Rutgers Cancer Institute of New Jersey

The improvement of SPR calculation with triple energy CT extracting atomic number of tissue

J. ZHU[1], B. LIU[1], X. WANG[1], Y. ZHOU[2], K. NIE[1], R. PARIKH[1], R. DAVIS[1], N. YUE[1], Y. ZHANG[1]
1 Department of Radiation Oncology, Rutgers Cancer Institute of New Jersey, USA
2 Department of Radiation Oncology, Zhongshan Hospital, Fudan University, China

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INTRODUCTION

This study is aimed to extract coherent atomic number ($\hat{Z}$) and photoelectric atomic number ($\tilde{Z}$) of tissues with triple energy CT (TECT) obtained from a virtual CT and to evaluate the corresponding improvement on stopping power ratio (SPR) calculation for proton therapy.

The benefit is to obtain $\hat{Z}$ and $\tilde{Z}$ which will, theoretically, not be influenced by the CT spectra. According to the comparison of SPRs from TECT, dual energy CT (DECT) and single energy CT (SECT), an increase in the accuracy of SPR calculation using TECT was observed.

AIM

- Study the feasibility of TECT in atomic number calculation of tissue
- Develop an end to end procedure from TECT scan to SPR calculation
- Compare the accuracy of SPRs derived from TECT, DECT and SECT

METHOD

In the derivation of tissue stopping powers, dual energy CT (DECT) degenerates the subtle tissue differences while assuming $\hat{Z}=\tilde{Z}=Z_{eff}$ [1]. By adding a third energy, $\hat{Z}$ and $\tilde{Z}$, presenting the atomic number in coherent and photoelectric interaction, can be differentially derived mathematically to potentially improve the CT based tissue SPR derivation.
To verify this method, a virtual CT scanner was simulated in Geant4 and 3 CT image sets using 90kVp, 120kVp and 140kVp of a water phantom including 4 standard human tissues (lung, brain, liver and bone) obtained from ICRU46. CT images were reconstructed using ifanbeam function in MATLAB. A 3D-monotonous conversion between $\hat{Z}$, $\tilde{Z}$ and mean excitation energy (I_m) was generated. Another CIRS phantom with 9 tissue inserts were also simulated to obtain K series that represent the feature of CT spectra [2]. Electron density is another unknown values that is needed to obtained for the SPR calculation. Saito et al. supposed an algorithm of electron density calculation with DECT[3]. We follow this well-accepted method to calculate electron density. Furthermore, we use the theoretical SPRs as the ground truth, rather than the nominal values from vendor if an actual phantom and CT were used. The accuracy of SPR calculated by TECT was compared to DECT approach using 90/140kVp and SECT approach (120kVp). Once three sets of CT images are obtained, the CT number would be imported to Eq. 1 where the $\hat{Z}$ and $\tilde{Z}$ were solved. The following work is to convert the Z to I_m with Fig. 1 which is built up using human tissue from ICRU 46. Stopping power ratio (SPR), subsequently, is calculated using Bethe equation (Eq. 2).

$$\begin{cases} \dfrac{HU_{90}+1000}{HU_{140}+1000} = \dfrac{1+\hat{Z}^{1.86}K_{90,1}+\tilde{Z}^{3.62}K_{90,2}}{1+\hat{Z}_w^{1.86}K_{90,1}+\tilde{Z}_w^{3.62}K_{90,2}} \times \dfrac{1+\hat{Z}_w^{1.86}K_{140,1}+\tilde{Z}_w^{3.62}K_{140,2}}{1+\hat{Z}^{1.86}K_{140,1}+\tilde{Z}^{3.62}K_{140,2}} \\ \dfrac{HU_{90}+1000}{HU_{120}+1000} = \dfrac{1+\hat{Z}^{1.86}K_{90,1}+\tilde{Z}^{3.62}K_{90,2}}{1+\hat{Z}_w^{1.86}K_{90,1}+\tilde{Z}_w^{3.62}K_{90,2}} \times \dfrac{1+\hat{Z}_w^{1.86}K_{120,1}+\tilde{Z}_w^{3.62}K_{120,2}}{1+\hat{Z}^{1.86}K_{120,1}+\tilde{Z}^{3.62}K_{120,2}} \end{cases} \quad (1)$$

Where $\tilde{Z} = [\sum_i \lambda_i Z_i^{3.62}]^{1/3.62}$, $\hat{Z} = [\sum_i \lambda_i Z_i^{1.86}]^{1/1.86}$

$$\lambda_i = \frac{\omega_i Z_i}{A_i} \Big/ \sum_i \frac{\omega_i Z_i}{A_i}$$

$$SPR = \rho_e \frac{\ln \dfrac{2m_e c^2 \beta^2}{I_m(1-\beta^2)} - \beta^2}{\ln \dfrac{2m_e c^2 \beta^2}{I_{water}(1-\beta^2)} - \beta^2} \quad (2)$$

RESULTS

TECT generates three sets of CT images, from which $\hat{Z}$ and $\tilde{Z}$ of images are calculated. A calibration curve between $\hat{Z}$, $\tilde{Z}$ and I_m is built for the conversion to I_m in Fig. 1. A monotonic rise between $\hat{Z}$, $\tilde{Z}$ and I_m is observed in the calibration curve.

Once I_m value is obtained, SPR is calculated using Bethe equation. To compare the SPRs with TECT, the X-ray CT images and SPR images derived from TECT, DECT and SECT approaches are illustrated in Fig.2. The first row is the CT images with 90kVp, 120kVp and 140kVp. The second row is the SPR images from TECT, DECT and SECT approaches.

The measured SPR are shown in Table 1. The comparison of SPRs shows TECT and DECT have better performances in SPR calculation than SECT. Moreover, the SPR of lung, conventionally having a larger uncertainty, shows closer values to the theoretical SPR, with less than 1% for TECT approach, comparing to 3.26% for DECT approach and 4.04% for SECT approach. The accuracy of SPRs for liver and muscle from TECT overcome that of SECT and DECT as well with less than 2% totally. However, the SPR of breast has a different trend with the higher accuracy from SECT than DECT or TECT.

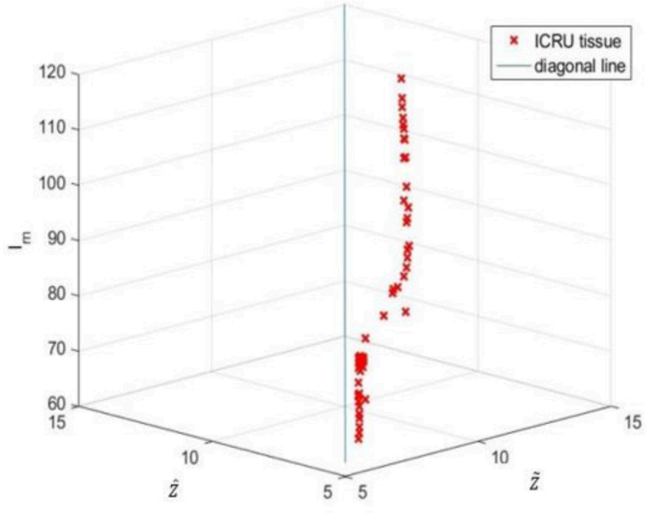

Fig. 1. The relation between $\hat{Z}$, $\tilde{Z}$ and I

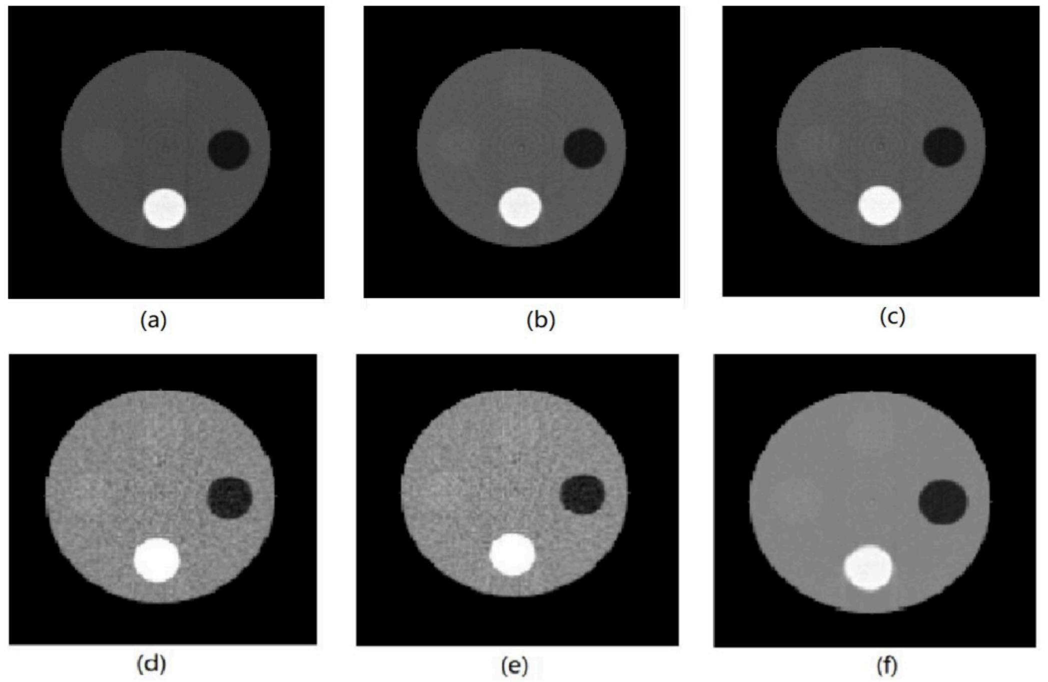

Fig. 2. X-ray CT images at 90kVp, 120kVp and 140kVp are illustrated on the top row. The SPR images derived from TECT, DECT and SECT approaches are shown in the second row.

Table 1. The relative errors of SPR derived from different methods.

	Theoretical SPR	Relative error of TECT method	Relative error of DECT method	Relative error of SECT method
breast	1.0208	2.17%	2.57%	-1.94%
lung	0.2576	-0.23%	3.26%	4.04%
liver	1.0496	-0.72%	-1.01%	-1.30%
muscle	1.0401	-1.16%	-1.74%	-1.84%

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CONCLUSIONS

The study compared the accuracy of SPRs with TECT, DECT and SECT. From this measurement, TECT shows a better performance in SPR calculation than SECT. In addition, TECT is superior to the other two types of CT for SPR calculation of lung tissue. Moreover, this method enables us to provide a more consistent conversion from Z to I. Comparatively, dual energy CT (DECT) approach must build up an effective atomic number with the power n which could be 3.3, 3.1 or 2.94, depending on the CT spectrum. The following work is to analyze comprehensively the accuracy of SPR calculated by TECT and compare the value to the conventional approach. A experimental measurement is needed to verify the result.

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CONTACT INFORMATION

Jiahua Zhu
jz790@cinj.Rutgers.edu