beam and summed as shown in equation (3).

$$CTDI_{free \ in \ air} = \frac{L}{nT} \sum_{i=1}^{3} D_{i}$$

(3)

The CTDIIIAEA was then evaluated by multiplying the weighted average dose from the reference width scan by the ratio of the CTDIfree in-air values of the reference and protocol width scans as shown in equation (4).

$$CTDI_{free \ in \ air} = \frac{L}{nT} \sum_{i=1}^{3} D_{i}$$

(4)

2.3 AAPM Task Group 111 Methodology
A custom made PMMA phantom was constructed in house following the TG-111 recommendations for phantom length to achieve scatter equilibrium in the centre of the phantom. The phantom was cylindrical of diameter 32cm with 5 plug housings for weighted average measurements. The phantom was 45cm in length.

Measurements were taken in each position with a 2571 0.6cc Farmer ionisation chamber. The plug containing the chamber was custom made to conform to the chamber geometry to eliminate air gaps. The weighted average dose was determined for Pelvis and Thorax protocols on the OBI and XI systems using the chamber readings (converted to dose in-air) and equation (2). The charge readings from the ionisation chamber were converted to dose to air following the AAPM TG-61 guidelines [14].
3. Results

Weighted average dose values for OBI and XI are shown in figure 1 (a) and (b). Measurements for each position within the phantoms are shown in figure 2(c)-(f).

Figure 1. Positional dose values for the Pelvis and Thorax modes on the OBI (c,e) and XI (d,f) imaging systems. The measurements were taken following CBCT, IAEA and TG-111 recommendations. The weighted averages for the three methodologies are given for OBI (a) and XI (b).

Across all imaging systems, the TG-111 protocol gave the highest dose due to the increased scatter from the longer phantom. The CBCT methodology gives slightly lower dose across all protocols, with the exception of the right position in the OBI pelvis scan which is considerably less, likely due to a delay between the X-Ray tube starting and the gantry beginning its rotation, with the tube directly above the chamber. The central measurement for the TG-111 is considerably lower than the other two methods for the Pelvis XI scan, perhaps due to the smaller chamber volume not collecting as much scatter dose compared to the longer chamber, or misalignment of the chamber, which would have a more pronounced effect on the smaller volume chamber. Measurements in the bottom position were all slightly less than the other peripheral positions due to couch attenuation.
Weighted dose values for each protocol are shown in figure 2 (a) for OBI and (b) for XI. For the XI system there was a 17.96% and 1.14% variation from the TG-111 protocol to the IAEA and CBDI protocols for the Pelvis mode, while the Thorax mode had 18.15% and 13.10% variations. The OBI variation was 16.46% and 7.14% for Pelvis mode and 15.93% to the CBDI protocol in Thorax mode.

4. Conclusion
Three alternative methodologies were compared on two CBCT imaging systems. The TG-111 protocol gave the highest dose value across all scan modes on both the OBI and XI imaging systems due to the increased scatter from the longer custom phantom. The CBDI method gave the second highest dose, while the IAEA method gave the lowest dose. Across all scans, the central dose was lower than the peripheral values due to the primary beam contributing less, and the scatter dose contributing more relative to the peripheral positions.

The TG-111 protocol, with its higher dose due to increased scatter length gives a more realistic indication of dose from wide-beam CBCT scanning. Future work is required to investigate how the TG-111 values correspond to patient dose, including the influence of patient thickness.

5. References
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