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Evaluation of Effect of Different Computed Tomography Scanning Protocols on Hounsfield Unit and Its Impact on Dose Calculation by Treatment Planning System

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ABSTRACT

Introduction: In radiotherapy treatment planning system (TPS), basic input is the data from computed tomography (CT) scan, which takes into account the effect of inhomogeneities in dose calculations. Measurement of CT numbers may be affected by scanner-specific parameters. Therefore, it is important to verify the effect of different CT scanning protocols on Hounsfield unit (HU) and its impact on dose calculation. This study was carried out to analyse the effect of different tube voltages on HU for various tissue substitutes in phantom and their dosimetric impact on dose calculation in TPS due to variation in HU–relative electron density (RED) calibration curves.

Materials and Methods: HU for different density materials was obtained from CT images of the phantom acquired at various tube voltages. HU-RED calibration curves were drawn from CT images with various tissue substitutes acquired at different tube voltages used to quantify the error in dose calculation for different algorithms. Doses were calculated on CT images acquired at 120 kVp and by applying CT number to RED curve obtained from 80, 100, 120, and 140 kVp voltages.

Results: No significant variation was observed in HU of different density materials for various kVp values. Doses calculated with applying different HU-RED calibration curves were well within 1%.

Conclusion: Variation in doses calculated by algorithms with various HU-RED calibration curves was found to be well within 1%. Therefore, it can be concluded that clinical practice of using the standard HU-RED calibration curve by a 120 kVp CT acquisition technique is viable.

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Introduction

Accuracy of treatment planning system (TPS)-based planning is highly hinged upon computed tomography (CT) images. The quality of these CT images influences the recognition and delineation of target volumes and the surrounding normal organs. Substandard image quality may result in improper delineation of the target volume and normal organs by omission or over-inclusion of a portion of normal organ volume and significant misconception. Thus, it is essential to sustain the optimal image quality of CT scanners used for simulation of radiotherapy patients. The accuracy of dose calculation using these radiotherapy TPS, taking into account the effect of tissue inhomogeneities, is based on such CT data and calibration of CT Hounsfield units (HU) to relative electron density (RED).

CT number or HU from CT images provide information on the attenuation characteristics of X-ray beam in a particular volume element in patient body with respect to that of water at a specific kVp. HU is associated with attenuation coefficient with the following formula [1-3]:

$$HU_{tissue}=[(\mu_{tissue} - \mu_{water})/\mu_{water}]\times 1000 \quad (1)$$

Where μ_{tissue} is attenuation coefficient for tissue and μ_{water} denotes attenuation coefficient for water.

Variation between 1% and 2% has been reported in the measurement of HU values in a uniform homogeneous material [4, 5], and this variation in HU values can reach up to 3% depending upon the location of the material in the image [6]. In addition, the measurement of high HU for different density objects varies among CT scanners and can significantly alter the calibration. Constantinou et al. [4] presented electron density variation of 10% relative to the type of scanner. Moreover, the CT scanner-specific parameters, including scan diameter, matrix size, and photon energy, significantly affect quantification of the CT number.

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In previous studies, the impact of various kVp settings and electron density (ED) distributions on the accuracy of dose calculation in high-energy photon beams was found to be well within 2% [2-7]. In the current study, we aimed to evaluate the effect of different CT scanning protocols, i.e., diverse kVp settings, on HU number variation and their dosimetric impact on dose calculation using different algorithms, e.g., Monte Carlo, collapsed cone, anisotropic analytical algorithm (AAA), and pencil beam.

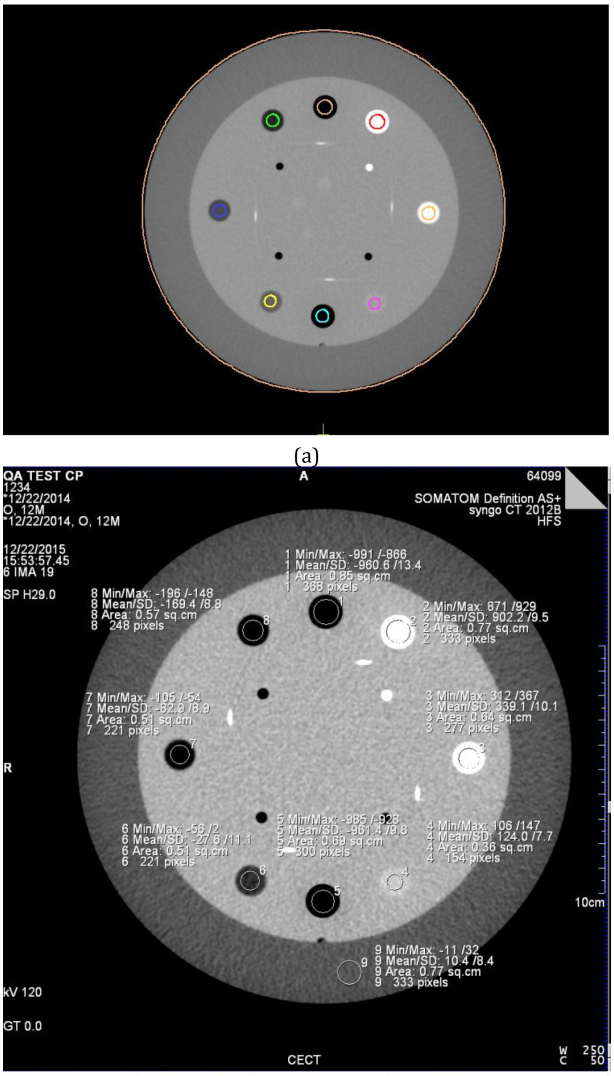
Materials and Methods

Catphan 504 phantom (The Phantom Laboratory, Salem, NY, USA) was employed in our study, which is especially designed and used worldwide for the evaluation and assessment of different image quality parameters in CT such as scan slice thickness, circular symmetry of display system, spatial linearity, and contrast. The Catphan 504 phantom is approximately 20 cm long and 20 cm in diameter with a cylindrical shape. The Catphan phantom contains a number of modules for performing different image quality assurance tests. Densitometry module is one of the modules known as CT404, which contains a numbers of different density inserts. Thus, to measure HU on a wide HU range, CT404 is appropriate.

The image quality and CT number linearity is evaluated using CTP 404 module of Catphan phantom having different density materials, including teflon, delrin, acrylic, polystyrene, low density polyethylene (LDPE), polymethylpentene (PMP), and air. The corresponding estimated HU values according to the Catphan data sheet provided by the manufacturer are -1000 for air, 990 for teflon, 120 for acrylic, -100 for LDPE, 340 for delrin, -35 for polystyrene, and -200 for PMP [8]. The RED values of each material quoted in the data sheet were used and the electron density of water was assumed to be 1.

Siemens SOMATOM Definition AS scanner (Siemens Medical Systems, Germany) was used to acquire CT images of the Catphan phantom. The phantom was placed on CT couch, levelling of the phantom was ensured. As in radiotherapy treatment planning simulation different kVp settings are used depending on the different body sections to be imaged, CT images of the phantom were acquired at different tube voltages of 80 kVp, 100 kVp, 120 kVp, and 140 kVp with slice thickness of 1.5 mm.

Circular regions of interest (ROI) were defined on the CT images of the phantom within the sensitometric inserts, and mean CT numbers for different materials were obtained (as shown in figures 1[a] and [b]) using Monaco TPS version 5.0 (Elekta, Impac Medical Systems, Inc., USA) and Siemens Coherence Dosimetrist workspace System version 2.2 (Siemens medical solutions, USA). ROI selected for the HU measurement of density inserts was less than the physical area of the insert materials, but it was within sufficient distance to the boundaries of the inserts. All the ROIs had an area of approximately 60 mm^2.

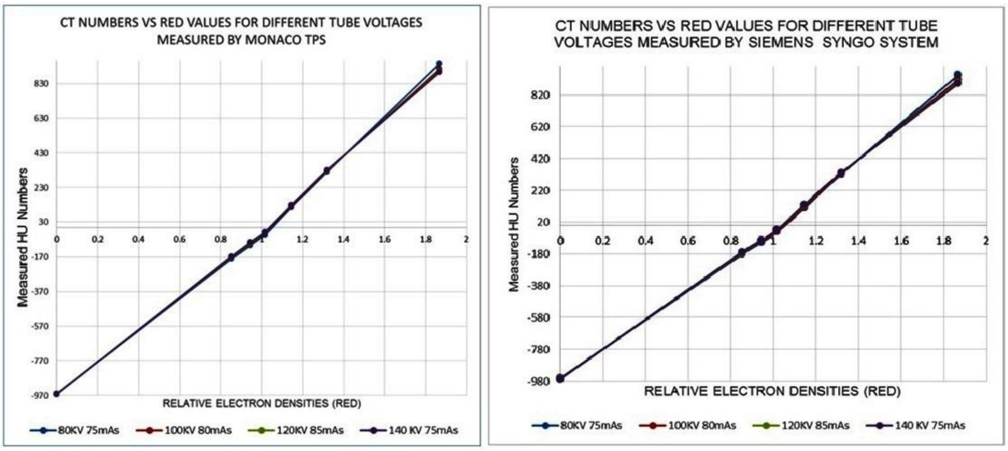


(a)

(b)

Figure 1. Region of interest defined for different sensitometry targets in (a) Monaco TPS and (b) Siemens Coherence Dosimetrist Workspace System

The HU values obtained from the systems were plotted against RED of the materials. Figures 2 (a) and (b) illustrate CT-RED calibration curves obtained for different tube voltages from both systems.



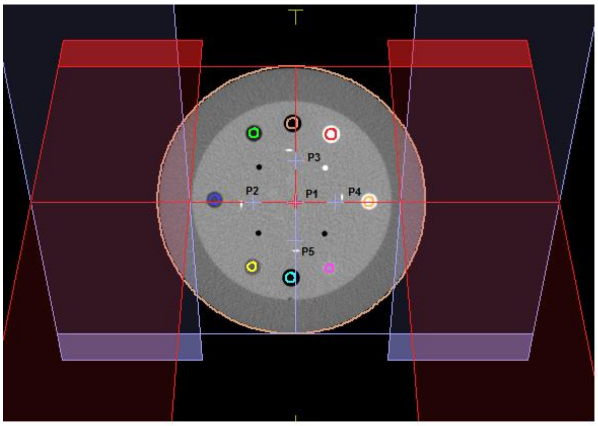
(a) (b)

Figure 2. Computed tomography to relative electron density calibration curve obtained from (a) Monaco TPS and (b) Siemens Coherence Dosimetrist Workspace System

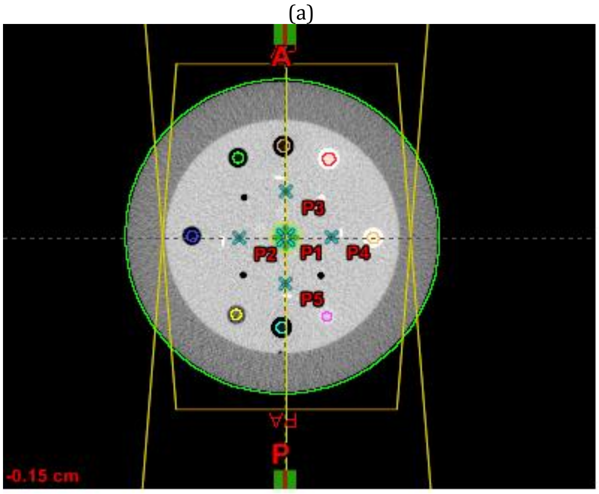
Dosimetric comparison was performed for various CT to RED calibration curves obtained for diverse tube voltages, i.e., 80 kVp, 100 kVp, 120 kVp, and 140 kVp, on Monaco TPS version 5.0 and Eclipse TPS (Varian Medical Systems, Palo Alto, CA, USA) on the images scanned at 120 kVp of Catphan phantom.

An isocenteric plan using 6 mega voltage (MV) beam at gantry angle 0deg and 180deg with the isocenter placed at the centre of the phantom for dose of 2 Gray (Gy) as shown in figures 3 (a) and (b). Dose calculations were performed with Monte Carlo, collapsed cone, and pencil beam algorithm on Monaco TPS version5.0 and with AAA algorithm on Eclipse TPS version8.9 for Oncor Expression machine (Siemens AG, Germany) with calculation grid size of 3 mm to quantify the impact on dose calculation because of variation in CT-RED calibration curves resulted from variation in CT numbers due to different tube voltages.

Since images of the phantom used for dosimetric comparison were obtained on 120 kVp, 120 kVp plan was considered as the reference plan for comparative analysis of doses. Dose comparison was performed for five interest points created on CT images of the phantom as shown in figures 3(a) and 3(b).



(a)



(b)

Figure 3. Dose evaluated at five interest points in (a) Monaco TPS and (b) Eclipse TPS for computed tomography to relative electron density files at different kVp values

Results

Herein, we evaluated and quantified the variation in HU-RED calibration curves for different tube voltages used in CT scanning protocols and its impact on radiation treatment planning and dose calculation in a phantom (while the phantoms used in this work are often confined to QA purposes).

In tables 1 and 2, the HU numbers of different materials for various kVp values on Monaco TPS and Siemens Coherence Dosimetrist workspace system are presented, respectively. No significant difference was found between the HU numbers obtained from both kinds of systems. The estimated *p*-values using two-tailed *t*-test were 0.9952, 0.9925, 0.9965, and 0.9945 (>0.05) for 80, 100, 120, and 140 kVp, respectively.

Table 1. Mean Hounsfield unit values from Monaco TPS for different tube voltages

Density Insert material	Relative electron density	80 kVp	100 kVp	120 kVp	140 kVp
Air	0	-961	-962	-962	-963
Polymethylpentene	0.853	-181	-173	-170	-166
Low density polyethylene	0.944	-105	-96	-93	-87
Polystyerene	1.017	-43	-29	-28	-26
Acrylic	1.146	115	123	127	129
Delrin	1.319	320	326	329	332
Teflon	1.867	944	913	902	895

Table 2. Mean Hounsfield unit values from Siemens Coherence Dosimetrist Workspace System for different tube voltages

Density Insert material	Relative electron density	80 kVp	100 kVp	120 kVp	140 kVp
Air	0	-961	-962	-963	-966
Polymethylpentene	0.853	-182	-175	-172	-168
Low density polyethylene	0.944	-107	-100	-96	-93
Polystyerene	1.017	-41	-39	-29	-28
Acrylic	1.146	110	115	125	130
Delrin	1.319	324	327	331	332
Teflon	1.867	946	916	900	892

Table 3. Dose evaluated on Monaco TPS and Eclipse TPS for different algorithms at five interest points in cGy for a plan created for 200 cGy dose at isocenter using 6 MV for different computed tomography-relative electron density curves from different tube voltages

Defined interest points	Monte Carlo				Collapsed Cone				Pencil Beam				Anisotropic analytical algorithm			
	80kVp	100 kVp	120 kVp	140kVp	80 kVp	100 kVp	120 kVp	140 kVp	80 kVp	100 kVp	120 kVp	140 kVp	80 kVp	100 kVp	120 kVp	140 kVp
P1	199.2	199.9	199.0	199.2	199.6	199.6	199.7	199.7	199.7	199.6	199.6	199.6	199.4	200.1	200.0	200.0
P2	198.1	200.3	199.5	199.8	199.5	199.7	199.8	199.8	204.3	204.1	204.1	204	199.6	200.2	200.1	200.1
P3	202.2	203.0	201.7	202.0	202.9	202.9	202.9	203.0	202.4	202.2	202.2	202.2	202.1	203.1	203.4	203.4
P4	201.5	202.7	201.2	201.3	202.4	202.4	202.4	202.4	202.2	202.0	202.0	202.0	202.2	203.1	203.3	203.3
P5	195.1	196.1	194.5	195.1	195.6	195.5	195.6	195.6	200.3	200.1	200.1	200.1	197.8	196.8	196.8	196.7

Maximum CT number difference was observed within the range of 7-34 HU for PMP, LDPE polypropylene, and acrylic when the measured values were compared with nominal values quoted in the manual of both systems. However, the measured CT numbers were in agreement with one another within 20 HU for all density inserts, except for Teflon, i.e., 54 HU. The reason for variation of HU values in high-density materials could be explained by the non-uniform beam hardening effect of the scanning beam passing through various density materials.

Doses calculated with the images of phantom acquired on 120 kVp and applying the CT number to RED curve obtained from 80, 100, 120, and 140 kVp voltages were well within 1%.

Table 3 exhibits the doses evaluated on Monaco TPS and Eclipse TPS for different algorithms at five interest points in cGy for a plan created for 200 cGy dose at the isocenter using 6 MV for different CT-RED curves from various tube voltages.

The maximum percentage difference in the doses evaluated at five interest points were 0.82%, 0.15%, 0.1%, and 0.64% for the TPS calculations performed with Monte Carlo, collapsed cone, AAA, and pencil beam, respectively; as shown in Table 4, they were within the acceptable range. The differences were greater for the higher density inserts.

Table 4. Percentage variation in doses evaluated for different algorithms at five interest points for different computed tomography-relative electron density curves from different tube voltages

Defined interest points	Monte Carlo			Collapsed Cone			Pencil Beam			Anisotropic analytical algorithm		
	80 kVp	100 kVp	140 kVp	80 kVp	100 kVp	140 kVp	80 kVp	100 kVp	140 kVp	80 kVp	100 kVp	140 kVp
P1	-0.10	-0.45	0.10	0.05	0.05	0.00	-0.05	0.00	0.00	0.30	-0.05	0.00
P2	0.70	-0.40	0.15	0.15	0.05	0.00	-0.10	0.00	-0.05	0.25	-0.05	0.00
P3	-0.25	-0.64	0.15	0.00	0.00	0.05	-0.10	0.00	0.00	0.64	0.15	0.00
P4	-0.15	-0.74	0.05	0.00	0.00	0.00	-0.10	0.00	0.00	0.54	0.10	0.00
P5	-0.31	-0.82	0.31	0.00	0.05	0.00	-0.10	0.00	0.00	-0.51	0	-0.05

Discussion

Results obtained in this study for standard CT volume configuration were in fair agreement with previously reported HU variations with respect to different CT scanning protocols (tube voltages) and reported the maximum variation for high-density tissue substitutes[9,10]. In the current study, the highest variation in CT numberfrom nominal value was noted in Teflon.

The reported HU variations may be explained due to non uniform beam filtration of scanning beam passing different density inserts. Many researchers have reported the large deviations between nominal and measured CT number of Teflon for different CT scanners [11-13].

Also as in air the deviation from nominal value of CT number is observed as the electron density of air is extremely low, and thus, becomes more sensitive to the imaging noise over variation in tube voltages, causing more variation in HU values for air.

In literaturefor various CT scanners, difference between the measured CT numbers and nominal CT number valueshave been reported especially for lowest and highest density sensitometric inserts and this variation depends upon the Scanner specific factors like spectral energy, reconstruction algorithms and filtration of radiation [14].

The HU-RED curves, as shown in figures 2 (a) and (b), reflected no specific difference in the curves obtained by using HU from both systems. CT number linearity increased with increment in kVp, except for Teflon. The results of measurements with both systems were consistent. The differences were within 990-892 HU for 140 kVp and 944 HU for 80 kVp.

Nobah *et al.* [7] demonstrated that geometric arrangements of electron density plugs and variation in kVp settings during the CT simulation do not introduce significant error in heterogeneity-based dose calculations for high-energy photon beams. In the current study, dose distribution obtained by using different CT-RED calibration curves at various kVp settings and evaluated for four different algorithms were well within 1%. Cozzi *et al.* [10] also reported that even when varying the kVp, change in doses calculated after applying different tissue heterogeneity corrections for high-energy photon beams remained well within 1%. The very same trend for low-energy (6 MV) photon beams appeared in our study.

Conclusion

We found that different kVp settings show no statistically significant variation in the measured HU values. The highest variation was noted in case of high-density materials and CT scan at the lowest kVp. Variations in doses calculated with various CT to RED calibration curves and calculation algorithms were observed well within 1%. Therefore, it can be concluded that the clinical practice with applying the HU-RED calibration curve by CT acquisition technique of 120 kVp is viable.

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