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Ranges of Electrons for Human Body Substances

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Abstract

We present a relation for continuous slowing down approximation (CSDA) ranges for electrons of substances such as bones, muscles, fat and water in terms of energy from 30 keV to 1000 keV and have been fitted by three parameters. These parameters depend upon the total energy, density and effective atomic number of the absorber. It has been found that this method gives better agreement with the available experimental data.

Keywords: CSDA ranges, bones, muscles, fat.

Introduction

Cancer (malignant disease) is the second cause of death after cardiovascular system diseases[1]. Every year 7.6 million people die worldwide because of cancer and by the W.H.O. report number of cancers is expected to increase by 50 percent[2]. Radiotherapy is one of the main cancer treatment methods together with chemotherapy and surgery. The clinical radiation therapy works with high-ionising radiation and aims to destroy tumour cells without damaging healthy cells or tissue. Naturally this therapy can damage healthy tissue. To preserve this unwanted damage on healthy tissue, a high accuracy of dose delivery is needed.

Clinical dosimetry and treatment planning are aimed to reduce the risk for the patient to a minimum and to get a high accuracy in preparation for the therapy. The total inaccuracy for radiotherapy is expected to be 7.3%[1] but the recommended overall inaccuracy in tumour dose delivery is ±5% *(ICRU)*. Therefore clinical dosimetry and treatment planning care for the limitation of this uncertainty with precise work. The accurate determination of absorbed dose is crucial to the success of radiation therapy because there are relatively steep sigmoidal dose-response curves for both tumour control and normal-tissue damage[3]. To measure absorbed dose-to-water in clinical electron beams, current dosimetry protocols (IAEA TRS-398) recommend plane-parallel or thimble ionization chambers. Plane-parallel ionisation chambers are recommended in all dosimetry protocols for use in electron beams, especially at low energies where cylindrical ionizations chambers can need fluence perturbation correction of 5% or more. In comparison to cylindrical chambers they have better depth resolution and, for a well guarded chamber, the lack of fluence perturbation effect for low-energy electron beams[4]. For well-guarded parallel-plate chambers it is assumed, that $Q\ p$ (perturbation correction factor) is unity for all electron energies[5].

Stopping media are characterized by their stopping power (SP), the inelastic mean free path (IMFP), the continuous slowing down approximation-range (CSDA-range) (R) and the energy straggling parameter. These physical quantities are important for application such as radiation biology, electron beam lithography, and chemical analyses of surface regions of a solid and in calculation of radiation dose in radiotherapy. The principal characteristic of ionizing radiation is that it has sufficient energy to break any chemical bond and to cause ionization in all materials. Whenever the energy of a particle exceeds the ionization potential of a molecule, a collision with the molecule might lead to ionization. The knowledge of the mean free path and CSDA-range of electrons is important, especially at low energies; in line with this, number of authors has made associated studies of biological compounds[5-10].

The exact knowledge of range of electrons and positrons in several media is of practical interest for many applications in nuclear physics, radiation protection and semiconductor detector fabrication. The main effects produced by the passage of electrons through matter are: i. Non radiative collision process and ii. Radiative collision process.

Therefore the total energy loss during the passage of electron will be the sum of these two losses. In determining CSDA ranges fluctuations in energy losses are neglected and electrons are assumed to loss energy continuously along their track with a mean energy loss per unit path length given by the stopping power. In this paper, we propose a method to obtain the CSDA ranges for electrons at energy (30–1000 keV). Results obtained by this procedure are compared with the available data, derived from the Born–Bethe approximation.

Methodology

For electrons of low energies, the inelastic interaction characteristics, the stopping power, the mean free path and the

CSDA-range cannot be obtained directly from experiments or from Bethe's SP theory, the latter giving accurate SPs at energies larger than 10 keV. At lower energies, the theory is, in general, invalid. For low-energy electrons, a method has been used to estimate the mentioned characteristics, based on the use of the complex dielectric function ε (q, ω), ħq and ħω being the momentum and energy transfer, respectively. As mentioned by Akkerman and Akkerman[8] restrictions in these theories prevent their use for a wide range of non-organic and organic materials[8]. To calculate the mean free path and the CSDA-range, another method is to make use of the inelastic differential cross section (IDCS) suggested by[11] with the generalized oscillator strength (GOS). For this, the GOS has to be calculated from matrix elements that involve numerical integration of atomic wave functions. This calculation is too complicated.

During the last few years, a number of optical data models have been proposed to compute the inelastic scattering of electrons, avoiding the calculation of the GOS from matrix elements. In recent years, Verne et al[10] have calculated the IMFP and the CSDA-range in DNA (thymine–adenine or cytosine–guanine) for low and intermediate energy ranges. These calculations were also studied for liquid water, guanine and organic molecules[5,10].

Nelms[12] has calculated CSDA ranges using collisions loss expressions. Using collision loss expressions the following equation was solved numerically by Simpson's 1/3rd rule.

$$R_{csda} = \int_0^E \left[\left| -\left(\frac{1}{\gamma}\right)\frac{dE}{dx} \right|^{\pm} \right]^{-1} dE \qquad (1)$$

Rohrlich et al[13] have tabulated CSDA ranges of electrons and positrons for several media at different energies. Tung et al[14] calculated electron ranges using electron gas model. Berger and Seltzer[15] published extensive tables containing CSDA ranges from 10 KeV to1000MeV. Gupta et al[16] also presented an empirical formula for CSDA range but it is not applicable in low energy region. According to him an empirical equation has been derived for the csda ranges of monoenergetic electrons in the energy region 0.2-10 MeV by using the empirical relation for total stopping power. The corresponding equation for csda ranges is

$$R(T_O) = \frac{mc^2}{sz + 1.3230}\left[\frac{\gamma^{az+b-1}}{az+b-1} + \frac{1}{\gamma}\right]_{1.1957}^{\gamma} \qquad (2)$$

In general the linear polynomial fitting is a simple method for searching out any empirical relation. However, the ration for continuous slowing down approximation ranges should be simple enough to get easily evaluation. One can infer from equations (1 and 2) that the CSDA ranges of electrons depend not only upon the incident kinetic energy of these particles, but also on the nature of the material through which they traverse. Tan et al[17] have proposed a simple empirical relation for CSDA ranges for electrons with energies between 25 to 200 keV by the following relation,

$$R_{csda}^{-} = 190\times10^{-6}\left(\frac{A}{Z}\right)^{2.5} E^{1.6} \quad g/cm^2 \qquad (3)$$

where A, Z and E are atomic weight, atomic number and energy respectively. This relation is valid for atomic numbers 30 to 92 with error comprising 2 to 10%. The drawback of the relation is that it is valid for very small energy range and does not give any information for lower atomic number. We have plotted graphs between available CSDA ranges values vs $\left(\frac{D}{Z}\right)E^{1.5}$ and data are fitting with linear polynomial equation. Which are presented in following figures 1 to 4. Using this idea we have been able to find analytically convenient and simple empirical relation for CSDA ranges of electrons in the energy regions 30 to 1000 keV by the following relation,

$$R = A + B\,X \qquad (4)$$

where A and B are constants. The value of $X = \left(\frac{D}{Z}\right)E^{1.5}$ depends on density (D), effective atomic number (Z) and energy (E). The values of constants, density and effective atomic number are presented in table 1.

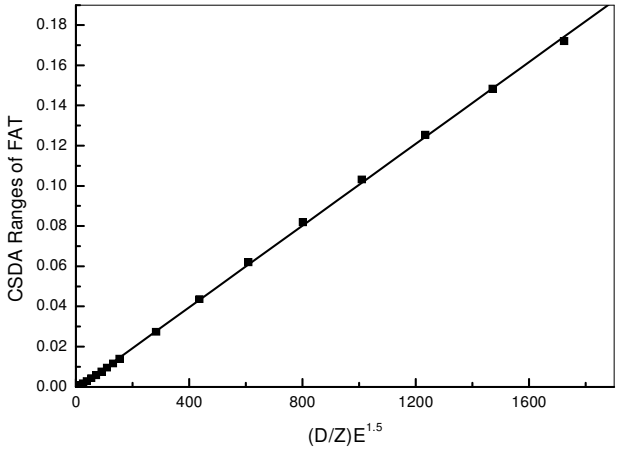

Figure-1
In the plot of CSDA ranges (for electrons) and (D/Z)E$^{1.5}$ of Fat lie on a linear regression line. In this figure all CSDA ranges values are taken from Ref. [15]

Results and discussion

The equation (4) has been used to calculate CSDA ranges of electrons in different elements for various energies in their prescribed energy regions[15]. The calculated values for electrons thus obtained were compared with the standard values due to Berger and Seltzer[15]. In order to compare evaluated values of CSDA ranges of positrons, following method has been adopted. The evaluated values of CSDA ranges have been presented in the tables 2 and 3. We note that the values of CSDA ranges evaluated by proposed relation are in close agreement with the reported data as compared to the values reported by previous researchers so far.

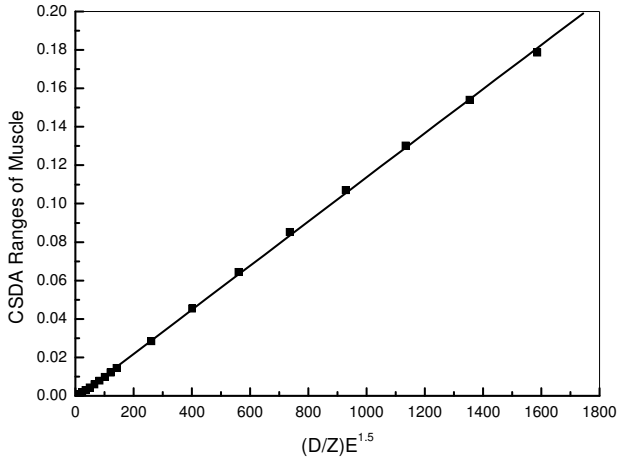

Figure-2
In the plot of CSDA ranges (for electrons) and $(D/Z)E^{1.5}$ of Muscle lie on a linear regression line. In this figure all CSDA ranges values are taken from Ref. [15].

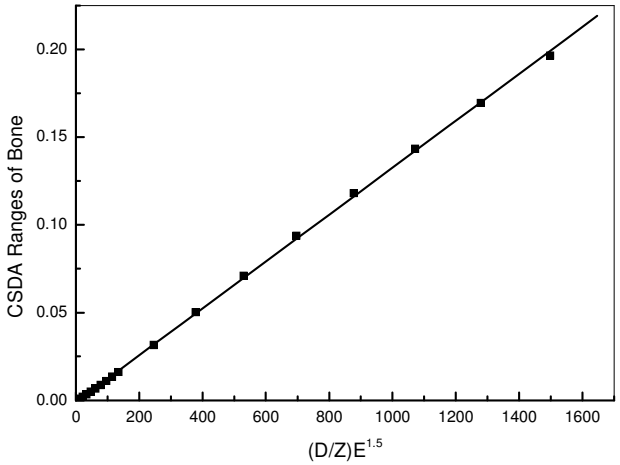

Figure-3
In the plot of CSDA ranges (for electrons) and $(D/Z)E^{1.5}$ of Bone lie on a linear regression line. In this figure all CSDA ranges values are taken from Ref. [15].

Table-1
Values of constants for electrons

Substances	A	B	D	Z	Regression coefficients
Fat	$-0.00112 \pm 3.16924 \times 10^{-4}$	$1.01683 \times 10^{-4} \pm 4.34596 \times 10^{-7}$	0.91	5.9	0.99986
Muscle	$-0.0011 \pm 3.39566 \times 10^{-4}$	$1.14739 \times 10^{-4} \pm 5.06158 \times 10^{-7}$	1.05	7.4	0.99985
Bone	$-0.00108 \pm 3.84271 \times 10^{-4}$	$1.33596 \times 10^{-4} \pm 6.06267 \times 10^{-7}$	1.85	13.8	0.99985
Water	$-0.00109 \pm 3.36822 \times 10^{-4}$	$1.19184 \times 10^{-4} \pm 5.2717 \times 10^{-7}$	1	7.4	0.99985

Table-2
Values of CSDA ranges for electrons of Fat and Muscle

E	X Value of Fat	Fat [15]	Fat this work	% error	X Value of Muscle	Muscle [15]	Muscle this work	% error
30	25.34377	0.00169	0.001457	13.8	23.31522	0.00178	0.001575	11.51
40	39.01929	0.00282	0.002848	1.0	35.89612	0.00295	0.003019	2.33
50	54.53112	0.00418	0.004425	5.9	50.16636	0.00437	0.004656	6.55
60	71.68301	0.00575	0.006169	7.3	65.94539	0.00601	0.006467	7.60
70	90.33092	0.00751	0.008065	7.4	83.10069	0.00785	0.008435	7.45
80	110.3632	0.00946	0.010102	6.8	101.5296	0.00988	0.010549	6.78
90	131.6901	0.01159	0.012271	5.9	121.1494	0.01209	0.012801	5.88
100	154.2373	0.01387	0.014563	5.0	141.8919	0.01447	0.015181	4.91
150	283.352	0.02734	0.027692	1.3	260.6721	0.02848	0.028809	1.16
200	436.2489	0.04359	0.043239	0.8	401.3309	0.04537	0.044948	0.93
250	609.6764	0.06194	0.060874	1.7	560.8769	0.06442	0.063254	1.81
300	801.4405	0.0819	0.080373	1.9	737.2919	0.08513	0.083496	1.92
350	1009.93	0.1031	0.101573	1.5	929.094	0.1071	0.105503	1.49
400	1233.898	0.1253	0.124346	0.8	1135.135	0.1302	0.129144	0.81
450	1472.34	0.1483	0.148592	0.2	1354.492	0.154	0.154313	0.20
500	1724.425	0.172	0.174225	1.3	1586.4	0.1785	0.180922	1.36
1000	4877.411	0.4275	0.49483	15.7	4487.016	0.4418	0.513736	16.28

Table-3
Values of CSDA ranges for electrons of Bone and Water

E	X Value of Bone	Bone [15]	Bone this work	% error	X Value of water	Water [15]	Water this work	% error
30	22.02797	0.002	0.001863	6.86	22.20497	0.00176	0.001556	11.56
40	33.91428	0.00331	0.003451	4.25	34.18679	0.00292	0.002985	2.21
50	47.39665	0.00488	0.005252	7.62	47.77749	0.00432	0.004604	6.58
60	62.30451	0.0067	0.007244	8.11	62.80514	0.00594	0.006395	7.67
70	78.51266	0.00875	0.009409	7.53	79.14352	0.00776	0.008343	7.51
80	95.92408	0.011	0.011735	6.68	96.69483	0.00977	0.010434	6.80
90	114.4607	0.01345	0.014211	5.66	115.3804	0.01196	0.012661	5.87
100	134.058	0.01607	0.01683	4.73	135.1351	0.01431	0.015016	4.93
150	246.2802	0.03155	0.031822	0.86	248.2591	0.02817	0.028499	1.17
200	379.1732	0.05015	0.049576	1.14	382.2199	0.04487	0.044464	0.90
250	529.9107	0.07111	0.069714	1.96	534.1685	0.06372	0.062574	1.80
300	696.5857	0.09386	0.091981	2.00	702.1828	0.08421	0.082599	1.91
350	877.7982	0.118	0.11619	1.53	884.8514	0.106	0.10437	1.54
400	1072.464	0.1433	0.142197	0.77	1081.081	0.1288	0.127758	0.81
450	1279.71	0.1695	0.169884	0.23	1289.992	0.1523	0.152656	0.23
500	1498.814	0.1964	0.199156	1.40	1510.857	0.1766	0.17898	1.35
1000	4239.285	0.4857	0.565272	16.38	4273.348	0.4367	0.508225	16.38

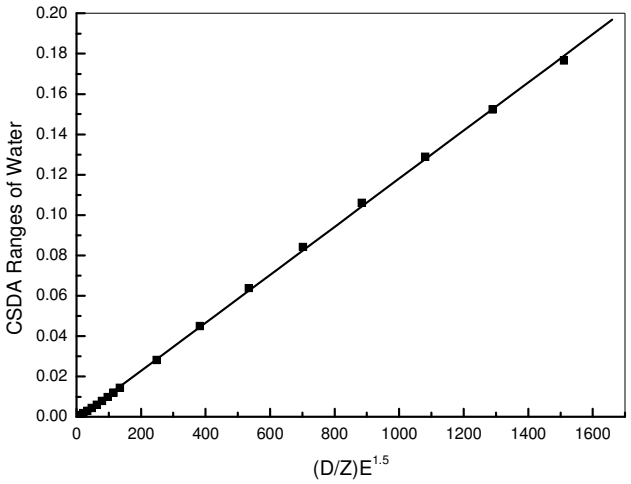

Figure-4
In the plot of CSDA ranges (for electrons) and $(D/Z)E^{1.5}$ of Water lie on a linear regression line. In this figure all CSDA ranges values are taken from Ref. [15]

Conclusion

From the above results obtained using the proposed empirical relation (4), it is quite obvious that the CSDA ranges of materials can be expressed in terms of energy, density and effective atomic number of the material. We come to the conclusion that energy of the material is key parameter for the calculation of CSDA ranges. It is also noteworthy that proposed empirical relation is simpler, widely applicable and values obtained are in better agreement with the theoretical data as compared to the empirical relations proposed by previous researchers[16,17,18].

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