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Effect of Physical Factors on Electromagnetic Radiation Therapy Planning Dose Calculation in Computed Tomography

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The tube voltage in computed tomography (CT) changes the Hounsfield Unit (HU) and affects the electromagnetic radiation therapy planning (RTP) dose calculation. In this study, physical factors (tube voltage, tube current) of CT were analyzed for their RTP effects. A CT density phantom (CTDP) was exposed to measure the HU with an RTP system while we controlled the physical factors. The human body phantom was exposed with different CT tube voltages (70 kVp, 80 kVp, 100 kVp, 120 kVp, and 140 kVp) and electromagnetic radiation dose calculations were performed with the RTP system. The HU decreased when tube voltage was increased, in particular, the largest gap was found in bone, which has a high density (1792 ± 54 at 70 kVp, 1065 ± 13 at 140 kVp). However, a remarkable HU gap was not observed with the changes in tube current. In RTP the calculated dose increased when the tube voltage was raised, in particular, we observed a 3 % gap in brain tissue and bone, a remarkable HU gap. The chest had a small HU gap because of its relatively low density. The RTP dose calculation with changes in tube voltage had a 3 % error, which is acceptable. However, it can be eliminated of because daily QA/QC was performed and a CT density curve with rational exposure condition can be applied to brain or spine patients who experience large errors. This method enables reduction of the error caused by the physical factors in CT.

Keywords : electromagnetic radiation, computed tomography, hounsfield unit, radiation therapy planning, tube voltage, tube current

1. Introduction

Most external beam radiation therapy uses high-energy electromagnetic radiation with medical linear accelerators [1]. Recent radiation therapy uses computed tomography (CT) images and accounts for the planning target volume (PTV) and organs at risk (OAR). Three-dimensional conformal radiation therapy (3D-CRT) and intensity modulated radiation therapy (IMRT) have the potential to provide a dose distribution to the PTV with a steeper dose gradient, which increases the dose to the PTV and reduces the irradiated volume in OAR [2-4]. Therefore, it is important to accurately contour the PTV and the OAR on CT images. CT images can revise the value of PTV and the form of organs and their positions. In particular, intensity-modulated radiation therapy (IMRT) is possible with CT, and so CT is major part of radiation therapy [2].

CT uses the Hounsfield unit (HU), which reflects each organ's X-ray absorption difference.

$$\mathrm{HU} = 1000\,\frac{\mu - \mu_w}{\mu_w} \tag{1}$$

The HU standard is −1000 for air and 0 for water. (It may vary depending on the manufacturer.) Where μ and μ_w are the attenuation coefficients of a material and water, respectively.

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$$\mu = N_e\left(a\frac{Z_C^m}{E^k} + b\frac{Z_R^n}{E^l} + c(E)\right)\ (\text{cm}^{-1}) \quad (2)$$

Where N_e is the electron density expressed in terms of the number of electrons per unit volume, and E is the photon energy. Z_C, Z_R are the effective atomic numbers for photoelectric absorption and Rayleigh scattering. a, b, m, n, k, and l are correction factors. μ depends on atomic number and X-ray energy in accordance with (2) [5-7].

The physical factors, X-ray tube voltage (kVp) and X-ray tube current (mA), cause diverse effects in CT images [7, 8]. In particular, tube voltage affects the HU because it is related to penetrating power [8]. These factors can affect radiation therapy planning (RTP) [10]. Therefore, this study was conducted to verify how the physical factors can change the CT-HU and electromagnetic radiation dose calculation and propose a method to minimize error in the RTP dose calculation.

2. Materials and Methods

2.1. Equipment and materials

1) SOMATOM definition AS open CT (Siemens, Germany)

2) RMI CT density phantom (Gammex, USA)

3) Human body phantom

4) Radiation therapy planning system: Pinnacle 8.0 m (Philips nuclear medicine, USA)

2.2. Methods

1) Measurement of HU depending on CT physical factors

Fig. 1. (Color online) The electron density CT phantom of GAMMEX RMI 467.

Table 1. The CT HU to electron density conversion measured with Gammex RMI phantom.

Phantom material	Physical Density (g/cm^3)	Electron Density Relative to Water
LN-300 lung	0.280	0.276
LN-450 lung	0.480	0.463
adipose	0.943	0.926
Breast	0.983	0.960
Solid Water	1.016	0.987
Brain	1.053	1.049
Liver	1.106	1.074
Inner bone	1.129	1.082
B-200 Bone	1.146	1.099
CB2-30 % $CaCo_3$	1.334	1.279
CB2-50 % $CaCo_3$	1.559	1.469
Cortical bone	1.822	1.694

In radiation therapy, high-energy (6 MV-15 MV) electromagnetic radiation transfers energy mostly by Compton scattering. Because Compton scattering interacts only with free electrons in materials, it correlates not only with atomic number but also electron density [7, 11]. Radiation therapy planning systems (RTPS) convert the pixels of a CT image to electron density and revise the density imbalance density for radiation dose calculation.

GAMMEX's RMI CT density phantom (USA) was used to convert HU to electron density (Fig. 1). This phantom can accept diverse plugs (solid water, lung, breast, brain, liver, bone and six other materials) that have different densities with the same size (5 cm diameter).

To measure the HU changes depending on the physical factors (tube voltage, tube current), we used the CT density phantom and set a 2 mm slice thickness in a SOMATIOM definition AS open CT (Siemens, Germany) and exposed it with various serial tube voltage and tube current values (70, 80, 100, 120, and 140 kVp at 200 mAs; 100 to 260 mA at 20 mA intervals at 120 kVp).

We transmitted CT images to a Pinnace 8.0 (Philips nuclear medicine, USA) RTPS and measured the HU of the phantom plug's 2 cm ROI slices.

2) Radiation dose calculation depending on CT physical factors

To compare radiation dose calculation depending on the changes of tube voltage, we used the human body phantom (brain and chest) with a 200 mAs tube current and 2 mm slices with serial tube voltages (70, 80, 100, 120, and 140 kVp) transmitted to the RTPS.

The field size was 15 × 15 cm for the brain phantom and 20 × 20 cm for the chest phantom we exposed the

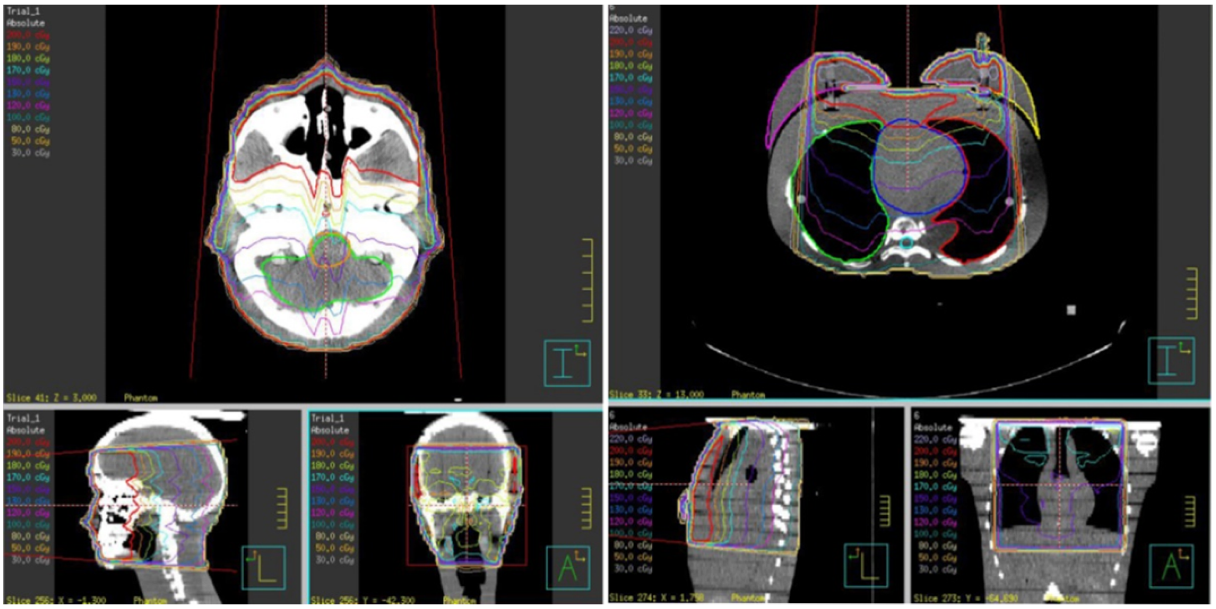

Fig. 2. (Color online) The radiation dose calculation form brain phantom (left) and chest phantom (right) are displayed isodose lines on the CT slice. (Brain 15 × 15 cm AP 1 field, Chest 20 × 20 cm AP 1 field)

phantoms with 6 MV and 15 MV X-ray (2 Gy) in the anterior posterior direction (Fig. 2).

3. Results

3.1. HU measurement depending on CT physical factors

The HU changed with changes in serial tube voltage, but exhibited no evident difference with changes in tube current. In the same material, the HU decreased when tube voltage increased. In the range of 0.0-1.0 density, no changes in HU were observed, even when tube voltage increased. HU sharply decreased when density increased, especially in cortical bone because of its high density (80 kVp: 89 %; 100 kVp: 73 %; 120 kVp: 65 %; 140 kVp: 60 %; standard was 70 kVp), as shown in Fig. 3. No notable changes in HU were observed with changes in serial tube current (Fig. 4).

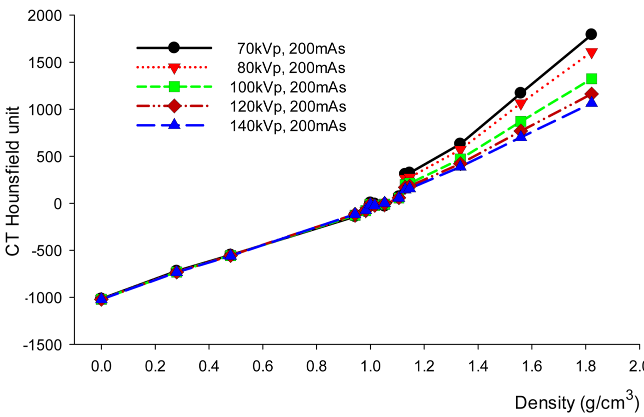

Fig. 3. (Color online) The CT Hounsfield unit density curves from different CT voltage.

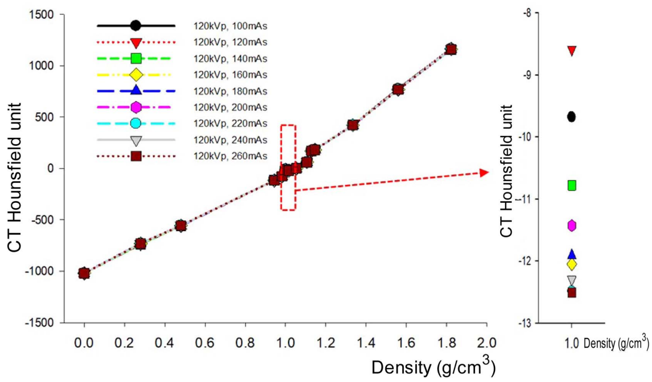

Fig. 4. (Color online) The CT Hounsfield unit density curves from different CT current.

3.2. Radiation dose calculation depending on CT physical factors

We compared CT images of the human body phantom exposed with serial tube voltage (Table 2). In the chest phantom exposed with serial tube voltage, there were no striking changes in HU, but a large (–40 %) rate of change occurred in the mandible included in brain phantom. The large changes in HU were –63 % in the whole phantom (Table 2). In RTP, there were no large changes in the

Table 2. CT Hounsfield unit depending on CT voltage form human body phantom.

Brain phantom	70 kVp	80 kVp	100 kVp	120 kVp	140 kVp
Whole phantom	189.74	156.53	111.59	91.45	71.14
Brain	−25.028	−29.399	−37.986	−37.797	−43.955
Rt Parotid	−84.339	−67.342	−57.132	−50.469	−52.695
Lt parotid	−116.653	−90.167	−69.441	−63.587	−65.753
Rt eye	−34.632	−35.202	−43.207	−40.597	−46.203
Lt eye	−51.179	−49.448	−61.465	−56.298	−59.395
Lt SMG	−55.626	−56.664	−57.297	−50.855	−58.143
Rt SMG	−54.074	−55.054	−61.125	−58.816	−64.699
Lt nerve	0.38	−10.71	−23.88	−25.411	−33.011
Rt nerve	−8.09	−16.23	−22.42	−26.64	−33.547
Tongue	−41.537	−45.743	−52.715	−48.114	−53.273
Brain stem	−22.08	−28.249	−35.235	−37.018	−40.06
Spinal cord	−12.36	−19.89	−31.069	−31.235	−37.27
Mandible	995.28	906.07	774.68	686.53	609.64
Chest phantom	**70 kVp**	**80 kVp**	**100 kVp**	**120 kVp**	**140 kVp**
Heart	−77.574	−76.264	−77.285	−76.552	−78.707
Lt Lung	−524.79	−522.336	−517.216	−514.738	−516.812
Rt Lung	−531.762	−529.009	−525.938	−522.927	−522.897
Lt Breast	−88.211	−87.126	−89.723	−89.448	−90.945
Rt Breast	−90.768	−89.822	−93.816	−93.893	−94.194
Cord	−0.98	−9.43	−20.29	−25.086	−32.428

chest phantom, but remarkable dose increases were shown in the brain phantom when tube voltage increased. Remarkable dose increases occurred in the 140 kVp images (maximum 3 % for 6 MV, maximum 2 % for 15 MV).

A maximum 1 % dose increase occurred in the chest phantom (Table 3).

4. Discussion

In this study, we calculated the HU of CT for diverse density phantoms depending on serial physical factors and evaluated the results of electromagnetic radiation dose calculation with a human body phantom.

HU varies by material. As shown in (1) and (2), HU has an attenuation coefficient. Because it depends on X-ray exposure, it decreases when tube voltage increases. However, for tube current, there were no changes in HU because it does not affect X-ray energy. Below a density of 1.0 g/cm^3 there were no significant changes in HU with serial tube voltage. However, in the case of high-density materials such as cortex bone, a large gap of 40 % was observed (70 kVp: 1792 ± 54, 140 kVp: 1065 ± 13). With respect to the changes in the CT's X-ray spectrum, there was little change in soft tissue but high variance in bone, because when X-ray energy decreases, the photo-electric effect becomes more dominant, because bone has a large effective atomic number, it increases the collision cross section and line attenuation constant [12]. For this reason, the HU is relative to μ, and μ increases when energy is decreased, thus increasing HU.

Figure 2 shows RTP with human body phantom CT images. Table 3 shows the result of RTP with serial tube voltage. The result of RTP is that a greater change in HU corresponds with a higher dose gap. Large HU changes were observed when density was over 1.0 g/cm^3. Radiation dose calculation was a 3 % dose increase was observed when 140 kVp was used in the brain phantom.

Low (6 MV) and high (15 MV) energy were used in the dose calculation to verify the difference in exposed energy. A large difference was observed when 6 MV low energy was used compared with 15 MV. There was no high contrast with a density of 1.0 g/cm^3 as shown in Fig. 3, because the relative electron density of water has little relation with CT HU.

During RTP, the dose calculation error is small in accordance with the change in HU. A 2 % dose error occurred when the gap in electron density was between 4-10 % [10], and the error was 1 % when the RTP with CT density curve dose was not revised [12]. A larger field size corresponds with a smaller photon weight. These results coincide with those of advanced research. With

Table 3. Radiation dose calculation depending on CT voltage from human body phantom. (70 kVp is standard, unit: %)

Brain phantom	6 MV					15 MV				
	70 kVp	80 kVp	100 kVp	120 kVp	140 kVp	70 kVp	80 kVp	100 kVp	120 kVp	140 kVp
Whole phantom	100	100.23	100.63	100.95	101.17	100	100.15	100.51	100.66	100.87
Brain	100	100.44	100.59	101.03	101.25	100	100.33	100.46	100.86	100.99
Mandible	100	99.9	100.46	100.1	100.31	100	99.75	100.2	99.56	99.61
Lt eye	100	100.92	99.77	99.82	100.69	100	101.58	99.65	100.1	101.28
Rt eye	100	99.68	98.69	98.82	99.05	100	99.95	98.59	98.49	98.88
Lt nerve	100	100.49	99.96	100.31	100.36	100	100.81	99.92	100.08	100.47
Rt nerve	100	100.13	99.65	99.87	99.96	100	100.17	99.54	99.37	99.54
Brain Stem	100	100.87	101.68	102.48	103.1	100	100.72	101.27	101.88	102.38
Spinal Cord	100	100.57	101.43	102.01	102.39	100	100.43	101.03	101.37	101.71
Tongue	100	99.55	99.94	99.33	98.99	100	99.84	99.84	99.57	99.19
Lt SMG	100	99.89	100.38	99.78	99.24	100	100.16	100.38	99.46	99.13
Rt SMG	100	99.5	100.34	100	99.83	100	99.27	99.95	99.58	99.32
Lt Parotid	100	100.23	100.68	100.74	100.51	100	100.27	100.37	100.7	100.27
Rt Parotid	100	100.18	100.61	100.61	101.23	100	100.22	100.6	100.7	101.09
Chest phantom	6 MV					15 MV				
	70 kVp	80 kVp	100 kVp	120 kVp	140 kVp	70 kVp	80 kVp	100 kVp	120 kVp	140 kVp
Heart	100	99.88	99.88	99.82	99.88	100	99.94	99.94	99.89	99.89
Lt lung	100	99.876	99.86	99.79	99.73	100	99.94	99.94	99.81	99.81
Rt lung	100	99.93	99.86	99.79	99.73	100	99.94	99.94	99.88	99.84
Lt Breast	100	100.07	100.07	99.25	100.07	100	99.93	99.86	99.07	99.86
Rt Breast	100	99.92	99.92	99.5	99.5	100	99.74	99.66	99.32	99.32
Spinal cord	100	100.54	100.9	100.99	101.08	100	100.32	100.71	100.79	100.79

this study, we found that a maximum 3 % dose increase occurs depending on changes in tube voltage from the CT scan [13].

In summary, based on formula (1), (2) the changes in tube voltage which is the physical factor of CT affects HU. About 40 % of HU was decreased when a high tube voltage (140 kVp) in organs which has a high density (Fig. 3, Table 2). Because of the decrease in 40 % of HU, it induces the error of organ's density (0.3 g/cm^3 became smaller) and finally, radiation dose calculation was a 3 % dose increase when 140 kVp was used in the high density like a bone (Table 3). This means that the patients with this condition can get 3 % of overdose then principally needed. However, the change of tube current did not make any change of HU because It does not affect the energy of X-ray (Fig. 4).

A 3 % error is usually accepted by most radiation oncology agencies, even when they have their own permitted range. This is in accordance with the medical radiation safety standard of the American Association of Physicists in Medicine (AAPM) and the Korean Nuclear Safety and Security Commission (NSSC) [14]. Following this standard, the RTP error incurred depending on tube voltage is allowable. However, this error can be reduced. Overall, there are additional factors that cause errors, such as the RTP system, output of the LINAC, changes in the patient's body, movement, and setup. These factors together could overrun the 3 % daily allowable error [14-16].

Therefore, if the error caused by the changes in physical factors can be reduced, the dose calculation accuracy can improve.

5. Conclusion

In this study, we examined the changes in HU depending on physical factors (tube voltage, tube current) and the effects on electromagnetic radiation dose calculation.

Using a high CT voltage decreases HU and ultimately causes a dose increase of up to 3 %, which is in the allowable range.

However, this error is easily reduced by simple methods. Thus, if a moderate CT ED curve is applied to brain or spine patients, who could experience a large error because of the high tissue density, and coupled with an electromagnetic radiation dose calculation, more accurate radiation therapy can be performed.

References

[1] J. H. Kim, J. M. Seo, G. J. Kim, and J. H. Kim, J. Magn. **22**, 676 (2017).

[2] J. U. Jang, M. S. Han, M. J. Kim, and H. S. Kang, J. Korean Magn. Soc. **26**, 173 (2016).

[3] H. S. Li, J. H. Chen, W. Zhang, D. P. Shang, B. S. Li, T. Sun, X. T. Lim, and Y. Yin, Asian Pac. J. Cancer Prev. **14**, 1609 (2013).

[4] G. Williams, M. Tobler, D. Gaffney, J. Moeller, and D. D. Leavitt, Med. Dosim. **27**, 275 (2002).

[5] G. N. Hounsfield, Br J. Raiol. **68**, 166 (1995).

[6] Y. Watanabe, Phys. Med. Biol. **44**, 2201 (1999).

[7] M. C. Jeon, M. S. Han, J. U. Jang, and D. Y. Kim, J. Magn. **22**, 227 (2017).

[8] D. K. Han, K. J. Park, and S. K. Ko, Korean J. Digit. Imaging Med. **12**, 127 (2010).

[9] H. Guan, F. F. Yin, and J. H. Kim, Phys. Med. Biol. **47**, 233 (2002).

[10] S. J. Thomas, Br J. Raiol. **72**, 781 (1999).

[11] F. M. Khan, Lippincott Williams & Wilkins (2010).

[12] P. W. Henson and R. A. Fox, Phys. Med. Biol. **29**, 351 (1984).

[13] L. Cozzi, A. Fogliata, F. Buffa, and S. Bieri, Radiother Oncol. **48**, 335 (1998).

[14] S. H. Choi, D. W. Park, K. B. Kim, D. W. Kim, J. Lee, and D. O. Shin, Prog. Med. Phys. **26**, 294 (2015).

[15] J. U. Jang, H. S. Lim, M. S. Han, Y. K. Kim, and M. C. Jeon, J. Digital Convergence **11**, 577 (2013).

[16] T. J. Choi and O. B. Kim, Kor. J. Med. Phys. **22**, 92 (2011).