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Upgrading a Computed Tomography Dose Index (CTDI) Phantom to an Electron Density (ED) Phantom for Commissioning a CT Simulator

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ABSTRACT

Introduction: A crucial step in commissioning a CT simulator is measuring the conversion relationship between the CT number and Relative Electron Density (RED) and transferring it to the radiotherapy TPS for accurate dose calculation.

Material and Methods: In order to automatically reconstruct a DE-Rho series with relative electron density maps of the materials used, 14 tissue-mimicking material plugs were made, their properties were measured, and the developed density phantom was scanned by CT-simulator using the Dual Energy^DE_Direct Density protocol.

Results: CT numbers (HU) for various densities of materials were determined. Utilizing the resultant HU from CT scans, the relative electron density, or RED, was computed. The HU-RED calibration curve was created using CT scans that were obtained with different tissue replacements.

Conclusion: Particularly for the CT-number calibration in radiation therapy planning, the new Tissue Equivalent Materials (TEMs) may simplify the calibration process without sacrificing the accuracy of the stoichiometric calibration. Our objective was met and the purchase cost was avoided thanks to the developed phantom.

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Introduction

Cancer is a severe health issue globally, roughly half of all cancer patients receive radiotherapy treatment. This form of treatment uses complex technology that includes megavoltage radiation that if not handled with extreme caution, can lead to significant errors in the treatment of patients and staff exposure. Radiation oncology technology has advanced rapidly in recent years. A major factor contributing to this rapid development has been the development of technology of computer and its applications in (a) the Diagnosis of the patient using advanced computerized diagnostic imaging and (b) the Radiotherapy planning process using computerized radiotherapy treatment planning systems (TPSs) that use data from diagnostic imaging equipment [1].

Computed tomography (CT) has been used extensively, since the late 1970s for radiation therapy planning by advantages such as patient position optimization, arrangement of the treatment beam, dosage computation, and delineation of tumors. Unlike diagnostic CT scanners, CT simulators typically use a broad bore (>80 cm) scanner to handle very large people, breast cancer patients whose ipsilateral arm is rounded about 90 degrees, as well as those who have specialized fixing devices. For radiation CT simulators, a flat couch and a laser system that moves also are required. To ensure accuracy, the performance of the oncology CT scanner and its characteristics should be evaluated before performing patient CT simulations [2].

(TPS) converts Hounsfield Units (HUs) into electron densities relative to water for precise dose distribution estimates, according to the American Association of Physicists in Medicine (AAPM, Task Group 53), and the International Atomic Energy Agency (IAEA, TEC DOC-1583) (tissue heterogeneity corrections). This is typically done with electron density reference materials that enable the verification procedure for TPS commissioning [3,4].

CT electron density phantom is used for calibration of the CT unit by finding the relation between the CT numbers (in Hounsfield units, HUs) and relative electron densities of different tissues. The conversion from the CT No. to the relative electron density depends on the atomic number of the

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material. Then, this data can be sent to a treatment planning system for more accurate corrections of tissue heterogeneity. The phantom also has a pattern of small air holes with known spacing around the center to evaluate the CT machine's geometric accuracy. Scanning this phantom periodically provides useful data for the quality assurance program of both the treatment planning system and the CT scanner [1]. The CT electron density phantom is used for: a. CT scans data evaluation. b. Correction for heterogeneity. c. Documenting the relation between CT number and tissue electron density. d. Simulation indicated tissue within the diagnostic energy range. e. A rapid evaluation of distance registration [1,5].To commission a CT simulator we must have a CT electron density phantom or upgrade a Computed Tomography Dose Index (CTDI) phantom with several tissue-mimicking materials to a density phantom aiming to simulate tissues and acquire the corresponding CT numbers or Hounsfield Units (HUs). An alternative to the typical commercial density phantom is provided by the created phantom. This study was conducted to upgrade the Computed Tomography Dose Index (CTDI) phantom to a density phantom by creating multiple materials with different densities in the laboratory to provide a full range of HU to relative electron density to cover a wide range of electron density values in human tissues.

Materials and Methods

CT Simulator (Siemens Somatom) Confidence model with 64 detector rows and serial number S. N. (100343). Three-dimensional radiation treatment planning system 3D-RTPS prowess panther TPS model, (Version 5.51), (Build Number 4608). Standard PMMA CTDI phantom (head and body phantom) (Siemens Somatom). Multiple tissue-mimicking materials (TMMs) are shown in Figure (1). The Advanced Materials Laboratory, Physics Department, Faculty of Science, Mansoura University, Egypt is where the majority of TMMs were moulded.

CT- simulator & RTPS were installed, and The Clinical Oncology & Nuclear Medicine Department, Faculty of Medicine, Mansoura University, Egypt, employed the CTDI phantom in its Radiotherapy Unit.

In this study, 14 unique tissue-mimicking materials (TMMs) were made shown in Figure (1) to provide a full range of HU to relative electron density to cover a wide range of electron density values in human tissues; table 1, to ensure accurate calculations of dose distributions in radiotherapy. The materials were selected with the help of the International Commission on Radiation Units and Measurements (ICRU, Report No. 44), Medical Internal Radiation Dosimetry (MIRD) [6,7], and the table described in detail the elemental composition, mass density (ρ), and relative electron density (ρe) for various selected body tissues [6-8].

The CTDI phantom has a cylindrical shape and is made of acrylic, representing the human head and body. The head phantom was 16 cm in diameter and when nested within the body phantom represented the body 32 cm in diameter. Overall dimensions were 32 cm x 32 cm x 15.2 cm with a total weight of 14.5 kg. The head cylinder contained 5 probe holes, one in the center and four around the perimeter, 90 degrees apart and 1 cm from the edge. The body contained 4 probe holes 90 degrees apart and 1 cm from the edge. Different solid and liquid materials could be inserted into the holes as tissue-equivalent materials. The phantom's center and peripheral probe holes were designed to allow the insertion of an ionization chamber for ionizing radiation (IR) dose measurements.

If TMMs were put in the probe holes, one material in each hole at its proper place inside the phantom, we would have a density phantom [9]. Firstly, we could make a scan with 5 materials only from the 14 materials as the phantom has 5 probe holes only, then the scan was repeated with the rest 5 materials. The materials should be characterized (density, concentration, and structure) before use in the fabrication to ensure accuracy.

Table1. The molded tissue-mimicking materials (TMMs)

Recommended	Teflon, Acrylic, Polystyrene, True water, Polyethylene, Wood, Cork, and Air
Optional	Aluminum, Titanium, and Stainless-Steel
Extra	Paraffin wax, Sugar, Salt, and Quartz.

Figure 1. Multiple tissue-mimicking materials (TMMs).

So, the density of materials was measured at the National Research Center, Cairo, Egypt, and the concentration, and structure of materials was measured by energy dispersive x-ray (EDX) composition analysis using scanning electron microscopy (SEM) instrument at an Electron Microscope unit (JEOL JSM 6510 Iv model), Faculty of Agriculture, Mansoura University, Faculty of Agriculture, Mansoura University, Egypt.

In order to automatically reconstruct a DE-Rho series with relative electron density maps of the materials used, the CT electron density phantom that was developed from the CTDI phantom would be scanned on the CT simulator using the Dual Energy^DE_Direct Density protocol (120 KVp& 211 mAs and slice thickness 3mm). The phantom was centered under the tomographic

x-ray field with the three internal laser lines (right, left, and sagittal), in the head-first supine (HFS) position; Figure 2 (a,b).

Using Prowess Panther TPS version 5.51, circular areas of interest (ROI) were established on the phantom's CT pictures within the sensitometric inserts, and mean CT numbers for various materials were determined (as shown in Figure 3).

Finally, the CT No. to Relative Electron Density (RED) calibration curve could be obtained by plotting RED and HU values of the TMMs on the vertical and horizontal axes of the coordinate system, respectively, using published known values, or calculated values.

The CT number by the equation could be calculated[1٠-13]:

$$\text{CT number or HU} = \frac{\mu_t - \mu_w}{\mu_w} \times 1000 \qquad [1]$$

Where: μ_t is the linear attenuation coefficient of the pixel of certain tissue, and μ_w is the linear attenuation coefficient of the water pixel.

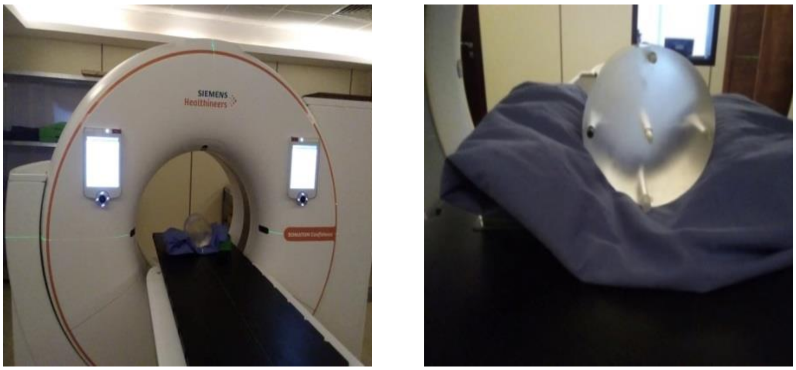
Relative electron density RED could be calculated easily by the equations:

$$\text{RED} = \frac{\text{HU}}{1000} + 1, \text{ If HU<100} \qquad [2] \quad [1٠, 11, 14]$$

$$\text{RED} = \frac{\text{HU}}{1950} + 1, \text{ If HU≥100} \qquad [3] \quad [1٠, 11, 14]$$

Also used the following equations**:**

$$\text{RED} = \frac{\text{electron density ED of material}}{\text{electron density ED of water}} \qquad [4] \quad [11, 15, 16]$$



(a) (b)

Figure 2. (a, b). The scanning geometrical set-up of the phantom.

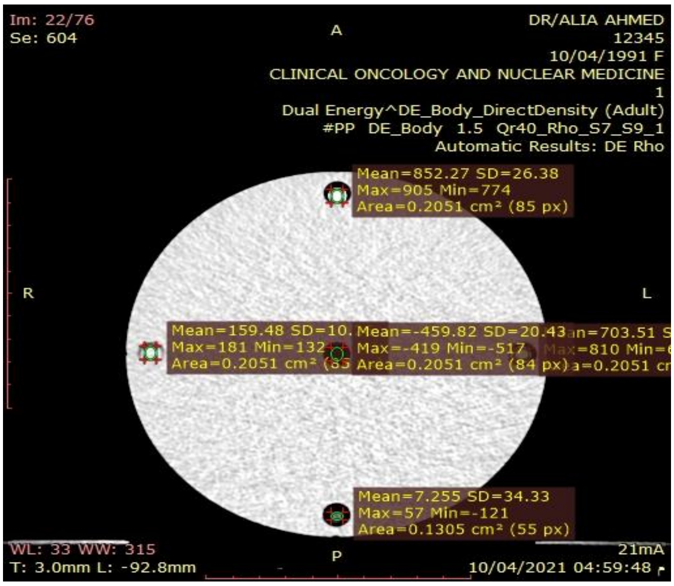


Figure 3. Region of interest defined for different sensitometry targets

$$ED = \rho_m \times N_A \sum \frac{W_i Z_i}{A_i} \qquad [5] \quad [15\text{-}17]$$

Where: ρ_m is the material's physical density, N_A is Avogadro' 's number of material (= 6.022 045 × 10^{23} mol^{-1}), A_i and Z_i are the atomic weight and the atomic number of the i^{th} element, and W_i is its proportion by weight. Then the RED was calculated by dividing the material's electron density by the electron density of water.

All values of mean CT No. and calculated RED for all the plugs were input into the (TPS) and get the conversion curve for more accurate dose distribution calculations. Also, the CT scan of the fabricated phantom could be opened on the radiation TPS from a patient browser, and check the CT number and physical density values at any point of the phantom by the mouse to check calculated values.

Results

The materials were scanned using the following protocol: the dose length product (DLP) = 53.2mGy.cm and the X-ray tube calibration using the Dual Energy^DE_Direct Density protocol (120 KVp, 211 mAs) CTDI\ volume = 0.52mGy. Following the stages of inspection and reconstruction, the HU measured could use DICOM (digital imaging and communication in medicine) to record the known value of relative electron density together with a file format and transmission protocol.

Table 2. Characteristics calculated and published CT number, and RED values for the molded materials

Tissue substituted	Tissue Mimicking Material Characteristics through EDX	Published *RED [19, 2٠]	Calc. RED	Published mean CT(HU) No.[2٠, 21]	Calc. Mean CT No. (HU)
Bone	*Recommended:* Teflon [Polytetrafluoroethylene PTFE $(C_2F_4)_n$] (23.23% C, 76.77% F) ρ_m= 2.11 gm/cc	1.867 Or 1.868	1.87	1000.5	1005
Muscle	Acrylic [Polymethylmethacrylate PMMC $(C_5O_2H_8)_n$] (37.25% C, 42.61% H, 20.14% O) ρ_m=1.163 gm/cc	1.146 Or 1.147	1.054	(40-60)	54
Soft tissue	Polystyrene [PS $(C_8H_8)_n$] (40.29% C, 59.71% H) ρ_m = 1.03 gm/cc	0.999	1.025	47 Or (20-40)	25
Water	True water [(distilled water), Oxidane H_2O] (64.59% H, 35.41%O) ρ_m=0.997 gm/cc	0.998	0.995	0	-5
Fat	Polyethylene [PE $(CH_2)_{2n}$] (53.33% C, 46.67% H) ρ_m= 0.93 gm/cc	0.945	0.926	-(70-30)	-74
Lung (deflated)	Low-Dense Wood (60% C, 6% H, 34% O), ρ_m=0.45 gm/cc	0.489	0.439	-(515-200)	-561
Lung (inflated)	Cork (80% C, 20% H), ρ_m=0.24 gm/cc	0.190	0.22	-(830-515)	-780
Air gaps	Air (multiple gases) ρ_m= 0.001 gm/cc	0	0	-1000	-1000
Metallic hip prosthesis	*Optional:* Aluminum ($^{27}Al_{13)}$ (100% Al) ρ_m= 2.57 gm/cc	2.36	2.39	1351	2711
Tumors, femur rods, metallic hip prosthesis, and implants	Titanium alloy (nail) (47.25% Ti, 44.00% O, 3.53% P, 3.09% Al, 1.31% V, 0.82% Ca) ρ_m= 4.00 gm/cc	3.73 Or 3.79	3.84	8140	5538
Surgical wires, screws, and some spinal fixation	Stainless Steel (56.20% Fe, 13.55% Cr, 3.06% Ni, 6.21% Mn, 10.17% C, 10.81% Tb) ρ_m= 8.60 gm/cc	6.58	6.83	14127	11369
Unspecified tissues	*Extra:* Paraffin (wax C_nH_{2n+2}) (68.30% H, 31.70% C) ρ_m= 0.88 gm/cc	-----	0.877	-----	-239
	Sugar (Sucrose $C_{12}H_{22}O_{11}$) (39.43% H, 40.28% C, 20.29% O) ρ_m= 1.58 gm/cc	-----	1.39	-----	390
	Salt (Sodium Chloride NaCl) (39.05% Na, 60.95% Cl) ρ_m= 2.25 gm/cc	-----	1.998	-----	998
	Quartz (Silicon dioxide SiO_2) (76.20% O, 23.80% Si) ρm= 2.60 gm/cc	-----	2.458	-----	1458

*Relative electron density RED is relative to water.

Radiation interaction and dosimetry were required to verify the coherence of the molded phantom materials with the simulated tissues, therefore the material's properties were measured at the National Research Centre in Cairo, Egypt.

Although many useful references and phantom manufacturers (CIRS, The Phantom lab, Sunetc.) have tabulated and published values of RED for many tissue-mimicking materials, we had to calculate RED as some of the materials in this study have no published and known values. Also, published CT No. values of some materials were at energies different from those in our study. Characteristics, published and calculated RED, published and calculated CT No. values of the materials used in our study are detailed in the following Table 2.

The HU values obtained from the systems were plotted against the calculated RED of the materials. All values of mean CT No. and calculated RED for all the plugs were input into the Prowess Panther TPS (as shown in Figure 4).

Figure 4. Shows the conversion curve for all materials on Prowess Panther TPS

Discussion

The lack of density phantom in our department was the main motive for doing this work. The tissue-mimicking materials were made and molded in the advanced materials laboratory at the faculty of science, physics department, Mansoura University. The titanium nail was obtained from the orthopedic department, Mansoura University Hospitals; Figure 1.

The study used 14 unique tissue-mimicking materials to provide a full range of HU to relative electron density to cover a wide range of electron density values in human tissues. Commercial plastics and other materials used are known to have considerable density variation. So, there was material study or testing (to verify the material concentration, structure, and density) on all the 14 tissue-mimicking materials suggested in this study, by energy dispersive x-ray (EDX) composition analysis using scanning electron microscopy (SEM) instrument Table 2.

Not all the selected materials were made based on the International Commission on Radiation Units and Measurement (ICRU) and Medical Internal Radiation Dosimetry (MIRD), but some materials were selected based on their known considerable density values.

It is well known that differences in attenuation correction, beam hardening, scatter, etc can produce very different CT numbers in the same samples placed in head size vs body size phantoms. This is even more apparent with the movement to volume CT scanners. So, each material was put in the appropriate probe hole in the head and body phantom.

As all the materials with their cylindrical shape had the same volume (length and diameter); 15.6cm & 0.7cm (circle area= πr^2=3.14×0.35×0.35=0.38cm^2), the Defined region of interest (ROI) 0.3cm^2 with a sufficient number of pixels in the ROI to avoid the pixels at the boundary of the cylinder due to possible partial volume averaging CT artifact that can affect the mean CT number, and made sure that there was enough scatter during measurement.

John Paul Bustillo et al., 2018, created a 3D-printed radiation phantom based on a patient's computed tomography CT scan for the purpose of ensuring the quality of intensity-modulated radiation therapy (IMRT). To obtain the mean CT number, they scanned at 130 KVp, employed a circular ROI with a diameter of 1 cm, and placed a 0.3 cm2 ROI in the middle of each slice [18].

Hyun Joon An et al., 2019, scanned a Model 62M electron density phantom (CIRS Inc., Norfolk, VA, USA) and utilized it to determine the Hounsfield Unit (HU) value or related CT number for any substance that is tissue equivalent. A 211mAs, 120kVp body scanning technique with a 2mm slice thickness was used to scan this phantom [2].

But Reza Mahmoudi et al., 2016, utilized the tissue-equivalent materials-designed phantom and set it atop a CT scanner table. They collected data at three different X-ray energies (80, 110, and 130 kVp) using a brain-scanning protocol with a constant milliampere-second generated at 230 for each of the three energies. Their results varied according to the conventional definition of the CT number for kVp [9].

Mohamed Bahaaeldin Afifi, et al., 2019, also examined the association between the CT number to RED and the voltage fluctuations in the CT x-ray tube. They employed CIRS 062M phantom with 10 tissue density equivalent inserts and step voltages of 70, 80, 100, 120, and 140 kV. The CT number to the RED connection is significantly impacted by variations in the voltage of the CT x-ray tube, it was discovered [13].

So we recommend that treatment planning systems consider the impact of differences in CT number values due to changes in kVp on radiation dose estimations, so the dual energy protocol was used in our future work and get the benefit of the automatic relative electron density mapping of the materials as an automatic result.

In the calibration curve, Stainless steel represented the highest point of the curve, and air represented the lowest point of the curve.

The total curve obtained from the Excel sheet resembled the curve obtained with the prowess radiation treatment planning system (TPS) (with the same slope=0.0005), which confirmed our results.

It was determined that there was no significant difference (p>0.05) between the calculated and published mean CT number and between the calculated and published RED for various tissue-mimicking materials using a T-test with a computed P-value.

Conclusion

Particularly for the CT-number calibration in radiation therapy planning, the new Tissue Equivalent Materials(TEMs) may simplify the calibration process without sacrificing the accuracy of the stoichiometric calibration. Our updated density phantom satisfies our clinical and workflow requirements while lowering the chance of dosage estimations made by the treatment planning system and saving significant time and money, particularly in developing nations.

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