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The Stopping Powers of Water and Lung for Protons in Radiotherapy

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Authors' contributions

This work was carried out in collaboration between all authors. All authors read and approved the final manuscript.

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Short Research Article

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ABSTRACT

Aims: This study aims to calculate the energy losses in unit length of protons during their movement within water and lung by using two analytical equations.
Study Design: One of the equations used in this study is the mass stopping power equation suggested by Bethe-Bloch (1930-1933) and modified by Tsoulfanidis (1995) and a new approach has been suggested in the other one.
Methodology: The suggested new approach was obtained by substituting effective z*, Z* and ***I**** values into the equation reported by Tsoulfanidis. Although the energy range of protons used in the radiotherapy is 75-250 MeV, in this study 0.001-250 MeV energy ranges were performed to identify the stopping power. In addition, a new empirical relation was given to simplify the expressions for stopping power. The results were compared with the other researcher's results.
Results: The suggested approach for the mass stopping power (Equation 2) can be used for both high- and low energy protons. Stopping power values of protons should be especially useful in such medical fields as radiobiology, biomedical applications, radiotherapy and so on.

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Keywords: Stopping power; proton therapy; water; lung.

1. INTRODUCTION

In radiotherapy, the idea is that the maximum dose of ionized radiation energy given to patient tissue should not be so high as to damage the healthy organ. The photons used in medical fields for treatment leave a portion of their energy in healthy tissues until they arrive on the tumour. This situation led to an examination of proton therapies having high linear energy transfer (LET). Because of the large mass of protons, the scattering from the tissues is relatively less. The proton beam delivered to the target was focused on the tumour without much scattering and so the healthy tissue was spared. All the protons arrive at the target with the same energy with the exception of only a few protons. This means that the maximum radiation dose is given to the target.

The world's first hospital-based proton therapy centre was opened in UK in 1989 and followed in 1990 at the Loma Linda University, California. Although it has been used for treatment for 40 years there is still no accurate knowledge of how protons interact with healthy tissue. Accurate energy loss (or stopping power) values are crucial for tumour radiotherapy.

Stopping power (SP) equations were given by H. Bethe in 1930 [1] and by F. Bloch in 1933 [2] using quantum mechanical approximations. Although these approximations have yielded good results for the SP of particles with high energy, they were not so successful for low energy particles. The dielectric theory given by Lindhard [3] is important in the calculation of SP for electrons with low energy. Dielectric theorem is inadequate for calculating the SP of organic material for protons. A new SP statement for protons was given by Akerman [4]. They have calculated the SP for organic materials and water in the range of proton energies 50-500 keV. Also Tsoulfanidis [5] developed SP equations for protons, deuterons and alpha particles. Singh et al. [6] present a simple method for the calculation of mass SPs. The stopping power of tissue, especially water, for charged particles has been investigated by several researchers [1-11].

In this study the electronic mass stopping powers of water and lung for protons within the 0.001 MeV – 250 MeV energy range were calculated using two different approximations explained in Section II. The results were compared with the other studies.

2. METHODOLOGY

The electronic SPs for protons were calculated using two approximations: One of them was the Bethe–Bloch [1,2]. Equation modified by Tsoulfanidis [5]. The other was an equation in which the z, Z and ***I*** values in the Tsoulfanidis approximation were replaced by values z*, Z* and ***I****. The modified Bethe-Bloch Equation for protons is the following:

$$\frac{1}{\rho}\frac{dE}{dx} = 4\pi r_0^{\,2} z^2 \frac{mc^2}{\beta^2}\frac{N_0}{A} Z\left[\ln\left(\frac{2mc^2}{I}\beta^2\gamma^2\right) - \beta^2\right] \quad (1)$$

Here, (1/ρ) dE/dx is the mass collision SP; r_0= 2.818 × 10^{-15} *m* that is the classical electron radius; mc^2 is the rest mass energy of electrons (0,511MeV); Mc^2 is the rest mass of protons (931,5 MeV); N is the number of atoms in the target material per m^3; A is the atomic weight, and Z is the atomic number of the target material. One of the important parameters to determine the SP is also average ionization energy, I. It characterizes the properties of the target. I value was taken from the NIST [12] program. A and Z values were calculated using the following Equations [5]:

$$A_{ave.} = \sum_i \left(A_i w_i\right), \quad \text{and}$$

$$Z_{ave} = \frac{\sum_{i=1}^{n}\left(\frac{w_i}{A_i}\right) z_i^2}{\sum_{i=1}^{n}\left(\frac{w_i}{A_i}\right) z_i}$$

Where *n* is the number of elements in the target, w_i is the weight fraction (w_i=N_iA_i / M) of the ith element, N_i is the number of atoms of ith element and A_i is the atomic weight of ith element. The modified equation inserted z*, Z* and I*was described as follows,

$$\frac{1}{\rho}\frac{dE}{dx} = 4\pi r_0^2 (z^*)^2 \frac{mc^2}{\beta^2}\frac{N_0}{A}(Z^*)\left[\ln\left(\frac{2mc^2}{(I^*)}\beta^2\gamma^2\right) - \beta^2\right] \quad (2)$$

where the z* and Z* are the effective charge of the proton and target respectively. I* is the effective mean excitation energy of the targets. These quantities are given as,

$$z^* = 1 - \exp(-2200\beta^{1,78}) \quad [13]$$

$$Z^{*} = Z\frac{b^2\left(3x+b\right)}{\left(x+b\right)^3} \quad [14]$$

$$I^{*} = 213,6\gamma Z C_0^{-3/2} exp(\alpha) \quad [15]$$

bisnormalization constant and, is chosen as

$$b = \left(\frac{8}{\pi}\right)^{2/3} \quad [16]$$

$$x = -2\left(\frac{b}{3}\right) + \frac{\left(\frac{b}{3}\right)^3}{\left[\frac{a}{2}+\left(\frac{b}{3}\right)^3+\sqrt{\left(a/2\right)^2+a\left(b/3\right)^3}\right]^{1/3}} + \left[\frac{a}{2}+\left(\frac{b}{3}\right)^3+\sqrt{\left(a/2\right)^2+a\left(b/3\right)^3}\right]^{1/3}$$

Here, $a = \frac{b^2}{0,60647}\frac{V_0^2}{V^2}Z^{4/3}$ [17]

$V_0 = 2.42x10^6\ m/s$; $\beta = \frac{V}{c}$ and

C_0=0.6064741718, and

$$\alpha = \frac{Z}{2Z^*}\left[x^2\left(x+3b\right)\ln x + x\left(x+b\right)b + x\left(\ln 6-2\right)3b^2 + b^3\left(\ln 6-10/3\right) + \left(3x+b\right)b^2\ln\frac{b^2}{\left(x+b\right)^4} - \left(x+b\right)^3\ln\left(x+b\right)\right]/\left(x+b\right)^3$$

γ was evaluated by using $I_2 = 10,4621\,\gamma\,Z_2$ [15,17].

3. RESULTS AND DISCUSSION

3.1 WATER

Water is one of the most important target materials for medical physics. So in first, the A_{ave}, Z_{ave} and I values for water were calculated using the definition given in Methodology as 14.3216, 6.6011 and 74.60 eV respectively.

If the results of stopping power reported by various researchers are analyzed it can be seen that there is not an agreement between them at low proton energies (about < 100MeV). In this study, the SPs of water for protons were calculated using Equation (1) and Equation (2) in the 0.001–250MeV energy range. The SP graphs plotted for water show that there was good agreement between the results at high proton energy (> 0.035MeV) (Fig. 1). Equation 1 has been used extensively for SP but there is a scarcity of data at low energy levels. While Equation (1) cannot calculate the SPs of water below ~35keV but it is possible from Equation (2).

The results found in this study were also compared with the results by Singh et al. [6], Akerman et al. [4] and NIST [12]. Singh et al. [6] present a simple method for the calculation of mass stopping power of protons from 0.5 MeV to 200MeV energy range for some biological human body substance and water. A fairly good agreement was found between the results from Equation 2 used in this study and their results. Of course, one of the important results was that the SP values can be found at low energy (0.001 MeV – 0.030 MeV) using Equation 2 (Fig. 1). Also, the study by Akerman et al. [4] has not reported the SP results in the low proton energies (< 0.01 MeV).

The SPs of water calculated by using Equation (1) and (2) were plotted as a function of proton energy (in the 70–250 MeV energy range) (Fig. 2). The following equation was obtained for Equation (2):

$$(1/\rho)S = 191.09E^{-0,706}$$

That is, the SP varies with the $1/E^{0.706}$.

The SPs values as a function of proton energy using the data given by Singh et al. [6] fit the following Equation (Fig. 3):

$$(1/\rho)S = 292.8E^{-0,798}$$

3.2 LUNG

For lung the A_{ave} and Z_{eff} values were calculated as 14.20 u and 6.02 respectively and I = 75.30 eV was taken from NIST programme.

Fig. 4 shows the SP results of lung for protons. It can be seen that the SP values using Equation 2 were found to be lower than that of Equation (1). There is a good agreement between the results found by using Equations (1) and (2) at high proton energies (> 0.3 MeV). However Equation (1) cannot calculate the SP values at < 0.035 MeV, the Equation (2) can.

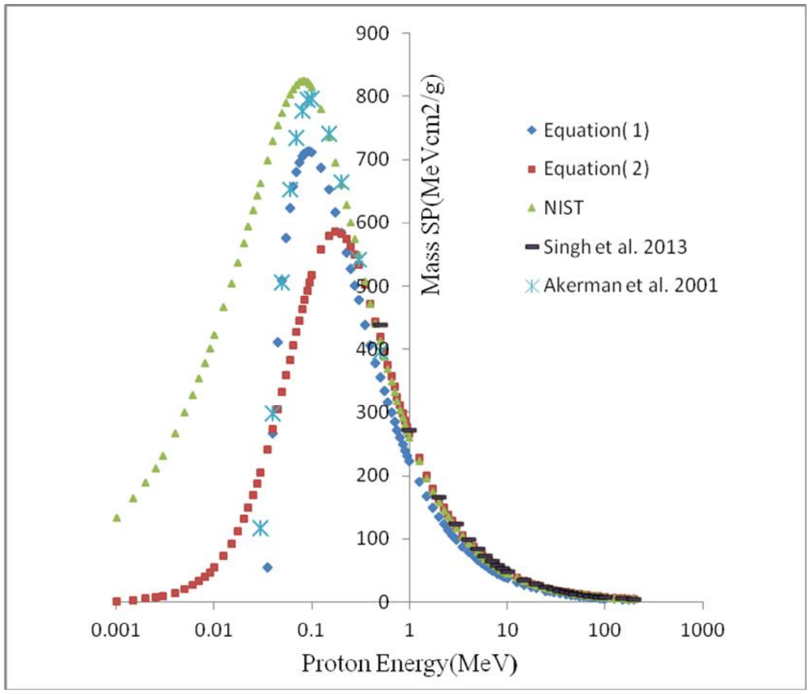

Fig. 1. The mass stopping power versus proton energy in water
After E>0,5 MeV, Attention to the overlap of the NIST and Equation 2 data.
At lower energies from 0,05 MeV, only NIST data and Equation 2 expression gives results

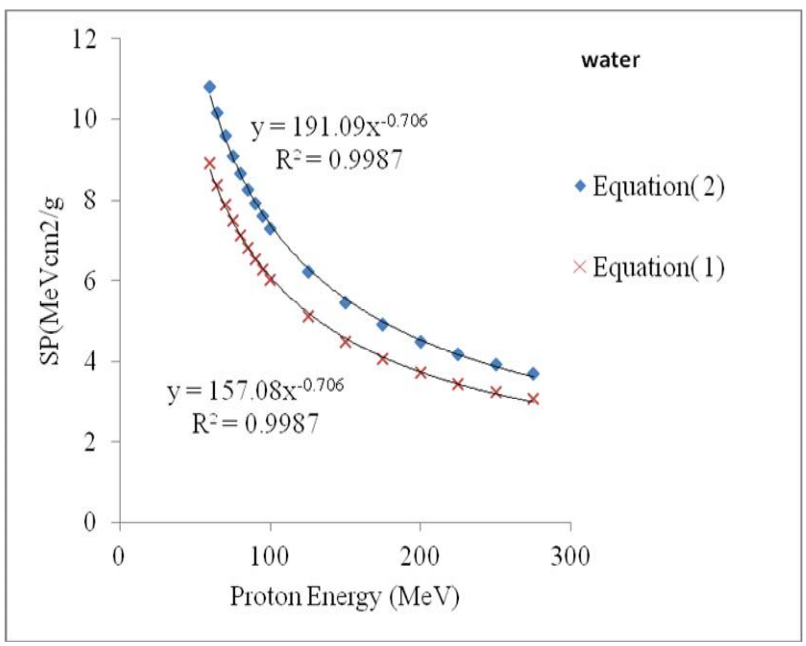

Fig. 2. The mass stopping power versus proton energy above 70 MeV

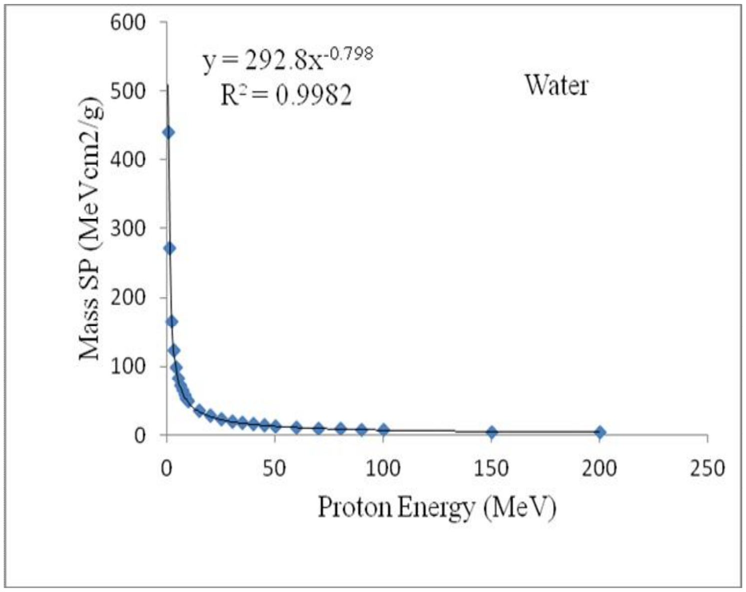

Fig. 3. The data given by Singh et al. [6]

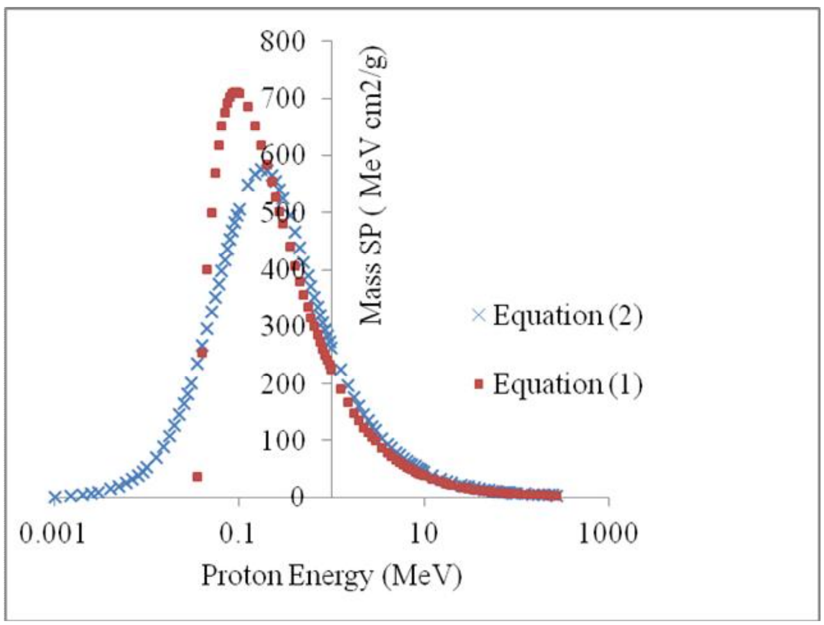

Fig. 4. The mass stopping power versus proton energy in Lung

This graphic, when considered together with the above graphic for water, gives similar results as expected.

In the 70–250 MeV energy range when the SPs of lung for protons as a function of energy was plotted (Fig. 5), the following equation was obtained as,

$$(1/\rho)S = 197.2E^{-0,715}$$

That is, the SP varies with the $1/E^{0.715}$. This is the same as the value found for water. The SP value versus proton energy in tissue by using the data given by Singh et al. [6] was plotted in Fig. 6. It can be concluded that the results are agreement with that of lung.

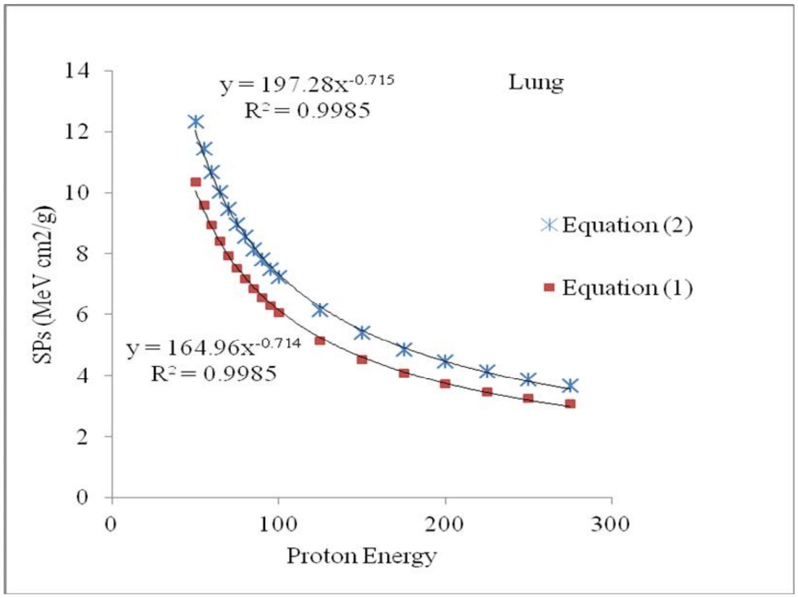

Fig. 5. The mass stopping power versus proton energy in Lung above 70 MeV

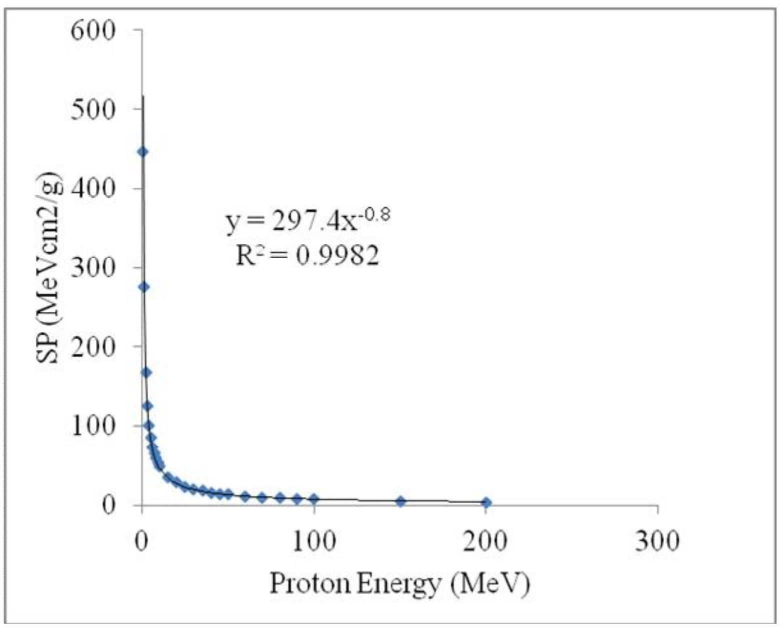

Fig. 6. The data given by Singh et al. [6] for tissue

4. CONCLUSION

The SP values of materials for radiation are needed in many areas especially in the field of medicine. In radiotherapy the calculation of SP should be accurately made so that the correct dose is given to the patient. Given the Bragg peak for protons it is important that the correct energy and SP values are calculated.

As can be seen from the figures, the maximum SP values for water and lung are nearly identical. The SP results calculated using Equation (2) should be considered in the absorbed dose calculations in the medical field, especially at low proton energy ranges.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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