Determination of the test-samples electron density via dual energy computer tomography

A A Grigorieva[1], A A Bulavskaya[1], I A Miloichikova[2,3], Yu M Cherepennikov[2] and S G Stuchebrov[1]

[1] Research School of High-Energy Physics, Tomsk Polytechnic University, Tomsk, Russia
[2] School of Nuclear Science & Engineering, Tomsk Polytechnic University, Tomsk, Russia
[3] Cancer Research Institute of Tomsk NRMC RAS, Tomsk, Russia
E-mail: anngrigorievabr@gmail.com

Abstract. In this work we determines electron density using data obtained via CT scanner with one radiation source operating in two modes: with 80 kV and 120 kV voltage. We perform tomography study of calibration phantom with predetermined electron densities. Single linear relationship between energy-subtracted Hounsfield unit and relative electron density is determined. Using determined relationship the relative electron densities of phantom calibration samples is calculated. The comparison of calculated and nominal values proves the possibility of the samples relative electron density determination using energy-subtracted Hounsfield unit with error less than 2%.

1. Introduction

Radiation treatment planning is one of the most important point in current medical practice to provide high quality of radiotherapy [1, 2]. In the process of radiation planning, the rate of radiation absorption in different tissues is calculated using their electron density value, while physical characteristics of patients' organs and tissues are observed using tomography. However, tomography determines object sizes and internal structure as a distribution of Hounsfield units (HU) in investigated volume. One of the main stage impacting dose calculation accuracy is a transformation of the HU values of patient tissues to the electron density relative to water (ρ_e) [3]. This transformation are usually performed using calibration curves obtained with special phantoms containing samples with predetermined electron density [4, 5]. Nevertheless, HU and electron density do not have particular correlation, as far as determined using CT scanner HU depends not only on effective atomic number and electron density of the particular material but also on CT scanner operating mode and geometrical parameters of investigated object, that causes significant differences in obtained calibration curves [6].

Goodsitt et al [7] showed the possibility to determine sample's electron density based on results of Dual-energy computed tomography (DECT). Saito M. [8] proposed an approach to calculate single linear relationship between energy-subtracted Hounsfield unit and relative electron density, which can be used both for single-source or dual-source DECT systems, and conventional CT scanners with one radiation source.

In previous works we proposed 3D printing applications for radiation therapy [9, 10]. However, using of 3D printed samples for radiation field modulations in radiotherapy sessions it is necessary to perform radiation planning taking into account parameters of these samples. Therefore, one need an experimental method to determine electron density of 3D printed samples. Using of single linear relationship between energy-subtracted Hounsfield unit and relative electron density is the one of possible approaches.

In this work we describe the algorithm to obtain the calibration curve, which allows to determine relative electron density of 3D printed samples using energy-subtracted Hounsfield unit measured using conventional CT scanner with one radiation source operating in two voltage modes: 80 kV and 120 kV.

2. Materials and methods

2.1. Method to determine electron density of the sample.

To determine relative electron density of the sample it is possible to use dual-energy computed tomography image data [11]. The relative electron density ρ_e^{cal} depends linearly on energy-subtracted Hounsfield unit (ΔHU), and can be calculated using following equation:

$$\rho_e^{cal} = k\frac{\Delta\mathrm{HU}}{1000} + b\,, \tag{1}$$

where *k* and *b* is an linear equation coefficients.

The sample energy-subtracted Hounsfield unit, depends on dual-energy computed tomography image data and corresponds to the following equation [11]:

$$\Delta\mathrm{HU} = (1+\lambda)\cdot\mathrm{HU_H} - \lambda\cdot\mathrm{HU_L}\,, \tag{2}$$

where $\mathrm{HU_H}$ – material HU, obtained for the higher X-ray tube voltage; $\mathrm{HU_L}$ – material HU, obtained for the lower X-ray tube voltage; λ – weighting factor for the subtraction [8].

Iterative method is used to describe calibration curve connecting samples relative electron density and energy-subtracted Hounsfield unit and to determine *k*, *b* (equation 1) and λ (equation 2) coefficients, by varying λ in a wide range for each particular calibration sample. Approximating resulting data for each λ it is possible calculate coefficient of determination r^2. Analyzing dependence of r^2 on λ one finds λ value corresponding to maximum r^2 value. In the ideal case coefficients *k*, *b* (equation 1) and r^2 are unity. However, in practical calculation of *k* and *b* (equation 1) for calibration ΔHU to ρ_e it is necessary to minimize standard deviation of ρ_e^{cal} from nominal values ρ_e.

2.2. Equipment

Experimental data is obtained in Dmitry Rogachev National Research Center of Pediatric Hematology, Oncology and Immunology (Moscow, Russian Federation) using the CIRS Model 062 Electron Density Phantom (Computerized Imaging Reference Systems, INC., Norfolk, Virginia, USA) [4] and CT scanner GE LightSpeed 16 (General Electric, Boston, Massachusetts, USA) [12]. CT data of calibration phantoms is obtained in two voltage modes: 80 kV and 120 kV (Figure 1).

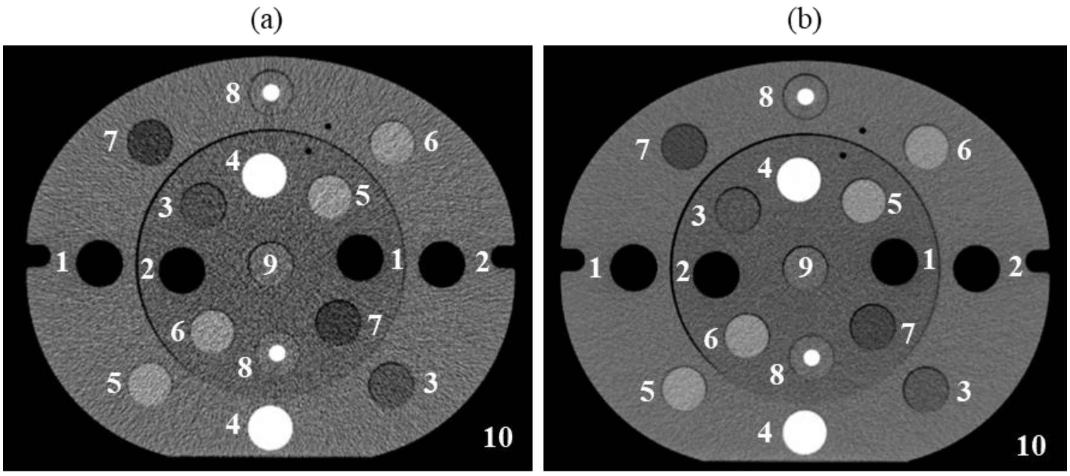

Figure 1. CT images of calibration phantoms, obtained at voltage of (a) 80 kV and (b) 120 kV.

Numbers on Figure 1 corresponds to the different calibration samples manufactured from CIRS tissue equivalent materials. Table 1 shows physical density and electron density relative to water (ρ_e) for each sample [4].

Table 1. Nominal physical/electron densities of CIRS Model 062 electron density phantom rod materials.

№	Rod materials	Physical density, g/cm^3	Electron density relative to water (ρ_e)
1	Lung (Inhale)	0.200	0.190
2	Lung (Exhale)	0.500	0.489
3	Breast	0.990	0.976
4	Solid Trabecular Bone	1.160	1.117
5	Liver	1.070	1.052
6	Muscle	1.060	1.043
7	Adipose	0.960	0.949
8	Solid Dense Bone	1.530	1.456
9	Water	1.000	1.000
10	Air	0.001	0.001

3. Results and discussions

To obtain ΔHU to ρ_e calibration curve, Hounsfield units for rod materials of CIRS Model 062 electron density phantom measured by a GE LightSpeed 16 CT scanner at two voltage modes: 80 kV (HU_L) and 120 kV (HU_H). The HU_H and HU_L is determined for each particular material as average value in region of interest (ROI) of 2 cm^3 located in the center of each sample. However, for Solid Dense Bone material ROI equals 0.4 cm^3.

Using the method described above λ coefficient is determined and equals to 1.294 that corresponds maximal value of the coefficient of determination r^2 (0.9994). For this purpose, dependence of r^2 on weighting factor λ is plotted (Figure 2). The coefficients k and b (equation 1) equals to 0.991 and 0.992 respectively, as far as standard deviation of the calculated values ρ_e^{cal} from nominal values ρ_e is minimum for this coefficients.

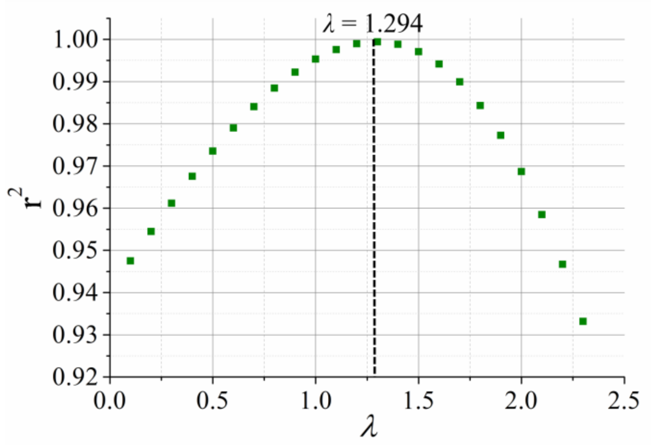

Figure 2. The dependence of r^2 as a function of the weighting factor λ.

To demonstrate the necessity of using single linear relationship between energy-subtracted Hounsfield unit and relative electron density, dependences of ρ_e on HU_H, HU_L and ΔHU is shown on Figure 3.

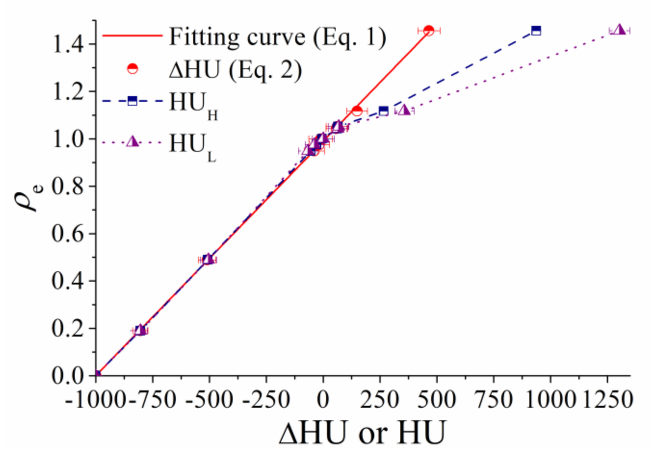

Figure 3. The dependence between the CIRS phantom rod materials relative electron density and Hounsfield units.

As one can see on Figure 3, dependences of relative electron density on Hounsfield unit, obtained via only one X-ray tube voltage HU_H or HU_L, is not linear unlike ΔHU. The latter is that is particularly evident for positive HU. In a 50 HU – 1250 HU range the error of Hounsfield unit determining impact significantly on sample relative electron density calculation. Accounting of single linear relationship between energy-subtracted Hounsfield unit and relative electron density avoids the above disadvantages.

Calculated relative electron density (ρ_e^{cal}) for rod materials of CIRS Model 062 electron density phantom based on equation 1 is shown in Table 2, where ρ_e – nominal electron density relative to water value.

Table 2. Relative electron density for rod materials of CIRS Model 062 electron density phantom based on energy-subtracted Hounsfield unit (ΔHU).

Rod Materials	ΔHU	ρ_e	ρ_e^{cal}	$\left|\rho_e^{cal} - \rho_e\right|$
Lung (Inhale)	-804.590	0.190	0.195	0.005
Lung (Exhale)	-510.444	0.489	0.486	0.003

Breast	-16.345	0.976	0.976	0.000
Solid Trabecular Bone	148.840	1.117	1.140	0.023
Liver	61.194	1.052	1.053	0.001
Muscle	57.164	1.043	1.049	0.006
Adipose	-39.099	0.949	0.953	0.004
Solid Dense Bone	465.087	1.456	1.453	0.003
Water	-11.493	1.000	0.981	0.019
Air	-999.730	0.0010	0.0013	0.0003

Table 2 proves the applicability of relative electron density determining based on energy-subtracted Hounsfield unit (ΔHU). The error of calculation is less than 2% that corresponds to requirements of international recommendations [13].

4. Conclusion

In this work we obtain calibration curve for considered equipment, allowing determining of the sample relative electron density in a wide range from 0.001 (air) up to 1.5 (solid dense bone). Investigation performed using GE LightSpeed 16 CT scanner with one radiation source operating in two voltage mods 80 kV and 120 kV. Calculated values of electron densities relative to water for rod materials of CIRS phantom obtained using energy-subtracted Hounsfield unit, is in a good agreement with nominal ones. Considered approach is prospective to applicate in clinical practice for experimental determining of 3D-printed samples relative electron density, which is designed for radiation field modulating.

Acknowledgments

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