ORIGINAL PAPER

DETERMINATION OF RELATIVISTIC ELECTRON INTERACTION PARAMETERS OF HUMAN TISSUES UNDER DIFFERENT PATHO PHYSICAL CONDITIONS

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Abstract. *We determined experimentally the electron interaction parameters like stopping cross section, mass stopping power and effective atomic number of normal and cancerous - solid and fluid tissues by taking their composition from ICRU-44. The mass stopping power is determined using ^{137}Cs and ^{207}Bi internal conversion electrons and Si (Li) detector coupled to an 8K multichannel analyzer as the spectrometer to record the incident and transmitted spectra. The effective atomic numbers of these tissue samples for the relativistic electron interactions are determined by substituting the measured mass stopping power in the semi empirical relation between the mass stopping power and atomic number obtained by plotting the mass stopping power of organic elements against their atomic number. Our experimental results are compared with the theoretical values computed using direct method and found to agree within ±3%. The effective atomic number of the tissues for both electron and photon interactions are observed to be more under cancerous conditions than the normal, paving a way for unambiguous diagnosis of cancer.*

Keywords: *Relativistic electrons, Interaction Parameters, Mass Stopping Power, Effective atomic number, Effective atomic number for electron interaction.*

1. INTRODUCTION

Physical effect of any radiation is the ionization of the matter to release electrons. It is these electrons which interacts with the matter to damage it chemical nature and hence its biological functions. Thus it is necessary to study the electron interaction with matter to understand the radiobiological damages produced in radiotherapy and nuclear medicine.

Hence the measurement of electron interaction parameters (EIP) like Mass Stopping Power (MSP), Energy Loss Straggling, Stopping Cross Section (SCS), Effective atomic Number (Z_{eff}) and Effective electron density became more essential for the medical applications of radiation.

The base of radiotherapy namely radiation dosimeter totally depends on the accurate value of stopping power of electrons in matter. SCS has several applications in radiobiology, medical physics and electron transport modelling.

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Effective atomic number, Z_{eff} is widely used in radiation studies, particularly to characterize the interaction processes in composite materials to opt the biological substitutes for dosimetery purposes. Effective electron density, N_e is the number of electrons per gram and is used in radio diagnosis to decide the contrast and in nuclear medicine to estimate the emitted radiation. The energy absorption in any composite material can be obtained using well established formula, if their interaction parameters namely Z_{eff} and N_e are known.

As mentioned in our earlier paper [1], many authors have determined photon interaction parameters for various organic and inorganic materials. Several investigators have studied the charged particle interaction parameters in many organic materials using the MSP from NIST-ESTAR database [2]. The MSP and ELS of protons in biological absorbers have been studied and observed that ELS in onion membrane absorbers and filter membrane absorbers are different from simulation results based on SRIM code [3]. Taylor et al. [4,5] have calculated Z_{eff} for radiative, collisional and total electron interaction processes in dosimetric materials. Parthasarathy et al. [6], Kurudirek et al. [7] and Guru Prasad et al. [8] have computed Z_{eff} of several medically significant materials for photon, electron proton alpha particles.

However, the experimental study of EIP around the minimum ionization point in biological and non-biological absorbers is very rare. There is only theoretical estimation of EIP in biological and non-biological absorbers for high energy electrons. In our earlier papers [1] we have derived a semi empirical relation between MSP and Z using which we could experimentally determine Z_{eff} of any organic materials accurately. In the present research work we wish to investigate the difference in EIP of human tissue under different patho physical conditions. Hence we have experimentally determined the EIP at 594 keV and 911 keV in normal and cancerous tissues using the above semi empirical relation [1]. To the best of our knowledge; this is first attempt to understand experimentally the interaction of relativistic electrons in tissue of various physical state and pathological conditions.

2. MATERIALS AND METHODS

2.1. MATERIALS

Interaction parameters are the parameters providing essential information about the interactions. The five important interaction parameters of electron interaction are:

1. Mass Stopping Power (MSP) which can be determined accurately by measuring the absorber thickness, the incident and transmitted spectra. As MSP is easily measurable, it is often used to derive all other interaction parameters.
2. Energy Loss Straggling (ELS) is the fluctuation of the energy loss around its mean value. It can be determined from the FWHM of the incident and transmitted spectra. As it demands high degree of target thickness uniformity and accurate spectral fitting it is used mainly for very large scale modeling programs to create analytic functions of ion implantation distributions.
3. Stopping Cross Section, σ is the stopping power per atomic density of the sample and is derived from MSP as below:

$$\mathrm{SCS} = \frac{\mathrm{SP}}{\mathrm{atoms/cc}} = \frac{\mathrm{MSP}}{\mathrm{N}} \tag{1}$$

where

$$\mathrm{N} = \text{Number of atoms per gram} = N_A / A_{eff} \quad (2)$$

If the sample contains n_i number of i^{th} element of atomic weight A_i then:

$$\text{Effective atomic weight of the sample} = A_{eff} = \sum_i ni\ Ai\ / \sum_i ni \quad (3)$$

4. Effective atomic number, Z_{eff} is a weighted arithmetic mean of the atomic number of the constituent atoms with the weighing factor accounting for the type of radiation, material and interaction. Hence it is widely used in radiation studies, particularly to characterize the interaction processes in composite materials. It can be determined accurately from the knowledge of MSP of the sample and MSP-Z relation of pure elements in the energy range of interest. It can also be determined with fairly good accuracy by using the following formula of direct method [9].

$$Z_{eff,ei} = \frac{\sum_i Fi\ Ai(MSP)i}{\sum_i Fi\ Ai(MSP)i/Zi} \quad (4)$$

where $(MSP)_i$, A_i and F_i are the MSP, mass number and molar fraction of the element "i" in the mixture or compound.

5. Effective electron density, N_e is the number of electrons per gram and is derived from effective atomic number as below.

$$N_e = \mathrm{N}\ Z_{eff} \quad (5)$$

In our earlier paper [1] we have established that the variation of MSP of organic elements, against their atomic number can be represented by a first order exponential decay equation as

$$MSP\ (MeV - cm^2/gm) = A_0 + A_1 e^{-BZ} \quad (6)$$

where A_0,A_1 and B are the energy dependent fitting parameters as given in Table 1.

Table 1. Fit Parameters for 594 keV and 911 keV internal conversion electrons.

Einc (keV)	**A_0 (MeV-cm^2/gm)**	**A_1 (MeV-cm^2/gm)**	**B**
594	1.7457	36.8402	2.7714
911	1.6730	37.0786	2.8383

The curve fitting process for 594keV and 911keV electron interactions are as shown in Fig. 1. The correctness of the formula is verified by calculating and comparing the MSP of H, C, N and O with the NIST-ESTAR [2] values as in Table 2.

Table 2. *MSP* determined using NIST and equation (1) for Organic elements.

Elements		H	C	N	O
Atomic Number [Z]		1	6	7	8
Atomic Weight [A]		1.010	12.010	14.010	16.000
594 keV	NIST value	4.0510	1.7320	1.7640	1.7370
	Fitted Value	4.0510	1.7457	1.7457	1.7457
	PD	0.0012	-0.7911	1.0374	-0.5009
911keV	NIST value	3.8430	1.6380	1.6890	1.6650
	Fitted Value	3.8430	1.6730	1.6730	1.6730
	PD	-0.0007	-2.1368	0.9473	-0.4805

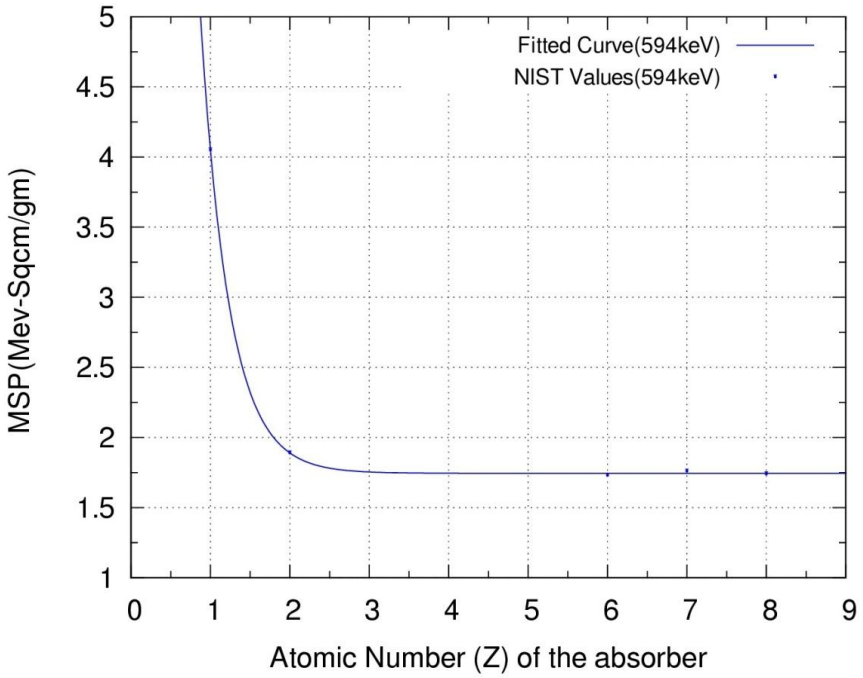


Figure 1. a) Exponential variation of MSP with Z for 594 keV EI.

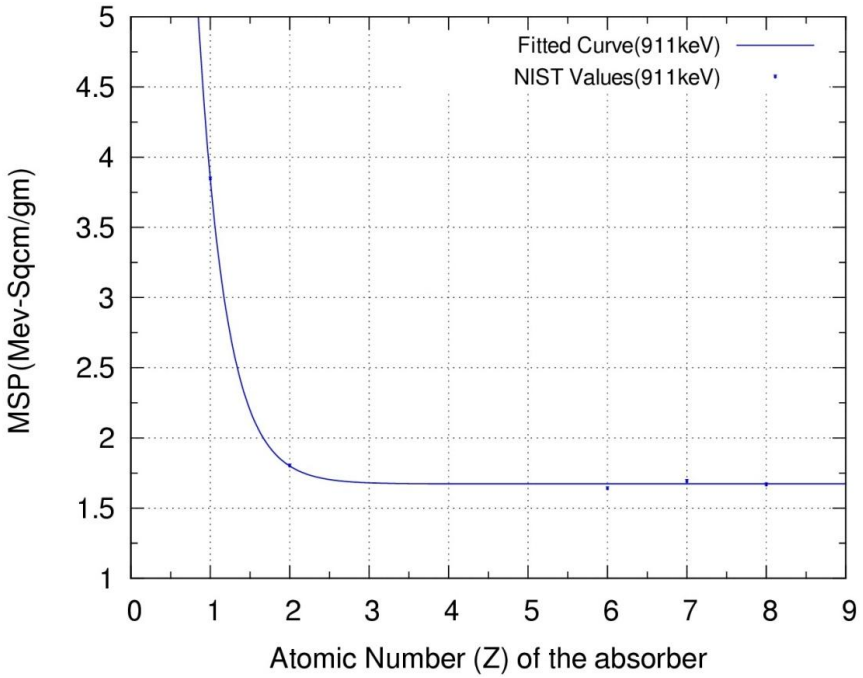


Figure 1. b) Exponential variation of MSP with Z for 611 keV EI.

2.2. METHODS

Experimental arrangement

The experimental arrangement to measure the MSP of the tissues of various physical and pathological conditions are as detailed in our earlier paper [10]. In nutshell, Fig. 2 is the schematic representation of the experimental setup with two collimators C_1 and C2 between which the sample is to be placed.

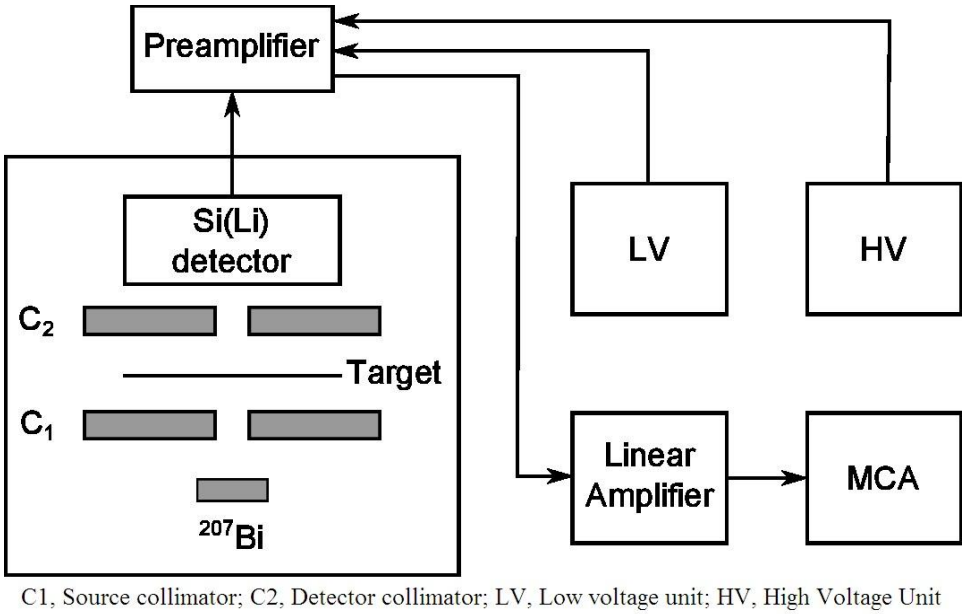


Figure 2. Experimental arrangement.

The selection-grade NE Si(Li) detector used in this experiment, has 0.2 cm depletion area and 15 cm^2 active area. Detector output is connected to an 8K MCA through a charge sensitive ORTEC preamplifier of charge sensitivity 15 mV/MeV (Si eq.) and a delay line amplifier. The entire assembly is placed in a light tight box as in Fig. 2. The absorbers are the tissue samples digested by a mixture of H_2O_2 and HNO_3 in the ratio 1:2 by volume. After correcting for the attenuation in the sample holder the 942 keV and 614 keV internal conversion electrons of ^{207}Bi and ^{137}Cs become 911 keV and 594 keV respectively. The inner area of the sample holder measured using travelling microscope is taken as the area of the sample. The mass of the sample is found using and a sensitive balance.

The ^{207}Bi internal conversion source used in this experiment is electroplated on a platinum foil and encapsulated in stainless steel of 1.52cm outer diameter with 18.8 mg/cm^2 thick beryllium window to prevent the source spilling and contamination. It emits 481.699, 555.399, 975.699 and 1049.399 keV IC electrons. After correcting for the attenuation by the beryllium window of the source and the air column between the source and detector, their effective energies will be 444, 519, 942 & 1016 keV respectively.

We have also used ^{137}Cs radioactive source which emits 624.2keV K shell internal conversion electrons. The source is covered with thin Mylar foil of thickness 1.2 mg/cm^2 to avoid the source spilling and contamination. After correcting for this coverings and air attenuation between the source and the detector, the effective energy of the internal conversion electrons becomes 614 keV.

Experimental Procedure

After checking for the stability of the spectrum over time, the ^{207}Bi spectrum with four peaks due to 444, 519, 942 and 1016 keV IC electrons is acquired without any material between the source and detector. All these 4 peaks are fitted to exponentially modified Gaussian to get the channel number corresponding to Most Probable Energy, MPE of these peaks as in figure-3. A plot of these MPE against the corresponding channel numbers, used as the calibration graph of the spectrometer is shown in as inset in Fig. 3. The calibration factor of the spectrometer is found to be 0.29675±0.0003 keV/channel.

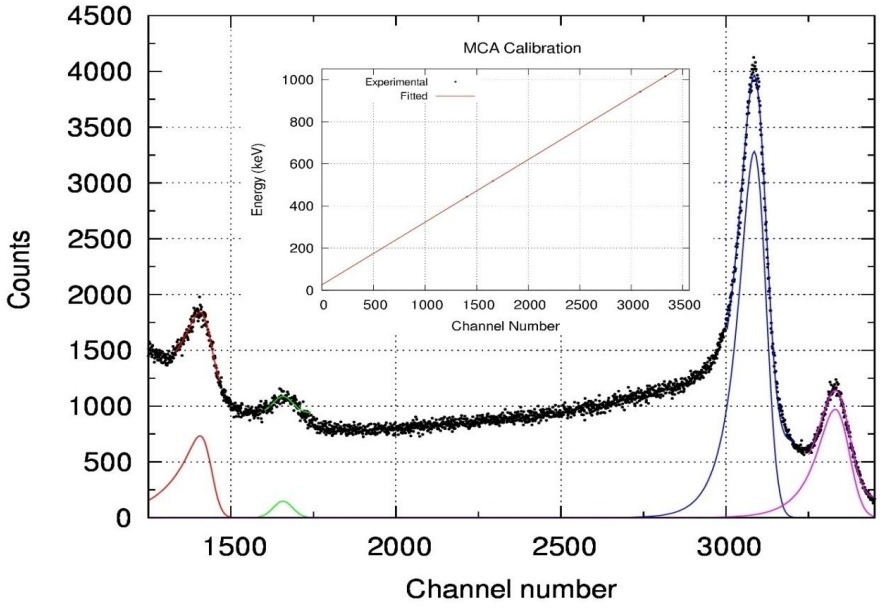
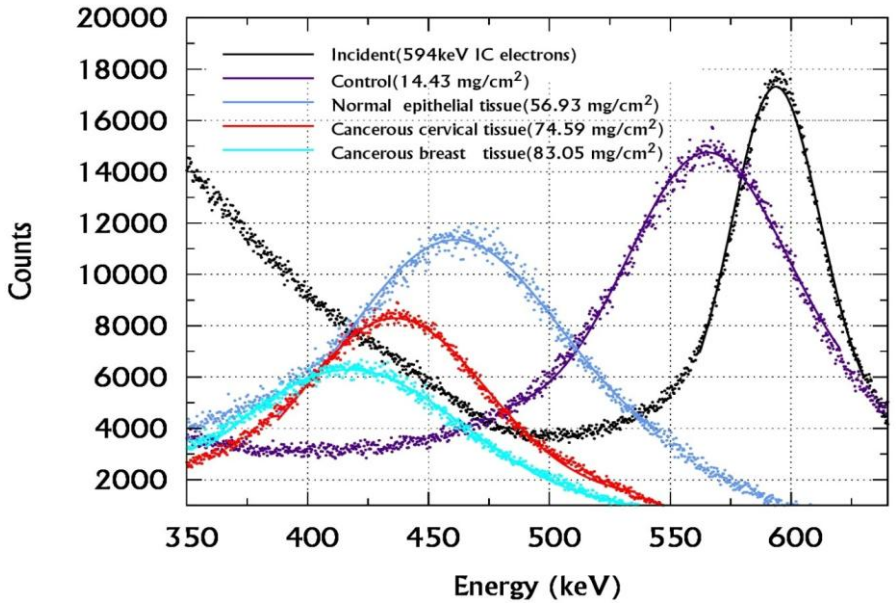


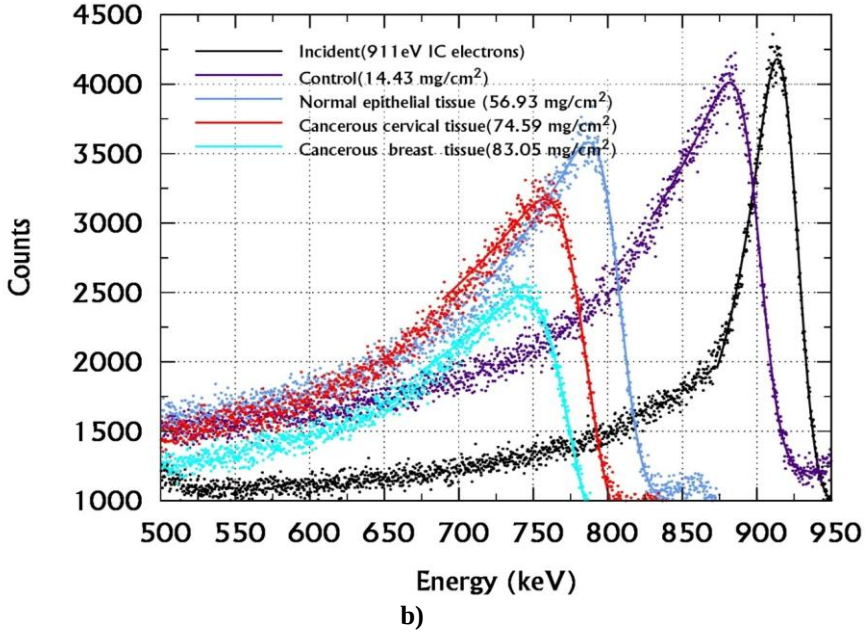
Figure 3. Incident Bi-207 spectrum with MCA calibration graph.

The incident and transmitted spectra of ^{137}Cs are acquired without and with the sample between the collimator C_1 and C_2. From these spectra MPE and hence the energy loss are obtained and used to evaluate their MSP in the sample. Thus evaluated MSP are substituted in the empirical relation (6) to determine the Z_{eff} of normal epithelial tissue, cancerous cervix tissue, cancerous breast tissue, normal blood, chronic lymphatic leukaemia (CLL) blood and acute lymphatic leukaemia (ALL) blood for 594 keV electron interactions. The SCS is computed from MSP using the equations (1), (2) & (3). Thus determined EIP are as presented in Table 3 for the electron beam energy of 594 keV.

This study is repeated with ^{207}Bi source to obtain the EIP for the 911 keV electrons in the normal and cancerous tissue samples and presented in Table 4. Fig. 4 presents the curve fitted spectra of 594 keV and 911 keV electrons transmitted through various solid tissues. Fig. 5 presents the same for fluid tissues.

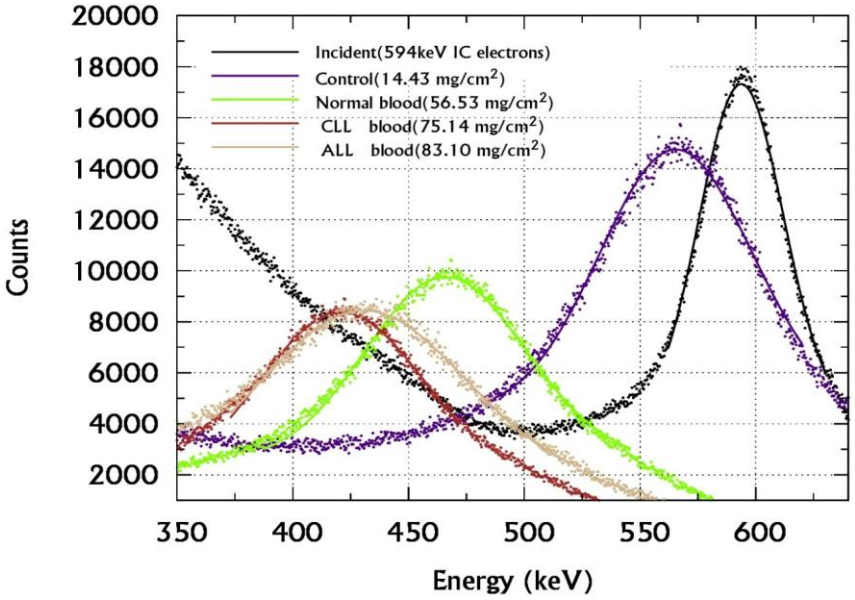


a)

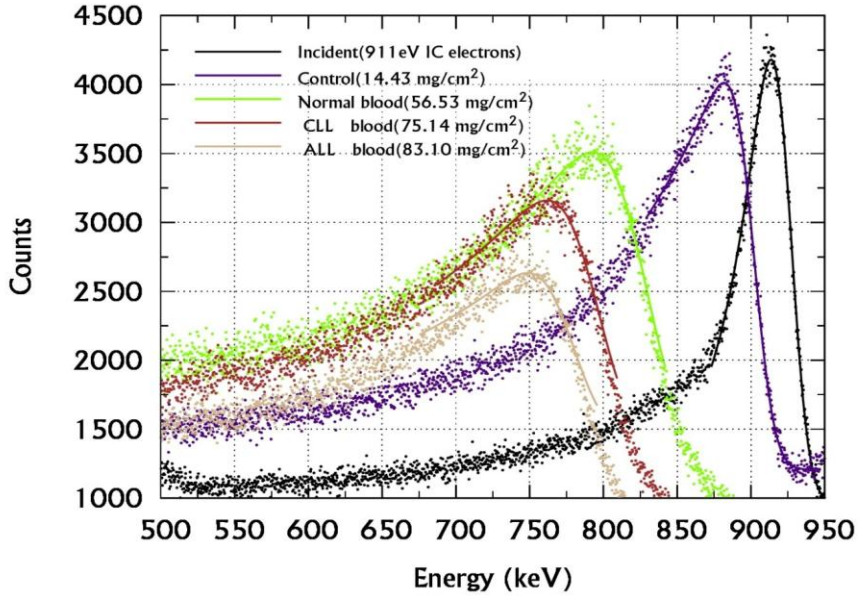


b)

Figure 4. a) 594 keV spectra transmitted by solid tissues; b) 911 keV spectra transmitted by solid tissues.



a)



b)

Figure 5. a) 594 keV spectra transmitted by fluid tissues; b) 911 keV spectra transmitted by fluid tissues.

3. RESULTS AND DISCUSSION

3.1. RESULTS

In Tables 3 and 4, we present the experimentally measured EIP of solid and fluid tissues under different pathological conditions for 594 keV and 911 keV electron interactions. The A_{eff} is got by taking the Z_{eff}/A_{eff} as 0.5. The Z_{eff} is observed to be more for cancer tissues than for normal tissue, irrespective of the type of radiation and physical states of the tissue.

3.2. DISCUSSION

It was specifically opted for internal conversion sources to obtain mono energetic electrons. Further choice of Bi^{207} internal conversion source follows the fact that, it emits wide ranges of conversion electrons, all of which can be used simultaneously for the MCA calibration under the same environmental conditions to enhance the accuracy of the calibration. Further the 942 keV represents a wide energy range of 1-5 MeV for photon and 1-10 MeV for electron interactions over which the energy dependence of the total interaction is the least [8].

Table 3. *EIP* of normal and cancerous tissues of different physical states at 594 keV.

Sample	Thickness [mg/cm^2]	MPE [keV]	Energy Loss [keV]	*MSP* [MeV-cm^2/ gm]	N= N_A/A_{eff} [10^{23} mol/ gm]	*SCS*= *MSP*/ N [10^{23} MeV-cm^2]	$Z_{eff,EI}$		$Z_{eff,PI}$
							Experiment	Theory	Theory
Incident		614.400					….	….	
Blank solution	14.43	568.007	26.207	1.816	1.467	1.238	2.258		
Normal epithelial tissue	56.93	468.252	99.754	1.752	1.063	1.649	3.117	3.1660	3.4091
Cancerous cervical tissue	74.59	437.474	130.533	1.750	1.014	1.726	3.267		
Cancerous Breast tissue	83.05	422.515	145.491	1.752	1.055	1.660	3.138	3.0479	3.2766
Normal Blood	56.53	468.994	99.012	1.752	1.048	1.671	3.159	3.1803	3.4265
CLL Blood	75.14	436.495	131.512	1.750	1.019	1.717	3.249		
ALL Blood	83.10	422.575	145.432	1.750	1.016	1.723	3.261		

Table 4. *EIP* of normal and cancerous tissues of different physical states at 911 keV.

Sample	Thickness [mg/cm^2]	MPE [keV]	Energy Loss [keV]	*MSP* [MeV-cm^2/ gm]	N= N_A/A_{eff} [10^{23} mol/ gm]	*SCS*= *MSP*/ N [10^{23} MeV-cm^2]	$Z_{eff,EI}$		$Z_{eff,PI}$
							Experiment	Theory	Theory
Incident		911.197					….	….	
Blank solution	14.43	885.998	25.198	1.746	1.510	1.157	2.194		
Normal epithelial tissue	57.18	790.043	95.955	1.678	1.058	1.586	3.131	3.1785	3.4053
Cancerous cervical tissue	74.59	760.927	125.072	1.677	1.023	1.639	3.238		
Cancerous Breast tissue	83.25	746.354	139.644	1.677	1.040	1.612	3.184	3.0562	3.2749
Normal Blood	56.73	790.874	95.124	1.677	1.023	1.639	3.237	3.1935	3.4235
CLL Blood	75.14	760.096	125.903	1.676	0.982	1.707	3.374		
ALL Blood	83.10	746.769	139.229	1.675	0.976	1.716	3.393		

The data acquisition time is so chosen that the total count under each spectral peak is greater than 10,000 and hence the counting error is less than 1%. The fractions by weight

composition of tissues are taken from ICRU-44. Further as the inorganic elements, Na, P, S, Cl, K, Fe are all in trace amount, their presence ignored.

The tissue samples are treated as organic molecules with H, C, N & O so that the semi empirical formula between MS and Z meant for Z<10 can be used. For the given sample and energy of radiation, the Z_{eff} is observed to be higher for photon than electron interactions. This is because; photon due to their high penetrating power looses their energy over a long distance than electrons. Thus, the energy loss per unit path length is less for photon than electron.This results in higher Z_{eff} for photon interaction ($Z_{eff,PI}$) than the Z_{eff} for electron interaction ($Z_{eff,EI}$).

In Tables 3 and 4, it has also compared our measured Z_{eff} for electron interactions with theoretical values calculated by direct method for both electron and photon interactions of the same energies. We observe a deviation of ±3% between the experimental and theoretical values. This may be due the unaccountability of traces of inorganic elements present in the tissue samples. The deviation between the $Z_{eff,EI}$ and $Z_{eff,PI}$ are around ±7% as is the case with all other organic materials. This infers the variation of Z_{eff} with the type of radiation for organic materials of Z<10.

4. CONCLUSIONS

In this study it was measured the interaction parameters of human tissues under various physical and pathological states for 594 keV and 911 keV electron interactions. These experimental values are compared with the theoretical values computed for electron and photon interactions of same energy. It was observed a good agreement of ±3% between the experimental and theoretical Z_{eff} for electron interaction; a deviation of ± 7% between the Z_{eff} of photon and electron interactions, which reconfirms the dependence of Z_{eff} on the type of radiation for low Z materials; relatively higher Z_{eff} for cancer cells than the corresponding normal cells in all radiation interactions. It proposed further study in this regard with a variety of normal and cancer tissues to devise an easy and accurate way of cancer diagnosis.

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