Stopping power ratio databases for proton therapy dose calculation

N Pischom¹,²*, S Asavaphatiboon¹, P Tangboonduangjit³ and T Liamsuwan³,⁴

¹ Master of Science Program in Medical Physics, Department of Diagnostic and Therapeutic Radiology, Faculty of Medicine Ramathibodi Hospital, Mahidol University, Bangkok, Thailand
² Division of Radiotherapy, Department of Radiology, Surin Hospital, Surin, Thailand
³ Faculty of Medicine and Public Health, HRH Princess Chulabhorn College of Medical Science (PCCMS), Chulabhorn Royal Academy, Bangkok, Thailand
⁴ Nuclear Research and Development Division, Thailand Institute of Nuclear Technology (Public Organization), Nakhon Nayok, Thailand

* Email: Narueporn.pis@yahoo.com

Abstract. In modern radiation therapy, ion beams are increasingly used for cancer treatment. Protons are light ions that have Bragg peak characteristic in the depth dose distribution that is optimal for minimizing dose to surrounding normal tissues. In proton therapy treatment planning, the stopping power ratio (SPR) of a given medium to that of water is used for calculating the water-equivalent pathlength (WEPL) of tissues in the patient. Since SPR is related to the computed tomography (CT) number, the conversion from CT numbers to SPRs can be used to find WEPLs of tissue voxels, which are sequentially applied in selecting the initial proton energy. In this work, we investigated the effect of using different CT number to SPR conversion models on proton pencil beam dose calculation. In the SPR calculation, either elemental mean excitation energy (I-value) from the ICRU report or elemental mass stopping power from SRIM software were used. For each approach, four energy dependent scenarios were investigated. The ICRU model and the SRIM model showed a monotonic correlation of SPRs for most tissue types. The 2D dose distribution was calculated by a MATLAB-based proton therapy treatment planning system, PSPLAN. The results suggest that elemental I-values and elemental mass stopping power can be used interchangeably for SPR calculation. Moreover, CT number to SPR conversion models obtained for specific proton energy and average proton energy did not cause difference in pencil beam dose calculation unless the proton energy was relatively low.
1. Introduction
To date, around 190,000 people have been treated by proton therapy worldwide [1]. Protons are light ions that have the Bragg peak characteristic in the depth dose distribution. The Bragg peak is the maximum of dose near the end of the proton range, the region is where the majority of energy deposition occurs. Behind the Bragg peak, the deposition dose falls practically to zero. This physical characteristic of a proton beam makes it possible to deliver a conformal dose to the target while sparing surrounding healthy tissues. There are two beam delivery techniques used in proton therapy. The first one is the passive scattering technique, through which pristine Bragg curves are modulated to cover the target volume using different beam shaping devices. The other technique is the pencil beam scanning (PBS) technique, which uses a magnetic field to scan proton pencil beams across the target volume. PBS is favoured over passive scattering because it needs less materials in the beam path; thus, fewer neutrons are produced during the treatment.

In the proton therapy treatment planning system (TPS) for both delivery techniques, dose in tissues is typically scaled from dose to water. The stopping power ratio (SPR) of a tissue of interest to water is used for calculating the water equivalent pathlength (WEPL) of the tissue voxel, which is sequentially used for the calculation of the required proton energy in the beam axis. The WEPL is also used to scale dose in the water equivalent system to dose in tissues [2].

The SPR can be converted from the CT number of the tissue voxel. In clinical use, the stoichiometric calibration method [3] is commonly used to find the conversion model. In that method, CT numbers of tissue-equivalent materials are measured and subsequently used for determination of SPRs associated with CT number ranges. The conversion of a CT number to SPR has been shown to contribute to approximately 1.6% range uncertainty in proton dose calculation [4]. Moreover, elemental compositions of tissue equivalent materials are not exactly the same as human tissues. Therefore, Schneider et al determined the correlation between CT numbers and human tissue parameters (density and elemental composition) for patient-specific Monte Carlo simulation and analytical dose calculation [5].

In this work, we investigated different approaches for constructing CT number to SPR models to be used in an in-house proton therapy treatment planning system by using the tissue parameters derived by Schneider et al [5]. Both elemental mean excitation energy (I-value) from the ICRU report [6] and elemental mass stopping power from SRIM software [7] were used, separately, for SPR calculation. For each approach, four energy dependent scenarios were investigated. The effects of the different CT number to SPR conversion models on proton pencil dose calculation will be discussed.

2. Materials and Methods
2.1. Construction of CT number to SPR conversion models
First, the conversion from CT numbers or HU (Hounsfield unit) ranges to elemental compositions were organized into 24 groups according to Schneider et al [5] as shown in Table 1.

In this work, both elemental mean excitation energy (I-value) from the ICRU report 49 [6] and elemental mass stopping power from SRIM software [7] were each used separately to construct the CT number to SPR conversion models. The first model is called the “ICRU model”, and the latter is the “SRIM model”.

2.1.1. ICRU model. The ICRU model uses the mean excitation energy (I-value) to calculate the SPR as follows [8]:

\[
SPR_m^{\text{RED}} = \frac{\ln[2m_e c^2 \beta^2 / (I_m (1 - \beta^2))] - \beta^2}{\ln[2m_e c^2 \beta^2 / (I_{\text{water}} (1 - \beta^2))] - \beta^2}
\]  

(1)

where RED is the relative electron density, \( \beta c \) is the velocity of the proton, \( m_e \) is the mass of the electron and \( I_m \) is the mean excitation energy of the material of interest. ICRU reports the I-values for elements and some compounds [8]. To calculate the I-values of tissues, Bragg’s additivity rule [9] was applied as follows:
\[ \ln I_{\text{tissue}} = \frac{\sum_i n_i Z_i \ln I_i}{\sum_i n_i Z_i} \]  \tag{2}

where \( I_{\text{tissue}} \), \( n_i \), \( Z_i \) and \( I_i \) are the mean excitation energy of the tissue, the number of atoms of the element \( i \) in the compound, the atomic number of the element \( i \) and the mean excitation energy of the element \( i \), respectively.

2.1.2. SRIM model. The SRIM model uses the mass stopping power for protons from the SRIM software for calculating the SPR of tissues, using Bragg’s additivity rule [9] as follows:

\[ \left( \frac{S}{\rho} \right)_{\text{tissue}} = \sum \omega_i \left( \frac{S}{\rho} \right)_i \]  \tag{3}

where \( \omega_i \) is the weight fraction of the element \( i \) in the tissue and \( \left( \frac{S}{\rho} \right)_i \) is the mass stopping power of the element \( i \) for protons. The SPR is calculated from:

\[ SPR = \frac{\rho_{\text{tissue}}}{\rho_{\text{water}}} \times \left( \frac{S}{\rho} \right)_{\text{tissue}} \]  \tag{4}

where \( \rho \) is the density and \( S/\rho \) is the mass stopping power. The SPRs of different tissues, as obtained from the ICRU model and the SRIM model, were compared using Spearman’s correlation.

The CT number to SPR conversion model involves comparison of the CT number (or HU) shown in Table 1 with the SPR, calculated as described in equations (1) and (4). For both models, four different energy dependent cases of SPR calculations were investigated. For the first case, the SPRs were averaged from 70 to 250 MeV protons (the so-called average-energy model), covering the energy range commonly used in proton therapy [10]. For the other three cases, SPRs at the specific energy levels of 70, 100 and 250 MeV were used for the conversion (the so-called effective-energy models). Pencil beam dose distributions of ~92 MeV protons were calculated with an in-house developed treatment planning system PSPLAN [11] based on the newly developed CT number to SPR conversion models, using meningioma as the study case. Proton ranges and 2D dose distributions obtained from the different conversion scenarios were compared.

### Table 1. HU ranges organized into 24 groups of tissues, according to Schneider et al [5].

| HU<sub>min</sub> | HU<sub>max</sub> | Tissue type | HU<sub>min</sub> | HU<sub>max</sub> | Tissue type  |
|-----------------|-----------------|-------------|-----------------|-----------------|-------------|
| -1000           | -950            | Air         | 400             | 500             | Cartilage   |
| -950            | -120            | Lung        | 500             | 600             | Humerus 1   |
| -120            | -83             | Adipose 1   | 600             | 700             | Humerus 2   |
| -82             | -53             | Adipose 2   | 700             | 800             | Clavicle    |
| -52             | -23             | Breast      | 800             | 900             | Rib         |
| -22             | -7              | CSF         | 900             | 1000            | Cranium 1   |
| 8               | 18              | Bone marrow | 1000            | 1100            | Cranium 2   |
| 19              | 80              | Brain       | 1100            | 1200            | Mandible    |
| 80              | 120             | Liver       | 1200            | 1300            | Femur       |
| 120             | 200             | Connective tissue | 1300         | 1400            | Cortical Bone 1 |
| 200             | 300             | Soft tissue | 1400            | 1500            | Cortical Bone 2 |
| 300             | 400             | Sternum     | 1500            | 1600            | Cortical Bone 3 |
3. Results

3.1. Comparison of CT number to stopping power ratio conversion models

The Spearman’s correlation coefficients for the comparison of the SPRs calculated by the ICRU model and the SRIM model are shown in Table 2. Most of the tissue types showed strong, positive monotonic correlation between the ICRU model and the SRIM model ($r_s = 0.80 – 1.00$, $p<0.001$) except for lung, brain, liver, connective tissue and soft tissue. Figure 1 shows the relation of the CT number and stopping power ratios of both the ICRU model and the SRIM model for the four different energy dependent cases. The plots showed no substantial difference between these models.

### Table 2. The Spearman’s correlation coefficients ($r_s$) between the SPRs calculated by the ICRU model and the SRIM model ($p$-value<0.001).

| Tissue type       | $r_s$   | $p$-value | Tissue type       | $r_s$   | $p$-value |
|-------------------|---------|-----------|-------------------|---------|-----------|
| Air               | 0.999   | <0.001    | Cartilage         | 0.966   | <0.001    |
| Lung              | -0.454  | 0.170     | Humerus 1         | 0.995   | <0.001    |
| Adipose 1         | 0.998   | <0.001    | Humerus 2         | 0.999   | <0.001    |
| Adipose 2         | 0.999   | <0.001    | Clavicle          | 0.999   | <0.001    |
| Breast            | 0.998   | <0.001    | Rib               | 1.000   | <0.001    |
| CSF               | 0.993   | <0.001    | Cranium 1         | 1.000   | <0.001    |
| Bone marrow       | 0.992   | <0.001    | Cranium 2         | 1.000   | <0.001    |
| Brain             | -0.851  | <0.001    | Mandible          | 1.000   | <0.001    |
| Liver             | -0.831  | <0.001    | Femur             | 1.000   | <0.001    |
| Connective tissue | -0.932  | <0.001    | Cortical Bone 1   | 1.000   | <0.001    |
| Soft tissue       | 0.147   | 0.464     | Cortical Bone 2   | 1.000   | <0.001    |
| Sternum           | 0.803   | <0.001    | Cortical Bone 3   | 1.000   | <0.001    |

3.2. Pencil beam dose distribution

In this work, four different energy dependent cases of SPR calculation were compared for the same condition of tissues and proton pencil beam energy. Figure 2a shows the pencil beam dose distribution for treatment of meningioma. The proton energy was ~92 MeV. The comparison between the average-energy ICRU and SRIM models is shown in figure 2b. Figure 3 compares the pencil beam dose distributions obtained from both the ICRU model and the SRIM model for 70, 100 and 250 MeV effective energies.
Figure 2. (a) Pencil beam dose distribution for treatment of meningioma. The proton energy was ~92 MeV. (b) Pencil beam dose distributions at proton energy ~92 MeV obtained from the average-energy ICRU and SRIM models (solid line and dashed line, respectively).

Figure 3. Pencil beam dose distributions at proton energy ~92 MeV obtained by the effective-energy ICRU and SRIM models (solid line and dashed line, respectively): (a) 70 MeV (b) 100 MeV and (c) 250 MeV.

4. Discussion
The CT number to SPR conversion model is required for proton dose calculation in a treatment planning system. In this work, different approaches to CT number to SPR conversion models were investigated in terms of pencil beam dose distribution. The stopping power ratio values obtained from both the ICRU model and the SRIM model were very close to each other, although there were differences in the details of the SPR calculations between the two models. The ICRU model is based on the experimental $I$-value of each element tabulated in the ICRU report [6], while the SRIM model is based on the experimental stopping power of each element given by SRIM software [7]. The Spearman’s correlation showed monotonic correlation between the SPRs calculated by both models for most tissues, except for lung.
and soft tissue (p-value <0.001). The Spearman’s correlation coefficients ($r_s$) for lung and soft tissue were -0.454 and 0.147, respectively. For lung and soft tissue, carbon and oxygen are highly present in the tissue composition, which could be the reason for the non-monotonic correlation observed between the SPRs calculated by the ICRU model and the SRIM model.

By comparing pencil beam dose distributions for treatment of meningioma using four different energy-dependent scenarios in the CT number-to-SPR conversion models, it was found that the proton range differed by 2 mm at maximum, while the 2D dose distributions were relatively close to each other, except for the 70 MeV effective-energy model. The cause of the slight difference at low proton energy may lie in the difference of stopping powers obtained from the experimental mean excitation energy and those obtained directly from the stopping power measurement for low energy protons.

5. Conclusions
The ICRU model and the SRIM model produced very similar values of SPRs. In proton pencil beam dose calculation, the 70 MeV effective-energy ICRU model gave slightly larger water-equivalent pathlength than those obtained by the other models and energy dependent scenarios, with a maximum difference of 2 mm in the proton range. It can be concluded that the $I$-values from the ICRU report and the mass stopping powers from the SRIM database produced the CT number to SPR conversion models that are very similar to each other. In terms of energy dependence, the average-energy model and the effective-energy model produced nearly the same dose distribution, with the maximum difference in the proton range of ~2 mm. The results suggest that elemental $I$-values and elemental mass stopping power can be used interchangeably for SPR calculations. Moreover, CT number to SPR conversion models obtained for specific proton energy and average proton energy did not; in this study, cause difference in pencil beam dose calculation, unless the proton energy was relatively low (i.e. 70 MeV).

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