KOMMISSION DER EUROPÄISCHEN GEMEINSCHAFTEN
COMMISSION DES COMMUNAUTÉS EUROPÉENNES
COMMISSIONE DELLE COMUNITÀ EUROPEE
COMMISSIE VAN DE EUROPESE GEMEENSCHAPPEN
COMMISSION OF THE EUROPEAN COMMUNITIES
EURATOM

Tagungsberichte — Actes — Atti — Handelingen

Proceedings

THIRD SYMPOSIUM ON MICRODOSIMETRY

Stresa (Italy), October 18 - 22, 1971

edited by H.G. EBERT
Directorate General for Industrial, Technological and Scientific Affairs
Biology Division

II

Published by the Commission of the European Communities
Directorate General for Dissemination of Information
Centre for Information and Documentation — CID
Luxembourg, February 1972

EUR 4810 d-f-e

INHALTSVERZEICHNIS

TABLE DES MATIERES

TABLE OF CONTENTS

SESSION VIII Chairman : Mr BOOZ

SESSION IX Chairman : Mr DELATTRE

SESSION X Chairman : Mr BROERSE

SESSION XI Chairman : Mr CAMPION

SESSION XII Chairman : Mr CASNATI

SESSION XIII Chairman : Mrs PARMENTIER

SESSION XIV Chairman : Mr KATZ

SESSION XV Chairman : Mr ROSSI

SESSION I Chairman : Mr BARENDSEN

OPENING OF THE SYMPOSIUM

SESSION II Chairman : Mr BLANC

SESSION III Chairman : Mr BURGER

SESSION IV — Chairman : Mr KELLERER

SESSION V — Chairman : Mr ROSSI

SESSION VI — Chairman : Mr ARNAUD

SESSION VII Chairman : Mr JACOBI

EVENT FREQUENCY IN SMALL CYLINDERS EXPOSED TO γ-RAYS[x]

Dusan Srdoč, Institute Ruder Boskovic, Zagreb
Albrecht M. Kellerer, Columbia University, New York

ABSTRACT: Event frequencies in microscopic cellular regions exposed to x-rays, γ-rays, and to fast electrons are utilized in various lines of radiobiological reasoning. For spherical regions of diameters up to about 0.1μm diameter these frequencies, Φ, can be obtained according to the associated volume method of LEA. For diameters larger than 0.5μm they can be and have been measured with the commonly employed ROSSI counters. However in the region between 0.1μm and 0.5μm one encounters difficulties both in the experimental and in the theoretical determination of the quantity Φ. An attempt will be described to bridge this gap. Experimental data are reported for cylindrical proportional counters of diameter between 0.1 to 10μm. The observed frequencies of ionizing events are compared to theoretical results. The influence of such factors as energy loss straggling, LET-distribution, and variation of traversal length through the reference region is discussed.

---

[x] Based on work performed under contract AT-(30-2)-2740 for the U.S. Atomic Energy Commission

1. INTRODUCTION

The frequencies of energy deposition events[1,2] produced by various qualities of ionizing radiations in microscopic cellular regions are used in the determination of the size of sensitive sites in the cell or in subcellular structures. Extensive studies have been performed on extremely small spherical regions with diameters of the order of 100 Å. Particularly suited for this case is the associated volume method developed by LEA[3]. For much larger volumes whose diameters are of the order of magnitude of 1 μm experimental results have been obtained by the use of tissue-equivalent proportional counters, the socalled ROSSI-counters. Proportional counters can, however, not be used for the simulation of microscopic regions much smaller than 0.5 μm in diameter. Below this point the gas pressure has to be so low that the region of multiplication extends over a considerable fraction of the sensitive region. Energy deposition near the center of the sensitive region is then weighted less than energy deposition near the periphery of the region. While this effect makes it impossible to obtain reliable microdosimetric spectra $f_1(z)$ one can still try to determine event frequencies. In the following an attempt is described to determine event frequencies in wall-less cylindrical proportional counters which simulate regions down to a diameter of about 0.1 μm and which are exposed to γ-rays.

2. THEORETICAL CONSIDERATIONS

2.1 Formulae for the Frequency of Charged Particle Passages

If an event were defined as the appearance of a charged particle in the reference region then the event frequency would be merely a function of the particle fluence, the mean particle range, and the surface and volume of the region. A charged particle can, however, pass the reference region without energy deposition in this region. Such a zero-event is not included in the event frequency. In microdosimetric measurements one has the further condition that an ionization has to be produced if the particle is to be counted. The probability of zero-events is largest for small stopping powers and for small diameters of the simulated region. A further reason for the difference between the observed event frequency and the frequency of charged particle traversals is the fact that particle passages can be associated with each other; the sensitive region can for example be simultaneously traversed by a charged particle and one of its delta-rays. Such simultaneous passages are counted as one event. The extent of this effect has been analyzed elsewhere[4]; for electrons it is relatively small.

In the following the formulae for the frequency of particle passages will be given. These formulae can be used for the derivation of the event frequencies in regions of the diameter 1μm or more for x-rays and γ-rays and also for much smaller regions in the case of neutrons and heavy charged particles. The deviations from these formulae will be discussed in section 2.2. The frequency Φ_s of charged particle segments in the reference region is given by the following relation:

$$\Phi_s = 0.0624\ (1+\bar{r}/\bar{\ell})\ V/\bar{E}_0 \qquad (1)$$

where $\bar{r}$ is the mean range of the charged particle tracks and $\bar{E}_0$ is the mean initial energy of the charged particles. V is the volume of the regions and $\bar{\ell}$ is its mean chord-length. The range is the total integrated range of the particle including the length of the tracks of all those delta-rays which are not counted as separate charged particles. The mean chord-length $\bar{\ell}$ is equal to 4V/S, where S is the surface of the region. The numerical constant in eq.(1) reflects the choice of units; Φ_s is measured in rad^{-1}, V in μm^3, and $\bar{E}_0$ in keV. The derivation of this formula whose validity is not restricted to straight particle tracks has been given in an earlier work[4].

In many cases, and this is especially true for γ-rays and x-rays, one deals with particle tracks which are long as compared to the dimension of the reference region. In this case one obtains the simplified form of eq.(1):

$$\Phi_S = 0.0156\ \bar{r}S/\bar{E}_0 \tag{2}$$

$$= 0.0156\ S/\bar{L}_T$$

where $\bar{L}_T = \bar{E}_0/\bar{r}$ is the track average LET. One has to use a restricted LET, which includes only delta-rays up to the energy beyond which they are counted as separate charged particles.

For a cylinder of height h and diameter d one must insert the following value $\bar{\ell}$ in eq.(1):

$$\bar{\ell} = hd/(d/2 + h) \tag{3}$$

Eq.(2) then takes the form:

$$\Phi_S = 0.049\ d\ (d/2 + h)/\ \bar{L}_T \tag{4}$$

where Φ_S is in rad^{-1}, d and h are in μm, and $\bar{L}_T = \bar{E}_0/\bar{r}$ is in keV/μm.

For comparison one can give the equation for a sphere of diameter d:

$$\Phi_S = 0.049\ d^2/\ \bar{L}_T \tag{5}$$

and for a cube of side length d:

$$\Phi_S = 0.0936\ d^2/\ \bar{L}_T \tag{6}$$

2.2 Computation of Event Frequencies

As discussed in the preceeding section the counting rate of a proportional counter can be smaller than Φ_s for two reasons. Different track segments may belong to the same event and may therefore not be counted separately. Theoretical considerations indicate that for equivalent diameters up to 10μm and for ^{60}Co-γ radiation the effect is small; the probability for the occurence of simultaneous tracks in an event is well below 0.05. The wall effects which increase this probability to a value of roughly 0.2 need not be discussed because the theoretical results will be compared to data obtained by a wall-less counter.

The effect which concerns us here is the depression of the counting rate due to the fact that at low gas pressure electrons can pass the counter without producing ionizations.

In order to derive the ratio, q, of the counting rate Φ and the frequency Φ_s for ^{60}Co-γ radiation the fluence due to electrons of energy exceeding 10 keV will be considered.[x] It will be assumed that these electrons lose energy in primary collisions with a mean energy transfer δ_1. The value of δ_1 is taken to be independent of the energy of the electron. The mean number of collisions per unit track length is assumed to be L_{10keV}/δ_1; and it is further assumed that the electron passes the volume in a straight track with constant LET.

Under these assumptions one can calculate q as a function of the mean diameter, $\bar{\ell}$, of the region. The expectation value of energy deposition for a particle of linear energy transfer L and for a chord length ℓ is $E=L\ell$ and the distribution p(E) of passages in E is:

---

[x] The fraction of track length contributed by electrons of energy below 10 keV is less than 3% in the case of ^{60}Co-γ radiation, and is therefore neglected in the present calculations.

$$p(E) = \int_0^\infty t(E/\ell)\ c(\ell)\ \frac{1}{\ell}\ d\ell \qquad (7)$$

where t(L) is the distribution of track length in LET and $c(\ell)$ is the chord length distribution. Since E/δ_1 is the expected number of collisions one obtains the following probability that a charged particle passage leads to at least one ionization:

$$q = \int_0^\infty (1 - e^{-E/\delta_1})\ p(E)\ dE \qquad (8)$$

According to eq.(1) the segment frequency Φ_s is proportional to $(1+\bar{r}/\bar{\ell})\bar{\ell}^{3}$ if the fluence is constant and the density of the reference region is constant. In the simulation of microscopic regions with proportional counters the fluence is kept constant but the density varies as $\bar{\ell}^{-2}$; the segment frequency Φ_s is therefore proportional to $(\bar{\ell}+\bar{r})$. The count rate is therefore proportional to $q(1+1/\bar{r})$ and this function is plotted as full line in Fig.1. On the basis of a comparison with the experimental data the value of 105 eV has been chosen for δ_1. The comparison between theoretical and experimental data will be discussed in section 4. The LET distribution t(L) for ^{60}Co-γ radiation and a cut-off energy of 10 keV has been used[5]. The chord-length distribution $c(\ell)$ for a cylinder of elongation 4 has been obtained according to a method described earlier[6,7].

One can give an indication of the relative importance of the variations of LET and the variations of chord length by deriving the counting rates which result if one substitutes the LET distribution and the chord length distribution by their mean values. The dotted line in Fig.1 results if the LET distribution is substituted by its mean value. The broken line results if both the LET distribution and the chord-length distribution are substituted by their mean values.

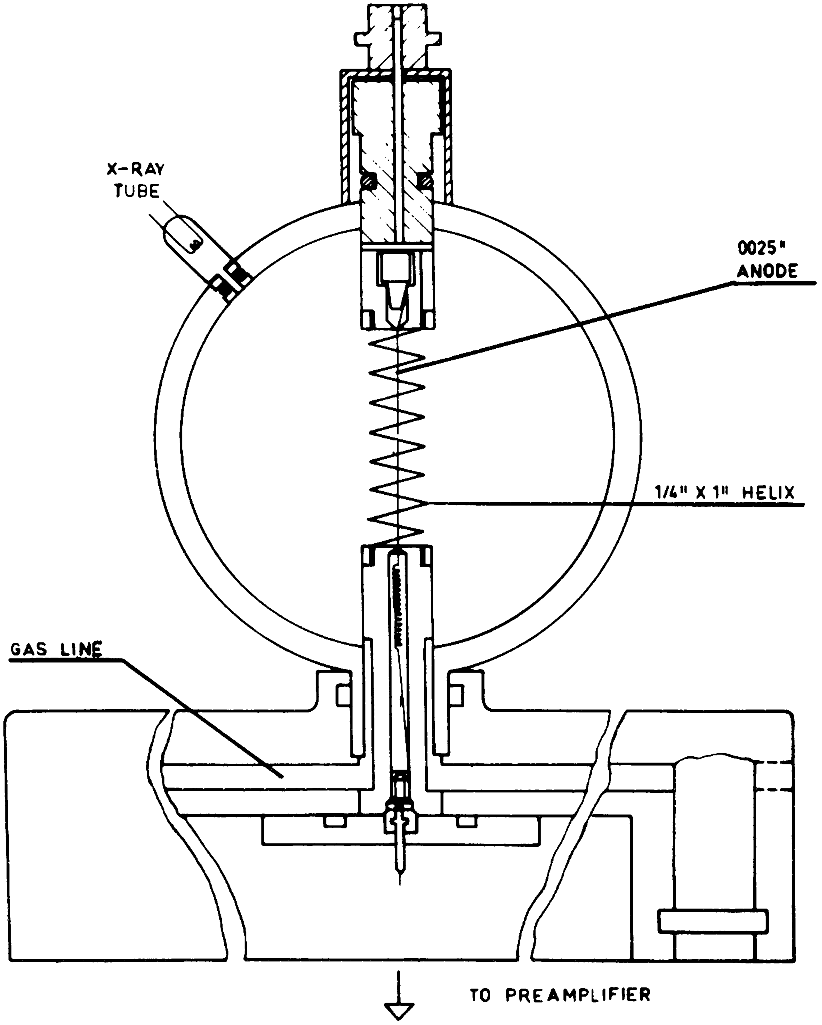

Fig.1 Theoretical counting rate versus mean chord-length of the cylinder (full line). The broken and the dotted line represent approximations (see text). The experimental points correspond to the data in Fig. 3 (• measured counting rate; x values from measured spectra).

The theoretical curves for a spherical region has also been computed. The curve is nearly identical to the one for a cylindrical counter of elongation 4. It is for this reason not shown in Fig.1.

3. EXPERIMENTAL

3.1 The Counter

The wall-less proportional counter which has been used is represented schematically in Fig.2. The counter consists of a helix, 6.35 mm in diameter and 2.54 mm long, mounted in a sphere of tissue-equivalent plastic which has an interior diameter of 50.4 mm. The anode is a 0.06 mm stainless steel wire coaxial within the helix. A tissue-equivalent mixture of propane (64.4 %), carbon dioxide (32.4 %), and nitrogen (5.2 %) is used as counting gas. Pressure is adjusted by means of a manostat within a range from 8 to 600 torr. The corresponding range of the simulated tissue cylinder reaches roughly from the diameter .12μm and the length .48μm to the diameter 9μm and the length 36μm. Calibration of the proportional counter is performed with the 1.48 keV Al line from the x-ray tube.

3.2 Electronics

Pulses from the proportional counter are processed by the electronic system consisting of the FET Preamplifier, the main amplifier, the operational amplifier with logarithmic characteristic and the scaler. The purpose of the operational amplifier is to reduce the spread of the pulse height distribution from the proportional counter to a manageable size. The counting rate at different gas pressure has to be measured within the same energy limits. This has been accomplished by setting the

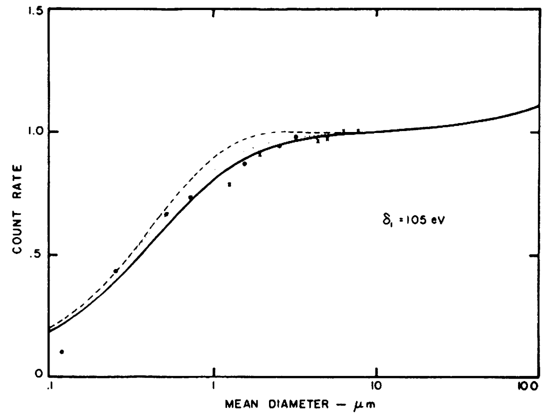

Fig.2 Diagram of the wall-less proportional counter

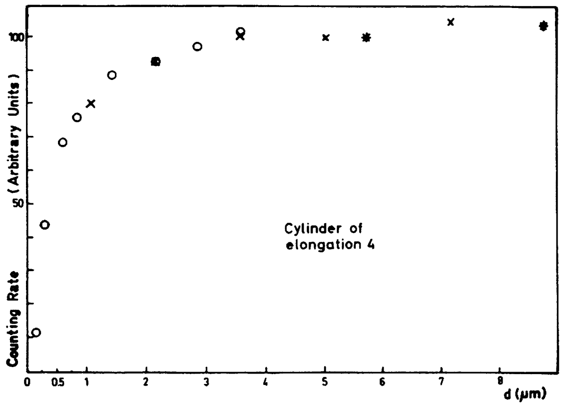

Fig.3 Counting rate versus diameter of simulated tissue cylinder.
(O counting rate, x extrapolated values from measured spectra).

lower and upper discriminator levels exactly to the specified pulse heights which correspond to the lower and upper energy levels.

3.3 Measurements

The counter represented in Fig.2 has been exposed to a constant flux of γ-rays from a ^{60}Co-source. The counting rates have been determined in the pressure range between 8 and 600 torr. The gas multiplication has been kept below $5 \cdot 10^4$. In addition to a simple determination of counting rates, complete spectra have been determined at several pressures and the total number of counts has been summed up. The data are represented in Fig 3. The values of the counting rate obtained by the two methods are in good agreement. This indicates that no significant part of the counting rate is lost when the measurement is performed with a scaler.

4. COMPARISON OF THEORETICAL AND EXPERIMENTAL DATA

The experimental data are inserted in Fig.1 for a comparison with the theoretical curve. One obtains the best overall fit for the value δ_1=105eV and the theoretical curves are therefore given for this value. The fact that the value exceeds the 70eV which have been deduced as mean energy loss per primary collision in experiments on solid foils[8] is understood from the fact that in the latter experiments all primary collisions are counted regardless whether they lead to an ionization. If one disregards the non-ionizing collisions the mean energy loss pro collision is correspondingly increased. At a mean diameter of 0.12μm the counting rate is markedly lower than the theoretical counting rate. This indicates loss of pulses due to the fact that the multiplication region spreads over an appreciable fraction of the counter region at this small equivalent diameter. In order to obtain microdosimetric measurements in this range one would have to use a field shaping electrode around the multiplication wire. On the other hand it can be concluded from the good agreement between experiment and theory for $\bar{\ell}$ = 0.25μm that event frequencies obtained with the proportional counter are still reliable at mean equivalent diameters of 0.25μm.

The ascending part of the curve in Fig.1 at diameters beyond 10μm can not be compared to the present experiments, since they do not extend to this region. The value of $\bar{r}$ used in the derivation of the curve is 1000μm. As one can see from eq.(1) the counting rate increases as $1+\bar{\ell}/\bar{r}$ for large values of $\bar{\ell}$. One concludes that the increase must be much more expressed for soft x-rays, and that in this latter case one can not expect a plateau in the counting rate as a function of pressure.

REFERENCES:

1) Fundamental Quantities and Units, ICRU Report 19, Washington DC (1971)

2) A.M. Kellerer and H.H. Rossi, Summary of Quantities and Functions Employed in Microdosimetry, p. 843, in Proc. 2nd Symposium Microdosimetry, Stresa (1969)

3) D.E. Lea, Actions of Radiations on Living Cells, Cambridge University Press (1946)

4) A.M. Kellerer, Event Simultaneity in Cavities, Theory of the Distortions of Energy Deposition in Proportional Counters, Radiat. Res., in press, (November 1971)

5) Linear Energy Transfer, ICRU Report 16, Washington, D.C. (1970)

6) A.M. Kellerer, Theory of Microdosimetry, in Report on Research Project, Radiol.Res.Laboratories, Columbia University, New York, USAEC (1970)

7) A.M. Kellerer, Considerations on the Random Traversal of Convex Bodies and Solutions for General Cylinders, Radiat. Res. 47, 359-376 (1971)

8) A.M. Rauth and J.A. Simpson, The Energy Loss of Electrons in Solids, Radiat. Res. 22, 643-661 (1964)