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Reducing dose of Cone-Beam CT used for patient positioning in radiooncology

Abstract: Cone-Beam computed tomography (CBCT) has become the most important component of modern radiotherapy for positioning tumor patients directly before treatment. In this work we investigate alternations to standard acquisition protocol, called preset, for patients with a tumor in the thoracic region. The effects of the changed acquisition parameters on the image quality are evaluated using the Catphan Phantom and the image analysis software Smári. The weighted CT dose index ($CTDI_w$) is determined in each case and the effects of the different acquisition protocols on the patient dose are classified accordingly. Additionally, the clinical suitability of alternative presets is tested by investigating correctness of image registration using the CIRS thorax phantom. The results show that a significant dose reduction can be achieved. It can be reduced by 51% for a full rotation by adjusting the gantry speed. A more patient-specific uptake protocol for patients with laterally located tumor was created which allows a dose reduction of 54%.

Keywords: cone-beam, computer tomography, dose, reduction, patient position, radiooncology

<https://doi.org/10.1515/cdbme-2021-2058>

1 Introduction

Image-guided radiotherapy using cone-beam CT (CBCT) has a high significance in the precision treatment of patients with tumor. It allows accurate positioning of the target volume with imaging of surrounding organs at risk immediately prior to irradiation. However, the associated increased dose contribution to the patient must be considered. This work investigates possibilities to keep patient's radiation exposure by CBCT as low as possible when using it for positioning patients before radiotherapeutic treatment.

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2 Methods

CBCT images were acquired with the integrated XVI system version 5.0 of the Synergy® linear accelerator from Elekta (Elekta Ltd, Crawley, UK). The Chest M20 preset is used as a reference to control patients with tumor in the thoracic region.

The recording dose is determined with the dosimeter NOMEX® (TW-Freiburg) and the ionization chamber TL30009. A PMMA-CT phantom (IBA-Dosimetry) is used for the trials. The CTDI measurement is conducted according to the IEC60601-2-44 (2009) standard [1]. The weighted $CTDI_w$ is calculated using:

$$CTDI_w = \frac{1}{3}CTDI_c 100 + \frac{2}{3}CTDI_p 100, \quad (1)$$

where $CTDI_c$ is the $CTDI_{100}$ central, which corresponds to the calculated value of the $CTDI_{100}$ in the central position measurement. The $CTDI_p$ is the $CTDI_{100}$ periphery and is composed of the respective mean value of the $CTDI_{100}$ at the measurement position at the angles 0°, 90°, 180° and 270°; it is determined 10mm below the surface.

The image quality is obtained using the Phantom Catphan® Model 503 (Salem, NY, USA). It was accessed by analyzing homogeneity, low contrast resolution and spatial resolution and was performed by the image analysis software Smári (The Phantom Laboratory). The determination of the values for low-contrast resolution (LCV) (<1.5% limit), uniformity (<16% limit), and spatial resolution (>3LP/cm limit) is done following recommendations of the manufacturer [2]. A value exceeding the limit value is considered as an exclusion criterion of the preset alternation.

Due to the impact of insufficient image quality on the automatic patient positioning matching results, a clinical control is performed to verify the registration accuracy. The planning CT used for radiation planning serves as a reference data set and is fused with the CBCT. The spatial alignment of the patient and the target area occurs by a given registration algorithm. The CIRS thorax phantom is used to create a

reference data set for full rotation and partial rotation. After ensuring correct positioning, misalignment is simulated. The registration process is considered successful if the correction values match those of the misalignment with a tolerance of ± 0.1 cm. If the image quality is not sufficient, the correction values are not generated.

3 Result & Discussion

All results refer to the "Chest M20" acquisition protocol for performing CBCT for patients with thoracic tumor. The following acquisition parameters of the "Chest M20" preset have been varied in this work:

- Field-of-View (FOV): Small, Medium, Large.
- Filter element: Bowtie filter (F1), empty (F0)
- Gantry speed: 180°/min, 270°/min, 360°/min
- Current (20ms/frame): 25mA, 20mA, 16mA, 12mA
- Rotation angle: 270°, 225°, 200°, 180°.

3.1 Full rotation

Figure 1 demonstrates that the images of the Small-FOV show the highest dose values. In relation to the Medium-FOV, the dose of the CTDI_w increases from 5.1mGy to 6.02mGy. Using the Large-FOV, on the other hand, reduces the CTDI_w to 3.77mGy.

Figure 1: Effect of FOV, Bowtie filter on CTDI_c, CTDI_p and CTDI_w.

This is due to the geometric arrangement of the CBCT at LINAC. The different FOV are generated by the collimation of the cone beam at the X-ray tube. For Small-FOV, a symmetric cone beam is incident vertically on the detector center. For Medium-FOV and Large-FOV CBCT images, an increasingly asymmetric cone beam is generated. The position of the detector is laterally adjusted accordingly by 115mm and 190mm [2]. Due to the asymmetric

collimation, the divergence of the beam cone to the deflected detector side increases.

Figure 1 also demonstrates the significant reduction in dose due to the bowtie filter. At medium FOV, the dose decreases from 8.69mGy to 5.1mGy. The influence on the CTDI_p by the Bowtie filter is higher than on the CTDI_c. While the CTDI_p almost doubles due to the removal, the CTDI_c increases by about one third, which is due to the biconcave shape of the filter. A dose reduction of 44.69% in CTDI_p is achieved at medium FOV. The medial part of the filter provides an additional dose saving in the center of the irradiated volume of 26.21%. The results are consistent with the publication by Maul et al [3]. Thus, the filtering of the low-energy radiation of the cone beam allows a significant reduction of the patient's skin dose [3].

Increasing the gantry speed from 180 to 270°/min results in a reduction in dose from 5.1mGy to 3.34mGy at Medium-FOV. If the speed is doubled to 360°/min, the dose is reduced by approximately the half to 2.5mGy. The CBCT acquisitions are performed with a fixed frame rate of 5.5Hz; the behavior is linearly related to the number of projections.

Table 1: Image uniformity in % obtained by the Smári software. For Medium-FOV no results could be obtained for an empty filter.

Gantry speed	Small-FOV		Medium-FOV	Large-FOV	
	Bowtie	Empty	Bowtie	Bowtie	Empty
180°/min	9	10	12,3	312	539,0
270°/min	4,1	7,6	12,0	297,7	590,7
360°/min	5,3	11,1	12,7	288,3	525,7

As listed in Table 1 Small-FOV shows the best results in terms of uniformity. Due to the collimation of the cone beam, there is slight deterioration of uniformity at Medium-FOV, which increases considerably by further aligning the cone beam more asymmetrically to generate Large-FOV. Considering the image quality, no dose reduction is allowed by changing to Large-FOV.

Table 1 also shows that the removal of the bowtie filter significantly worsens the uniformity. The values at 360°/min increase from 5.3% to 11.1% for Small-FOV and from 288.3% to 525.7% for Large-FOV. This is also shown in Figure 2. The use of the Bowtie filter achieves a significantly more homogeneous image due to the fluence modulation of the cone beam.

Figure 2: Left homogeneous image of the Catphan® from medium FOV with Bowtie filter, right without filter an increasing deterioration of homogeneity, starting from the center of the phantom, visible.

Due to the additional 46% reduction in the recording dose due to the absorption of low-energy radiation, the use of the Bowtie filter is indispensable.

Table 2: Low contrast (LCV) in % obtained by the software Smári.

Gantry speed	Small-FOV		Medium-FOV		Large-FOV	
	Bowtie	Empty	Bowtie	Empty	Bowtie	Empty
180 °/min	0,80	0,77	0,87	1,20	1,23	1,07
270 °/min	0,83	0,83	1,07	1,37	1,27	1,20
360 °/min	1,03	1,10	1,27	1,70	1,53	1,33

Table 2 shows that the low-contrast (LCV) resolution is influenced by the selection of the corresponding FOV. Small-FOV provides the best results, while Medium-FOV as well as Large-FOV show low contrast differences of soft tissue worse. The reason for this is the increased scattering fraction associated with increasing FOV, which leads to a deterioration of the contrast-to-noise ratio [4]. In addition, the LCV is affected by the change in gantry speed. At a gantry speed of 360°/min, it increases in all measurement series. With these small losses in the visualization of the low-contrast soft tissue, the radiation exposure to the patient can be halved, which makes the adjustment of the gantry speed essential.

With an adjusted gantry speed of 360°/min, the current is reduced at medium FOV with Bowtie filter for further dose reduction. It can be shown that the patient dose is linear to the adjusted current amplitude per image. With a current strength of 16mA, the dose is reduced to 1.97mGy. However, when analyzing spatial resolution at 16mA, an evaluation of CBCT is incomplete, although the results obtained are within specifications at 4.1LP/cm. Uniformity results remain unaffected by the reduction in electric current and are within

the specified tolerance of 16%. For low contrast resolution, the mean value also remains constant at 1.3% when the current is reduced to 16mA. Only after further reduction of the current down to 12mA the LCV exceeded 1.7%. Due to the incomplete results, an adjustment of the electrical current is not recommended.

3.2 Particular rotation

Figure 3 shows a significant image loss due to the reduction of the rotation angle at Medium-FOV. The image is therefore unsuitable for clinical use.

Figure 3: CBCT image of the Catphan phantom acquired using a rotation angle of 200° and Medium-FOV (left), Small-FOV (right).

A reduction of the rotation angle at Small FOV achieves the complete representation of the phantom, which is due to the symmetrical collimation of the cone beam. This offers the possibility to create another preset.

Table 3: Acquisition dose with reduced rotation angle.

Rotation angle	270°	225°	200°	180°
Acquisition dose	2,28	1,90	1,73	1,59

The reduction of the rotation angle has a proportional effect on the dose since it is directly related to the number of projections acquired. In addition to the dose reduction, the diameter of the image field of the CBCT is reduced to 270mm and the scanned body volume is reduced. It also allows a further reduction in treatment time for the patient.

Reducing the angle of rotation achieves results that are significantly above the 16% threshold in uniformity, except for 200°. At 200°, a mean value of 15.5% is obtained, with only one single measurement (18%) exceeding the threshold limit. Therefore, the electrical current is increased to 25mA. As a result, values below the limit value are obtained in all individual measurements. The mean value of the measurement series for the uniformity is 15.7%.

When adjusting the current to 25mA for Small-FOV with Bowtie filter and using rotation angle of 200° the creation of another preset for patients with laterally located tumors is possible. In all measurement series, the minimum requirement of spatial resolution of 3.0LP/cm and LCV of 1.5% is achieved.

3.3 Clinical test

In full rotation, the automatic image registration achieves correction values within the tolerance of $\pm 1\text{mm}$ for all gradations of current intensities. Likewise with the preset current of 16mA, the analysis of the spatial resolution was incomplete. The table correction of the partial rotation with the current amplitude of 20mA and 25mA provided correct test results in all three spatial directions.

The clinical test also allowed the usage of the presets of full rotation Medium-FOV, Bowtie filter and with current amplitude of 16mA as well as partial rotation Small-FOV, Bowtie filter with 20mA, which were eliminated due to incomplete analysis. On average, both achieved compliance with all required limit values of the image quality parameters. Due to the optimal conditions of image registration to be considered, it cannot be assessed whether the setting of this current amplitude is still sufficient for clinical application. Compared to the present results, a further reduction of 10.38% could be achieved for the full rotation with a recording dose of 1.97mGy and an additional reduction of 11.60% for the partial rotation with the dose of 1.73mGy.

4 Conclusion

The dose exposure to the patient from CBCT can be significantly reduced. The optimized standard acquisition protocols, i.e., presets, for full rotation, Medium-FOV,

Bowtie filter, gantry speed of 360°/min and a current amplitude of 20mA allows a dose saving of 50.99 % with an acquisition dose of 2.5mGy. Reducing the current down to 16mA provides further dose savings. Despite successful image registration, the analyses are preliminary and require additional verification.

Because of the maximum of 1.6% of LCV, this also applies to the preset of partial rotation at 20mA which should only be used by increasing the current up to 25mA. At 2.31mGy, our newly created preset achieves a 54.47% reduction. With a shortened rotation angle of 200° at Small-FOV with Bowtie filter, it can be used for laterally located tumours. The use of Small-FOV allows the limitation of the imaging area to the affected half of the body and thus an additional protection of healthy tissue.

Our investigations demonstrate that a significant reduction of dose exposure is possible by optimizing the pretended presets without compromising the precision of image-guided irradiation. Optimization of the presets for other body regions should be undertaken to enable dose reduction.

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