Biomedical Dosimetry

Proceedings of a Symposium
Vienna
10-14 March 1975

INTERNATIONAL ATOMIC ENERGY AGENCY, VIENNA, 1975

PROCEEDINGS SERIES

BIOMEDICAL DOSIMETRY

PROCEEDINGS OF AN INTERNATIONAL SYMPOSIUM ON
ADVANCES IN BIOMEDICAL DOSIMETRY
HELD BY THE
INTERNATIONAL ATOMIC ENERGY AGENCY
IN VIENNA, 10-14 MARCH 1975

INTERNATIONAL ATOMIC ENERGY AGENCY
VIENNA, 1975

FOREWORD

The uses of radiation in medicine and biology have grown in scope and diversity to make the radiological sciences a significant factor in both research and clinical practice. Of critical importance in the applications and development of biomedical and radiological techniques is the accuracy with which the dose may be determined at all points of interest in the absorbing medium. The requirements of accuracy and precision in dosimetry have burgeoned as a result of efficacy investigations in clinical radiation therapy, concern for patient safety and diagnostic accuracy in diagnostic radiology, the advent of clinical trials and researches into the use of high LET radiations, and environmental monitoring in radiologic facilities and around nuclear installations.

Thus, advances in the techniques and hardware of biomedical dosimetry have been rapid since the IAEA Symposium on Dosimetry Techniques Applied to Agriculture, Industry, Biology and Medicine, held in Vienna in 1972. It is for these reasons that the present symposium was organized in a concerted effort to focus on the problems, developments and areas of further research in dosimetry in the life sciences. Papers on a range of topics, including instrumentation, techniques and experimental and theoretical studies, were solicited to provide as broad a coverage as possible of the subjects of current research interest.

The first three sessions of the symposium were concerned with neutron dosimetry since the greatest number of proffered papers were devoted to this subject. This is a clear reflection of the increasing practical importance which neutron sources are assuming in experimental clinical radiotherapy studies.

An extensive session was devoted to a review of the status of neutron capture therapy, a subject which has excited renewed interest in the USSR, Japan and the United States. The historical development of this subject was explored from the first clinical trials in the United States to the present status of studies in Japan.

Developments in dosimetry technology to include detectors which are homogeneous with the irradiated material and thermocurrent dosimetry were viewed as providing potential alternatives to existing systems. As in past meetings, the physical aspects of radiation therapy and treatment planning were examined and new methods proposed. In general, it is clear that there is a developing structure extending from the 'Convention du Mètre' in 1875 through the International Bureau of Weights and Measures (BIPM) and the network of the affiliated primary standards laboratories to regional and national secondary standards dosimetry laboratories. In this way, the laborious work of the various international organizations concerned with radiation metrology is coalescing in the widespread dissemination of dosimetry services.

Advances in diagnostic instrumentation and imaging systems promise a reduction of the hazard to the patient without a sacrifice in image fidelity. In both radiation protection and nuclear medicine, it has become increasingly important to assess the dose to tissues accurately – an objective impeded by gross theoretical and experimental difficulties. This topic has come under increasing scrutiny in recent years, and some new insights have been gained.

Approximately 150 participants and observers representing 31 countries and five international organizations attended the symposium in Vienna from 10-14 March, 1975.

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CONTENTS

NEUTRON SOURCES AND MIXED-FIELD DOSIMETRY (Sessions I and II)

Dosimetry of mixed radiation fields (IAEA-SM-193/78) 3
H. Bichsel, J. Eenmaa, K.A. Weaver, P. Wootton
Silicon diodes for fast neutron dosimetry (IAEA-SM-193/4) 19
H. Frank, J. Šeda, J. Trousil
Discussion 37
Chambres d'ionisation opérationnelles pour la dosimétrie des rayonnements à transfert linéique d'énergie élevé (IAEA-SM-193/7) 39
M. Chemtob, C. Fiche, R. Medioni, C. Naudy, V.D. Nguyen, J.P. Noël, Nicole Parmentier, A. Ricourt
Physical parameters of the Heidelberg neutron therapy facility (IAEA-SM-193/15) ... 63
W.J. Lorenz, K.-H. Höver, K.E. Scheer
Discussion 69
Mixed field phantom dosimetry (IAEA-SM-193/18) 71
G. Burger, F. Grünauer, E. Maier
Discussion 84
Physical factors affecting neutron dose in a tissue-equivalent phantom (IAEA-SM-193/87) 87
B. Dörschel, K. Prokert, V. Schuricht
Discussion 94
Measurement of neutron dose by thermally stimulated current in insulating materials (IAEA-SM-193/36) 95
N.W. Ramsey, L.Y. Joesoef
Discussion 103
A precise method for measuring the neutron response of a "neutron-insensitive" dosimeter (IAEA-SM-193/51) 107
Franca T. Kuchnir, C.J. Vyborny, L.S. Skaggs
Discussion 115
Neutron build-up and attenuation in tissue from a ^{252}Cf needle source (IAEA-SM-193/17) 117
E. Piesch, A.M. Sayed
Discussion 131
Gamma and neutron dosimetry of californium brachytherapy sources by means of TLD and plastic track detectors (IAEA-SM-193/26) 133
U. Madhvanath, A.S. Pradhan, G. Venkataraman, K. Ayyangar
Discussion 141

PHYSICAL ASPECTS OF NEUTRON CAPTURE THERAPY (Session III)

Slow-neutron capture therapy for malignant tumours: its history and recent development (IAEA-SM-193/79) 147
H. Hatanaka, W.H. Sweet
Discussion 174

New approaches to the dosimetry of boron neutron capture therapy at MIT-MGH (IAEA-SM-193/48) 179
B.W. Murray, O.L. Deutsch, R.G. Zamenhof, R.I. Pettigrew, R.A. Rydin, G.L. Brownell
Discussion 202
Elimination of gamma rays from a thermal neutron field for medical and biological irradiation purposes (IAEA-SM-193/68) 205
K. Kanda, T. Kobayashi, K. Ono, T. Sato, T. Shibata, Y. Ueno, Y. Mishima, H. Hatanaka, Y. Nishiwaki

DEVELOPMENTS IN DOSIMETRY (Session IV)

Dosimétrie par déclin de la fluorescence de verres radiophotoluminescents (IAEA-SM-193/13) 227
J. Barthe, D. Blanc, L. Commanay, H. François
Discussion 239
Химическая дозиметрия в радиобиологии (IAEA-SM-193/85) 241
И.К. Соколова
(Chemical dosimetry in radiobiology: Ida K. Sokolova)
Discussion 247
High sensitivity thermocurrent dosimetry (TCD) with alumina (IAEA-SM-193/49) ... 249
G.D. Fullerton, J.R. Cameron, M.R. Mayhugh, P.R. Moran
Discussion 263
Bone-and-muscle-equivalent solid chemical dose meters for photon and electron doses above one kilorad (IAEA-SM-193/52) 267
W.L. McLaughlin, M. Rosenstein, H. Levine
Discussion 280

PHYSICAL ASPECTS OF RADIATION THERAPY AND TREATMENT PLANNING (Sessions V and VII)

LET calculations based on spectral measurements of primary and scattered radiation from radiotherapeutic sources (IAEA-SM-193/5) 285
K.A. Jessen
Discussion 291
Simulation du transport des électrons de radiothérapie dans un milieu irradié à travers un cache diffuseur (IAEA-SM-193/12) 293
J.P. Patau, R. Pandelle, M. Terrissol
Discussion 313
A new concept of dose determination for treatment planning (IAEA-SM-193/23) 315
J.K. Böhm, G. Hehn, G. Pfister, G. Prillinger
Discussion 325
Dose distribution in the paraxial regions of cobalt-60 and caesium-137 brachytherapy line sources (IAEA-SM-193/28) 327
S. Jayaraman, P.S. Iyer
Discussion 334
The usefulness of thermoluminescence dosimetry in clinical radiation therapy (IAEA-SM-193/42) 335
C.M. Mansfield, N. Suntharalingam
Discussion 345

An integrated ultrasound-computer dosimetry system for radiation therapy (IAEA-SM-193/47) 347
J.M. Slater, W.T. Chu, J.E. Chrispens, I.R. Neilsen
Discussion 353
Cell survival and iso-effect contours in irradiated tissues (IAEA-SM-193/69) 355
L. Cohen
Discussion 367
Low energy electron dose measurements in the design of large-field applicators and moving field techniques (IAEA-SM-193/66) 371
S.C. Lillicrap, B. Breyer
Discussion 382

INTERNATIONAL, NATIONAL AND REGIONAL RADIATION METROLOGY PROGRAMMES (Session VI)

Installations et méthodes d'étalonnage des dosimètres au laboratoire de mesure des rayonnements du Centre d'études nucléaires de Grenoble (IAEA-SM-193/10) 389
H. de Choudens, Yvonne Herbaut, A. Haddad, J. Giroux, J. Rouillon
Discussion 404
Primary standard dosimetry in Hungary and international dose intercomparisons since 1938 (IAEA-SM-193/25) 405
L. Bozóky, K. Zsdánszky, J. Hizó
Discussion 415
Techniques and uncertainties in the calibration of dose meters against national standards in a regional reference centre (IAEA-SM-193/30) 417
I.S. Sundara Rao, A. Kannan, V.W. Naik, S.B. Naik, P.N.M.R. Vijayam, G. Subrahmanian
Discussion 422
Centro Regional Standard Secundario de Calibración y Dosimetría de la SSA de México establecido por la OMS y el OIEA (IAEA-SM-193/32) 423
V.M. Tovar Muñoz, R. Diaz Perches
Discussion 439
Current activities of the Brazilian secondary standard dosimetry laboratory with regard to clinical dosimetry (IAEA-SM-193/82) 441
P.H. Nette, G. Drexler, R.N. Alves, R.G. Roenick, E.J. Pires, J.L.B. Leão
Discussion 449
SI units in biomedical dosimetry (IAEA-SM-193/35) 451
K. Lidén
Discussion 459
Calibration of dose meters (IAEA-SM-193/84) 463
P. Pychlau
Discussion 470

DIAGNOSTIC MEDICAL X-RAY SOURCES, IMAGING SYSTEMS AND PATIENT DOSE (Session VIII)

Xeroradiography and ionography: a review (IAEA-SM-193/83) 475
J.W. Boag
Discussion 498
A new fluorescence X-ray source (IAEA-SM-193/20) 499
G. Drexler, M. Gossrau, W. Panzer, H. Schöfer
Discussion 506

Standardization of the output from diagnostic X-ray generators (IAEA-SM-193/54) 509
J.A.B. Gibson, G.M. Ardran, L.H.J. Peaple, M. Marshall, H.E. Crooks, R. Birch
Discussion 519
The use of channel electron multipliers for the analysis of X-ray beams emitted by diagnostic tubes (IAEA-SM-193/74) 521
M. Martinelli, M. Paganini Fioratti, S. Ricci Piermattei, A. Marchetti
Discussion 526
Study of certain aspects affecting patient dose and diagnostic accuracy (IAEA-SM-193/29) 529
T.Y. Ambiger, P. Ayappan, Hatimbhai, P.S. Viswanathan, P.S. Iyer
Image quality and patient exposure in mammography, tomography, angiography and bone radiography (IAEA-SM-193/41) 539
A.G. Haus, K. Rossmann, K. Doi, J.T. Chiles
Discussion 554
Assessment of population dose in X-ray diagnosis in Brazil (IAEA-SM-193/81) 557
R.N. Alves, A.M. Araujo, P.H. Nette, J.E. Peixoto, V.R. Reis, H.C. Tostes, J.M. Vasconcellos

HIGH-ENERGY ELECTRON AND GAMMA-RAY DOSIMETRY (Session IX)

Experience in the use of $FeSO_4$ in some practical aspects of high-energy electron dosimetry (IAEA-SM-193/73) 563
A. Wambersie, A. Dutreix, M. Prignot
Discussion 574
Absolute determination of high-energy electron dose in the light of recent results in ionization dosimetry (IAEA-SM-193/16) 579
B. Markus
Discussion 587
Stopping-power ratios for electron dosimetry with ionization chambers (IAEA-SM-193/39) 589
M.J. Berger, S.M. Seltzer, S.R. Domen, P.J. Lamperti
Discussion 609
Contribution à la connaissance des constantes fondamentales $\overline{W}$ et G intervenant dans les mesures de dose absorbée (IAEA-SM-193/71) 611
J.P. Guiho, J.P. Simoen
Discussion 622
Silicon detectors for measurement of high exposure rate gamma rays (IAEA-SM-193/60) 623
Margaret Osvay, V. Stenger, G. Földiák
Discussion 631
A calorimetric approach to the calibration of liquid dose meters in high-intensity electron beams (IAEA-SM-193/70) 633
B.B. Radak, M.M. Kosanić, M.B. Šešić, W.L. McLaughlin

DOSE DETERMINATION FOR INGESTED OR ADMINISTERED RADIONUCLIDES (Session X)

Specific energies in cell nuclei from incorporated isotopes: computer calculations for plutonium-239 (IAEA-SM-193/21) 645
G. Tisljar-Lentulis, L.E. Feinendegen, H. Walther
Discussion 653

Radiation absorbed dose from medically administered radiopharmaceuticals (IAEA-SM-193/14) 655
H.D. Roedler, A. Kaul
Discussion 664
Problèmes de dosimétrie et de radioprotection dans l'emploi des radioisotopes à des fins diagnostiques (IAEA-SM-193/31) 667
L. Conte, L. Mombelli
Discussion 681
Radiation dose patterns for inhaled radionuclides (IAEA-SM-193/64) 683
M.B. Snipes, A.J. Hulbert, G.E. Runkle

Chairmen of Sessions and Secretariat of the Symposium 695
List of Participants 697
Author Index 707

NEUTRON SOURCES AND MIXED-FIELD DOSIMETRY

(Sessions I and II)

Session I

Chairman: H. Bichsel (United States of America)

Session II

Chairman: G. Burger (Federal Republic of Germany)

DOSIMETRY OF MIXED RADIATION FIELDS*

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Abstract

DOSIMETRY OF MIXED RADIATION FIELDS.

Concepts of radiation dosimetry are examined. A generalized definition of "mixed radiation fields" is presented, and examples are given. Various parameters needed to describe mixed fields and methods of determining them are discussed. Particular attention is given to the use of proportional counters. Dual device techniques and associated errors are examined in detail.

1. INTRODUCTION

The purpose of radiation dosimetry[1] is to provide a description of the properties of ionizing radiations. In radiation damage studies, for example, the particle fluence is used for this purpose. Usually though, the energy deposited in a material is considered to be relevant. Due to the stochastic nature of the radiation interaction processes the distribution of energy deposited at a molecular level is highly inhomogeneous (p. 44 of [1]). To give a really complete physical description of energy deposition the following information would have to be provided:

A) The distribution function ϕ for all possible collisions. In particular, distribution in space, in time, and in local energy deposition would have to be included. In each energy loss event, the "local energy" ε inside a small volume shall be defined as the difference between the energy lost by the particle and the energy carried out of the volume by secondaries (e.g., δ-rays, Auger electrons, fluorescence radiation, and bremsstrahlung). The average value of ε shall be denoted by $< \varepsilon >$ and probably is less than 30 eV. The volume under consideration can be assumed to be of atomic size (about 3Å in diameter). For collective excitations though, energy may be deposited somewhat further from the track of a particle.

B) The absolute number n of collisions that have taken place during a given irradiation.

As an example, irradiation by neutrons will be considered. The following processes would contribute to the function ϕ:

a) The production of primary charged particles (protons, deuterons, alpha particles, oxygen ions, etc.). For each particle produced, there will be an

* This project was supported by Grant No. CA12441, awarded by the National Cancer Institute, DHEW.

[1] The narrow meaning of "dosimetry" refers to the measurement of absorbed dose in a material at a point of interest. An extended meaning is used here [1].

initial collision event (for a recoil proton, the binding energy of the proton in the lattice of the material will be the energy lost locally), and subsequent collisions as the particle travels through the material.

b) The production of secondary charged particles (mainly electrons, usually called delta rays; for present purposes, no lower limit for the energy of a δ-ray shall be assumed). Most secondaries will produce further collisions.

c) Excitation processes in the material. In organic solids (probably including tissue), the most probably energy loss occurs at an energy of about 25 eV [2], resembling a "collective excitation" [3]. We believe that one (or possibly several) secondary electrons with an energy of around 20 eV usually will appear shortly after the collision occurs.

In practice, the distribution ϕ cannot be measured; in fact, it is unique for each irradiation.

The function customarily used to describe various aspects of energy deposition (e.g., LET distributions) are summations over ϕ. For example, in microdosimetry, the ionization (which is related to the energy deposition) produced by a number of collisions in a volume of the order of $1\mu m^3$ in a short time interval[2] is summed . Usually, the collisions are due to the passage of a single charged particle through the gas in a proportional counter.

In macrodosimetry (routine dosimetry), the description of the radiation effects is greatly simplified: the absorbed dose D is a single number expressing the average value of ϕ:

$$D \equiv n_1 \cdot < \varepsilon >$$

where n_1 is the number of collisions per gram of material (in a small volume containing of the order of 1 mg of material). Frequently the total dose D is measured with a gas filled ionization chamber.

In the irradiation of a gas, the quantities observed in an ion chamber are closely related to the quantities defined above: the average energy to produce an ion pair, W, corresponds to $< \varepsilon >$, and the number of ion pairs produced is related to n defined in B) above, but no information about ϕ is obtained.

In general, our measurements have to be tailored to the requirements of the user of the data. Unfortunately, it is not at all clear which physical data are needed to correlate, e.g., to biological effects. An attempt at a general discussion has been given by Kellerer [4]. Typically, average quantities such as LET, mean event size in a small volume, etc., are used. It is conceivable though that some particular geometrical pattern (in a space-time-energy continuum) of ϕ is needed to produce certain biological effects. If the biological material also has many sensitive loci in a given pattern, requiring energy deposition in only a few sites to produce a given effect, the possible combinations of the two patterns producing the final effect could be very large. Clearly, average values describing ϕ in the cell (such as the moments of ϕ) may not be sufficient to correlate the biological effect to the physical dosimetry. In particular, this implies that identical LET-spectra do not necessarily produce identical biological effects [5] for the same dose.

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[2] Limited by the resolution of the electronic equipment used for the measurement (typically about 1 μsec).

2. MIXED RADIATION FIELDS

2.1. Definitions

Usually mixed fields are understood to consist of two or more species of radiation (e.g., neutrons and photons). From the point of view of energy deposition, this is too simplistic. We will have to define fields producing or containing particles with a range of LET values[3] including LET greater than a few keV/μm as mixed radiation fields. The total absorbed dose D delivered to a material is then not adequate to relate radiation effects to radiation dose.

Radiations with LET of less than about 2 keV/μm have an RBE close to 1. Thus, even though photons produce electrons of a wide range on energies, photon radiation fields are not considered to be mixed fields. Similarly, we would have to consider protons of energies above 30 MeV and pions with energies greater than 5 MeV as equivalent to photons.

Of great importance is the mixed field encountered in neutron irradiation: a fraction of the dose is always delivered by photons.

A fast pion beam is always contaminated with muons, electrons, and photons. Since these are low LET particles, the beam can be considered homogeneous. However, the heavy ions produced by fast pions may produce a high LET component. In addition, at the end of the range of the pion, various heavy charged particles and neutrons are produced. Here, the radiation field is mixed indeed.

A beam of fast heavy ions (e.g., protons, Ne-ions) travelling through a material will produce various charged particles in nuclear reactions, and thus may produce a mixed field.

2.2. Physical Description of Mixed Fields

As mentioned above, we cannot expect to be able to calculate biological effects from even a ϕ distribution. However, if biological measurements have been performed for a given radiation field and if the new field does not differ substantially from the original one (e.g., a change from ^{137}Cs-photons to ^{60}Co-photons), then we can hope to predict the change in biological effect. For a large change in the two fields, we will need many parameters to describe the change.

The simplest description is given by two parameters; e.g., neutron dose D_n and photon dose D_γ can be used for neutron-photon fields. A description with many parameters would be given by the energy deposition spectrum in biological cells under investigation.

In a pion beam, very substantial changes in RBE are observed in the stopping region of the pions [6]. A very detailed study of energy deposition patterns will have to be made if physical data are to be related to biological effect.

On the other hand, in neutron radiation therapy, it has been found that relatively small changes occur in the spectrum of the neutron beams from Be (d,n) reactions once the radiation has entered the body. Correspondingly, small changes in RBE for the neutrons would be expected, and a description of

---

[3] LET here is used as a convenient way of classifying various radiations. We do not intend to endorse its use in the description of biological effects.

the changes in ϕ with only one or two parameters may be sufficient. One of the most important changes in penetrating deeper into the body will be the increasing fraction of γ-rays produced in the body and accompanying the neutron beam. An identical tumor located at different depths in the body would have to be irradiated with different total doses to produce the identical biological effect. From the narrowest point of view, it may not be possible to reproduce the biological effects exactly. It is conceivable that the regression rate functions would be different at the different depths even if at some time during the course of treatment the total doses might be adjusted such that the regression rates would coincide for a short period of time. In the end, these differences would disappear because the tumor must not contain any living cells and the effective change in total dose would be dictated by this requirement.

While we do not have any assurance that superimposed radiation of various types will produce additive biological effects, for preliminary purposes this assumption can be made, and a determination of the fraction of γ-ray dose accompanying a neutron dose may be just adequate to predict the biological effect. We must always remember though, that our total biological effect calculated from the γ-dose fraction will be wrong - though maybe not be a large amount.

For neutron beams which are monoenergetic initially (especially the 15-MeV neutrons from the T(d,n) reaction), it is to be expected that the neutron spectrum changes substantially as the beam penetrates into a material. A determination of the photon component of the dose might not be sufficient to predict the biological effect at a depth of 10 - 15 cm.

Determination of dose fractions is also important if one wishes to change shielding or collimation. This will alter the relative composition of a mixed field. Finally, knowledge of relative dose fractions or of the energy-deposition spectrum is necessary for estimating quality factors of mixed fields.

3. PRINCIPLES OF MIXED FIELD DOSIMETRY

3.1. Calculations

The collision distribution function ϕ and quantities derived from it can be calculated. In order to do this, it is necessary to know the particle fluence in the volume under consideration. Then, from our knowledge of differential atomic collision cross sections and differential nuclear cross sections, we can calculate ϕ and derived average quantities (microdosimetric spectra, average dose, etc.).

3.2. Measurement of Energy Deposition Spectra

For some applications, a satisfactory amount of information can be obtained from microdosimetric measurements. In particular, calculations of averages over ϕ can be tested experimentally.

3.3. Special Methods for Neutrons Mixed with Photons

Frequently, only two parameters are used to describe this mixed field, viz., D_n and D_γ. A number of methods are available to distinguish between neutron and photon components of the field:

3.3.1. Use of the LET difference between the electrons produced by photons and the heavy ions produced by neutrons.

Examples of instruments sensitive to this difference are proportional counters, organic scintillators (rise time difference) and thermoluminescent dosimeters (TLD, changes in glow curve structure [7, 8]).

3.3.2. Direct difference effects of the primary interactions.

Devices highly sensitive to neutrons and photons are combined with devices with low sensitivity to neutrons and high sensitivity to photons. If the sensitivity of each device is known, the respective fractions of photon dose and neutron dose can be calculated. A typical example would be the ion chamber pair consisting of polyethylene-ethylene and graphite-CO_2.

In general, any pair of devices, one containing a large amount of hydrogen and the other no hydrogen at all, will fall into this category. Various instruments of this type will be described later.

3.3.3. Devices to measure neutron fluence, such as neutron activation foils, time-and-flight measurements or proton recoil spectrometers.

4. INSTRUMENTS

4.1. Proportional Counters

4.1.1. General discussion

An energy deposition of as little as one ion pair has been observed with proportional counters [9]. We therefore can use them in the measurement of the distribution of energy-deposition events in very small amounts of gases. In particular, it will be possible to distinguish to some extent between events caused by electrons and by heavy ions, especially of those with charge $z > 1$, but also of those with $z = 1$ at moderate energies (e.g., protons below about 30 MeV).

An extensive literature about proportional counters and their uses exists [10], but the application to the determination of the photon component in a neutron field is described infrequently [11, 12, 13]. At present, counters with tissue-equivalent walls are used. Based on our knowledge of nuclear reaction cross sections, we can anticipate that for neutrons with moderate energies a proportional counter with Be, C [14], or Mg walls might permit a determination of a photon component with better separation between electrons and neutron reaction products. Caswell's experience indicates the difficulties of operating a counter with graphite walls.

Proportional counters with walls of Be might, however, be quite suitable. The Be (n, p) reaction has a very small cross section, so that few low LET particles will be produced by neutrons. Discrimination against all other charged particles produced will be easy. The problems with photons produced in the Be by neutrons are similar to those for C.

Early work with proportional counters lined with polyethylene relied on the rejection of γ-ray pulses with a single discriminator in order to establish the dose due to neutrons alone [15, 16].

4.1.2. Measurements at the University of Washington

Spherical proportional counters[4] are used with standard amplifiers and multichannel analyzers for the measurements[5]. In order to be able to measure very small event sizes, tissue equivalent gas of composition (by volume) 54% propane, 41% CO_2 and 5% N_2 is used. The measured energy deposition E_d (obtained by assuming a constant value of W for all particles) is reduced to "event-size" $Y = E_d/d$ where d is the diameter of the sphere expressed in terms of tissue-equivalent material of density 1 g cm^{-3}. Usually Y is expressed in keV/μm.

Rather than considering the observed event spectra f(Y), it is advantageous to plot Yf(Y) versus Y or $Y^2f(Y)$ versus log Y [17]. The area A under the curve between two values Y_1 and Y_2,

$$A = \int_{Y_1}^{Y_2} Yf(Y)dY = \int_{Y_1}^{Y_2} Y^2 f(Y)\, d\log Y$$

is then equal to the contribution to the dose from this event size interval, Fig. 1.

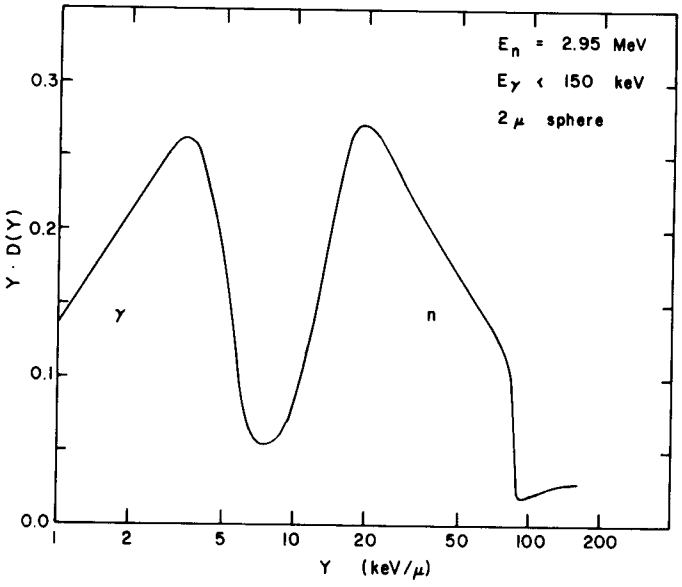

FIG. 1. Dose spectrum due to X-rays and 2.95-MeV neutrons. In this case, dose separation can be accomplished with a pulse-height discriminator.

[4] Interior diameter 1.27 cm, tissue-equivalent walls. Model LET - ½. Available from EG&G Co., Goleta, California.

[5] Details available from the authors.