Stopping power and range calculations of protons in human tissues

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Abstract:
In this research, the stopping power and range of protons in biological human soft and hard tissues (blood, brain, skeleton-cortical bone, and skin) of both child and adult are calculated at the energies ranging from 1 MeV to 350 MeV. The data is collected from ICRU Report 46 and calculated the stopping power employing the Bethe formula. Moreover, the simple integration (continuous slowing down approximation) method is employed for calculating protons range at the target. Then, the stopping power and range of protons value in human tissues have been compared with the program called SRIM. Moreover, the results of the stopping power vs energy and the range vs energy have been presented graphically. Proper agreement is found between the gained and the SRIM results and varies almost linearly with energy up to 250 MeV.

Key words: Human tissue, Proton, Range, SRIM, Stopping power.

Introduction:
In recent years, the theoretical and experimental studies of the stopping power (SP) and range of charged particles have been increasing immensely in radiation physics. Many theoretical, as well as experimental studies have been established on this topic quite efficiently. The calculation of stopping power and range of protons plays an important role in proton and cancer therapy (1). Hence, precise knowledge of SP and range of protons are needed for the exact dosimetry of proton radiation (2-4). When studying the SP and range of protons in a biological target, one must determine or collect data from experimentally or ICRU report. Scientists are working on the SP and range of protons in human tissues (skin, bone, blood, kidney, liver, brain, breast, etc.) in order to improve proton therapy in medical physics (5).

The composition of the human body gradually changes as the child becomes adult until the associate organs mature completely (6). As the body growth begins, the water content starts to decrease from fetal tissues while the lipid and protein contents increase. The mass and densities of the human body are made up of some basic elements like hydrogen, carbon, oxygen, nitrogen, etc. and these elemental compositions vary from bone to bone, body to body, and age to age (6). The prime concern in this study is selecting some body tissues with different ages to get the difference in values in the same body tissues. The values of SP and range can vary depending on the difference in the composition of targets (7). The aim of this study is to get the difference in results that can be beneficial for clinically relevant work like proton therapy.

In this study, the elemental compositions data of some human tissues (blood, brain, skeleton-cortical bone, and skin) of both child and adult is collected and that is given below in Table 1. The Bethe formula is implemented for the theoretical calculations of the protons SP at clinically relevant proton energies ranging from 1 MeV to 350 MeV (8). And the Continuous Slowing Down Approximation (CSDA) method is used for protons range calculations in the targets (9). Then the SP and CSDA range values are tabulated and compared them with the SRIM data. Finally, the results of our study and SRIM are presented graphically so that interested readers can simply understand the abbreviation of the paper.
Table 1. The elemental compositions and mass densities of some human body tissues (6).

| Tissues                  | H  | C    | N   | O   | Others       | ρ (g/cm³) |
|-------------------------|----|------|-----|-----|--------------|-----------|
| Blood (child)           | 10.0 | 13.1 | 4.0 | 72.0 | 0.1 Na, 0.1 P, 0.2 S, 0.2 Cl, 0.2 K, 0.1 Fe | 1.07      |
| Blood (adult)           | 10.2 | 11.0 | 3.3 | 74.5 | 0.1 Na, 0.1 P, 0.2 S, 0.3 Cl, 0.2 K, 0.1 Fe | 1.06      |
| Brain (child)           | 10.7 | 9.1  | 1.6 | 77.6 | 0.2 Na, 0.3 P, 0.1 S, 0.2 Cl, 0.2 K | 1.03      |
| Brain (adult)           | 10.7 | 14.5 | 2.2 | 71.2 | 0.2 Na, 0.4 P, 0.2 S, 0.3 Cl, 0.3 K | 1.04      |
| Skeleton-cortical bone (child) | 3.8 | 16.0 | 4.4 | 44.3 | 0.1 Na, 0.2 Mg, 9.9 P, 0.3 S, 21.0 Ca | 1.83      |
| Skeleton-cortical bone (adult) | 3.4 | 15.5 | 4.2 | 43.5 | 0.1 Na, 0.2 Mg, 10.3 P, 0.3 S, 22.5 Ca | 1.92      |
| Skin (child)            | 10.4 | 10.4 | 2.8 | 75.5 | 0.2 Na, 0.1 P, 0.2 S, 0.3 Cl, 0.1 K | 1.05      |
| Skin (adult)            | 10.0 | 20.4 | 4.2 | 64.5 | 0.2 Na, 0.1 P, 0.2 S, 0.3 Cl, 0.1 K | 1.09      |

Methods:

Calculations of stopping power

SP is a convenient variable that describes the effects of particle radiation in materials and predicts the ionization properties of the target matter. SP is defined by the ICRU (International Commission on Radiation Units and Measurements) as the ratio of the differential energy loss for a particle within the target matter to the corresponding differential path length of travel:

\[ S = -\frac{dE}{dx} \quad \text{(1)} \]

Where \(-dE/dx\) is known as the rate of energy loss or simply specific energy loss and the negative sign makes the result positive. Here, \(S\) is in negative sign because the energy of charged particles gradually decrease as long as they are interacting with the material. When the particles velocity decrease, \(S\) starts to increase. The total SP is defined as the sum of nuclear SP and electronic SP:

\[ S_{\text{tot}}(E) = S_{\text{nuc}}(E) + S_{\text{el}}(E) \quad \text{(2)} \]

At high velocity, slowing down of a projectile particle due to the inelastic collisions with the target's electrons is referred as the electronic SP (11). It is problematic to determine the electronic SP at energies below 100 keV. At low velocity, the nuclear SP arises from elastic Coulomb collisions with the target's nucleons and lose energy quickly. The nuclear SP is so small compared to electronic SP that it is only significant at very low energies (12). In this study, the nuclear SP is not counted because protons SP are calculated at high energies up to 350 MeV for clinically relevant work. So, here total SP means entire electronic SP and neglected nuclear SP.

Bethe is a common formula to determine SP of any charged particle. According to the Bethe formula, the stopping power of the charged particle will increase as the charged particle starts to collide with matter and decreases its energy (13). This formula agrees very well with the experiment at high energies because the charged particle does not carry any electrons with it (14). So, this formula requires no correction in this study. This formula can be described using relativistic quantum mechanics. For heavy charged particles like proton, the equation is:

\[ dE = \frac{4\pi\varepsilon_0^2ke^4}{mv^2} \left[ \ln \frac{2mv^2}{I} - \ln(1 - \beta^2) - \beta^2 \right] \]

\[ \text{dx} = \frac{\ln(1 - \beta^2)}{3} \]

Where,

- \(e\) = electronic charge, \(k = 1/4\pi\varepsilon_0\), \(v\) = velocity of the particle, \(m\) = electron rest mass, \(z\) = multiple of electron charge, \(I\) = mean excitation potential of the absorber, \(n\) = number of electrons per unit volume in the absorber, \(\beta\) = \(v/c\) (\(v\) is the speed of the particle and \(c\) is the speed of light in a vacuum)

The mean excitation potential of the absorber \(I = h\omega\) is one of the challenging parameters in the Bethe formula to evaluate. It is the only nontrivial material property in this formula. The SP of protons mostly depends on the accuracy of the mean excitation potential of the absorber, \(I\). The mean excitation potential of the absorber should be determined by experiment to get accurate results.

But there are three major theories to determine the value of \(I\). First is to use the dipole oscillator strength spectrum for the nth energy level over the logarithmic excitation energy range (15). But this method is difficult because of calculational complexity and more based on experimental research. In this study, here is some fixed materials like C, N, Na, K, etc. those have low atomic numbers (<40), so an empirical formula is employed. Dalton and Turner proposed that mean excitation potential is more close to the atomic number specially when the atom has a lower atomic number (<40). This formula gave reasonable agreement with the experimental values in previous author's work (16). The empirical equation is (17):
\[ I = 11.2 + 11.7Z, Z \leq 13 \] \[ I = 9.76Z + \frac{58.5}{Z^{0.16}}, Z \geq 13 \]

The speed of a charged particle is commensurable to the speed of light that requires relative correction and so Bethe-Bloch formula is also called relative correction formula. \( \beta \) is the proton’s velocity and can be determined by experiment or employing,

\[ E = \frac{1}{2}mv^2 \quad \text{Or,} \quad v = \sqrt{\frac{2E}{m}} \]

Here, the number of electrons per unit volume in the absorber can be calculated by,

\[ n = \frac{N_A Z \rho}{A M_u} \]

Where, \( Z \) = atomic number of the target material, \( \rho \) = density of the target material, \( N_A \) = Avogadro number, \( A \) = atomic mass of the target material, \( M_u \) = molar mass constant.

Comparisons with SRIM method:

SRIM (Stopping and Range of Ions in Matter) is an immensely popular program in the ion implementation research, computer program. SRIM has provided valid and approximately experimental results in previous radiation material research papers among other programs like ASTAR, MSTAR, PSTAR, etc. Though experimental measurement of SP is quite a challenging task so we choose the SRIM program to generate data. SRIM program’s calculation method is based on this Bethe formula:

\[ S = 4\pi \alpha Z^2 \left[ f(\beta) - \ln I > -\frac{C}{Z_2} - \frac{\delta}{2} \right] \]

Or, \( S = \frac{k Z_2}{\beta^2} \left[ L_0(\beta) + Z_1 L_1(\beta) + Z_2^2 L_2(\beta) \right] \)

where \( k \equiv 4\pi \alpha \eta^2 m_c^2 \)

And \( L_0, L_1, L_2 \) are called respectively correction factors of the Fano formula, Barkas correction, Bloch correction. After introducing stopping number \( L(\beta) \), this eq becomes,

\[ S = \frac{k Z_2}{\beta^2} Z_1^2 L(\beta) \]

Bethe formula has some limitations specially when particles come with low velocity because at this velocity positively charged particle has a tendency to pick up electrons from the target materials (18). This process reduces its charge effectively and leads to a consequent linear energy loss of this charged particle. So, there is a good possibility that the charged particle accumulates with electrons and at the end becomes a neutral atom. SRIM program is based on this above corrected Bethe formula so that this program can calculate SP of any particle (low particle energy to high particle energy up to 2 GeV/amu) simultaneously (19). But in this study, the protons SP are calculated at energies ranging from 1 MeV to 350 MeV for clinically relevant work. As the study is entirely based on protons high energy, so the low-velocity limit of the Bethe formula is neglected.

The mean excitation potential is an important parameter which characterizes the stopping of target materials. From equation 8, mean excitation potential is defined as:

\[ \ln < I > = \sum_n f_n E_n \]

Where \( I \) and \( E_n \) has the same unit of eV. Bloch had shown that mean excitation potential is practically proportional to the atomic number \( (Z) \) of the target materials and close to Rydberg energy \( I = 13.5Z \text{eV} \). In this program, the Rydberg energy equation is used to calculate the mean excitation potential of all the materials. But, the mean excitation potential is calculated from equations 4 and 5 in this work. The atomic number of the material is taken into account whether it is greater than 13 or not. Because, body tissues are composed of different materials such as H, C, N, O, Na, P, etc. and they have different atomic numbers. These two equations are employed to get proper mean excitation potential values in this study for the theoretical calculations of the protons SP.

Calculations of range

Range, \( R \) of a charged particle is defined as the distance of that charged particle travel from its source to the target material. Light particles like electrons, positrons can be scattered in the path of the targets with large angles due to their low weight and it is difficult to calculate their path length. Monte Carlo methods that are based on a broad class of computational algorithms have been using in a successful manner specially for calculating the path length of light particles. On the other hand, the path length of heavy particles like protons is almost straight line. The range of protons can be calculated by some numerical integration methods. But the Continuous slowing down approximation (CSDA) is a simple and common method to calculate the range of the heavy particles like protons in the targets and this method is employed in this study. Incident particles continuously lose their energy in the path of the targets and the CSDA method
neglects energy loss fluctuations. The range, R for an incident proton in the CSDA method is given as:

\[ R = \rho \int_{E_i}^{E_f} \frac{dE}{S(E)} \]

Where,
\( \rho \) = density of the target material,
\( E_i \) = initial energy of incident charged particle in material,
\( E_f \) = final energy of incident charged particle in material.

**Results and Discussion:**

Ageing is a continuous process of natural change that brings many changes in the fundamental compositions of most soft and hard body tissues. Genetics, state of health, sex, disease, physical activity, metabolism, nutrition are the main factors that are affecting the body compositions. The aim of this study is to show how ageing can be an affecting factor in order to determine the SP and range of protons energy.

From eq. 3, the SP of protons are calculated at the energies ranging from 1MeV to 350 MeV of blood, brain, skeleton-cortical-bone, and skin for both child and adult. Then these data are compared with the data obtained from the SRIM code. Previous papers on SP and range of proton efficiently showed that SRIM code was the best fit with their values compared to other programs (20). And, the percentage difference of this theoretical work has been compared with the values of SRIM code in Table 2 and 3 and also illustrated graphically in Fig.1.

**Table 2. Showing the proton energy in MeV and the stopping power for values for Blood and Brain in MeV/g/cm².**

| Energy (MeV) | Stopping power in MeV/g/cm² for Blood (child) | Stopping power in MeV/g/cm² for Blood (adult) | Stopping power in MeV/g/cm² for Brain (child) | Stopping power in MeV/g/cm² for Brain (adult) |
|-------------|-----------------------------------------------|-----------------------------------------------|-----------------------------------------------|-----------------------------------------------|
|             | SRIM This work %T                             | SRIM This work %T                             | SRIM This work %T                             | SRIM This work %T                             |
| 1           | 250.50 283.15 13.03                           | 250.20 282.18 12.78                           | 250.31 282.71 12.94                           | 250.81 284.55 13.45                           |
| 2           | 163.21 189.67 16.21                           | 162.81 188.43 15.74                           | 163.91 190.14 16.00                           | 163.62 190.03 16.14                           |
| 3           | 119.97 138.23 15.22                           | 119.68 137.66 15.02                           | 120.48 139.41 15.71                           | 120.28 139.17 15.71                           |
| 4           | 95.92 107.75 12.33                           | 95.68 106.68 11.50                           | 96.27 108.38 12.58                           | 96.12 108.21 12.58                           |
| 5           | 80.45 86.29 7.26                             | 80.27 85.51 6.53                             | 80.76 86.45 7.05                             | 80.63 86.35 7.09                             |
| 6           | 69.62 74.81 7.45                             | 69.46 74.02 6.56                             | 69.87 75.06 7.43                             | 69.76 74.94 7.43                             |
| 7           | 61.56 66.39 8.58                             | 61.42 66.14 7.68                             | 61.78 66.79 7.81                             | 61.69 66.53 7.85                             |
| 8           | 55.30 59.61 7.79                             | 55.17 59.44 7.74                             | 55.50 60.07 8.23                             | 55.41 59.88 8.07                             |
| 9           | 50.29 53.22 5.83                             | 50.18 52.91 5.44                             | 50.48 53.32 5.63                             | 50.39 53.19 5.56                             |
| 10          | 46.19 48.42 4.83                             | 46.09 48.12 4.40                             | 46.36 48.53 4.68                             | 46.29 48.47 4.71                             |
| 20          | 26.26 28.38 8.07                             | 26.21 28.28 7.90                             | 26.36 28.51 8.16                             | 26.32 28.45 8.09                             |
| 30          | 18.87 20.91 10.81                           | 18.84 20.83 10.56                           | 18.95 20.99 10.77                           | 18.92 20.95 10.73                           |
| 40          | 14.96 16.25 8.62                           | 14.93 16.13 8.04                            | 15.02 16.28 8.39                            | 14.99 16.27 8.54                            |
| 50          | 12.51 13.61 8.79                           | 12.48 13.56 8.65                            | 12.56 13.71 9.16                            | 12.53 13.65 8.94                            |
| 60          | 10.83 11.59 7.02                           | 10.81 11.52 6.57                            | 10.87 11.65 7.18                            | 10.85 11.62 7.10                            |
| 70          | 9.59 10.35 7.92                           | 9.58 10.33 7.83                            | 9.63 10.44 8.41                            | 9.61 10.39 8.12                            |
| 80          | 8.65 9.36 8.21                           | 8.64 9.32 7.87                            | 8.69 9.42 8.40                            | 8.67 9.40 8.42                            |
| 90          | 7.91 7.55 4.55                           | 7.90 7.53 4.68                            | 7.94 7.62 4.03                            | 7.92 7.58 4.29                            |
| 100         | 7.31 7.09 3.01                           | 7.30 7.05 3.42                            | 7.34 7.11 3.13                            | 7.33 7.10 3.14                            |
| 125         | 6.21 5.76 7.24                           | 6.20 5.75 7.26                            | 6.24 5.79 7.21                            | 6.23 5.77 7.38                            |
| 150         | 5.46 5.03 7.88                           | 5.45 5.01 8.07                            | 5.48 5.07 7.48                            | 5.47 5.05 7.68                            |
| 175         | 4.91 4.66 5.09                           | 4.90 4.64 5.31                            | 4.93 4.68 5.07                            | 4.92 4.67 5.08                            |
| 200         | 4.50 4.37 2.89                           | 4.49 4.35 3.12                            | 4.52 4.39 2.88                            | 4.51 4.38 2.89                            |
| 225         | 4.18 3.98 4.78                           | 4.17 3.96 5.04                            | 4.19 3.98 5.01                            | 4.18 3.98 4.78                            |
| 250         | 3.92 3.68 6.12                           | 3.91 3.66 6.39                            | 3.93 3.70 5.85                            | 3.92 3.68 6.12                            |
| 275         | 3.70 3.31 10.54                           | 3.69 3.29 10.84                            | 3.72 3.35 9.95                            | 3.71 3.33 10.24                            |
| 300         | 3.52 3.07 12.78                           | 3.51 3.06 12.82                            | 3.54 3.09 12.71                            | 3.53 3.08 12.75                            |
| 350         | 3.24 2.82 12.96                           | 3.24 2.82 12.96                            | 3.26 2.85 12.58                            | 3.25 2.84 12.62                            |
Table 3. Showing the proton energy in MeV and the stopping power for values for Skeleton-cortical-bone and skin in MeV/g/cm².

| Energy (MeV) | Stopping power in MeV/g/cm² for Skeleton-cortical-bone (child) | Stopping power in MeV/g/cm² for Skeleton-cortical-bone (adult) | Stopping power in MeV/g/cm² for Skin (child) | Stopping power in MeV/g/cm² for Skin (adult) |
|-------------|---------------------------------------------------------------|---------------------------------------------------------------|-------------------------------------------|---------------------------------------------|
|             | SRIM This work %T                                              | SRIM This work %T                                              | SRIM This work %T                          | SRIM This work %T                           |
| 1           | 214.26 242.67 13.26                                            | 211.26 236.37 11.89                                            | 250.00 281.88 12.75                       | 251.80 284.31 12.91                       |
| 2           | 138.49 160.13 15.63                                            | 136.49 155.51 13.94                                            | 162.91 188.69 15.82                       | 163.21 190.20 16.54                       |
| 3           | 102.76 117.38 14.23                                            | 101.46 115.44 13.78                                            | 119.78 137.81 15.05                       | 119.98 139.42 16.20                       |
| 4           | 82.73 90.45 9.33                                               | 81.66 88.96 8.94                                               | 95.75 106.79 11.53                       | 95.87 108.10 12.76                       |
| 5           | 69.72 75.76 8.66                                               | 68.85 74.79 8.63                                               | 80.33 85.57 6.52                          | 80.42 87.25 8.49                        |
| 6           | 60.52 65.13 7.62                                               | 59.79 64.36 7.64                                               | 69.51 74.17 6.70                          | 69.58 75.69 8.78                        |
| 7           | 53.66 58.21 8.48                                               | 53.02 57.63 8.69                                               | 61.46 66.23 7.76                          | 61.53 67.19 9.20                        |
| 8           | 48.32 52.32 8.28                                               | 47.75 51.48 7.81                                               | 55.21 59.51 7.79                          | 55.28 60.28 9.04                        |
| 9           | 44.01 48.19 9.50                                               | 43.51 46.86 7.70                                               | 50.22 52.99 5.52                          | 50.28 53.36 6.13                        |
| 10          | 40.49 43.11 6.47                                               | 40.02 42.72 6.75                                               | 46.12 48.19 4.49                          | 46.18 48.43 4.87                        |
| 20          | 23.23 25.68 10.55                                              | 22.99 25.04 8.92                                              | 26.23 28.35 8.08                          | 26.29 28.56 8.63                        |
| 30          | 16.77 18.09 7.87                                               | 16.60 17.85 7.53                                              | 18.85 20.86 10.66                         | 18.91 21.07 11.42                       |
| 40          | 13.32 14.76 10.81                                              | 13.19 14.48 9.78                                              | 14.94 16.16 8.17                          | 14.99 16.38 9.27                       |
| 50          | 10.35 11.41 10.24                                              | 11.04 11.79 6.79                                              | 12.49 13.59 8.81                          | 12.54 13.75 9.65                       |
| 60          | 9.67 10.49 8.48                                               | 9.58 10.24 6.89                                               | 10.82 11.55 6.75                          | 10.87 11.69 7.54                       |
| 70          | 8.58 9.13 6.41                                               | 8.50 8.93 5.06                                               | 9.58 10.34 7.93                          | 9.58 10.34 7.93                        |
| 80          | 7.75 8.17 5.42                                               | 7.68 8.02 4.43                                               | 8.64 9.32 7.87                            | 8.65 9.35 8.09                        |
| 90          | 7.09 7.34 3.53                                               | 7.02 7.06 0.57                                               | 7.90 7.53 4.68                            | 7.90 7.53 4.68                        |
| 100         | 6.55 6.67 1.83                                               | 6.49 6.59 1.54                                               | 7.30 7.05 3.42                            | 7.30 7.06 3.29                        |
| 125         | 5.58 5.63 0.90                                               | 5.52 5.49 0.54                                               | 6.20 5.75 7.26                            | 6.20 5.75 7.26                        |
| 150         | 4.90 4.84 1.22                                               | 4.86 4.70 3.29                                               | 5.45 5.01 8.07                            | 5.45 5.01 8.07                        |
| 175         | 4.42 4.27 3.39                                               | 4.38 4.21 3.88                                               | 4.91 4.64 5.00                            | 4.91 4.64 5.00                        |
| 200         | 4.05 3.91 3.46                                               | 4.01 3.82 4.74                                               | 4.49 4.35 3.12                            | 4.49 4.35 3.12                        |
| 225         | 3.76 3.57 5.05                                               | 3.72 3.51 5.65                                               | 4.17 3.96 5.04                            | 4.17 3.96 5.04                        |
| 250         | 3.53 3.31 6.23                                               | 3.49 3.25 0.86                                               | 3.91 3.66 6.40                            | 3.91 3.66 6.40                        |
| 275         | 3.33 3.11 6.61                                               | 3.30 3.06 7.27                                               | 3.70 3.29 11.08                           | 3.70 3.29 11.08                        |
| 300         | 3.17 2.92 7.89                                               | 3.15 2.87 8.89                                               | 3.52 3.06 13.07                           | 3.52 3.06 13.07                        |
| 350         | 2.92 2.61 10.62                                              | 2.90 2.58 11.03                                              | 3.24 2.82 13.96                           | 3.24 2.82 13.96                        |

From Tables 2 and 3, the total percentage difference between SRIM and this work is 8.40%, 8.24%, 8.38%, 8.41%, 7.57%, 6.91%, 8.31%, 8.85% respectively for blood (child), blood (adult), brain (child), brain (adult), skeleton-cortical-bone (child), skeleton-cortical-bone (adult), skin (child), skin (adult). The percentage difference rate for all tissues is less than 10% which shows that this result is in good agreement with SRIM. Figure-1 shows the SP gradually decreases with the increase of protons energy.

Moreover, the difference between these work values and SRIM values at energies ranging from (1-10) MeV is quite high but there is almost no difference at energies ranging from (80-350) MeV. Because when proton enters in the target tissue, they start to interact with many electrons where the proton transfer energy in this encounter mostly by excitation and ionization (21). So, the SP of proton starts to decrease with the increase of proton velocity that is shown in Fig. 1.
Figure 1. a) The stopping power of blood (child) as a function of proton’s energy. b) The stopping power of blood (adult) as a function of proton’s energy. c) The stopping power of brain (child) as a function of proton’s energy. d) The stopping power of blood (adult) as a function of proton’s energy. e) The stopping power of skeleton-cortical-bone (child) as a function of proton’s energy. f) The stopping power of skeleton-cortical-bone (adult) as a function of proton’s energy. g) The stopping power of skin (child) as a function of proton’s energy. h) The stopping power of skin (adult) as a function of proton’s energy.
From eq.11, the CSDA range of protons are calculated at energies ranging from (1-350MeV) and compared with the SRIM code. Results are tabulated in Table 4 and 5 and also illustrated graphically proton range in cm vs. proton energy in MeV in Fig.2. From Table 4 and 5, the total percentage difference between SRIM and this work are 8.15%, 7.94%, 8.04%, 8.14%, 7.15%, 6.82%, 8.32%, 8.73% respectively for blood (child), blood (adult), brain (child), brain (adult), skeleton-cortical-bone (child), skeleton-cortical-bone (adult), skin (child), skin (adult). The percentage difference rate for all tissues is less than 10% which shows that this result is in a good agreement with SRIM.

### Table 4. Proton range for Blood (child and adult) and Brain (child and adult) for proton energy 1MeV to 350MeV.

| Energy (MeV) | Blood (child) | Blood (adult) | Brain (child) | Brain (adult) |
|--------------|---------------|---------------|---------------|---------------|
|              | SRIM This work | %T            | SRIM This work | %T            |
| 1            | 0.00427       | 11.71         | 0.00423       | 10.40         |
| 2            | 0.00655       | 13.89         | 0.00649       | 12.63         |
| 3            | 0.01783       | 13.18         | 0.01767       | 12.05         |
| 4            | 0.03346       | 10.97         | 0.03315       | 9.26          |
| 5            | 0.05320       | 6.77          | 0.03952       | 6.64          |
| 6            | 0.07684       | 6.94          | 0.07613       | 7.07          |
| 7            | 0.10428       | 7.27          | 0.10331       | 6.05          |
| 8            | 0.13543       | 7.22          | 0.13417       | 6.09          |
| 9            | 0.17021       | 5.50          | 0.16862       | 4.06          |
| 10           | 0.20847       | 4.60          | 0.20653       | 3.10          |
| 20           | 0.77417       | 7.47          | 0.76694       | 6.27          |
| 30           | 1.64440       | 9.76          | 1.62904       | 8.56          |
| 40           | 2.78943       | 7.94          | 2.76336       | 6.38          |
| 50           | 4.19104       | 8.08          | 4.15187       | 6.87          |
| 60           | 5.82917       | 6.56          | 5.77469       | 5.10          |
| 70           | 7.69864       | 7.34          | 7.62669       | 6.29          |
| 80           | 9.77224       | 7.59          | 9.68092       | 6.31          |
| 90           | 12.0392       | 4.77          | 11.9267       | 6.04          |
| 100          | 14.4911       | 3.10          | 14.3557       | 4.67          |
| 125          | 21.3655       | 7.81          | 21.1659       | 9.02          |
| 150          | 29.1996       | 8.55          | 28.9267       | 10.01         |
| 175          | 37.9185       | 5.36          | 37.5615       | 6.82          |
| 200          | 47.3178       | 2.97          | 46.8756       | 4.42          |
| 225          | 57.3397       | 5.03          | 56.8038       | 6.55          |
| 250          | 67.9668       | 6.52          | 67.3316       | 8.11          |
| 275          | 79.2378       | 11.78         | 78.4973       | 13.52         |
| 300          | 90.8890       | 14.66         | 90.0398       | 16.12         |
| 350          | 115.256       | 14.89         | 114.179       | 16.98         |
Table 5. Proton range for Skeleton-cortical-bone (child and adult) and Skin (child and adult) for proton energy 1MeV to 350MeV.

| Energy (MeV) | Skeleton-cortical-bone (child cm) | Skeleton-cortical-bone (adult cm) | Skin (child cm) | Skin (adult cm) |
|--------------|----------------------------------|----------------------------------|-----------------|-----------------|
|              | SRIM This work %T                  | SRIM This work %T                  | SRIM This work %T | SRIM This work %T |
| 1            | 0.00854                           | 0.00754                          | 11.71           | 0.00908         |
| 2            | 0.01321                           | 0.01412                          | 13.55           | 0.01406         |
| 3            | 0.03561                           | 0.03118                          | 12.44           | 0.03784         |
| 4            | 0.06636                           | 0.06069                          | 8.54            | 0.07053         |
| 5            | 0.10499                           | 0.09662                          | 7.97            | 0.11154         |
| 6            | 0.15118                           | 0.14048                          | 7.08            | 0.16056         |
| 7            | 0.20462                           | 0.18862                          | 7.82            | 0.21727         |
| 8            | 0.26510                           | 0.24483                          | 7.65            | 0.28146         |
| 9            | 0.33265                           | 0.30379                          | 8.68            | 0.35302         |
| 10           | 0.40676                           | 0.38204                          | 6.08            | 0.43178         |
| 20           | 1.49678                           | 1.35397                          | 9.54            | 1.58677         |
| 30           | 3.16457                           | 2.93366                          | 7.30            | 3.35421         |
| 40           | 5.35810                           | 4.83536                          | 9.76            | 5.67702         |
| 50           | 8.66378                           | 7.85889                          | 9.29            | 8.48331         |
| 60           | 11.1655                           | 10.2926                          | 7.82            | 11.8246         |
| 70           | 14.7168                           | 13.8302                          | 6.02            | 15.5859         |
| 80           | 18.6542                           | 17.6952                          | 5.14            | 19.7500         |
| 90           | 22.9718                           | 22.1894                          | 3.41            | 24.3419         |
| 100          | 27.6595                           | 27.1619                          | 1.80            | 29.2881         |
| 125          | 40.6667                           | 40.3055                          | 0.89            | 43.1304         |
| 150          | 55.6469                           | 56.3367                          | 1.24            | 58.8642         |
| 175          | 72.0407                           | 74.5714                          | 3.51            | 76.2740         |
| 200          | 89.9185                           | 93.1381                          | 3.58            | 95.2818         |
| 225          | 109.021                           | 114.823                          | 3.52            | 115.613         |
| 250          | 129.085                           | 137.665                          | 3.65            | 136.986         |
| 275          | 150.577                           | 161.228                          | 7.07            | 159.418         |
| 300          | 172.609                           | 187.387                          | 8.56            | 182.248         |
| 350          | 218.723                           | 244.701                          | 11.88           | 231.062         |

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Figure 2. a) The CSDA ranges of proton in blood (child) tissue. b) The CSDA ranges of proton in blood (adult) tissue. c) The CSDA ranges of proton in brain (child) tissue. d) The CSDA ranges of proton in brain (adult) tissue. e) The CSDA ranges of proton in skeleton-cortical-bone (child) tissue. f) The CSDA ranges of proton in skeleton-cortical-bone (adult) tissue. g) The CSDA ranges of proton in skin (child) tissue. h) The CSDA ranges of proton in skin (adult) tissue.

In Fig. 2, the percentage difference starts to increase rapidly at 250 MeV or above. Protons tend to pick up electrons from the target tissues when the CSDA method is applied at high energies. And as a result, this will give rise to linear energy loss and deviations. This is the severe limitation of the CSDA method and so, we calculated the range of proton up to 350 MeV. In Fig. 2, this work shows...
the best fit with SRIM at the energy range (5-250MeV) and varies almost linearly with these energies. And then, the rise of the curve has started so rapidly beyond 250 MeV and demolish this linearity. The first reason behind this rapid rise is due to increasing bremsstrahlung probability and the other reason is the CSDA method which is discussed above(22).

Conclusion:
In this work, we have done the SP and range calculations for protons incident on the 4 different human tissues (blood, brain, skeleton-cortical-bone, skin) of both child and adult. Though ageing brings many changes in the fundamental compositions of most tissues, we got slight difference between child and adult values of SP and range. Furthermore, it is observed from these tables that our results are in good agreement with SRIM specially at the energy range 50-250 MeV and this energy interval is essential in the clinically relevant work like proton therapy. In addition, the result shows the effectiveness and reliability of this study. Although, the stability of this work starts to break beyond 250MeV. So, more research should be conducted to improve the accuracy of the SP and range computation.

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Authors' declaration:
- Conflicts of Interest: None.
- We hereby confirm that all the Figures and Tables in the manuscript are mine ours. Besides, the Figures and images, which are not mine ours, have been given the permission for republication attached with the manuscript.
- Ethical Clearance: The project was approved by the local ethical committee in University of Chittagong.

References:
1. El-Ghossain M O. Calculations Of Stopping Power. And Range Of Electrons Interaction With Different Material And Human Body Parts. Int J Sci Technol Res. 2017;6(1):114–8.
2. Grimes DR, Warren DR, Partridge M. An approximate analytical solution of the Bethe equation for charged particles in the radiotherapeutic energy range. Sci Rep [Internet]. 2017;7(1):1–12.
3. Pedroni E, Bacher R, Blattmann H, Bohringer T, Coray A, Lomax A, et al. The 200-Mev proton therapy project at the Paul Scherrer Institute: Conceptual design and practical realization. Med Phys. 1995;22(1):37–53.
4. Newhauser WD, Zhang R. The physics of proton therapy. Phys Med Biol. 2015;60(8):R155–209.
5. Tufan MC, Namdar T, Gümiş H. Stopping power and CSDA range calculations for incident electrons and positrons in breast and brain tissues. Radiat Environ Biophys. 2013;52(2):245–53.
6. White D R, Griffith R V , Wilson I J. International Commission on Radiation Units and Measurement 46. Photon, electron, proton and neutron interaction data for body tissues. ICRU Report 46, 1992.
7. Amable AKS, Godsway BK, Nyaaba RA, Manson EN. A Theoretical Study of Stopping Power and Range For Low Energy (<3.0mev) Protons In Aluminium, Germanium, Lead, Gold and Copper Solid Materials. Open Sci J. 2017;2(2):1–17.
8. Knoll G. Radiation Detection and Measurement, 3rd ed - Glenn F. 2009. p. 1–796.
9. Usta M, Tufan MÇ. Stopping power and range calculations in human tissues by using the Hartree-Fock-Roothaan wave functions. Radiat Phys Chem.2017;140(Feb):43–50.
10. Paul H. Nuclear stopping power and its impact on the determination of electronic stopping power. AIP Conf Proc. 2013;1525:309–13.
11. Barradas NP, Alves E, Siketić Z, Bogdanović Radović I. Stopping power of He, C and O in GaN. Nucl Instruments Methods Phys Res Sect B Beam Interact with Mater Atoms. 2012;273:26–9.
12. Montanari CC, Dimitriou P. The IAEA stopping power database, following the trends in stopping power of ions in matter. Nucl Instruments Methods Phys Res Sect B Beam Interact with Mater Atoms [Internet]. 2017;408:50–5.
13. Jassim WN. Study of Proton Stopping Power in Be, C, Al and Cu with Energy (1-12) MeV. Int J Sci Res [Internet]. 2015;4(4):874–7.
14. Yadav V, Sirisha SNL, Bhatnagar S. Study for Stopping Power of Proton in Different materials – A Geant4 Simulation. Nucl Phys. 2012;57:3–4.
15. Ziegler JF, Chu WK. The stopping of 4He ions in elemental matter. Thin Solid Films. 1973;19(2):281–7.
16. Nguyen-Truong HT. Modified Bethe formula for low-energy electron stopping power without fitting parameters. Ultramicroscopy. 2015;149:26–33.
17. Stein JD. Appendix 7. LA Math. 2019;175–83.
18. Sigmund P, Schinner A. Progress in understanding heavy-ion stopping. Nucl Instruments Methods Phys Res Sect B Beam Interact with Mater Atoms [Internet]. 2016;382:15–25.
19. QH M, HA M. Alpha-particle Stopping Powers in Air and Argon. Res Rev J Pure Appl Phys. 2017;5(4):22–8.
20. Linares R, Ribas R V, Oliveira JRB, Medina NH, Santos HC, Seabra CC, et al. Electronic stopping power of Ti, V and Cr ions in Ge and Au at 150–500 keV/u energies. Nucl Instruments Methods Phys Res
Sect B Beam Interact with Mater Atoms. 2017;413(August):1–5.
21. Jassim WN. Study of Proton Stopping Power in Be, C, Al and Cu with Energy (1-12) MeV. Int J Sci Res [Internet]. 2015;4(4):874–7.
22. Barradas NP, Alves E, Siketić Z, Bogdanović Radović I. Stopping power of C in Si. Nucl Instruments Methods Phys Res Sect B Beam Interact with Mater Atoms. 2012;273:30–2.

CSDA للبروتونات في أنسجة السرطان الشائعة لدى الإنسان

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الخلاصة:
في هذا البحث، حسبنا قدرة التوقف ومدى البروتونات في الأنسجة البشرية البيولوجية الصلبة واللينة (الدم والدماغ والعظام القشرية الهيكلية والجلد) لكل من الأطفال والبالغين في طاقات تتراوح من 1 MeV إلى 350 MeV. فضلاً عن ذلك، حساب قدرة التوقف باستخدام صيغة Bethe وحساب المدى باستخدام برنامج SRIM. بعد ذلك، تم مقارنة قدرة التوقف وقيمة المدى للبروتونات في أنسجة الإنسان بالبرنامج المسمى SRIM. تم إيجاد علاقة بين النتائج المكتسبة وSRIM وتتغير بشكل خطي تقريباً مع طاقة تصل إلى 250 MeV.

الكلمات المفتاحية: الأنسجة البشرية، البروتون، المدى، SRIM.