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Improving radiation dose delivery for moving targets using image guidance

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5

Validation of dose calculation for Elekta CBCT for lung irradiation

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Submitted

5.1 Abstract

The aim of this study is to determine whether Elekta's cone-beam CT (CBCT) system XVI (x-ray volume imaging) is suitable for dose calculation for lung cancer irradiation. A thorax phantom and the data of two lung cancer patients treated with stereotactic body radiotherapy (SBRT) were used for this comparison. DICOM export parameters were changed such that the grey values resembled CT-Hounsfield units. In order to verify this correction method dose calculations on CBCT were compared to dose calculations on the planning CT. On the phantom 4 beam configurations were studied (with 1, 2 and 3 beams and a stereotactic plan). For the patients, the clinical stereotactic plans were studied with 14 and 15 6MV coplanar beams.

For the phantom beams and the stereotactic plans the percentage of voxels that failed the γ-analysis with a 3%/3mm criterion was around 1%. The mean doses of GTV, lung and spinal cord were within 1% in most cases and within 1.5 % in all cases. For the patients the errors were slightly larger, which is probably due to anatomical variation. This demonstrates that XVI CBCT is suitable for clinically reliable dose calculations for lung irradiation provided a proper scaling of the grey-values.

5.2 Introduction

Several years ago the kilovoltage cone-beam CT (CBCT) integrated with a linear accelerator became widely available in the radiotherapy clinic [19]. The CBCT is very suitable for position verification of stereotactic body radiation therapy (SBRT) for stage I/II non-small cell lung cancer patients, because of the good target visibility. A major risk in SBRT for lung tumors is the interfraction variation in the time-averaged tumor position relative to the bony anatomy: the baseline shift [34,35]. In case of a substantial shift of the tumor towards an organ at risk (OAR) an estimate has to be made of the effect on the dose in that OAR. As the change in geometry in such cases is significant, there may also be a relevant change in the local dose distribution. To facilitate an objective decision the actual (recalculated) dose distribution in that situation should be available.

When the patient geometry during treatment is known, using CBCT, the actual dose distribution could in principle be calculated. In cases with inhomogeneities, like lung, the resulting dose distribution depends strongly on Hounsfield units (HUs) which are converted to relative electron densities. Several studies have been dedicated to dose calculation on CBCT [65,72-77]. These studies have demonstrated a discrepancy between the CBCT systems OBI (on-board imager) from Varian and XVI (x-ray volume imaging) from Elekta. The HUs of OBI CBCT are close to that of a CT. On OBI CBCT, the difference in the calculated dose distributions using datasets of CBCT and CT is small, in the order of 1-3% [74,77]. The difference of the uncorrected HUs of XVI CBCT with respect to CT is reported to be large, yielding dose errors of 10-20% [65,76]. These studies corrected the HU values by choosing corresponding tissue regions on CBCT and CT by manual selection of corresponding regions [65] or by deformation [76]. After the correction, errors reduced to less than 2%. What has not been explored yet is a straightforward scaling of the grey values. For clinical use, such procedure would be much less tedious than the proposed methods.

The purpose of this study is to determine whether the XVI CBCT is suitable for dose calculation with a proper scaling of the grey values.

5.3 Materials and Methods

5.3.1 Image acquisition

The CBCT scans that were used in this study were acquired with the Elekta Synergy system, using XVI v3.5 (Elekta, Stockholm, Sweden). All CBCT scans were made using the same protocol: M20 collimator, 360^{o} scan, 120 kV, 25 mA/frame, 40 ms/frame and a bow-tie filter. The resolution of the CBCT scans was 1 mm in all dimensions.

The CT scans that were used in this study were acquired with a GE Lightspeed RT16 scanner (General Electric Healthcare, Waukesha, WI, USA). The in-plane resolution was 1 mm and the slice thickness was 2.5 mm.

5.3.2 Phantom and patients

We acquired scans of the CIRS dynamic thorax phantom (CIRS inc., Norfolk, VA, USA) (figure 5.1), without using the dynamic mode. In addition we used the clinical scans of two patients for verification (figure 5.2). These patients were chosen based on minimal discrepancies between the bone and tumor match (less than 1.5 mm in all directions). The similarity of the patient anatomy was studied by comparing the SSDs of the beams in the treatment plan. For patient 1 the average difference in SSD between CT and CBCT was 0.3 mm and for patient 2 the difference was 2.0 mm. The CT-scans of the patients were made using a slow scan protocol, in order to capture the full breathing cycle.

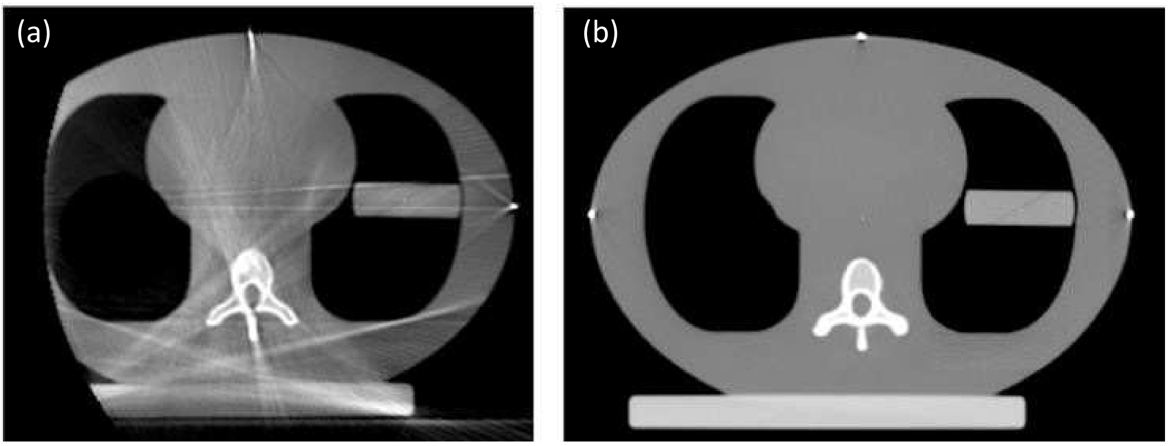

Figure 5.1: a: The CBCT scan of the CIRS phantom. b: The CT scan of the CIRS phantom.

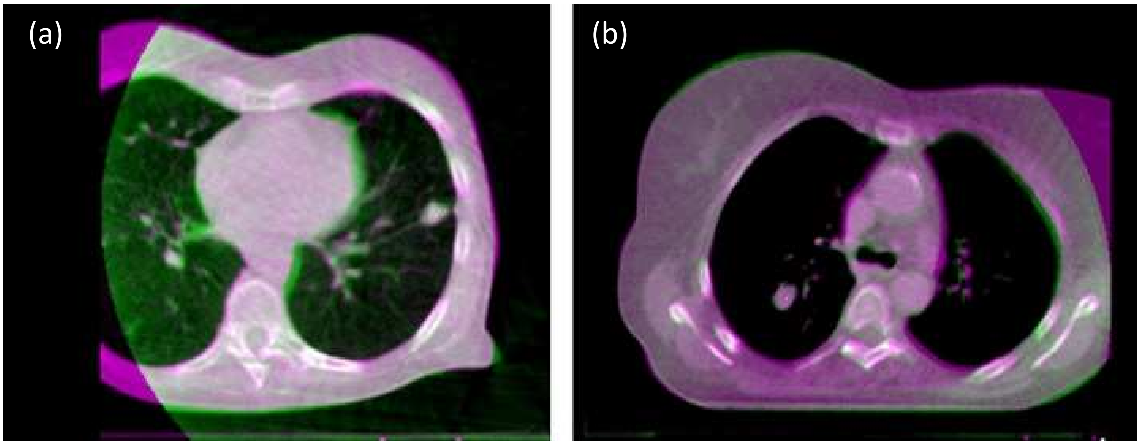

Figure 5.2: Registration of the CT and CBCT for the two patients selected for this study. The CBCT scan is displayed in green and the CT scan is displayed in purple. a: Patient 1. b: Patient 2.

5.3.3 Data export and Treatment plans

In order to perform the dose calculation, the CBCT scans are exported in the DICOM format. The HUs in the treatment planning system are reconstructed using the DICOM parameters:

$$HU = SV \times RS + RI, \tag{5.1}$$

Where SV is the stored value. RS (RescaleSlope) is 1 for both OBI and XVI. The value of RI is -1000 in OBI but the default value is -510 in XVI [78]. Following the DICOM standard for unsigned grey values, we set the value of RI to -1024 [79].

An example of the effect of changing the parameter RI to -1024 is shown in figure 5.3a-d. The grey values were similar to those of CT. However, streak artefacts on CBCT caused some local deviations.

All treatment plans for this study were made using Oncentra v4.0 (Nucletron B.V. Veenendaal, The Netherlands), using a collapsed cone algorithm [80]. For the phantom we made three treatment plans with open fields of 8x8 cm: with one, two and three beams (figure 5.4). We also made a stereotactic plan consisting of 15 non-coplanar beams. Of each plan on the phantom a version was made with 6MV and with 10MV photon beams. For the patients we used their clinical treatment plans, with 15 and 14 non-coplanar 6MV photon beams, for patient 1 and 2, respectively.

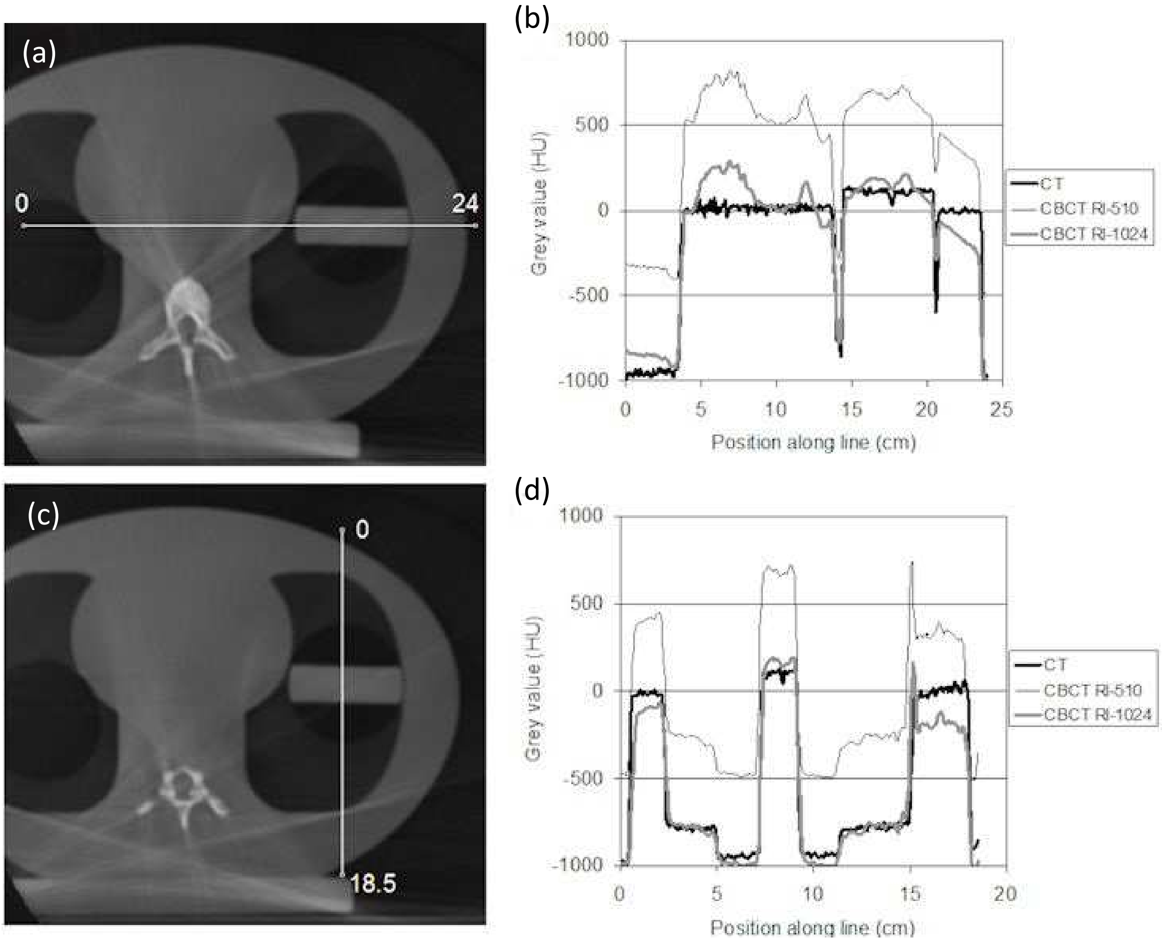

Figure 5.3: Comparison of profiles through the phantom. a and b: A profile was taken along the left-right axis. In figure a the line is shown on the CBCT scan and figure b shows the corresponding profiles of the CT, CBCT with the default RescaleIntercept (RI-510) and the CBCT with the adapted RescaleIntercept (RI-1024). c and d: A profile was taken along the anterior-posterior axis. In figure c the line is shown on the CBCT scan and figure d shows the corresponding profiles.

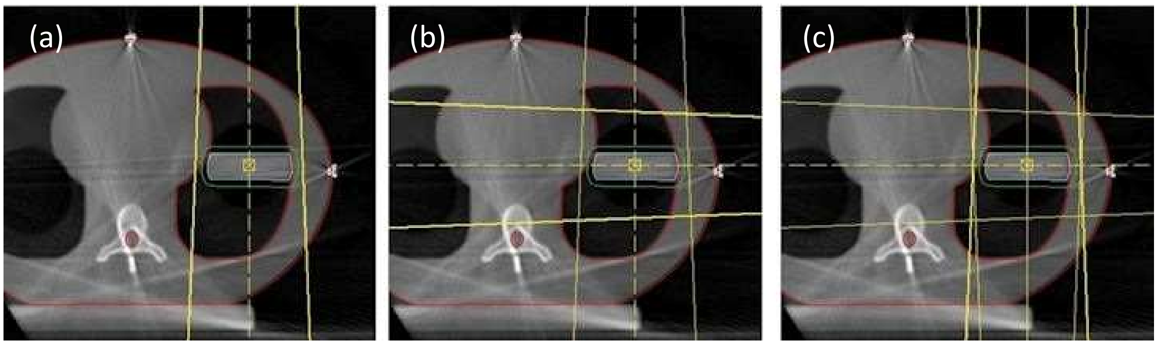

Figure 5.4: The beam configurations of the treatment plans on the phantom. a: One beam. b: Two beams. c: Three beams.

5.3.4 Analysis

For the phantom plans the following parameters were analysed: the mean dose (D_{mean}) of the gross tumor volume (GTV) and the lung and the maximum dose (D_{max}) in the spinal cord. For the patient plans we analysed D_{mean} of the internal target volume (ITV) and D_{max} of the spinal cord. D_{mean} of the lung was not evaluated for the patient plans because the lung was incomplete on the CBCT due to the limited field of view in the longitudinal direction. The error in the calculation on the CBCT (E_{CBCT}) was defined as:

$$E_{\mathrm{CBCT}}(\%) = 100\left(\frac{D_{\mathrm{CBCT}} - D_{\mathrm{CT}}}{D_{\mathrm{prescr}}}\right), \qquad (5.2)$$

where D_{CBCT} was the dose as calculated on the CBCT, D_{CT} was the dose as calculated on the planning CT and D_{prescr} was the prescription dose.

To analyse the global dose distribution we also performed a 3D γ-analysis with a dose difference of 3% and a distance to agreement of 3 mm [81]. We scored the percentage of voxels with γ > 1. To focus on the clinically most relevant area, we only took the voxels into account that received at least 20% of the prescribed dose.

5.4 Results

The errors of the calculation of D_{mean} on the CBCT of the GTV for the phantom were within 1% (figure 5.5a). The errors of D_{mean} of the lung were within 0.5%. The errors in the D_{max} of the spinal cord were within 1.5%. For the stereotactic plan all errors were within 0.3%. The percentage of voxels with γ > 1 was below 1.5%, except for the plan with one beam (figure 5.5b). In general, the E_{CBCT} was smaller with the 10MV plans than with the 6MV plans.

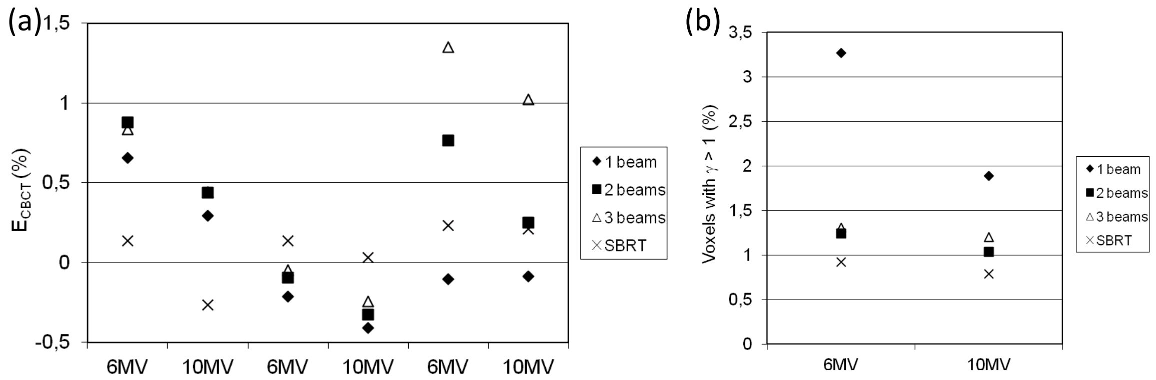

Figure 5.5: a:The results of the dose calculations in the pantom of several plans using two different energies. The results are presented as the error with respect to the dose calculation on CT (formula 5.2) b: The percentage of voxels in the phantom with γ > 1 when a 3%/3mm criterion was used.

The errors of D_{mean} of the ITV were 3.8% and 1.8% for patient 1 and 2, respectively. E_{CBCT} of D_{max} was 0.0% for patient 1 and -0.2% for patient 2. The percentages of voxels with γ higher than 1 were 1.2% and 0.1% for patient 1 and patient 2, respectively (table 5.1).

Table 5.1: The errors of the recalculation of SBRT plans on CBCT for two patients.

	Patient 1 (CC)	Patient 2 (CC)
E_{CBCT} D_{mean} ITV	3.8%	1.8%
E_{CBCT} D_{max} spinal cord	0.0%	-0.2%
Voxels with γ > 1	1.2%	0.1%

5.5 Discussion

In this study we verified the suitability of XVI CBCT for dose calculations for lung SBRT. When the grey values of the CBCT are scaled properly such that they are in the range of corresponding CT HU the dose calculation on CBCT is clinically satisfactory.

In case the system's default settings for RI would have been used, our study would largely confirm earlier findings for Elekta's CBCT regarding the erroneous dose calculations (figure 5.3) [65,76]. After applying a proper RI some discrepancies between the CT and CBCT HU values remain present. These discrepancies, however, do not yield dramatic errors in the dose calculation. Especially with multiple beams from more directions the errors tend to cancel and the impact on the clinical plans are minor.

In Patient 1, D_{mean} in the ITV was larger than deviations based on the phantom calculations (table 5.1, figure 5.5). However, the phantom has a fixed shape, whereas the patient's shape is never exactly the same (figure 5.2). Although the CBCT scans were selected carefully for their resemblance with the planning CT, some changes in the patient anatomy between planning CT and CBCT are inevitable.

All scans in this study were made using the same settings. Kamath *et al.* have shown that the grey values and the noise of a CBCT scan depend largely on the used protocol [78]. In our department scans of the thoracic region are made using the M20 collimator instead of the L20 collimator that is used in the default thorax protocol in XVI. By using the M20 collimator, the field of view (FOV) is reduced from 52.4x52.4 cm to 42.6x42.6 cm. The length of the scan is 27.6 with both collimators. By using the M20 collimator the image quality increases, but because of the smaller FOV the image is often incomplete, as can be seen in figures 5.1 and 5.2. For our application this is not a limitation, because beams entering the patient through the contralateral lung are usually avoided, so the missing part of the body does not influence the calculation of the dose. When a larger FOV is necessary for other applications further study needs to be performed to check if an additional correction is necessary.

5.6 Conclusion

XVI CBCT is suitable for dose calculation of lung treatment plans provided a proper scaling of the grey values is applied.

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