Tolerance levels of CT number to electron density table for photon beam in radiotherapy treatment planning system

Minoru Nakao1 | Shuichi Ozawa1,2 | Kiyoshi Yamada1 | Katsunori Yogo1 |
Fumika Hosono1 | Masahiro Hayata1 | Akito Saito2 | Kentaro Miki2 |
Takeo Nakashima3 | Yusuke Ochi3 | Daisuke Kawahara3 | Yoshiharu Morimoto4 |
Toru Yoshizaki5 | Hiroshige Nozaki6 | Kosaku Habara6 | Yasushi Nagata1,2

1Hiroshima High-Precision Radiotherapy Cancer Center, Hiroshima, Japan
2Department of Radiation Oncology, Institute of Biomedical & Health Science, Hiroshima University, Hiroshima, Japan
3Radiation Therapy Section, Department of Clinical Support, Hiroshima University Hospital, Hiroshima, Japan
4Department of Radiology, Hiroshima Prefectural Hospital, Hiroshima, Japan
5Radiation Therapy Department, Hiroshima City Hiroshima Citizens Hospital, Hiroshima, Japan
6Division of Radiology, Hiroshima Red Cross Hospital & Atomic-bomb Survivors Hospital, Hiroshima, Japan

Author to whom correspondence should be addressed. Minoru Nakao
E-mail: nakao@hiprac.jp
Telephone: +81-82-263-1330

Abstract
The accuracy of computed tomography number to electron density (CT-ED) calibration is a key component for dose calculations in an inhomogeneous medium. In a previous work, it was shown that the tolerance levels of CT-ED calibration became stricter with an increase in tissue thickness and decrease in the effective energy of a photon beam. For the last decade, a low effective energy photon beam (e.g., flattening-filter-free (FFF)) has been used in clinical sites. However, its tolerance level has not been established yet. We established a relative electron density (ED) tolerance level for each tissue type with an FFF beam. The tolerance levels were calculated using the tissue maximum ratio (TMR) and each corresponding maximum tissue thickness. To determine the relative ED tolerance level, TMR data from a Varian accelerator and the adult reference computational phantom data in the International Commission on Radiological Protection publication 110 (ICRP-110 phantom) were used in this study. The 52 tissue components of the ICRP-110 phantom were classified by mass density as five tissues groups including lung, adipose/muscle, cartilage/spongy-bone, cortical bone, and tooth tissue. In addition, the relative ED tolerance level of each tissue group was calculated when the relative dose error to local dose reached 2%. The relative ED tolerances of a 6 MVFFF beam for lung, adipose/muscle, and cartilage/spongy-bone were $\pm 0.044$, $\pm 0.022$, and $\pm 0.044$, respectively. The thicknesses of the cortical bone and tooth groups were too small to define the tolerance levels. Because the tolerance levels of CT-ED calibration are stricter with a decrease in the effective energy of the photon beam, the tolerance levels are determined by the lowest effective energy in useable beams for radiotherapy treatment planning systems.

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Key Words
CT number, electron density, flattening-filter-free beam, quality assurance, tolerance level
1 | INTRODUCTION

Computed tomography (CT) data have generally been used to calculate the dose to the body of a patient treated with a radiotherapy treatment planning system (RTPS). The natural body is complex and inhomogeneous with multiple tissue groups including lung, adipose, muscle, general organ, cartilage, bone, and tooth tissues. To calculate the appropriate radiotherapy dose for a human body, CT number to electron density (CT-ED) calibration is generally performed with a calibration phantom with several inserted tissue substitutes. The accuracy of CT-ED calibration is a key component for dose calculations in inhomogeneous mediums.

Kilby et al. established relative electron density (ED) tolerance levels based on the relative dose error to local dose using the tissue maximum ratio (TMR) and the maximum tissue thicknesses defined by multiple treatment plans. It was shown that the tolerance levels became stricter with an increase in tissue thickness and a decrease in the effective energy of the photon beam. For the last decade, a low effective energy photon beam (e.g., flattening-filter-free (FFF) beam) has been used in stereotactic body radiation therapy to treat lung or abdomen cancer. Therefore, new relative ED tolerance levels are required for a RTPS with an FFF beam.

The relative ED tolerance levels are useful to assure the suitability of the CT-ED calibration table of planning CT and cone beam CT. The purpose of this study is to establish a relative ED tolerance level corresponding to each tissue type for a RTPS with an FFF beam. Moreover, we attempted to establish the relative ED tolerance levels based on standard tissue data and validate the relative ED tolerance levels with an adult anthropomorphic phantom.

2 | METHODS

2.A | Effective depth

The effective depth has been used in the inhomogeneity correction method in an RTPS. The relationship between the effective depth and dose is given by

\[ D(d) \propto \text{TMR}(d_{\text{eff}}) \]  

where \( D \) is the dose, \( d \) is the depth, \( \text{TMR} \) is the tissue maximum ratio, and \( d_{\text{eff}} \) is the effective depth. \( d_{\text{eff}} \) is given by

\[ d_{\text{eff}} = \sum_{i} t_i \rho_{e,i} \]  

where \( t_i \) is the thickness of tissue \( i \) and \( \rho_{e,i} \) is the ED of tissue \( i \) relative to water.

The relationship between the dose error, \( \Delta D \), and the error in the relative ED, \( \Delta \rho_{e,i} \), are established by eqs. (1) and (2) and is given by

\[ \Delta \rho_{e,i} = \frac{\Delta D/D}{t_i \left( \frac{\text{dTMR}}{\text{dED}} \right)} \]  

where \( \Delta D/D \) is the relative dose error to local dose, \( (\text{dTMR}/d(\text{dED})) \) is the gradient of TMR relative to the local TMR, and \( \Delta \rho_{e,i} \) is the error in \( \rho_{e,i} \). TMR data were measured in water with a Varian TrueBeam STx (Varian Medical Systems, Palo Alto, CA, USA). \( (\text{dTMR}/d(\text{dED})) \) was also measured for a 10 cm x 10 cm field at a 10-cm depth. The relative dose error to local dose (\( \Delta D/D \)) was set as 2%.

2.B | Effective tissue thickness

Tissue thickness was required to estimate the dose error caused by the CT-ED calibration. We defined the effective tissue thicknesses using the adult reference computational phantom data (V1.2) in the International Commission on Radiological Protection publication 110 (ICRP-110). The effective tissue thicknesses were reasonable to determine the relative ED tolerance levels.

The anthropomorphic voxel phantoms are consist of 52 standard tissues and air. The 52 tissues were classified by mass density into five tissue groups including lung, adipose/muscle, cartilage/spong-ybone, cortical bone, and tooth tissues. The mass density border between lung tissue and adipose tissue is \( \rho = 0.90 \text{ g cm}^{-3} \). Only lung tissue had a mass density below the border value of \( \rho = 0.90 \text{ g cm}^{-3} \), while adipose, muscle, general organ, and some spong-ybone tissues had values between \( 0.90 \text{ g cm}^{-3} \) and \( 1.07 \text{ g cm}^{-3} \) (Male: cervical spine, sternum, and sacrum, Female: sacrum and femora). Skin, cartilage, and most spong-ybone tissues had values between \( 1.07 \text{ g cm}^{-3} \) and \( 1.25 \text{ g cm}^{-3} \). Furthermore, cortical bone tissue had a value of \( 1.92 \text{ g cm}^{-3} \), and tooth tissue had a value of \( 2.75 \text{ g cm}^{-3} \). The maximum thicknesses of the classified tissue groups were measured from axial plane to define the corresponding effective tissue thickness.

2.C | Relative ED tolerance level

The relative ED tolerance levels were generated using eq. (3) and the effective tissue thicknesses of each tissue group. The TMR of the 6 MVFFF beam was used to estimate tolerance levels because the effective energy is the lowest of the five photon beams and because the beam was used against deep tumours more frequently than the 4 MV beam.

2.D | CT number constancy

CT number constancy was required to evaluate the relative ED tolerance levels. A Catphan 700 phantom (The Phantom Laboratory, Salem, NY, USA) scanned with a CT scanner (GE Optima 580, GE Medical Systems) for routine quality assurance over a 20-month period. For this study, a geometry and sensitometry module (CTP682) was used.

2.E | Treatment planning with an adult anthropomorphic phantom

To validate the relative ED tolerance levels for clinical situations, the dose error caused by relative ED errors was validated in several typical
The goal of this work was to establish a new relative ED tolerance level with a RTPS using an FFF beam because the photon spectrum of an FFF beam was softer than that of a flattened beam. In a previous work, Kilby et al.\textsuperscript{2} established the relative ED tolerance levels of a 6 MV beam for lung, adipose/muscle, and cartilage/spongy-bone, respectively. The dose errors caused by the CT-ED calibration error were less than 2%, which was consistent with the tolerance level. In any case, the dose errors caused by the CT-ED calibration error were less than 2%, which was consistent with the tolerance level.

4 | DISCUSSION

The results of CT number constancy are summarized in Table 2. CTP682 was scanned with a CT scanner for routine quality assurance over a 20-month period ($n = 375$). The standard deviation (SD) of the CT number was converted to the relative ED with the CT-ED calibration table. All the $3 \times SD$ of the relative ED were lower than 0.01 from the CT number of air to teflon.

### 3.C | CT number constancy

The typical photon beam treatment plan results are summarized in Table 3. The dose errors were caused by an increase equal to the relative ED tolerance levels of a 6 MVFFF beam, which were 0.044, 0.022 and 0.044 for lung, adipose/muscle and cartilage/spongy-bone, respectively. The dose error of the 2 field (LR) plan for pelvic tumours was the largest of the errors in Table 3 because the effective depth was the longest compared to that of other plans. The impact with or without a flattening-filter was about 0.2% of the prescribed dose. In any case, the dose errors caused by the CT-ED calibration error were less than 2%, which was consistent with the tolerance level.
The tissue thicknesses (lung: 10 cm, adipose/muscle: 20 cm, cartilage/spongy-bone: 10 cm, cortical bone: 1 cm, tooth: 1 cm) by classifying the standard tissues of ICRP-110 and by measuring the classified tissue group thicknesses. Because the classified tissue group was defined using whole-body reference phantoms, the tolerance levels for cortical bone and tooth tissues were also estimated. Consequently, the thicknesses of cortical bone and tooth tissues were too small to define tolerance levels. In addition to these natural body components, man-made materials may be implanted into the human body such as a hip, leg, and arm prostheses as well as spinal cord fixation devices and various dental fillings. However, these man-made implants were beyond the scope of this work.

The tolerance levels were determined with a simple beam condition (10 × 10 cm field at a 10-cm depth). Therefore, the dose error...
caused by the CT-ED calibration error was simulated with an adult anthropomorphic phantom for a RTPS. In any case, the dose errors were less than 2%, which was consistent with tolerance levels. Although the impact with or without a flattening-filter was about 0.2% of the prescribed dose, the tolerance levels should be determined by the lowest energy in useable beams for an RTPS.

The definition of relative ED tolerance levels was useful for the quality assurance of the CT-ED calibration table of planning CT and cone beam CT. The CT-ED calibration table was generally obtained using a calibration phantom with tissue substitutes. The CT-ED calibration may slightly vary from that for calibration phantom types because of the phantom size and amount of solid water around the density inserts. Moreover, the CT-ED calibration may vary from radiotherapy institutions because of the difference in the phantom production accuracy, tissue substitute choice and CT scan conditions. The relative ED tolerance levels were useful to approve CT-ED calibration table for clinical use.

5 | CONCLUSION

We have established the relative ED tolerance levels for each tissue type with an FFF beam. Because the tolerance levels are stricter when the beam energy decreases, the tolerance levels are determined by the lowest useable energy in a RTPS.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

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