Inter-comparison of phantoms for CT numbers to relative electron density (RED)/physical density calibration and influence to dose calculation in TPS

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Abstract. Six different phantoms (2x CIRS, 1x Agmeco, 1x QUASAR, 1x Gammex, 1x CatPhan) and Varian formulas were used to evaluate their suitability for CT numbers to relative electron density (RED) calibration in the treatment planning system at two centres using two CT scanners. The variability in calibration curve and the influence to dose calculation in the TPS were estimated for 6 MV and 18 MV. The presence of scattering material around inhomogeneities and influence of CT spectra (90 kV, 120 kV, 140 kV) were evaluated. All phantoms were found convenient for calibration except CatPhan where large deviations were observed for dense bone. Phantoms without scatter material around inhomogeneities should be used with caution. Varian formula slightly overestimates calibration curve in the region of 200 - 300 HU. The tolerance level of 10% suggested for RED during commissioning is reasonable as it can cause change in dose of 3% and 1.5% for 6 MV and 18 MV respectively as a very conservative estimate. Calibration curves should be acquired for all scanning protocols with different CT spectra.

1. Introduction

The calibration from CT numbers to relative electron or physical densities in the treatment planning systems (TPS) is an essential part of TPS commissioning. The accuracy of the curve is important to assure correct material density as an input to the inhomogeneity correction algorithm. Medical physicists can use phantoms developed by different vendors or to use formula for its calculation. The aim of this work was to compare calibration curves obtained using phantoms of different vendors under different conditions and to evaluate if the accuracy of curves calculated by formula is sufficient. Because there might be different scanning protocols with different photon spectra, the influence of kV to the calibration curve was addressed. Different amount of scatter material around inhomogeneities was evaluated.

2. Materials and methods

Calibration curves were obtained for 6 different phantoms: 2x CIRS 062M (CIRS inc., USA), 1x Agmeco (Agmeco, Czech Republic), 1x QUASAR Multipurpose Body phantom (Modus QA, USA), 1x Gammex Phantom (Sun Nuclear, USA), 1x The CatPhan500® (The Phantom Laboratory, USA) at
two different centres using two different CT scanners. CIRS phantom was scanned either in pelvic geometry (inner part and outer part together) or head geometry (only inner part). The information from the vendor about the composition and densities of materials were used for the calibration. The calibration curves were compared to the theoretical curve calculated by Varian formulas (based on CT numbers from CIRS phantom), which had been usually pre-set in Eclipse TPS and were considered as a reference for the purpose:

\[
\text{for CT numbers} \leq 100: \quad \text{RED} = 1 + 1.001 \times CT \text{ number} \quad (1)
\]
\[
\text{for CT numbers} > 100: \quad \text{RED} = 1.052 + 0.00048 \times CT \text{ number} \quad (2)
\]

According to the IAEA recommendation, for the accuracy in RED defined by the treatment planning system the tolerance of 10% should be used [1].

All phantoms were scanned at two centres with 2 CT scanners under different protocols with different spectra. CT numbers were obtained as average values from the central parts of the inhomogeneities rods. The influence of different calibration curves on dose calculation in the TPS has been estimated. The presence of the scattering material around inhomogeneities in phantoms has been evaluated.

2.1. The sensitivity of relative electron density to absorbed dose
The sensitivity of RED to dose was determined for a reference 10 x 10 cm² field in the homogeneous medium (40 x 40 x 40 cm³) when the density of the phantom was changing from the air to the dense bone in the treatment planning system. The set of plans was created with prescribed dose of 2 Gy at the depth of 5 cm in the phantom, so the sensitivity to change in density was overestimated as such thick layers are usually not present in the human body. However, the intent was to perform the conservative evaluation. Calculations were performed for 6 MV and 18 MV with the result of different numbers of MU corresponding to dose of 2 Gy for particular density for PBC and AAA dose calculation algorithms implemented in TPS Eclipse (Varian).

2.2. The influence of CT spectra to CT numbers
The influence of CT scanner spectra to CT number was determined. The CIRS phantom was scanned in pelvic and head geometry at one department under different CT spectra conditions, i.e. with 90 kV, 120 kV, and 140 kV. The voltage was the only variable in the experiment, slice width and matrix size remained the same for all CT data sets.

2.3. The influence of scatter to CT numbers
It is well known that scatter conditions around heterogeneities in the phantom influence the final calibration curves [2]. The Agmeco phantom was tested on the influence of the presence of scatter material, because it was possible to separate part with rods from the whole anthropomorphic phantom. This part was CT scanned in air and in full scatter water tank (at least 20 cm to all directions from heterogeneities). The scatter was also addressed by scanning CIRS phantom, because it consists of two nested disks to represent either head or pelvic configuration.

2.4. Comparison between phantoms of different vendors
The comparison between results at two centres was made to keep the results more robust. At centre 1, Gammex, Agmeco, QUASAR, and CIRS phantom in pelvic and head geometry were scanned at CT scanner with 120 kV. At centre 2, CatPhan, Agmeco, QUASAR and CIRS in pelvic and head geometry were scanned at CT unit with 120 kV. CT scanners at centre 1 and centre 2 were different.
2.5. Comparison between phantoms of the same vendor

There were 2 different pieces of the same phantom type available (CIRS), therefore we analysed the uniformity of phantom type. The experiment was performed at centre 2. Both phantoms were scanned under identical conditions (120 kV) in pelvic and head geometry.

3. Results and discussion

3.1. The sensitivity of relative electron density to absorbed dose

The sensitivity to dose with change in RED is higher for materials with CT number higher than 100 HU, when 10% change in RED cause the change in dose of 3% for 6 MV and 1.5% for 18 MV for described geometry. The dependence is shown in Figure 1 when unfavourable scenario for thick layers of medium with current density was considered. The dose was calculated with pencil beam convolution (PBC) and anisotropic analytical (AAA) algorithms. For materials with RED higher than 0.6 the shape of curves was similar for both dose algorithms. For lower REDs, the values calculated by AAA were more random due to the coincidence of geometry, scatter conditions, and material density, therefore these were not included in the analysis.

![Figure 1. The relative deviations in dose (calculated with PBC dose algorithm in Eclipse Varian) for the same number of MU corresponding to change in relative electron density for 6 MV and 18 MV for one field 10 x 10 cm² for the layer of 5 cm thickness in material with particular density.](image)

3.2. The influence of CT spectra to CT numbers

The CT spectra can influence doses up to 4.5% and 2.5% for 6 MV and 18 MV respectively when voltage changes from 90 kV up to 140 kV due to the change in CT numbers. The curves are shown in Figure 2.
Figure 2. Calibration curves for CIRS phantom obtained at centre 2 with 90 kV, 120 kV and 140 kV at the same CT scanner. Curve obtained from Varian formulas is expressed as a line. Two values for CIRS pelvic express REDs obtained for plugs of the same density inserted at the inner part and outer part of the phantom respectively. In red circle left, difference in dose is indicated when compared phantom values and Varian formula. In red circle right, maximum dose differences are indicated for various CT numbers obtained for dense bone under different CT spectra.

3.3. The influence of scatter to CT numbers
The influence of presence of scattering material around heterogeneities to CT number is shown in Table 1. Agmeco phantom has a very similar geometry to QUASAR body phantom, therefore it can be assumed, that the same conclusions apply to QUASAR body phantom. The presence of the scatter around phantom influences significantly the shape of calibration curve. Difference can be seen also for cases when the rod of the same density was scanned in the inner and the outer part of CIRS phantom as can be seen in Figure 2. The curve is steeper when there is more of the surrounding scattering material. In practice, there is usually only one scanning protocol for particular anatomical site available which is not dependent on the volume of the scanned patient. So, final RED values are affected by this uncertainty.

Table 1. The influence of scattering material around heterogeneities for the Agmeco phantom. The columns “water” and “air” indicate that phantom was scanned in the water tank or in the air respectively. RED are calculated from CT numbers by formulas (1) and (2).

| Inhomogeneity     | CT number (HU) | RED | Relative deviation (%) |
|-------------------|----------------|-----|------------------------|
|                   | Water      | air | water      | air               |
| Lung inhale       | -801.5     | -820.7 | 0.199     | 0.179            | -10.7     |
| Adipose           | -75.1      | -82.2   | 0.925     | 0.918            | 0.8       |
| Trabecular bone   | 243.3      | 278.6   | 1.169     | 1.186            | -1.4      |
| Dense bone        | 942.8      | 1042.9  | 1.505     | 1.553            | -3.1      |
| Water equivalent  | 30.0       | 32.7    | 1.030     | 1.033            | -0.3      |
3.4. **Comparison between phantoms of different vendors**

The largest sensitivity (see Figure 3) was observed for dense bone (up to 3.6% in dose for 6 MV and 1.8% for 18 MV).

**Figure 3.** Calibration curves for various types of phantoms obtained at centre 1. All phantoms scanned at the same CT scanner (120 kV). Curve obtained from Varian formulas is expressed as a line. In red circle left, the values estimate the dose difference based on different phantoms (CIRS and Gammex). In red circle right, the values estimate the dose difference between calibration based on Gammex phantom and Varian formula for dense bone.

**Figure 4.** Calibration curves for various types of phantoms obtained at centre 2. Curve obtained from Varian formulas is expressed as a line. All phantoms were scanned at the same CT scanner (120 kV). In red circle left, the values estimate the dose difference between Varian formula and phantoms (CIRS, QUASAR). In red circle right, the values estimate the error in dose when CatPhan was used for calibration for dense bone.
As can be seen from Figure 4, CatPhan phantom should not be used for calibration at high density materials where the dose could be incorrect up to 16% and 8% for 6 MV and 18 MV respectively. In the phantom, the number of inhomogeneities is low and the slope of the curve would therefore be wrong. It could be only used for materials with negative CT numbers. All other phantoms could be used for calibration. We believe that in the case that more phantoms are available at the department, it would be useful to combine information from all phantoms and use them to construct a final calibration curve. For materials with CT numbers around 100 – 300 HU, Varian formula slightly overestimates the calibration curve.

In general, materials simulating soft tissues and lungs in phantoms were similar and in better agreement that materials simulating bones. Also in the region, where the slope of the curve changes (around 100 - 300 HU), appropriate materials should be used for calibration.

3.5. Comparison between phantoms of the same vendor
Two phantoms by the same vendor (CIRS) differed in CT numbers for dense bone up to 2% and 1% in dose for 6 MV and 18 MV respectively, other materials were in better agreement. However, the change in CT numbers and in RED was for all materials within recommended tolerances [1] and the vendor declares in the phantom brochure that “the actual physical density fo the insert can vary within ±1% of the manufacturing target density”.

4. Conclusion
Phantoms used for CT-RED calibration were compared and various conditions and their influence to dose calculated by TPS was evaluated. The accuracy of calibration curve is influenced by all considered factors: the phantom type, scattering material in the phantom, and setup scanning parameters at CT unit. Slightly different curves can be obtained with one phantom type in high density region. All tested phantoms were found convenient for calibration except CatPhan where large deviations were observed for dense bone. Phantoms without scatter material around inhomogeneities should be used with caution. Varian formula slightly overestimates calibration curve in the region of 200 - 300 HU. The tolerance level of 10% suggested for RED during commissioning is reasonable as it can cause change in dose of 3% and 1.5% for 6 MV and 18 MV respectively as a very conservative estimate. Calibration curves should be acquired for all scanning protocols with different CT spectra that are used for imaging of patients for treatment planning purposes.

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