EXPERIENCE WITH A
LINEAR ENERGY TRANSFER (LET)
CHAMBER AT CERN

T.R. Overton
Preface

This report is intended primarily to be a guide to future users of the linear energy transfer (LET) chambers. As such it is an attempt to present in a coherent form the basic theoretical ideas in conjunction with the physical characteristics of chamber response. The original theoretical presentation is due to Prof. H.H. Rossi and Dr. W. Rosensweig of Columbia University. However, redefinition of several quantities and subsequent changes in nomenclature give a clearer appreciation of the theoretical basis of this method.
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The physical parameters influencing the biological effects of ionizing radiation are the energy delivered to the tissues affected and the energy density along the paths of the charged particles producing the ions. Variations of this latter quantity are believed to be responsible for differences in relative biological effectiveness (RBE).

Zirker et al.1,2) suggested the use of the concept of "linear energy transfer" in tissue. This is more fundamental than specific ionization in a gas, but the latter, which may be measured more readily, may be presumed to be proportional to the former within about 10% in most cases.

Several experimental methods are available by means of which the total energy imparted to tissue by ionizing radiation can be determined. Of these methods the most frequently employed is a tissue-equivalent ionization chamber. This chamber was developed by Rossi et al.3). On the basis of the Bragg-Gray principle, one can obtain a measure of the total energy delivered to a gram of tissue by particles of any specific ionization. Since these chambers, when exposed to a radiation field, are traversed by ionizing particles of the same type, energy, and direction as would be tissue in the same place, a method was derived3) whereby the specific ionization of individual particles crossing the cavity could be determined. The instrument used is the LET chamber—a spherical cavity proportional counter with TE walls filled with TE gas at low pressure.

This device has provided the necessary experimental technique to open up the new field of Microdosimetry [Rossi4)].
1. THE "LET" CHAMBER

1.1 General ideas

Since the ionization produced in a gas by individual particles will often be too small to be detected directly, recourse must be made to gas multiplication. The chamber must therefore function as a proportional counter, and the pulse obtained at the output will be proportional to the total ionization produced by the particle traversing it. The total initial ionization is then the product of the specific ionization of the particle concerned and its path length in the gas volume.

Discrimination on the basis of pulse height alone cannot lead to a clear distinction between particles of different specific ionization, since the pulse produced by a lightly ionizing particle having a long trajectory may be equally as large as that produced by a heavily ionizing particle having a short path. Thus, if detailed information on specific ionization is required, allowance must be made for the distribution of geometric path lengths. This is most easily performed for the simplest type of cavity -- the sphere -- which has the additional advantage of being isotropic; directional response is thus absent.

1.2 Path length distribution

Consider the spherical geometry shown in Fig. 1a: the source $S$, a distance '$a$' from the centre of the sphere of radius $r$, with one particular 'ray' from $S$ intercepting a path length '$x$' in the sphere for an angle $\theta$ at $S$.

The geometry of the system gives the relationship between $x$, $\theta$, $r$ and $a$.

It is

$$\cos \theta = \sqrt{1 - \left(\frac{r}{a}\right)^2 \left[1 - \left(\frac{x}{2r}\right)^2\right]}.$$  \hspace{1cm} (1)
Furthermore, the number of rays lying within the solid angle defined by \((\Omega, d\Omega)\) is proportional to \(\sin \theta \cdot d\Omega\). Differentiation of Eq. (1) gives

\[
- \sin \theta \cdot d\Omega = \frac{\left(\frac{1}{2a}\right)^2 \cdot x \cdot dx}{\sqrt{1 - \left(\frac{r}{a}\right)^2 \left[1 - \left(\frac{x}{2r}\right)^2\right]}}.
\]

This expression is proportional to the required path-length distribution \(P(x)\).

It is clear that a condition for use of our counter to produce an output is that the 'rays' from \(S\) should intercept the chamber volume; the expression for \(P(x)\) is therefore normalized to contain this limit. This condition may be written as:

\[
- \int_{0}^{2} \sin \theta \cdot d\Omega = \left(\frac{1}{2a}\right)^2 \cdot 2r \int_{0}^{2} \frac{x \cdot dx}{\sqrt{1 - \left(\frac{r}{a}\right)^2 \left[1 - \left(\frac{x}{2r}\right)^2\right]}}.
\]

In particular, it follows that the normalized path-length distribution is given by:

\[
P(x) = \frac{x}{\sqrt{1 - \left(\frac{r}{a}\right)^2 \left[1 - \left(\frac{x}{2r}\right)^2\right]}} \int_{0}^{2} \frac{dx}{\sqrt{1 - \left(\frac{r}{a}\right)^2 \left[1 - \left(\frac{x}{2r}\right)^2\right]}}
\]

Two boundary conditions are of particular interest:

i) when the source \(S\) is located at a distance which is large compared to the sphere diameter, \(a \gg r\);

ii) when the source \(S\) is located at the surface of the sphere, \(a = r\).
\textbf{Case (i)} \( a \gg r \)

For this condition Eq. (4) gives

\[
P(x) = \frac{x}{2r} = \frac{x}{2r} \int_0^x \, dx
\]

and if \( P(x) \) is plotted as a function of \( x \), a triangular spectrum is obtained (Fig. 1b).

\textbf{Case (ii)} \( a = r \)

In this case

\[
P(x) = \frac{x}{2r} \int_0^x \, dx = \frac{1}{2r} \cdot \frac{x}{2r} \int_0^x \, dx
\]

This represents a rectangular spectrum (Fig. 1c).

1.3 Measurement of dose

For a measurement of the dose rate as a function of specific ionization, case (i) is of importance. The expression for the pulse-height spectrum \( P(h) \) for particles of a single specific ionization \( \sigma \) is obtained from Eq. (5) by letting the pulse height \( h \) equal the product of the specific ionization and the path length intercepted in the sphere, i.e., \( h = \sigma \cdot x \).

Let the number of particles traversing the counter/sec, of specific ionization lying in \((\sigma, \sigma + \Delta\sigma)\), be \( P(\sigma) \cdot \Delta\sigma \), and let \( T(h,\sigma) \cdot \Delta h \cdot \Delta\sigma \) be the number of pulses in the pulse-height interval \((h, h + \Delta h)\) due to ionization in the interval \((\sigma, \sigma + \Delta\sigma)\). Then,

\[
T(h,\sigma) \Delta h \cdot \Delta\sigma = a \cdot \frac{h}{2r^2} \cdot \Delta h \quad 0 < h < 2r\sigma
\]

\[
= 0 \quad h > 2r\sigma
\]
when

$$\int_0^\infty T(h,\sigma)\Delta h \cdot \Delta \sigma = F(\sigma) \cdot \Delta \sigma,$$

it follows that

$$\alpha \cdot \int_0^{2r\sigma} \frac{h \cdot \Delta h}{2r^2 \sigma} = F(\sigma)$$

where

$$\alpha = \frac{F(\sigma)}{\sigma}.$$  

Thus,

$$T(h,\sigma) = \frac{h}{2r^2 \sigma^2} \cdot F(\sigma) \quad 0 < h < 2r\sigma$$

$$= 0 \quad h > 2r\sigma$$

(7)

To obtain the dose delivered to the spherical cavity by particles of a given specific ionization \((\sigma, \Delta \sigma)\), we utilize the expression for \(T(h,\sigma)\) given in Eq. (7).

Let \(d(\sigma, h)\Delta \sigma \cdot \Delta h\) be the dose rate in erg/sec due to particles of specific ionization lying in \((\sigma, \sigma + \Delta \sigma)\) and pulse height lying in \((h, h + \Delta h)\). Then the dose rate is proportional to the number of traversals in \((h, h + \Delta h)\) multiplied by \(h\), that is

$$d(\sigma, h) \cdot \Delta \sigma \cdot \Delta h = K \cdot T(h,\sigma) \cdot \Delta \sigma \cdot \Delta h \cdot h$$

(8)

where \(K\) relates the pulse height to the number of erg/sec deposited in the chamber.

Let \(D(\sigma) \cdot \Delta \sigma\) be the dose rate over all pulse heights for ionization lying in the interval \((\sigma, \sigma + \Delta \sigma)\); then
\[ D(\sigma) \cdot \Delta \sigma = \int_{h} d(\sigma, h) \Delta \sigma \cdot dh \]

\[ = K \Delta \sigma \int_{0}^{2r_{0}} \frac{h^{n}}{2r^{2} \sigma^{2}} \cdot F(\sigma) \cdot dh \]

\[ D(\sigma) \cdot \Delta \sigma = K \cdot \Delta \sigma \cdot \frac{8r_{0}^{3} \sigma^{3}}{6r^{2} \sigma^{2}} \cdot F(\sigma) \cdot \Delta \sigma \]

Thus,

\[ D(\sigma) = K \cdot \frac{h}{r} \cdot \sigma \cdot F(\sigma) \cdot \Delta \sigma. \]  \hspace{1cm} (9)

This is the expression for the dose rate in erg/sec delivered by particles of specific ionization \((\sigma, \sigma + \Delta \sigma)\).

To obtain the dose rate as a function of specific ionization, consider the pulse-height spectrum \(Q(h)\) (Fig. 1d) which is due to a flux distribution \(F(\sigma)\) of particles of varying specific ionization, and let \(Q(h) \cdot \Delta h\) be the number of pulses in the pulse-height interval \((h, h + \Delta h)\) due to the spectrum \(F(\sigma)\).

With reference to Fig. 1d we have:

\[- [Q(h) - Q(h + \Delta h)] + F(2r_{0}, \sigma) \cdot \Delta \sigma = \frac{Q(h + \Delta h)}{h} \cdot \Delta h\]

that is

\[ \Delta Q(h) + \frac{F(\sigma)}{r_{0}} \cdot \Delta \sigma = \frac{Q(h)}{h} \cdot \Delta h. \]  \hspace{1cm} (10)

Since

\[ \frac{\Delta h}{h} = \frac{\Delta \sigma}{\sigma} \]

thus

\[ \frac{F(\sigma)}{r_{0}} \cdot \Delta \sigma = - \Delta Q(h) + \frac{Q(h)}{h} \cdot h \cdot \frac{\Delta \sigma}{\sigma} \]

\[ D(\sigma) \cdot \Delta \sigma = \frac{h}{3} K \cdot r^{2} \left[ -\sigma^{2} \Delta Q(h) + \sigma Q(h) \cdot \Delta \sigma \right]. \]  \hspace{1cm} (11)

The quantity of physical interest is the dose rate which is due to particles within a finite range of specific ionization \((\sigma_{1}, \sigma_{2})\).
This is obtained by integrating the expression for \( D(\sigma) \cdot \Delta \sigma \) in Eq. (11) between the appropriate limits.

Thus

\[
D_{1,2} = \frac{h}{2} K \cdot r^2 \left[ \sigma_1^2 \cdot \frac{\partial}{\partial \sigma} \left( 2\sigma_1 \right) - \sigma_2^2 \cdot \frac{\partial}{\partial \sigma} \left( 2\sigma_2 \right) + 1 \right] \int_{\sigma_1}^{\sigma_2} \frac{\partial}{\partial \sigma} \left( \frac{\varphi(h)}{\sigma} \right) \cdot \sigma \cdot d\sigma .
\]

1.4 Dose in LET

The purpose of the entire analysis given above is to set up a correspondence between the pulse height \( h \) and the specific ionization \( \sigma \), namely \( h = 2\sigma \), and the variable path length within the sphere has been eliminated.

Equation (11) can be re-written in the form

\[
D(\sigma) = \frac{2}{3} K \cdot r \left[ - h^2 \frac{d\varphi}{dh} + h\varphi \right]
\]

\[
= \frac{2}{3} K \cdot r \left[ - h^3 \frac{d}{dh} \left( \frac{\varphi}{h} \right) \right].
\]

The term in square brackets is dimensionless, except for \( t^{-1} \) if \( \varphi \) is a counting rate. Hence the units of \( h \) are arbitrary, the only requirement being a proper assignment between values of \( h \) and corresponding values of \( \sigma \).

This arbitrariness does not apply to the factor \( K \) which is defined as the dose delivered to the counter volume per unit pulse height.

As expressed up to the present, in the relationship \( h = 2\sigma \), \( h \) has units of ion pairs, \( r \) cm, and \( \sigma \) ion pairs/cm.

Since a dose evaluation is required, it is useful to replace \( \sigma \) by \( D = \text{linear energy transfer (LET)} \) (erg/cm), which is valid as long as the energy required to form an ion pair (\( \gamma \)) is constant.

Thus,

\[
h = 2rL \text{ (erg)}.
\]
By definition

\[ K = \frac{1}{\frac{1}{3} \pi r^2 \delta_g} \]

where \( \delta_g \) is the density of the gas in the counter (g/cm\(^3\))

\[ D(L) = \frac{1}{2\pi r^2 \delta_g} \left[ - h^3 \frac{d}{dh} \left( \frac{\rho}{h} \right) \right] \]

(13)

or, expressed in familiar units (for numerical values see Appendix 1):

\[ D(L_T) = \frac{1.6 \times 10^{-7}}{2\pi r^2} \left[ - h^3 \frac{d}{dh} \left( \frac{\rho}{h} \right) \right] \frac{\text{rad}}{\text{keV} \cdot \mu} \]

(14)

2. EXPERIMENTAL

2.1 General design and operation of the LST chamber

The chambers employed in the present studies were designed and constructed at the (Radiological Research) Laboratories of Professor H.H. Rossi.

The main features of the chamber are shown in Fig. 2. It is comprised of a spherical shell of tissue-equivalent plastic into which are mounted a central electrode wire of hard-drawn stainless steel, 0.005" in diameter, a helical grid wound from the same material to an outside diameter of about 1/8", and the various electrode supports made in perspex and aluminium.

The electrical connections are made to the central electrode, the helix, and the chamber wall by means of spring-loaded contacts. The signal output is coupled into an ORTEC type 103XL low-noise charge-sensitive preamplifier, the output from which is fed directly to the amplifier input of a TMC 256 multichannel analyser.
Brass connectors with O-ring seals provide connections to the vacuum and gas flow systems, shown schematically in Fig. 3.

The chamber is operated at low pressure under continuous flow conditions with a tissue-equivalent gas. Several variable parameters are inherent in the system, and the response of the chamber to changes in these parameters has been studied.

In the following sections the main results of various laboratory experiments made with this LET chamber are summarized. In all cases, the results confirmed the findings of Professor Rossi's group, and for a full account of the many experiments which have been made with these chambers the reader is referred to the extensive bibliography of Rossi et al.

2.2 Performance optimization using a plane $^{239}$Pu $\alpha$ source

For $a = r$, i.e. if the source is flush with the chamber wall, the distribution of path lengths within the sphere is rectangular (see Section 1.1). To simulate this condition experimentally, a thin $^{239}$Pu $\alpha$ source was plated onto the end of an aluminium plug, the dimensions of which ensured that the $\alpha$ source was flush with the inside surface of the chamber. With this source geometry, the variations in pulse-height distribution of the proportional counter with changes of central electrode potential, grid potential, and gas pressure have been studied.

2.2.1 Change in operating pressure

With the central electrode voltage fixed at 600 V positive and the grid maintained at 20% of the central electrode potential, the shape of the spectra from the flush $^{239}$Pu source has been studied as a function of the gas pressure. The results of these measurements are summarized in Fig. 4a where normalization to the same value of maximum pulse height has been made. It was noted that between pressures of 10 mm and 100 mm the spectral shape did not change very much. With an increase in pressure to 200 mm, the proportion of large pulses becomes greater, and eventually
a Bragg-type curve can be obtained at ~ 400 mm Hg. This situation has been analysed by Rosensweig and Rossi\(^5\).

### 2.2.2 Change in grid voltage with respect to central electrode potential

The response under these conditions with fixed pressure is shown in Fig. 4b. The effects of changes in grid potential are twofold. Firstly, there is a gain change; secondly, the spectral shape shows marked variations for small grid potential changes. If we accept that a criterion for optimization of chamber response is that one obtains the ideal rectangular shape, then the nearest approach is obtained at a grid potential fixed at 20% of the respective central electrode potential. This result was also found by Rossi\(^5\) who notes, however, that this rectangular spectrum criterion may be unduly severe, as experimental spectra taken with a neutron source did not show significant changes in shape with grid potential variations.

### 2.3 Performance optimization using a collimated \(^{244}\)Cm \(\alpha\) source

#### 2.3.1 Gas gain

Using a straight collimated \(^{244}\)Cm \(\alpha\) source (Fig. 5a), the gas gain, i.e. gain versus applied high voltage, was measured for both CH\(_4\) and tissue-equivalent gases. These results are shown in Fig. 6a for three values of operating pressure.

Figure 6a shows the typical response of the chamber to variations in pressure at several fixed EHT values. It may be noted that at most pressures the resultant pulse height varies exponentially with voltage, and for a given voltage the least variation of pulse height with pressure is in the region of 10-20 mm Hg.

#### 2.3.2 Resolution and spectra shape

Using the straight collimated \(^{244}\)Cm and \(^{210}\)Po \(\alpha\) sources (Fig. 5a, b) and operating the chamber at the "optimum" settings of the
various parameters, the resolution was measured for the principal lines in these α spectra.

As is noted in Fig. 7, which shows the straight collimated $^{244}\text{Cm} + ^{210}\text{Po}$ spectra, the nature of the source itself has a large influence upon the line width produced by the chamber. A few values of resolution as measured at several operating pressures are shown in this figure. Optimum performance is evident in the 10-20 mm $\cdot$ Hg region.

The main peak in each of the spectra is due to the traversal of an α particle of 5.8 MeV and 5.3 MeV, respectively, across a major diameter of the chamber.

The peak marked at half the principal pulse height is assumed to result from α particles which hit the central electrode and/or helix structure, the recoil energy being absorbed in the mechanical components (see Section 2.3.3). The shape of the spectrum on the large pulse side of the principal peak is explained on the basis of the $^{244}\text{Cm}$ α source being irregular and thick. In effect, what is seen is the contribution from α particles which stop in the chamber. These effects were studied more closely by placing thin absorbers between the collimated $^{210}\text{Po}$ α-particle beam and the gas volume. The result of this particular experiment is shown in Fig. 8; the relative pulse height is seen to increase to a maximum corresponding to the range of the $^{210}\text{Po}$ α particle.

2.3.3 Uniformity of ion collection and gas multiplication

For true proportionality and linearity in a counter of the type used, requirements of paramount importance are uniformity of ion collection and of multiplication along the central electrode. To check upon these two qualities, an angular collimator for the $^{244}\text{Cm}$ α source was constructed (Fig. 5c). The collimator allowed the 'beam' of α particles to sweep out the surface of a cone of 30° semi-vertical angle.

The spectra obtained as a function of collimated beam direction are shown in Fig. 9. It is seen that the pulse height of the principal peak remains unaffected with angular position of the α-particle
beam. The peak at half of the principal pulse-height value varies in intensity as the beam sweeps out the chamber volume, being more pronounced when the beam is directed towards the "helix volume". It was found that the enhancement of this peak was rapid at beam direction positions corresponding to the edges of the helix outer diameter. We were thus led to the conclusion that this peak was a direct result of 
particles hitting the electrode structure, thus having only one-half of their normal length within the gas volume.

Rosensweig and Rossi\textsuperscript{7}) studied the proportionality of their counter by covering parts of the surface of a collimated radium source with aluminium foils to produce a mixture of high and low LET particles. In their experimental spectra they show peaks at half and twice the principal pulse-height value, in addition to other lines. It appears that Rosensweig and Rossi attribute all peaks in their spectra to the source alone. However, in all spectra taken with collimated \( ^{244} \text{Cm} \) and \( ^{210} \text{Po} \) in both of the LMT chambers at CERN, three peaks are evident in the pulse-height ratio \( 1/2 : 1 : 2 \); these ratios would appear to be a characteristic of chamber design, particularly electrode structure, rather than a source/mounting effect.

2.4 Practical improvements

With the idea of bettering the usability of the LMT chambers around the CERN site, many laboratory tests of "possible" system improvements were made. The most obvious of these simplifications (from a user's point of view) would be to dispense with the vacuum and flow systems. To check this possibility the counter was mounted in a vacuum chamber and pumped down for about 20 hours. The vacuum chamber was then filled to atmospheric pressure with \( ^{4} \text{He} \) gas, and pumped down some hours later to the working pressure of 15 mm Hg. The response of the counter to the collimated \( ^{210} \text{Po} \) \( \alpha \) source was then studied as a function of time.

Initially (for about 2 hours), the pulse height for the \( ^{210} \text{Po} \) \( \alpha \) particles remained constant. After this time, a gradual deterioration was evident, and after 24 hours the pulse height had decreased to
two-thirds its original value. The pressure rise in the system during this time was less than 1 mm Hg. The explanation of this phenomenon is the emission of absorbed oxygen (air) from the porous TE plastic walls of the chamber. An experiment in which very small air leaks were allowed into the counting system showed that very small additions of air cause large changes in pulse height. Peterson\(^6\) notes that for one of their TE chambers, 500 hours outgassing still left an isolated closed system with a slow pressure increase. However, when the surface of their TE plastic was coated with glyptol, Rosenzweig found that the gas emission from the plastic was very much reduced but that the system was still not good enough for isolated operations.

The electronic system used with this chamber is shown in Fig. 10. The high voltage for the central electrode and helix is obtained from a 900 V positive battery supply via a fixed potentiometer chain. Care was taken to prevent noise pick-up in earth loops, and for this purpose the earth point for the chamber was isolated from that of the vacuum and gas-flow system. A graphite-coated polythene shield or a copper can surrounds the chamber to limit RF pick-up when in the vicinity of the accelerators. The signal output from the central electrode passes via a 0.01 \(\mu F\) high-voltage capacitor directly to the input of an ORTEC 103XL low-noise charge-sensitive preamplifier. The noise level in the system is of great importance with respect to the lowest measurable pulse height, and thus the capacity of the chamber needs to be reduced as far as possible and the input integrating resistor of the 103XL optimized for lowest noise values. The output of the preamplifier was fed to the amplifier input of a model 210 pulse-height logic unit of a TMC 256 multichannel analyser. Thus one obtains the pulse-height distributions corresponding to the energy deposits in the chamber of the various LET particles.

3. **SPECIAL ANALYSIS**

A brief outline of the practical methods for LET data analysis is presented in this section.
spectra is presented in this section to demonstrate the type of results that are obtained from analyses of the pulse-height spectra.

The spectra for the proton and neutron beams were taken only as a parasiting experiment. The parameters of the radiation field are thus not well defined.

However, in the pion beam studies those parameters were well controlled and some reliability can be attached to the dose-rate measurements.

The experimental LET spectra are presented in this section without any attempt at their interpretation or application. The reason for this type of presentation is that in most cases no additional information on the radiation field exists. Thus the spectra are simply "those obtained" under the various conditions enumerated below. The curves are, in general, similar to those presented in the various Rossi\textsuperscript{13)\textsuperscript{-15)} publications where the theory of Boag\textsuperscript{14)\textsuperscript{-15)} has been employed to compare experimental and theoretical spectra.

4.1 600 MeV extracted proton beam studies

Biological irradiations using the 600 MeV extracted proton beam were conducted by the Health Physics Group in May 1965 and March 1966.

In both cases the LET chamber was sited outside the proton beam shielding tunnel: in the first experiment, at the side and about 1.50 m above floor level; in the second experiment, on the roof of the tunnel.

A schematic diagram of those shielding conditions with measurement positions marked is given in Fig. 13, together with the LET-dose spectra and integrated dose rates at these two sites.

It should be noted that the integrated dose rates as calculated from the pulse-height spectra are in error in as much as the multichannel
analyser presents a lower threshold below which no account is taken of
the incident pulse. With the particular instrument we used (a TMC 256
channel), the zero pulse-height corresponds fairly accurately to
"channel 0". However, the sensitivity suppression for live-time conserv-
ation gives decreased counting efficiencies in the first few (~5)
channels. Thus the dose recorded is that which is delivered by particles
having, in general, LET values > 2 keV/μ. In addition, when the dose
rate becomes large, the effects of spectral distortion and analyser dead-
time will give rise to uncertain errors in dose evaluation.

4.2 70 MeV neutron beamtrap experiments

LET-dose spectra were obtained with the chamber placed in the
neutron beamtrap of the 70 MeV pion channel. These spectra are shown in
Fig. 1a, where the effects of placing hydrogenous absorbers in front of
the chambers are demonstrated. As is seen, the introduction of a modera-
tor produces a spread in the dose distribution to higher LET values and,
in the case of 20 cm polythene, a well-defined peak at approximately
90 keV/μ. This peak is attributed to the maximum energy loss of a
proton in the Bragg peak.

A probable reason for the moderately high LET values in the
run without absorber is that the neutral particles reaching the beamtrap
had a broad spectrum due to machine operating mode and also to multiple
scattering.

4.3 Pion beam dosimetry experiments

The purpose of these experiments was to look for a nuclear
contribution to the absorbed dose in the case of nuclear capture of a
π0 particle at rest -- a process which, theoretically, should give rise
to preferential α-particle disintegration of the compound nucleus
[Fowler's].

A full account of these studies will be given in a later pub-
lication by the Health Physics Group, and thus only a brief outline of
the LET results are given in the present report.
LET-dose spectra were measured for two absorber thicknesses for each of the $\pi^-$ and $\pi^+$ beams.

These absorber conditions corresponded to the chamber being placed at first well in front of the Bragg peak and, then, in the Bragg peak for these energetic pions.

The LET-dose spectra for these various irradiation conditions are shown in Fig. 15, where it is clearly demonstrated that in the $\pi^-$ case a substantial part of the dose is delivered at LET values appropriate to $\alpha$ particles with energies between 5 MeV and 15 MeV, the spectrum being peaked at a LET appropriate to an $\alpha$ particle of about 6 MeV.

5. CONCLUSIONS AND SUGGESTIONS FOR FUTURE UTILIZATION OF THE SPHERICAL PROPORTIONAL COUNTERS FOR LET STUDIES

The measurement of LET-dose spectra would appear to be an important addition to the available methods for radiological protection; the complexity of the method, however, will tend to preclude its general application.

Since the distribution of dose in LET obtained in any given radiation field depends upon the effective diameter of the unit density tissue sphere [Caswell\textsuperscript{16}], the "size" of the principal system "at risk" needs to be known. This latter requirement entails much more study, of a fundamental nature, in Radiobiology. However, it would appear that diameters of 1-2 $\mu$ (\textasciitilde chromosome dimensions) are extremely important, and our spectra were taken at TE gas pressures which simulated approximately this size of unit density sphere. Further details of special modifications as pressure is changed are given in Biavati et al.\textsuperscript{17}.

Two main practical improvements are suggested for future utilization of this technique. Firstly, the construction of a large bore (2 cm $\phi$) vacuum and flow system with high-grade valves and manometers will certainly lead to instrumental stability. Secondly, a robust, easily transportable system should be built to facilitate work in the experimental areas.

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With these modifications, the accumulation of data over long periods of time (for statistical accuracy) and under widely varying irradiation conditions is of great importance.

Simultaneously with the LNT spectra measurements, the QF chamber of Sullivan \(^{(3)}\) should be used to determine the average QF, and tissue-equivalent ionization chambers to measure the total dose.

The interpretation of all these different measurements should be of great interest in the continued search for a clearer appreciation of the real factors involved in radiological protection.

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* * *
Evaluation of constant terms

When the counter is filled with tissue-equivalent gas, the Bragg-Gray principle tells us that the dose in org/g is independent of the density of the material. Hence equal doses will be delivered in corresponding LET intervals.

Let \( L' \) represent the LET in unit density tissue (org/cm) corresponding to \( L \) in the gas. Then

\[
D(L) \cdot dL = D(L') \, dL' 
\]

so that

\[
D(L') = D(L) \cdot \frac{dL}{dL'} = D(L) \cdot \delta_g. 
\]

Thus when both sides of Eq. (13) are multiplied by the gas density, the resulting expression may be interpreted to give the dose distribution in \( L = \text{LET} \) (org/cm of unit density tissue). Equation (14) may now be written to give the dose distributed in \( L_T = \text{LET} \) (keV/\( \mu \) of unit density tissue). Employing the same arguments as outlined above,

\[
D(L_T) = D(L) \cdot \frac{dL}{dL_T} 
\]

and in particular, \( dL/dL_T = 1.6 \times 10^{-5} \delta_g \).

(This numerical value is derived from the conversion to keV/\( \mu \) from org/cm). Thus,

\[
D(L_T) = 1.6 \times 10^{-5} \left[ -h^3 \frac{d}{dh} \left( \frac{\delta_g}{h} \right) \right] \frac{\text{org}}{g \cdot \text{keV/}\mu} 
\]

or

\[
D(L_T) = 1.6 \times 10^{-7} \left[ -h^3 \frac{d}{dh} \left( \frac{\delta_g}{h} \right) \right] \frac{\text{rad}}{\text{keV/}\mu}. 
\]
Thus with the constant factor expressed in terms of known quantities, all that remains is the setting up of the correspondence between the pulse height \( h \) and \( L_T \) (LET in unit density tissue). This requirement is met by means of a collimated source which is directed across a major diameter of the chamber.
REFERENCES


9) W. Rosenzweig, Calculation of dose distribution measured with the spherical proportional counter. Private communication, 1955.


Pulse-length distribution in a spherical detector

(a)

Pulse-height distribution for $a \gg r$

(b)

Pulse-height distribution for $a = r$

(c)

Experimental pulse-height spectrum

(d)
LET Chamber - "OLD" design

Fig. 2

Flush $\alpha$-source
Fig. 3

Block diagram of vacuum and flow system
Pulse-height distribution depending on gas pressure in the chamber

(a)

(b)

Pulse-height distribution depending on the ratio of grid potential to the central wire potential
Fig 5

(a) Straight collimator 241Cm source with shut-off arrangement

(b) Straight collimator 209Po source with absorber holders

(c) Angular collimated 241Cm source
Gas amplification vs EHT: gas pressure in the chamber taken as parameter

(a)

Gas amplification vs gas pressure; EHT taken as parameter

(b)
Changes in spectral shape when absorbers are placed between $^{210}$Po source and gas.

- 0 mg/cm$^2$
- 1.0 mg/cm$^2$
- 3.5 mg/cm$^2$

Relative counts

Pulse height - arbitrary units
Spectral changes with rotation of angular collimated $^{244}$Cm source

positions 3a and 3b correspond to the edges of the helix volume

response between positions 3a and 3b

response in all other positions

pulse height - arbitrary units
LET values for $^{239}\text{Pu}$ and $^{244}\text{Cm}$ vs pulse length in the chamber

\[
d_0 = 0.1125 \text{ mm air at NTP}
\]

\[
d_0 = 0.1425 \rho_{\text{CH}_4} \text{ mm air at NTP}
\]

---

Equivalent unit density diameter vs gas pressure

\[
\text{Equivalent sphere diameter (microns of unit density tissue)}
\]

\[
gas pressure (\text{mm Hg})
\]
External proton beam experiment May 1965

LET chamber outside beam tunnel
Integrated dose rate = 3.98 mrad/hour
Equivalent sphere diameter = 2.0 microns

Fig. 13a

External proton beam experiment March 1966

LET chamber on top of shielding tunnel
Integrated rad dose rate = 6.6 mrad/hour

Fig. 13b
(a) 70 MeV Neutron Beamtrap Experiments

Beam composition not known - no absorber
Integrated dose rate = 4.5 mrad/hour

(b) Beam composition not known - 20 cm polythene as moderator
Integrated dose rate = 2.4 mrad/hour
3.5 μ sphere diameter

(c) Beam composition not known - 50 cm polythene as moderator
Integrated dose rate = 9.6 mrad/hour
Pion experiment - December 1965

Curves normalized to $4 \times 10^4$ particles per sec in counter # 2

<table>
<thead>
<tr>
<th>curve no</th>
<th>particle</th>
<th>polythene absorber</th>
<th>average dose rate $4 \times 10^4$ part/sec</th>
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<tbody>
<tr>
<td>1</td>
<td>$\pi^+$</td>
<td>179 mm</td>
<td>0.10 mrad/hour</td>
</tr>
<tr>
<td>2</td>
<td>$\pi^-$</td>
<td>0</td>
<td>0.13 mrad/hour</td>
</tr>
<tr>
<td>3</td>
<td>$\pi^+$</td>
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<td>0.26 mrad/hour</td>
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<tr>
<td>4</td>
<td>$\pi^-$</td>
<td>179 mm</td>
<td>0.46 mrad/hour</td>
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