# Determining the Effect of CT Simulator Imaging Tube Voltage on Radiotherapy Treatment Dose Calculation

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## ABSTRACT

Patient imaging is the initial step of radiotherapy treatment planning that is done by the CT (Computed Tomography) simulator. The quantity of radiation attenuation is expressed in Hounsfield Units (HU) and the density of human tissue is presented in Relative Electron Density (RED). In radiotherapy planning the conversion relationship between the CT number and RED feeds into the Treatment Planning System (TPS) and the TPS calculates the radiotherapy dose for the patient. Most TSPs contain a single CT-RED curve defined at a specific CT tube voltage (kV setting). This work studied the effect of CT imaging tube voltages using a CT simulator (GE) and TPS (XiO) at Teaching Hospital Karapitiya. Sixty radiotherapy plans were prepared for CT images scanned at 80, 120, and 140 kV tube voltages using a Thorax phantom (CIRS). According to the results, there were 1.45% and 0.92% maximum overdose errors with the treatment plans of CT image sets taken at 80 kV and 120 kV with respect to the 140 kV image set (CT to RED curve defined at 140 kV). Therefore, it is possible to conclude that the effect of imaging tube voltage on treatment dose calculation is considerable and the usage of the relevant CT-RED curve of imaging tube voltage is necessary to ensure the treatment calculation accuracy.
Key Words: CT, CT tube voltage, Radiotherapy, Relative Electron Density

## 1. INTRODUCTION

### 1.1 Background

The determination of dose distribution within the treated volume is an essential step of modern treatment planning in radiotherapy. Many factors influence the dose distribution, and the heterogeneity of the patient's body is one of them (Parker et al., 1979). Data customization for each patient is therefore required for the dose calculations. Computed Tomography (CT) has been used as a fundamental source and is used as a foundation for treatment planning. Furthermore, the presentation of CT is fundamental, as it provides information on the attenuation of radiation by the patient's tissues in the form of CT numbers, expressed in Hounsfield Units (HU) as shown in the following equation (Bryant et al., 2012):

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

Where $\mu_{tissue}$ is the linear attenuation coefficient of tissue and $\mu_{water}$ is the linear attenuation coefficient of water. It is known that a precise calculation of dose distribution in radiotherapy can be performed based on the fundamental knowledge of the Electron Density (ED) of the tissues. Treatment Planning System (TPS) usually converts HU values to $\rho_{el}$ (Relative Electron Density (RED), normalized to water) using the predefined relationship (CT to RED curve) between the two quantities (Witold et al., 2010). In some TPS, the relationship CT-RED curve is fixed and in others user can change it. Where at the XiO TPS (used for treatment planning of cobalt machines) at Teaching Hospital Karapitiya, the CT-RED curve is fixed and derived at 140 kV. Hounsfield numbers for a given tissue depend on the quality of the X-ray beam (Cozzi, et al., 1998) Therefore, the values can differ between scanners. Even for a single scanner, CT numbers for the same tissue depend on the kV setting. Different kV settings are selected for CT scan imaging to obtain a quality image. As a result, the dose calculated by TPS can be inaccurate if CT scans are obtained using 80 kV instead of 140 kV while using the same HU-$\rho_{el}$ relationship obtained at 140 kV. The HU-$\rho_{el}$ relationships can be measured (with the calibration of a CT simulator) with the use of phantoms with tissue-equivalent materials, i.e., materials that have an atomic composition similar to human tissues.

Figure 1**:** The GE CT Simulator (Source : https://ctmedicalscanners.com/ge-lightspeed-rt-16-ct-scanner/ )

CT measures the attenuation coefficient of an object and converts the value assigned to each voxel into a CT number. The absorbed dose to a patient in radiation therapy is calculated using the RED of each voxel in the CT image of the patient. The correlation between the CT number and the RED is derived from a CT scan of the materials with known REDs, and the points between the derived relations are filled up by interpolations. This relationship is applied during the dose calculation based on the CT image, and thus, the accurate measurement of the CT number and applying the value to the TPS is fundamental to radiation therapy. The attenuation coefficient varies with the chosen X-ray tube voltage (kV) from the CT scanner since attenuation coefficients have an energy-dependent property.

The main objective of this work is to determine the impact of kV setting differences in the CT simulation process on the treatment dose calculation of a treatment planning system that contains a single CT to RED curve. Accuracy of radiotherapy treatment planning is very important in radiotherapy as tumor control doses and normal tissue damage doses are close together. Inaccurate dose delivery may cause an underdose or overdose of the treatment. This study is beneficial to ensure and enhance the treatment accuracy of cancer patients

## 2. INSTRUMENTATION AND METHODOLOGY

This work was done at the Radiotherapy Unit of Teaching Hospital Karapitiya using the CT simulator machine (operated at 80 kV, 120 kV, 140 kV, and 10 mA to 440 mA in 5 mA increments) and CMS XiO TPS. Here we also used CIRS Body Phantom (model 002LFC) with five tissue-equivalent rods for the experiments (Figure 2). Tissue-equivalent rods are removable, and they can be inserted into the holes in the CIRS phantom. Such as lung, muscle, tissue, adipose (fat) and bone. Lead dots were applied to appropriate positions to find out the origin of the CT simulation on the test phantom. Three image sets were obtained by CT simulating the CIRS phantom at 80 kV, 120 kV, and 140 kV tube voltages and 80 mA (Figure 4).


Figure 2: CIRS Body Phantom (model 002LFC)

During the image loading, the CT-RED conversion was done. This process is performed by the radiotherapy TPS using the predefined CT-RED conversion curve (Figure 3) defined at 140 kV. That curve is the only curve contained in this TPS for dose calculation.

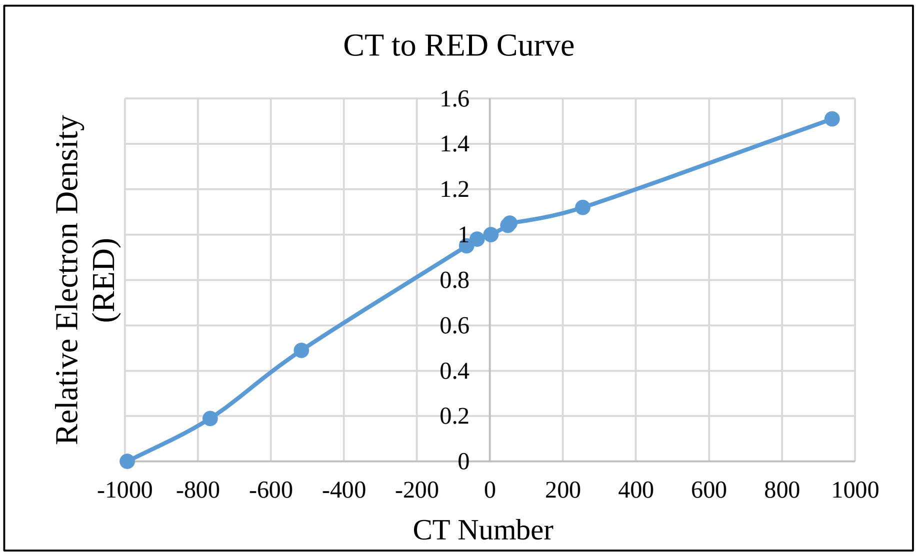


Figure 3: CT-RED Curve of XiO TPS

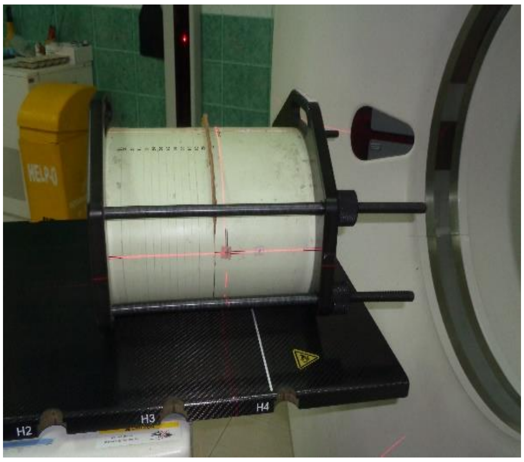


Figure 4: CT simulation of CIRS Phantom

The determination of the impact of varying kV settings (with a fixed CT-RED curve derived at a specific kV setting; tube voltage) on the dose calculation output of the treatment planning system was conducted by applying treatment plans to CT images of chest CIRS phantom. The impact was measured by analyzing the treatment time output of the radiotherapy treatment plans of image sets that have CT simulated at 80 kV, 120 kV, and 140 kV. Treatment time outputs of the treatment plans of image set CT simulated at 140 kV were considered as a reference data set to calculate the treatment time output error of treatment plans of image sets that had CT simulated at 80 kV and 120 kV. The 3-Dimensional Conformal Radiotherapy Treatment (3DCRT) treatment plans were planned by applying the same planning parameters by XiO TPS for three image sets. Treatment plans were done at the same Isocenter, (Dose prescribed to the isocenter). 10x10cm four fields were applied in anterior, posterior, left lateral, and right lateral directions (Box Fields). 200 cGy per fraction, dose was prescribed to isocenter by equally weighted method (50 cGy per field). Source to Axis Distance (SAD) technique was used. (For cobalt teletherapy treatments SAD always maintains at 80cm).

Twenty different points were selected in CT image sets. Coordinates (x,y,z) are compromise at each image set as three image sets were scanned by considering the same CT origin. (At CT origin x, y, z coordinates are equivalent to zero). Sixty treatment plans were done for twenty different isocenters in the CIRS chest phantom.

Sixty treatment plan outputs were analyzed to study the effect of treatment time obtained from the radiotherapy TPS by varying the kV setting and the same mA used within the scanning process while using a single CT -RED curve installed in the TPS (derived at 140 kV). Treatment time outputs of image sets scanned at 140 kV are considered as a reference to calculate the treatment time output error that occurs at image sets scanned at 120 kV and 80kV. Percentage dose error was calculated for the treatment plans of image sets scanned at 120 kV and 80 kV, by following equation no 2. There is no dose error for the treatment plans of the image set scanned at 140 kV as CT- RED conversion has been correctly applied. The calculation algorithm contained in Xio CMS 4.3.3 is the convolution algorithm.

Percentage Dose Error = [[CTT $_x$ – CTT $_{140kV}$]/ CTT $_{140kV}$] x 100%..................................(2)

Where,
CTT$_{140kV}$ = Cumulative Treatment Time of a treatment plan of an image set scanned at 140 kV (kV, that has derived CT-RED relationship)
CTT $_x$ = Cumulative Treatment Time of a treatment plan of an image set scanned at x kV

## 3. RESULTS

The treatment plan output (same isocenter) of image sets that had been scanned at 120 kV and 80 kV were compared with respect to the plan outputs of image sets that had been scanned at 140 kV, as defined by the CT-RED curve at 140 kV.

Table 1: Treatment Plan Outputs of Images Scanned at 80 kV, 120 kV, and 140 kV Tube Voltages using CT Simulator

| Plan No | Cumulative Treatment Time (4 Fields) 140 kV Image set (sec) | Cumulative Treatment Time (4 Fields) 120 kV Image set (sec) | Cumulative Treatment Time (4 Fields) 80 kV Image set (sec) | Cumulative Treatment Time Difference between 140 kV & 120 kV Images (sec) | %Dose error for 120 kV images | Dose error (120 kV Images For a (6600 cGy Treatment ) (cGy) | Cumulative Treatment Time Difference between 140 kV & 80 kV Images (sec) | %Dose error for 80 kV images | Dose error (80 kV Images) For a (6600 cGy Treatment (cGy) |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 124.2 | 124.2 | 126.0 | 0.0 | 0.00% | 0 | 1.8 | 1.45% | 96 |
| 2 | 127.2 | 127.8 | 129.0 | 0.6 | 0.47% | 31 | 1.8 | 1.42% | 93 |
| 3 | 126.0 | 126.6 | 127.2 | 0.6 | 0.48% | 31 | 1.2 | 0.95% | 63 |
| 4 | 109.8 | 109.8 | 110.4 | 0.0 | 0.00% | 0 | 0.6 | 0.55% | 36 |
| 5 | 126.0 | 126.6 | 127.2 | 0.6 | 0.48% | 31 | 1.2 | 0.95% | 63 |
| 6 | 109.2 | 109.8 | 110.4 | 0.6 | 0.55% | 36 | 1.2 | 1.10% | 73 |
| 7 | 130.8 | 131.4 | 132.6 | 0.6 | 0.46% | 30 | 1.8 | 1.38% | 91 |
| 8 | 130.8 | 131.4 | 132.6 | 0.6 | 0.46% | 30 | 1.8 | 1.38% | 91 |
| 9 | 124.8 | 124.8 | 126.0 | 0.0 | 0.00% | 0 | 1.2 | 0.96% | 63 |
| 10 | 127.8 | 127.8 | 129.0 | 0.0 | 0.00% | 0 | 1.2 | 0.94% | 62 |
| 11 | 126.0 | 126.6 | 127.2 | 0.6 | 0.48% | 31 | 1.2 | 0.95% | 63 |
| 12 | 109.8 | 109.8 | 110.4 | 0.0 | 0.00% | 0 | 0.6 | 0.55% | 36 |
| 13 | 126.6 | 126.6 | 127.2 | 0.0 | 0.00% | 0 | 0.6 | 0.47% | 31 |
| 14 | 110.4 | 110.4 | 111.0 | 0.0 | 0.00% | 0 | 0.6 | 0.54% | 36 |
| 15 | 130.8 | 132.0 | 132.6 | 1.2 | 0.92% | 61 | 1.8 | 1.38% | 91 |
| 16 | 131.4 | 132.0 | 132.6 | 0.6 | 0.46% | 30 | 1.2 | 0.91% | 60 |
| 17 | 124.2 | 124.2 | 125.4 | 0.0 | 0.00% | 0 | 1.2 | 0.97% | 64 |
| 18 | 130.2 | 130.8 | 132.0 | 0.6 | 0.46% | 30 | 1.8 | 1.38% | 91 |
| 19 | 126.0 | 126.0 | 127.2 | 0.0 | 0.00% | 0 | 1.2 | 0.95% | 63 |
| 20 | 109.8 | 110.4 | 110.4 | 0.6 | 0.55% | 36 | 0.6 | 0.55% | 36 |

According to the measured results in Table 1, the maximum cumulative treatment time difference presented for the 80 kV image set with respect to the 140 kV image set was 1.80 sec, and that made a maximum 1.45% overdose error. The maximum cumulative time difference presented for the 120 kV image set with respect to the 140 kV was 1.2 sec and that made a maximum 0.92% overdose error.

## 4. DISCUSSION

Computed Tomography (CT) measures the attenuation coefficient of an object and converts the value assigned to each voxel into a CT number. In radiation therapy, CT number, (which is directly proportional to the linear attenuation coefficient), is required to be converted to Electron Density (ED) for radiation dose calculation in the radiotherapy treatment planning system. CT imaging tube voltage effects on CT number of tissues (Ma et al., 2014). That effect was studied with the facilities of Teaching Hospital Karapitiya. According to the measured results, CT numbers decrease with increasing CT Tube voltage. Also, there were no errors in RED values of tissues at 120 kV, with respect to the 140 kV. But there were 5.55 %, 2.10 %, 0.99 %, 0.99 %, 0.95 %, and 1.34 % errors in RED for lung, adipose, water, T1420, muscle, and bone tissues respectively at 80 kV with respect to 140 kV. Therefore it was required to study the effect of imaging tube voltage on radiotherapy dose calculation accuracy.

The response of normal tissues to radiation is either a deterministic or stochastic effect. Where in the stochastic effects, the probability of the effects increasing with dose, but the severity of the effect is independent of the dose. Furthermore, deterministic effects (or tissue reactions) of ionizing radiation are directly related to the absorbed radiation dose, and the severity of the effect increases as the dose increases. There is a threshold (of the order of magnitude of 0.1 Gy or higher) for the deterministic effect. Below the threshold dose, the effect is not present. This radiation response follows a sigmoidal shape. The steep part of the slope indicates the region where a small deviation in dose may present large tissue toxicity as the tumor control curve and normal tissue damage curve are close together. (Auvinen et al., 2012).

Radiotherapy is a compromise between a cure and an acceptable risk of complication. Acceptable risk of complications depends on risk level, organ involved, and severity of complications. The level of risk may differ between physicians and patients. Therefore, it is very important to precisely calculate and deliver the radiotherapy dose to cancer patients. The findings of this research work are very important to improve the accuracy of dose calculation.

It was found that the dose calculation accuracy of TPS has considerable effects on the CT tube voltage setting (kV setting). Here the CT-RED curve is defined at 140 kV, and therefore the other two kV settings were analyzed with respect to the 140 kV. According to the measured results, the single calibration curve defined at 140 kV gives an overdose error of up to 1.45% and 0.92% for image sets scanned at 80 kV and 120 kV respectively. The CIRS chest phantom used for this research and dose error can be greater than the aforementioned dose error in patient treatments.

Same as this study according to Rhee et al (2015), the maximum dose difference caused by applying a wrong CT number to the electron density conversion curve was expected to be more than 1 %. Similarly as this study it was found that both CT x-ray tube voltage variations have considerable effects on the *RED*-CT number relationships. The differences between RED-CT number curves decrease when the CT voltages increase from 70 to 100 kV. At CT voltages 120 and 140 kV the differences are negligible. (Afifi et al., 2020) Third-generation algorithms such as Monte Carlo, show dependence on varying tube voltages in dose calculation. Calibration curves plotted at different kVp in TPS advised to be chosen wisely to avoid any dosimetric errors in different mediums. (Saini et al., 2021).

There were only three kV settings (tube voltages) available with the CT simulator machine, therefore study was limited to three voltage levels. Available CIRS phantom contained just 5 types of human tissues and also it doesn't contain any metal inserts (RED equivalent to Metal implants). Therefore, it was unable to examine the effect of metal implants.

According to the investigation of this study, it is recommended to use the relevant CT-RED curve when the different tube voltage (kV setting) would be used in the process of CT imaging. CT simulator that contains more kV settings (tube voltages) and a CIRS body phantom that has more human tissue types and metal inserts are more deserving in determination impact of CT tube voltage on CT- RED curve for further studies.

It is possible to derive CT- RED curves in the TPS for all available tube voltages with CT machine during CT simulator calibration process. Advanced electron density phantoms with known electron density tissue equivalent inserts can be used for the CT simulator calibration process.

## 5. CONCLUSION

There was a maximum 1.45 % cumulative overdose error for the treatment plans of image set taken at the 80 kV setting with respect to the 140 kV image set (CT to RED curve defined at 140 kV). Furthermore, there was a maximum 0.92 % dose error for treatment plans of the images scanned at 120 kV with respect to the 140 kV image set. It is possible to conclude that there is an effect on radiotherapy dose calculation with CT imaging tube voltage, and relevant CT- RED conversion during the radiotherapy treatment planning is very important to assure the treatment accuracy.

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