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Identification the Specific Relationships among Physical Parameters which Use to Quantify Inactivation Effect of Charged Particles at Low Doses

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Abstract: Problem statement: The relationships among physical qualities parameters which are characterized charged particles are not extensively determined for all types of ionizing radiations; the specific physical parameters that are also qualified to quantify the radiation effects of charged particles have been investigated. **Approach:** Secondary data of charged particles which are used to irradiate mammalian cells in vitro has been employed here to look for the possible relationship among physical quality parameters. **Results:** The biophysical mechanism of radiation action has been identified. Biological effects can be determined based on the average distance between each event of charged particle ionizations, which represent the most important physical quality parameter. **Conclusion:** The size of charged particle nucleus and the effective charge that carried by charged particles play an important role in determining the ultimate form of radiation damage.

Key words: Physical parameters, Linear Energy Transfer (LET), mean free path, low doses, biological effects, radiation damage, energy deposition, atomic number, protons particles, physical mechanism

INTRODUCTION

Specifying the physical properties of radiation field is crucial in determining the biological effectiveness. Physical parameters are of importance in radiation protection and radiation dosimetry. Without having specific defined physical quantities the practical measurements cannot be accurately performed in these fields. These quantities are necessary in determining the radiation effects in all levels of the matter. Utilizing these quantities to quantify the biological effects of ionizing radiation allows us to determine the hazardous of the exposure of these radiations. Choosing the appropriate quantity among these parameters to quantify the effect of radiation at low dose raises the question of accuracies. The familiar physical quality parameters (Katz, 2003) which characterize the charged particle properties are energy E, Linear energy transfer LET, linear primary ionization I and mean free path λ. The energy carried by charged particle is always represented in the magnitude of kinetic or potential energy, which serves as the fundamental quality that characterizes every charged particle. It is doubtful whether this quantity can be used to determine the effects of any type of ionizing radiation. Therefore other physical parameters are necessary in determining the differences among the effects of all types of ionizing radiations. The new term dose is introduced to determine the radiation effects in the specific mass, but this convenience parameter does not take into account all the processes of energy deposition by charged particles, whereby the absorbed dose been has considered inappropriate physical parameter in quantifying the radiation effects especially at low doses. Introducing the Linear Energy Transfer (LET), is defined as the linear energy deposited in the target per unit track length and its restricted forms enable measuring the energy deposited by charged particles in this specific tracks. A part from that, LET represents the first moment of energy transfer which means that, the energy transported by delta rays is unimportant. This parameter has been used by many biophysical researchers to quantify the biological effects of ionizing radiation. For example (Harder *et al*., 1988) used restricted linear energy transfer to quantify the radiation effects in nanometer dimensions because the distribution moments of the number of ionizations per delta rays within the site are independent of the type

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and energy of the charged particle. The statistical fluctuation of the number of primary ionizations within the site is determined by its mean value, which is proportional to restricted linear energy transfer. The physical determinants which steer the fluctuation of energy deposition of radiations in nanometer sites have been investigated by (Blohm, 1983; Blohm and Harder, 1985). The LET is given usually as a function of first momentum of energy transferred by charged particles or ionizing radiation. Watt, (1988) indicated that the mechanism of radiation damage depends on the number of ionizations and it does not rely on the amount of energy transferred. Consequently, absorbed dose and energy related parameters such as LET cannot be general and satisfactory quantities for interpreting biological effect mechanisms.

Harder *et al*., (1994) applied linear energy transfer as a distinctive physical parameter to quantify the inactivation effects in mammalian cells which is produced by heavy charged particles. This lethal effect is determined accurately by using LET parameter without taken into account the delta rays effect.

Alkharam and Watt (1997) used another physical quantity to analyze the bio-effect mechanisms of radiation damage to mammalian cells by heavy charged particles. This distinctive physical quantity is called mean free path λ. Mean free path represents the zero moment of energy transfer; it is the most fundamental quantity than other physical parameters which are used to quantify the biological effects of ionizing radiations. Furthermore λ represents the mean spacing between primary ionizations which is a linear quantity (number of linear primary ionizations per unit path).

Relationships between LET and λ and E is not well addressed in the literature. However, all these physical parameters which characterize the physical properties of all types of ionizing radiations are very important as quantifiers of biological effects of these radiations.

This research was carried out to determine the mathematical relationships among these physical quality parameters. As mentioned above, the study has also addressed certain important concerns about issues relating to each parameter and it has raised some questions about the accuracy and appropriateness of some of those measurement methods of radiation effects. It has also raised the question of generalization of physical parameters as determinant of biological effects mechanism at low dose of ionizing radiation.

MATERIALS AND METHODS

Research approach: This research is based on secondary data extracted from specified radiobiological experiments (Belli *et al*., 1989; Belli *et al*., 1994; Goodhead *et al*., 1992) which are used charged particles such as, protons (^{1}H), deuterons (^{2}H), helum-3 (^{3}He) and helium-4 (^{4}He), to irradiate the V79 cells in vitro. Energy of each charged particle is taken directly from the specific source, linear energy transfer LET of every charged particle is interpolated from the standard values of biophysical data for heavy charged particles that are presented for interpretation of radiation effects, which is determined by (Watt, 1996) in liquid water.

Other physical parameters, linear primary ionization I and radiation mean free path λ are also determined for every charged particle by utilizing extrapolation method; meanwhile the effective charge (Z_{eff}) of proton and helium particles is calculated utilizing Eq. 1-2 respectively. These forms give the effective charge that carried by charged particle when it crosses the medium, the effective charge is given here as a function of particle energy and atomic number, because of the relativistic conditions:

$$Z_{eff} = \left(\frac{E}{84 \times A}\right)^{1.2} \quad (1)$$

$$Z_{eff} = \left(\frac{E}{84 \times A}\right)^{0.9} \quad (2)$$

where, E represented the maximum particle energy and A is atomic number of every charged particle.

RESULTS AND DISSCUSSION

Figure 1 shows the relationship between linear energy transfer LET and energy E. As it noted in this figure, there is an inverse linear proportional relationship between these two parameters, when particle energy increases the linear energy transfer decreases, at the same energy of all particles, the helium-4 particles have the maximum density of ionizations. On the other hand, protons particles have the lower ionization density. This disparity between the two particles is the reflection to the effects of nucleus size in the magnitude of ionization density of charged particles. The relationship between linear energy transfer and energy in this range is given mathematically as:

$$LET(E) = C_1E + C_2$$

where, $C_1 = -0.77$, $C_2 = 3.74$ and $R^2 = 1$.

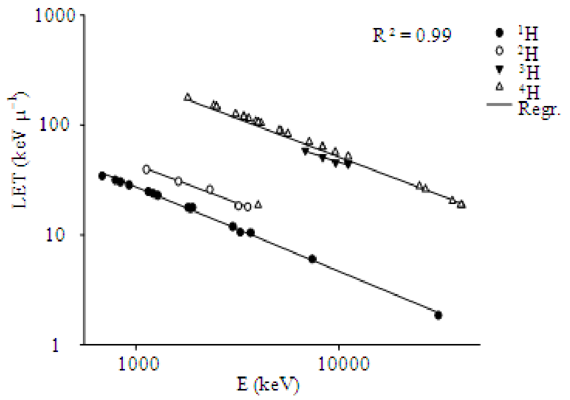

Fig. 1: The relationship between linear energy transfer LET and particle energy E

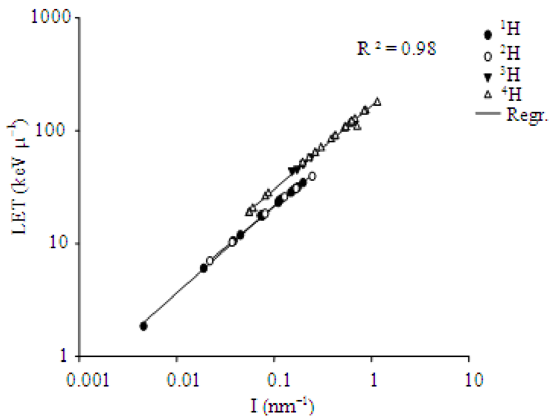

Fig. 2: The relationship between linear energy transfer LET and linear primary ionization I

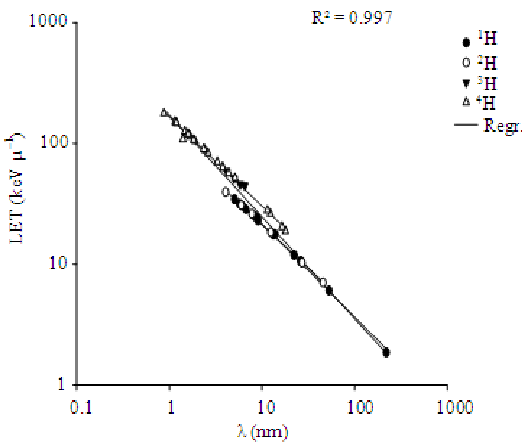

Fig. 3: The relationship between linear energy transfer, LET and mean free path λ

The relationship between ionization density LET and linear primary ionization I is represented in Fig. 2. There is a linear relationship between these parameters, linear energy transfer increases with increasing linear primary ionization, the helium-4 particle and proton both goes parallel. However, at the same number of ionizations per unit length of particle track, it is noticed that, helium-4 particles deposit much more energy than others. The size of the particle's nucleus and the effective charge play an important role in determining this difference between these two particles. The relationship between the two can modeled as follow:

$$LET (I) = C_3 I + C_4$$

where, $C_3 = 0.77$, $C_4 = 0.10$ and $R^2 = 0.98$.

Figure 3 represents the relation between ionization density LET and mean free path λ. There is an inverse linear relation between these parameters. As the trend shows, the increase in the linear energy transfer represent the decrease in the average distance between ionization events (energy deposition events), the ionization density of ^{4}He particles is bigger than the ionization density produced by ^{1}H particles. According to this relationship, one can conclude that ^{4}He particles with linear energy transfer is equal to 100 keV/λm is the most efficient in causing biological damage, because the average distance between energy deposition events occur within DNA dimensions (template action) which is equivalent to 2 nm. The distinctive relationship between these parameters can be presented mathematically as follow:

$LET (\lambda) = C_5 \lambda + C_6 \lambda^2 + C_7$ where $C_5 = -0.97$, $C_6 = -0.11$, $C_7 = 0.67$ and $R^2 = 0.99$

Figure 4 shows the relationship between linear primary ionization I and particle energy E of charged particles. All charged particles indicate inverse proportional relationship between particle energy and linear primary ionization. The linear primary ionization decreases versus increasing of particle energy. At the same energy of all charged particles, ^{4}He particles maintain the maximum linear primary ionization; the minimum values of linear primary ionization are indicated by protons particles. This response is in accordance with the response which is represented in Fig. 1. In other words, the similarity in both relationships is due to the dependence of ionization density LET and linear primary ionization density I on the nucleus size and the effective charge that is carried by each charged particle which play a crucial role in specifying the degree of radiation effect.

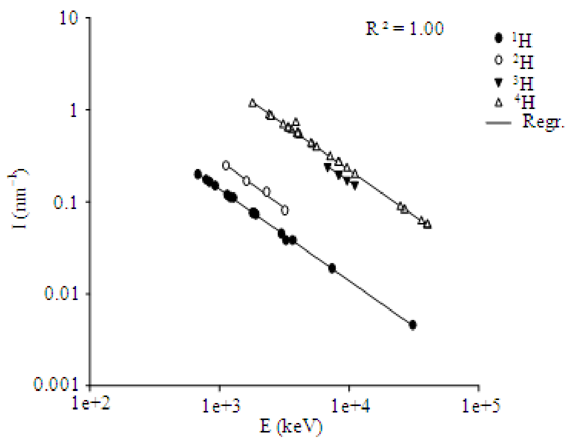

Fig. 4: The relationship between linear primary ionization I and particle energy E

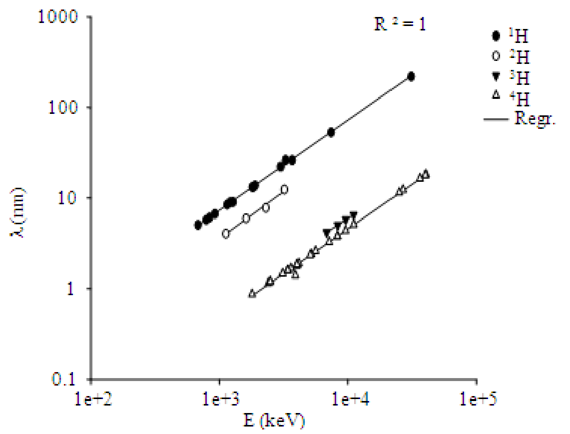

Fig. 5: The relationship between mean free path λ and particle energy E

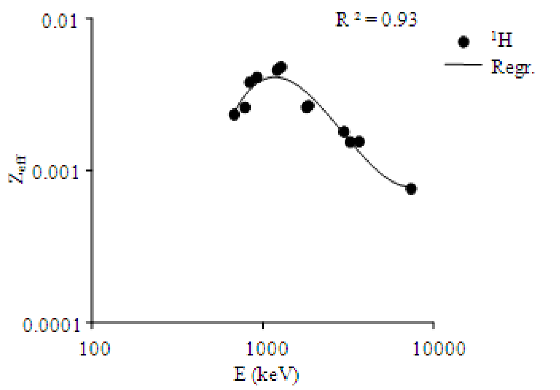

Fig. 6: The relationship between effective charge, Z_{eff} and particle energy E

The mathematical expression which describes this relationship is presented below:

$$I(E) = C_8E+C_9$$

where, C_8 = -0.99, C_9 = 2.12 and R^2 = 1.

The relation between mean free path λ and energy E is indicated in Fig. 5. This relationship shows that, there is a linear incremental relationship between these parameters. The mean free path increases with increasing energy of every charged particle. At the same energy of these charged particles, it can be observed that proton particles have the maximum mean free path, while the helum-4 particles having the minimum average distance between ionization events in the medium; this means that, at 2 nm of mean free path, helium-4 particles are the only one which is capable of causing DNA damage. The rest of the particles are very far from bringing about this damage as a result of great value in the average distance between ionization events. The mathematical form which represents this relation is given as:

$$\lambda(E) = C_{10}E+C_{11}$$

where, C_{10} = 0.99, C_{11} = -2.12 and R^2 = 1.

The relation between effective charge Z_{eff} of proton particles and their energy E is represented in Fig. 6. There is a linear quadratic relation between these parameters, the effective charge rises with rising proton energy until reach the maximum 1000 keV, after this point any rise in the effective charge offsets by a decline in energy. This relation is best represented by the following mathematical form:

$$Z_{eff}(E) = C_{12}E+C_{13}E2+C_{14}E3+C_{15}$$

where, C_{12} = 103.02, C_{13} = -30.11, C_{14} = 0.89, C_{15} = -11864 and R^2= 0.93.

Using some physical parameters to quantify the charged particle effect in biological materials, such as, absorbed dose bear uncertain responses. At that low dose the response could be anything in relation to the effects, as this parameter doesn't take into account the stochastic nature of energy deposition by charged particles in tinning volumes. Besides that, this parameter doesn't also consider the complex structures of biological entities. Therefore, this study has considered that, that approach as inappropriate method to quantify the biological effects in that region. Consequently, absorbed dose and energy related parameters such as LET cannot be general and satisfactory quantities for interpreting biological effect mechanisms.

The researcher suggested other alternative physical parameters such as mean free path which may accurately determine the exact effects of low doses and doesn't directly depend on absorbed energy.

CONCLUSION

The relationships between different physical parameters, which characterize radiation field and used as distinctive physical quality parameters to quantify the ionizing radiation effects in biological mediums, have been determined to identify the physical features of each physical parameter.

The physical mechanism of ionizing radiation action can be elucidated if the biological characteristics of targets are taken into account. On the other hand representing biological effects in terms of physical parameters does not give an appropriate approach to quantify these effects; bio-physical representation is a good method to interpret the biological effects accurately.

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