STATUS REPORT

THROUGH 1 NOVEMBER 1968

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Medical College of Virginia
Richmond, Va. 23219

Department of Radiology
(E. Richard King, M. D., Chairman)

Radiation Physics Division

STATUS REPORT

FOR

PERIOD THROUGH 1 OCTOBER 1963

on

NASA Grant NGR 47-002-004*

(Investigation of total energy absorption in omni-directional gamma-ray, Bremsstrahlung and neutron fluxes)

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Langley Research Center

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*Office of Advanced Research and Technology, Division of Biotechnology and Human Research

Introduction

All stages of NASA project NGR 47-002-004 (expiring March 1, 1969) - with the exception of Phases I(b), V and VII, where funds have proved inadequate - are proceeding as planned and results are being collated for inclusion in a final report. In the following summary of progress to October 1, 1968, the work is described under Phase numbers keyed to the most recent application for continued support.

Phase I (Gamma-spectroscopy)

It has been pointed out in earlier reports that the matrix-inversion method of obtaining photon spectra by "unscrambling" pulse-height distributions is seriously hampered by lack of gamma emitters with suitable energies. The group's proposal to eliminate this difficulty by generating essentially monoenergetic calibration radiation through selective Compton scattering has been successfully completed and the results have been incorporated in a paper "Production of Variable Energy Calibrating Radiation By Compton Scattering"*. The technique has been shown to be a relatively easy means of producing radiations of narrowly-defined and readily-adjustable energies up to at least 1 MeV.

The successful exploitation of the method has attracted some attention. Short accounts of it were given at the Winter meeting of the American Association of Physicists in Medicine and at the Spring meeting of the American

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*Manuscript included in this report as Appendix I; submitted for publication to Nuclear Instruments and Methods.

Physical Society. The principal investigator has also described the technique in a guest lecture at the Radiation Physics Division of the National Bureau of Standards, September 17, 1968. Interest arises because the technique is of particular value in the generation of response functions for semi-conductor detectors and because it employs a specially-designed collimating system which has revealed - and affords a means of excluding - the severe disturbing effects of scattered radiation in spectrometry below 1 MeV. One of the disadvantages of the technique is that intense sources (of order several curies) are required and that, as a consequence, the equipment is very cumbersome. A step towards rationalization has been taken by the provision of an air-carriage of the "hovercraft" type which permits precise angular positioning of very considerable masses of lead.

It is possible, as suggested in Appendix I, that the technique can be extended to very much higher energies using accelerator-produced de-excitation gamma rays as inputs, but this development is outside the scope of the present investigation.

The experiment suggested as Section b of Phase I has not been carried out because of lack of funds.

Phase II (Chemical Dosimetry)

Phase II, dealing with chemical dosimetry, has been completed as previously reported. Very considerable benefit has been obtained from this work and it has been applied to some investigations that have not only benefited the clinical work of the Medical College of Virginia, but have attracted widespread attention in the U.S. and abroad. A brief description of this "spin-off" work is given below.

Phase III (High-sensitivity Organic Scintillator Dosimeters)

Under Phase III, it was proposed to set up an organic scintillation detector working in the "pulse" rather than the "total-current" mode and this work has since been completed and an account given of it in a paper entitled "Scintillation Dosimetry, and an Application of It", which will shortly appear in the Journal of the New York Academy of Sciences*. This work has resulted in the production of a detector of extremely high sensitivity which, as pointed out in Appendix 2, has the capability - at least in principle - of yielding the energy deposition within the detector directly in ergs, without reliance on calorimetry.

Further work on this detecting system will involve a study of its energy dependence through the use of the Compton-scattered radiations mentioned under Phase I. This technique considerably simplifies the study of energy response over a very wide energy range.

Phase IV (Bremsstrahlung Inputs)

It was originally proposed that the Langley Research Center provide information on the Bremsstrahlung spectra to be expected from interactions of electron fluxes with the walls of space capsules - or alternatively provide access to electron-accelerating equipment with which the requisite measurements could be made - but neither of these approaches has been feasible.

Instead the group is attempting to carry out these measurements at the Medical College of Virginia. This has been made possible by the acquisition of a 2 MeV 250 μA Van de Graaff generator which has been installed and commissioned by the group. The machine, originally housed at the National Institutes of Health, has had to be completely overhauled and furnished with a new horizontal mounting, new vacuum components and other accessories; these

*Manuscript included here as Appendix 2.

Virginia Reactor Facility, a preliminary experiment was carried out* on the emission of neutrons produced in the (p,n) reactions of sodium-24 gamma rays (2.7 MeV) on heavy water, using sheathed sodium wires immersed in D_2O. Neutrons were detected at approximately the expected intensity; discrimination against the accompanying gamma rays was easily achieved. Further work using distributed sources will probably be undertaken in the next few months. Dr. Williamson, to whom we are very grateful, has indicated his willingness to continue these experiments in collaboration; if the present funds prove insufficient, as is likely, a joint proposal in respect of this development may be made in the near future.

Spin-Off

Several phases of the work under this project have proved of value in clinical areas. Of these the most important are:

Blood Irradiation: In collaboration with Dr. James Wolf of the Department of Surgery, a number of extra-corporeal blood irradiators have been fabricated and used extensively in the treatment of the rejection phenomenon in patients undergoing kidney transplantation. The dosimetry of these applicators would have been impossible were it not for the chemical dosimetry undertaken in Phase II - in particular, if the Balkwell-Adams modification of the Fricke system had not been investigated. This modified Fricke approach permits the use of very short irradiation times, since high optical densities are achieved at quite low absorbed doses. Furthermore, shielding problems arising from Bremsstrahlung production in the encapsulating materials has been solved by application of the gamma spectrometric techniques devised under Phase I, and it has been possible to demonstrate the superiority of aluminum-encapsulated sources in reducing external hazard.

This work has aroused considerable interest in the U.S. and abroad. An account of it was given at the Winter meeting of the Radiological Society of North America and at the Fifth Congress of the European Dialysis and Transplant Association, June 1968. A short paper by the principal investigator and Dr. Wolf has appeared+ and another is in preparation.

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*Dr. Williamson's account is included here as Appendix 3.

+Included here as Appendix 4.

Bone-Calcium Determinations: In collaboration with the Department of Orthopedic Surgery, an apparatus to determine bone calcification by observing absorption of a narrow gamma-ray pencil traversing the bone (the so-called Cameron technique) has been set up and brought into operation. Although no direct NASA support was involved, this technique could not have been initiated without the availability of the NASA project's multi-channel analyzer which, when operated in the multi-scale mode, is an adequate substitute for the digital rateмeter needed. Furthermore, the spectroscopic experience gained in the project and the availability of radiation standards used in it, have considerably simplified the work, which, having been "seeded" by the NASA project is now due to expand with support from other sources.

Radioactive Isotope Telemetry: In collaboration with Drs. Trombka and Schmadebeck of Goddard Space Flight Center (who have been extremely helpful through apparatus loans, interchange of standards, etc., in furthering the experiments described under Phase I) and of Dr. Alton Sharpe, Chairman of the Nuclear Medicine Division at the Medical College of Virginia, preliminary studies have been made of the possibility of remote radioisotope diagnosis. A brief account of this work was given in a paper delivered by Dr. Trombka at the American Chemical Society meeting+held in Atlantic City*; and further work is planned. Collaboration with the Goddard group is valuable in the gamma-spectroscopic work since there is access to the specialized computer programs under development at Goddard.

Scatter-Radius Function: In Status Report 2 of this project, it was pointed out that a new formulation of the scatter-radius function (which is of importance in calculating integral absorbed dose) had been worked out by project staff and in a later report construction of a Wheatley integrator permitting rapid application of this formulation was described. This work has continued in collaboration with Dr. Fred Schmidt of Emory University and a brief account of it has been given in the paper already mentioned (see Appendix 3).

It is hoped that tabulations of the quantities entering into this formulation will soon be published, leading to a rationalization of integral dose calculations in clinical practice.

Budget and Staff

Because of changes in the method of overhead calculations, funds have proved insufficient to press the work as vigorously as is desirable. Figures for expenditures are not given here, but can be obtained from Mr. L. Daniel Crooks, Vice-President, Business and Financial Affairs, Medical College of Virginia, Richmond, Virginia.

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*Abstract enclosed as Appendix 5.

+September 11, 1968

high degree of approximation (section 5). Knowing that equal fluxes of both types of radiation at the same mean energy produce Gaussians of equal area differing only in their half-widths, it is easy to calculate the expected peak shape for one kind of input if it is known for the other and if resolution data are available (as in Fig. 5) in both cases. The Compton continua can of course be corrected in the same way as the photopeaks but we have found that the resulting changes in shape are negligible except at the extreme upper end of the continuum.

To test the correction method we varied $\Delta\phi$ and hence the energy-spread, by changing the distance between the crystal and the scattering ball, keeping the mean energy constant. The observed spectra were then corrected for energy-spread in the way described; in all cases, the calculated shapes agreed exactly with those obtained when truly monoenergetic (unscattered) radiations were used in identical geometries. The results were equally good for two widely-differing values of the mean energy, showing that the method can be applied with confidence in the energy range of interest to us.

In applications where corrections for energy-spread are vital, they can be made very small by employing large source activities, which permit small values of $\Delta\phi$ to be used, and by working at large ϕ where E_s as a rule changes rather slowly with angle (Fig. 2).

5. Results

Fig. 6 and 7 show four typical spectra, generated by using the source energies and scattering angles shown in Table 1, where measured values of the true and apparent resolutions are also given. No corrections have been applied to the raw data except background subtraction and (in spectra [c] and [d]) elimination of the annihilation component.

The satisfactory shapes and relatively small heights - even in

Staffing problems have continued and Dr. R. A. Leimgruber, who had been with the group since April 1967, had to resign because of the impossibility of guaranteeing permanent support. The resignation means that no full-time staff are now available.

Production of Variable-energy Calibrating Radiation by Compton Scattering*

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Some uses of variable-energy gamma rays are described and methods of generating them are summarized. Experiments are reported on the use of one such method in calibrating scintillation detectors. Monoenergetic photons are Compton-scattered from a small object and those entering a small angle are viewed by the detector; selection of various scattering angles allows the calibrating energy to be varied at will. A method of correcting for the effects of the energy-spread inherent in the method is described and an account is given of a box-like ("cavity") collimator designed to eliminate unwanted radiation derived from scattering in the laboratory walls. Typical pulse-height spectra obtained by the method are presented, and their features are discussed. The failure of the method at low energies is pointed out and a scheme for applying it in the region up to 10 MeV is suggested.

1) Introduction

Many gamma-ray studies, among them the measurement of energy-dependent cross-sections, the investigation of nuclear resonant scattering and the calibration of detectors, would be simplified if it were possible to produce gamma photons of continuously variable energy. Availability of such radiations would also make it easier to construct response matrices used in unscrambling scintillation pulse-height spectra[3]; in such work the instrumental response should be known at as many energies as possible, but the nuclide-produced gamma rays usually used in studying it are inconveniently spaced and uncertain interpolations become necessary when results are needed at intermediate energies.

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*This work, briefly reported elsewhere[1,2], was performed under Grant NGR 47-002-004, U. S. National Aeronautics and Space Administration

*On leave of absence from Swiss Federal Institute for Reactor Research, Würenlingen, Switzerland

One way of generating variable-energy radiation is to excite characteristic x-rays by photon or charged-particle bombardment of various targets[4]. Since the characteristic energy varies smoothly with the atomic number of the target material a range of energies can be produced, but the method is unfortunately limited to the region below 0.1 MeV. Selection of sharp energy bands by crystal diffraction of x-ray continua is also possible[5] but the diffracted intensity is small and it is difficult to obtain beams that are wide enough to cover the input face of typical scintillation detectors. Another approach is to impart a high velocity to a radioactive source[6] thereby causing a controllable Doppler shift, but the equipment is complex and the effects are small at practicable speeds. Lastly it is possible to use radiation which has been Compton-scattered from an object struck by an initially monoenergetic beam[7]; Ricci[8] has applied this method in measuring crystal photopeak efficiencies and others[9,10] have used it in observing resonant nuclear scattering. In the following we report further studies of the technique, which we have applied[11] in the production of scintillation response matrices.

2) Principle of the Method

Fig. 1 shows an apparatus in which a well-collimated beam of mono-energetic photons strikes a small scattering object. The radiation scattered at a mean angle ϕ is selected by a second box-like collimator ("cavity collimator") surrounding the detector that is to be calibrated. The energy E_γ of the incident photons is reduced during scattering to a value E_s given by

$$E_s = \frac{E_\gamma}{1 + \frac{E_\gamma}{m_0c^2}(1 - \cos\phi)} \qquad (m_0c^2 = \text{electron rest-energy})$$

a relationship shown graphically in Fig. 2 for two of the initial energies (0.412 and 1.114 MeV) used in the present experiments; the dependence of curve shape on E_γ is gradual in the range of E_γ dealt with here and does not affect the following discussion.

An angular spread $\Delta\phi$ about the mean scattering angle ϕ is unavoidable if the entire crystal face is to be illuminated. The photons striking the crystal are therefore not truly monoenergetic, but are distributed over an energy interval whose width ΔE depends, at fixed E_γ and ϕ, on the value of $\Delta\phi$ used. Since the scattering process redistributes the incident photons over the entire space surrounding the scattering object, those entering the sector $\Delta\phi$ - which must be very small in order to keep ΔE within reasonable bounds - constitute only a tiny fraction of those striking the object. This severe geometrical attenuation (typically of order 10^{-4}) demands large incident fluxes at the scattering object if the intensity of the scattered beam is to be maintained satisfactorily above background levels; large source activities and very thick shields are therefore needed. The principal experimental difficulties of the method arise from these requirements.

3) Experimental

We first attempted to select a narrow energy interval by narrow-bore collimation of the crystal face, the crystal itself being at a short distance from the scattering object (Fig. 3[a]). At given $\Delta\phi$ this arrangement offers no advantage, as far as energy spread is concerned, over the simpler one shown in Fig. 3(b), but it was used because it occupies less space. We hoped that a properly-weighted summation of the spectra obtained for different points of photon impact on the crystal face would permit us to synthesize the spectral shape that would have been obtained if the whole

front surface were uniformly irradiated. The summation proved impossible because the spectrum obtained when the entire crystal face is exposed contains contributions from radiations scattered in the laboratory walls, while spectra obtained with narrow-bore collimation do not. The full-face spectrum cannot therefore be synthesized by combining the results obtained at various points on the crystal face. The presence of scatter contamination is clearly demonstrated by varying the distance d between the crystal and the narrow-bore collimator (Fig. 4); even though $\Delta\phi$ is fixed, the spectral shape is found to change rapidly as the distance increases, because unwanted scattered radiation, which is virtually eliminated when d = 0, has easy access to the crystal at larger separations. The scanning technique was therefore abandoned and the more unwieldy arrangement shown in Fig. 1, which effectively excludes all radiation except that entering along the collimator axis, was used instead.

Experiments were carried out with scattering objects of various sizes, shapes and materials, but the best combination of intensity and angular resolution was obtained with a lucite ball 0.5 cm in diameter at approximately 90 cm from the crystal; the energy was calculated to vary not more than $\pm$2% about the mean in the least favorable case. It was verified by photometry of films exposed at the position of the crystal face, that the entire front surface of the detector was uniformly irradiated. The detector to be calibrated was a 3" x 3" Harshaw type 12S12 working into a Victoreen "SCIPP" 400-channel pulse-height analyzer. It was possible to cover the entire range of energy in which we were interested (up to ~1 MeV) with only three sources, all of high specific activity; they were Au-198, Cs-137 and Zn-65, with energies 0.412, 0.662 and 1.114 MeV, respectively. Separate shields were used for each source, the dimensions increasing with the source energy. All of them were open towards the rear, in order to

reduce scattering in the region behind the sources; such parasitic radiation, if scattered at a suitable angle, could re-enter the collimator, traverse the source material and travel along the collimating channel towards the scattering ball. The cavity-collimator used to shield the crystal had internal dimensions of 40 x 40 x 120 cm and in order to reduce the effects of x-rays generated in its walls, it was lined with 0.5 mm Cu.

The spectrum of the background radiations (as, for example, of photons scattered into the collimator opening by the air surrounding the ball) was obtained by making observations in the absence of the ball while the source remained in position. The spectrum so obtained - whose shape varies from one source and scattering angle to another - was subtracted from that recorded when the ball was in place; although this method does not entirely eliminate background[11] it is accurate enough for our purposes. The spectra generated by the positron-emitter Zn-65 were also corrected for the presence of the annihilation component which is scattered in the ball simultaneously with the main gamma component. To carry out the correction, the pulse-height spectrum due to photons of the same energy as the scattered annihilation component was generated by scattering Cs-137 radiation through a suitable angle, and was then subtracted off after suitable normalization.

4) Energy-spread

The presence of the energy-spread mentioned in section 2 becomes apparent when the system resolution is measured as a function of photon energy. Using "direct" (unscattered) radiation from point isotopic sources, the solid curve of Fig. 5 is obtained while the results obtained with scattered radiation are represented by the dashed curve. It is seen that the resolution is better in the direct than in the"scattered"case, a result also noted by Ricci[8]. The worsened resolution in the scattered

case, arising in the main - though not solely[10] - from the finite solid angle employed, can never be eliminated, though its effects can be allowed for accurately (see below). It is also seen that the resolution values obtained with scattered radiation do not vary as smoothly with energy as do the direct results. This is because various combinations of primary energies and scattering angles are used in producing the calibrating radiations; since $dE/d\phi$ at given ϕ depends on the particular combination of $E\gamma$ and ϕ used in producing E_s, the fractional energy-spread varies in an irregular way (see Fig. 2). This effect could be entirely eliminated if combinations of $E\gamma$ and ϕ were so chosen as to give an energy-spread that was either independent of E_s or was a smooth function of it.

In some experiments it may be desirable to know the response of the spectrometer to radiation which is quite free of energy spread, and in these cases it is important to have a means of correcting the observed spectra. In our response matrix investigations, however, a knowledge of the spectral area enclosed between various pairs of ordinates is the only information required, and for this reason the correction method now described was not applied to any of the spectra presented in this paper. Nevertheless, it is given here for completeness:-

The areas of the peaks obtained when equal numbers of photons strike the crystal face must be almost exactly the same whether the radiation is direct or scattered, provided the mean energies of the two photon groups are identical. This is because the variation in crystal efficiency over the energy range ΔE corresponding with the angular interval $\Delta\phi$ is very small, and the variation of scattered intensity over $\Delta\phi$ is also very small; the number of full-energy interactions (that is, the peak area) is therefore the same in both cases. Furthermore, the photopeaks obtained with our equipment for both monoenergetic and scattered inputs are Gaussians to a

high degree of approximation (section 5). Knowing that equal fluxes of both types of radiation at the same mean energy produce Gaussians of equal area differing only in their half-widths, it is easy to calculate the expected peak shape for one kind of input if it is known for the other and if resolution data are available (as in Fig. 5) in both cases. The Compton continua can of course be corrected in the same way as the photopeaks but we have found that the resulting changes in shape are negligible except at the extreme upper end of the continuum.

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In applications where corrections for energy-spread are vital, they can be made very small by employing large source activities, which permit small values of $\Delta\phi$ to be used, and by working at large ϕ where E_s as a rule changes rather slowly with angle (Fig. 2).

5. Results

Fig. 6 and 7 show four typical spectra, generated by using the source energies and scattering angles shown in Table 1, where measured values of the true and apparent resolutions are also given. No corrections have been applied to the raw data except background subtraction and (in spectra [c] and [d]) elimination of the annihilation component.

The satisfactory shapes and relatively small heights - even in

the very low energy region - of the Compton continua, together with the unusually small size of the 180° backscatter peaks and the excellent peak/valley ratios, suggest that very little unwanted scattered radiation (as, for example, from the laboratory walls) is present, a result attributable to use of the cavity collimator. Those 180° peaks that are observed could have been produced, at least in part, by photons backscattered from the crystal-face plate and from the photomultiplier structure[12]; their increasing prominence as the incident energy rises would be explained if they are produced in this way, since photons of high energy can more readily penetrate the crystal and reach the scattering material behind it[13]. A study is now under way to determine the relative importance, in 180° peak production, of photons scattered after they have traversed the crystal and of those that are scattered (as is usually the case in experiments using conventional collimation) before approaching the detector.

Because the valley between the photopeak and the Compton continuum is quite sharp, the low-energy side of the photopeaks can be examined in considerable detail. Slight inflections were occasionally present in this region, suggesting the presence of more than one component in certain peaks. Those suspected of such contamination were analyzed by Boekelheide's probability-paper technique[14] and also by the more sensitive Berry method[15] which uses the observed ordinates at three evenly-spaced abscissae to calculate the maximum ordinate of an assumed Gaussian; the presence of contaminating components is revealed with great sensitivity if the results obtained with different triads of abscissae show any irregularities. The method failed to demonstrate the existence of satellites in any of the suspected peaks, all of which were shown to be Gaussian to a very high degree of approximation. It is concluded that the slight inflections and asymmetries, also noted by others[16], are caused by gain drift or other experimental errors.

6. Discussion

We have shown that essentially monoenergetic radiation can be produced by the Compton scattering technique, using moderately simple equipment. Theenergy spread inherent in the method can be reduced to a small value by using sources of very high activity in carefully-chosen geometries (section 4); in those cases where the effects of the remaining spread are objectionable, a simple correction - which we have tested experimentally - can be applied to the data. The technique is a relatively easy means of producing radiations of narrowly-defined and readily-adjustable energies up to at least 1 MeV. We believe that, in addition to its uses in the studies already listed (section 1), the method may be of especial importance in evaluating the performance of semiconductor detectors, for which extensive response-function catalogs are not always available.

The method has the disadvantage that E_s varies rather slowly with ϕ at lower values of E_γ. This slow variation, though reducing the inherent energy spread, makes the production of scattered radiation with E_s less than $\sim$0.1 MeV rather difficult unless primary sources in the same energy range are available. The scattering method is then no more convenient than using the low-energy primary sources directly. At high primary energies the method also becomes difficult to apply because E_s varies quite rapidly with ϕ when E_γ is large. Very small $\Delta\phi$'s are then needed in order to keep energy-spread within reasonable bounds, leading to severe intensity losses which in turn demand very large incident fluxes at the scattering object; adequate shielding of the sources needed to produce these fluxes is difficult. Apart from intensity considerations, limitation to small $\Delta\phi$ precludes irradiation of the whole crystal face in any apparatus of practical size. It is possible that the scanning technique might be used to overcome this

difficulty, if the detector and narrow-bore collimator were operated inside a shield of the cavity type, because the cavity shield would exclude the unwanted scatter that normally makes scanning impossible (section 3). Extremely narrow beams, obtained by scattering accelerator-produced de-excitation gamma rays with energies of several MeV, could be used in such scans and we have begun preliminary experiments in this direction.

The satisfactory spectral shapes obtained with our equipment show that the cavity collimator successfully excludes unwanted scattered radiation and this is further verified by observing spectra from monoenergetic sources placed at the position normally occupied by the ball. These spectra are in all cases of at least the same quality as those obtained in the most careful experiments reported by others[16]. We believe that the design of the cavity collimator as an incidental aspect of the Compton study is a significant advance in the production of scatter-free inputs and we shall discuss other results obtained with it in a later paper[11].

Acknowledgments

We thank the National Aeronautics and Space Administration, who supported this work in its entirety, and Dr. E. R. King, Chairman of the Department of Radiology at the Medical College of Virginia, for placing the facilities of his department at our disposal. Parts of the equipment were obtained through the generosity of the A. D. Williams Fund of the Medical College of Virginia and of the Richmond Chapter of the American Cancer Society.

We are especially grateful to our Grant Monitor, Mr. E. Rind of NASA-Langley, for his advice and constant assistance.

References

(1) Leimgruber, R. A., and O'Foghludha, F., Phys. Med. Biol., 13, (1968), 293 (Abs.).

(2) O'Foghludha, F., and Leimgruber, R. A., Bull. Am. Phys. Soc., 13, (1968), 559 (Abs.).

(3) Hubbell, J. H. and Scofield, N. E., IRE Trans. Nucl. Sci., NS-5, (1958), 156.

(4) Epp, E. R. and Weiss, H., Rev. Sci. Instr., 32, (1961), 651.

(5) Seppi, E. J. and Boehm, F., Phys. Rev., 128, (1962), 2334.

(6) Moon, P. B., Proc. Phys. Soc., 64, (1951), 76.

(7) Cormack, A. M., Phys. Rev., 96, (1954), 716.

(8) Ricci, R. A., Physica, 24, (1958), 289.

(9) Mouton, W. L., Sellschop, J. P. F. and Wiechers, G., Phys. Rev., 129, (1963), 361.

(10) Tandon, G. K., and McIntyre, J. A., Nucl. Instr. Meth., 59, (1968), 181.

(11) O'Foghludha, F. and Leimgruber, R. A. (to be published).

(12) Bisi, A., Zappa, L., and Germagnoli, E., Nuovo Cimento, 1, (1955), 1119.

(13) Lidén, K., and Starfelt, N., Ark. för Fysik, 7, (1954), 427.

(14) Boekelheide, I. F., Rev. Sci. Instr., 31, (1960), 1001.

(15) Berry, E., Virginia J. Sci., 18, (1967), 195.

(16) Heath, R. L., Helmer, R. G., Schmittroth, L. A., and Cazier, G. A., Nucl. Instr. Meth., 23, (1963), 218.

TABLE I

Spectrum (Figs. 7 and 8)	E_γ (MeV)	ϕ	E_s (MeV)	Apparent Resolution (%)	True* Resolution (%)
a	0.412	170° 0'	0.158	10.1	10.0
b	0.662	52°12'	0.450	8.9	7.8
c	1.114	50°23'	0.650	7.9	6.8
d	1.114	23°11'	0.950	6.9	6.1

*for monoenergetic radiation

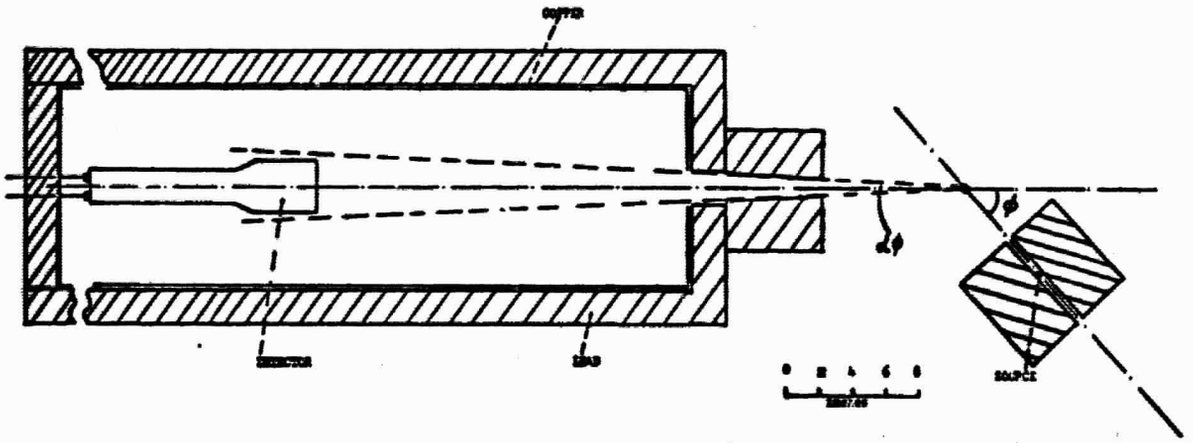

Fig. 1: Typical Experimental Arrangement

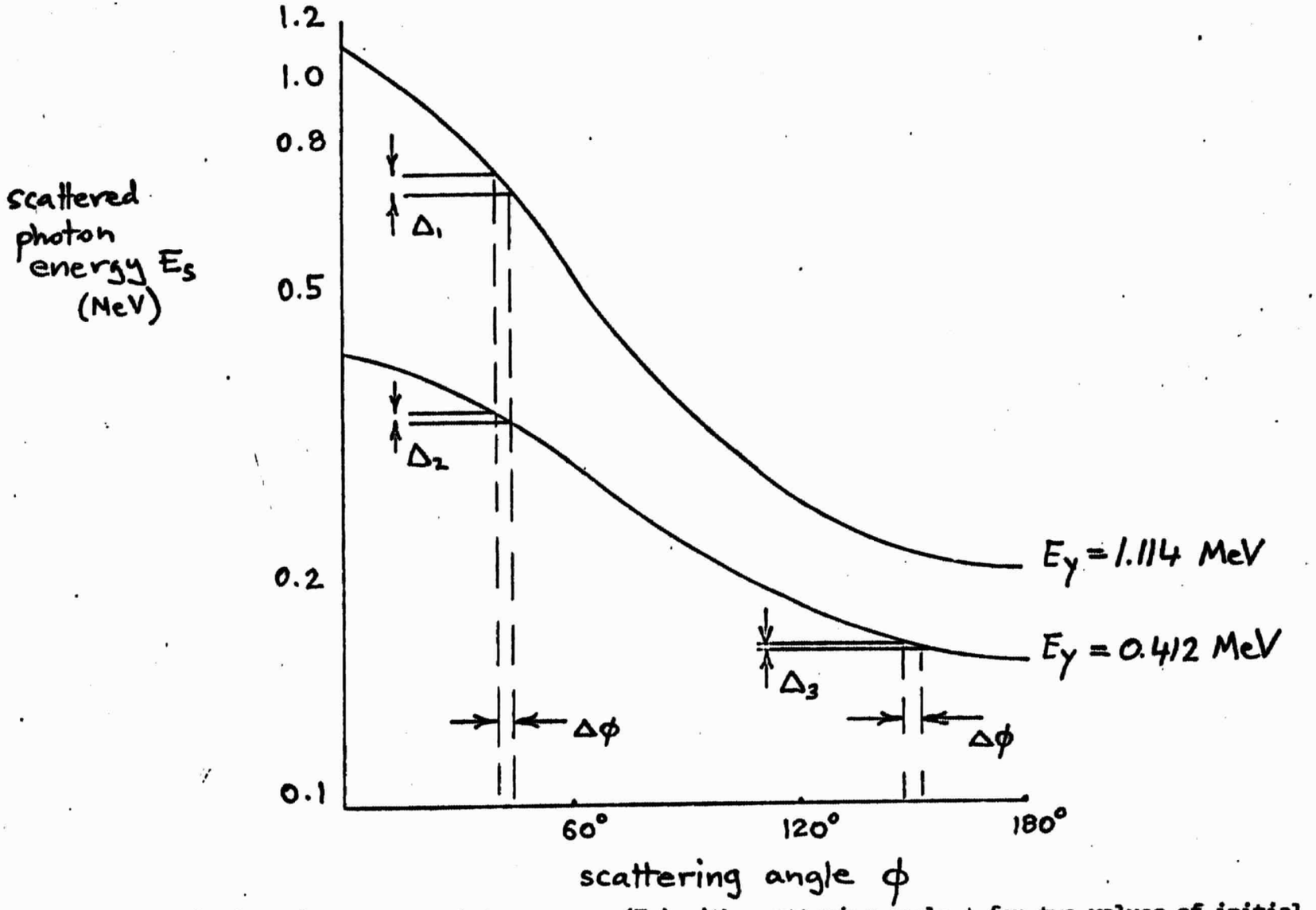

Fig. 2: Variation of scattered photon energy (E_s) with scattering angle ϕ, for two values of initial energy (E_γ). The figure also shows that the energy spread introduced by a fixed $\Delta\phi$ depends on E_γ at given ϕ (thus $\Delta_1 > \Delta_2$) and on ϕ at given E_γ (thus $\Delta_2 > \Delta_3$).

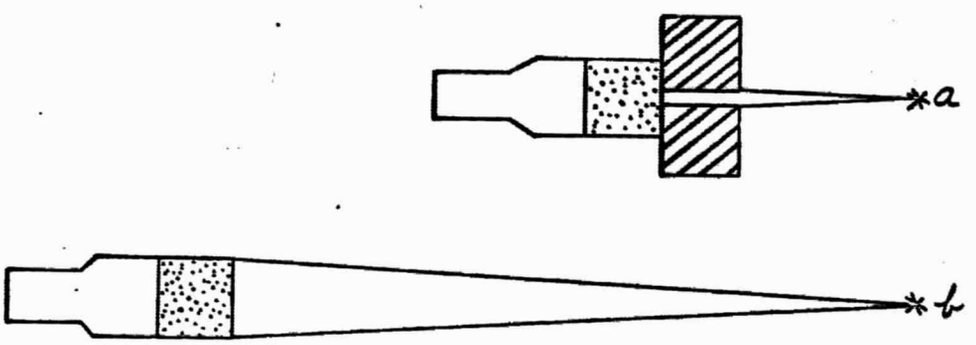

Fig. 3: Two possible experimental arrangements (see text).

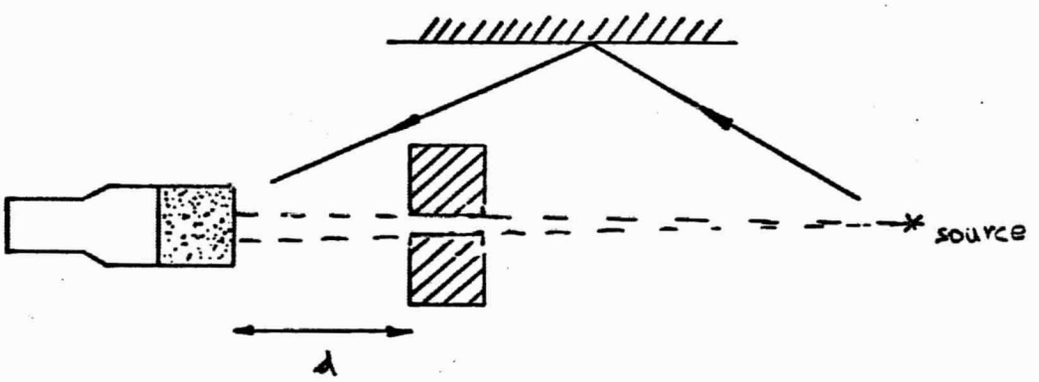

Fig. 4: Apparatus used in demonstrating the effects of radiation scattered in the surroundings. The spectral shape depends critically on the distance d, even though the area exposed to direct radiation from the source is constant.

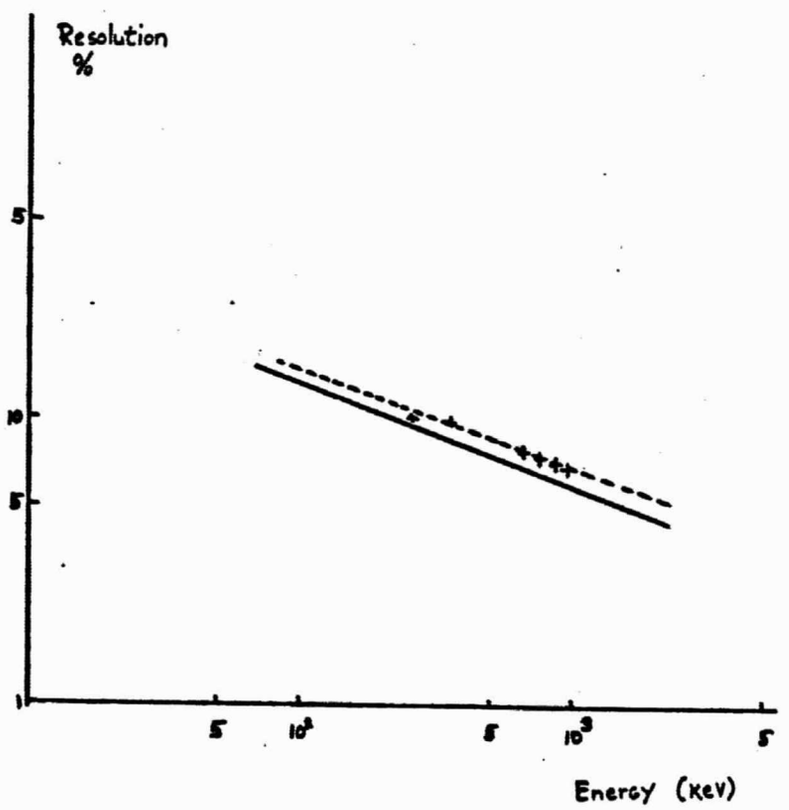

Fig. 5: Measured resolution as a function of energy. The upper curve was obtained with Compton-scattered radiations, the lower one with direct (unscattered) photons. The measured resolution is 6.8 % at 0.662 MeV (unscattered).

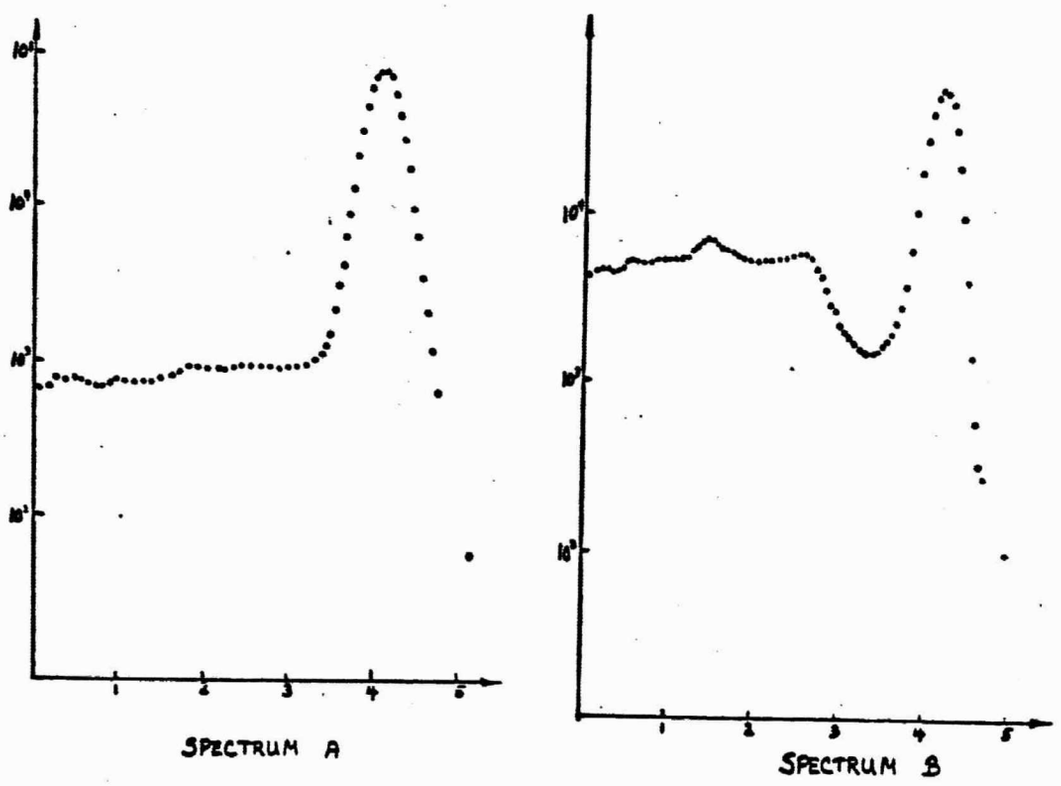

Fig. 6: Typical pulse-height spectra of Compton-scattered radiations at mean energies of (a) 158 keV (b) 450 keV.

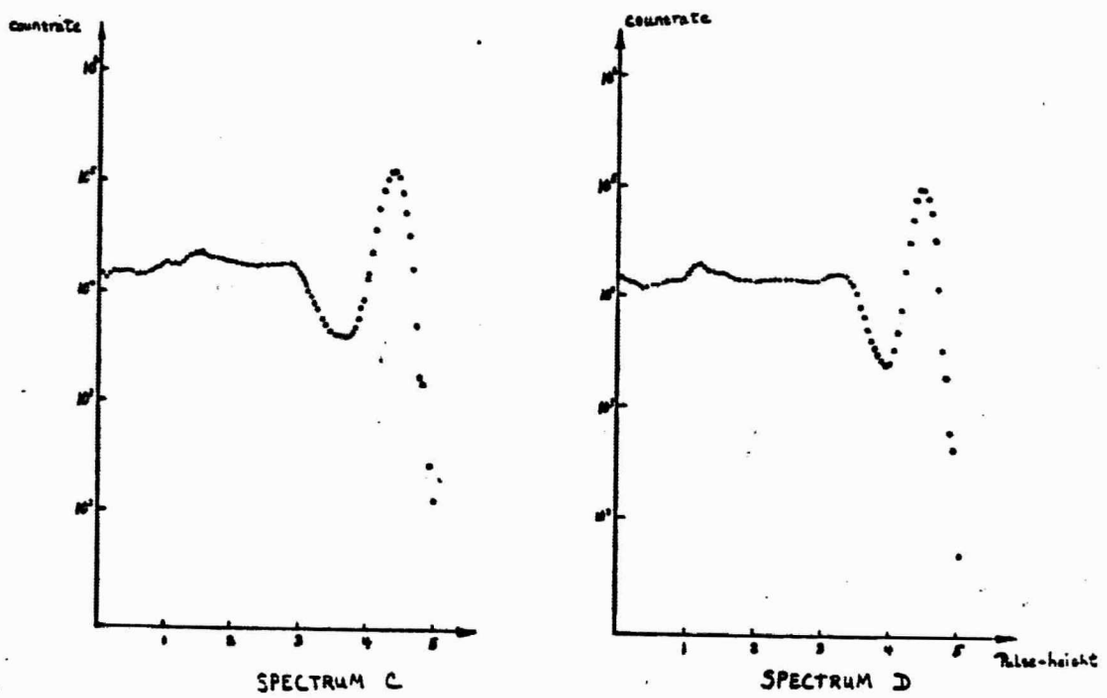

Fig. 7: Pulse-height spectra of scattered radiation:-
(c) 650 keV (d) 950 keV

APPENDIX 2

NYA-AAPM; O'Foghludha

Scintillation dosimetry, and an application of it

by

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One of the few methods of measurement not so far mentioned is scintillation dosimetry with low-Z phosphors. While the technique is never likely to supplant those described earlier, it nevertheless has some attractive features and hardly merits the relative obscurity that has befallen it. In the past, it has found its greatest use in intracavitary work, where the requirements of high sensitivity and good spatial resolution are adequately met by phosphors of small volume. Those who have used the method only in this application may unconsciously - and unfairly - associate the difficulties of intracavitary measurements especially with scintillation detectors, whereas in fact all instruments are troublesome when used under these less than ideal conditions.

The principal disadvantage of body-probe scintillation dosimeters is that weight limitations force one to use unshielded photomultipliers; in the uncollimated fluxes encountered in intracavitary work, this gives rise to serious dark current problems, and while it is true that the effect can be lessened by modulating the phosphor light (Herbert, 1956) or by using shutters to give the signal by difference, neither remedy is easy to apply. A second disadvantage is that low intensities and small crystal sizes force one to use photomultipliers and electrometers near the limit of their performance, leading to some instability. Lastly, the position of the probe tip is not usually known with any accuracy.

In high-energy therapy, where the fluxes to be measured are well collimated and are some 1000 times greater than in intra-cavitary work, these difficulties disappear. Because of the collimation, the photomultiplier can be placed outside the beam and can be shielded to any required degree, so that dark current is no

longer a problem. The photomultiplier can be bigger (13 or 14 stages) and, in intense fluxes, can be operated under much more favorable conditions of low anode voltage and large signal/noise ratio; furthermore, electrometric techniques of relatively low sensitivity and hence greater stability can be brought into play. When it is also remembered that a phosphor-multiplier combination is a true dosimeter in the sense that its output is a measure of the energy-deposition or dose in the phosphor - and if the phosphor is properly chosen, a measure also of the dose in the surrounding medium - it is clear that the scintillation technique is a valuable one.

A suitable construction (O'Foghludha, 1964) is shown in Fig. 1. Scintillation light is piped along a lucite guide to a point well outside the radiation field, where it strikes a heavily-shielded photomultiplier. The multiplier works at relatively low anode voltage, both to give stability and to prevent fatigue due to excessive signla; if this precuation does not suffice, the phosphor light can be attenuated at will with an iris diaphragm placed in front of the photo-cathode. Alternatively, a hollow light-pipe (which has the added advantage of eliminating the Cerenkov radiation generated in solid guides) can be used to diminish the light reaching the photo-tube. An instrument of this kind working off a stabilized power supply is quite easy to handle and we have had no trouble in measuring depth doses with it, at least below the ionization maximum. Day-to-day stability can be checked by using conversion electrons (see below); Cerenkov light from a calibration capsule containing a high-energy beta emitter could be used for the same purpose.

The supposed energy-dependence of scintillation techniques often causes some disquiet, possibly because the commonest scintillator, sodium iodide, is so notoriously energy-dependent as to be quite unusable, even in air, unless complex processing of the signal is undertaken (Moriuchi and Miyanaga, 1966). However, organic phosphors such as anthracene, or solid solutions of various

phenyl derivatives in polystyrene (Belcher and Geilinger, 1957) have a perfectly acceptable energy dependence. Fig. 2 shows the relative response of one of our instruments, which uses a commercial plastic phosphor (NE102) of the Belcher-Geilinger type, incorporating a small admixture of CdS to improve response at the lowest energies. The plateau of Fig. 2 is typical of phosphors in this general class and has been shown to extend up to some 7 or 8 MeV by Belcher (1953). The fall-off at low energies has little effect in commonly-encountered photon spectra and indeed the overall energy-dependence is far less extreme than (for example) that of film systems, which are nevertheless quite practical in high-energy photon studies.

The scintillation dosimeter has the further advantage of extraordinarily large range. We have seen how the problem of over-sensitivity can be dealt with in high photon fluxes, but it is perhaps not generally realized that, if one relies on pulse counting, the range can also be extended downwards to at least an order of magnitude below the level attainable when the multiplier output is measured with an electrometer. In the pulse technique, the pulse-height spectrum of the multiplier is first recorded with the help of a multi-channel analyzer. The integral:

$$\int_{E}^{E_{max}} E \cdot N(E)dE$$

which represents the number of events $N(E)dE$ in a given energy interval dE, multiplied by the energy E transferred in each event, now represents the dose in the phosphor; the procedure is of course equivalent to measuring the current but is much easier to carry out in low fluxes. The integration can be done by hand, or more conveniently by counting the number of pulses delivered during the period of observation by the clock generator in the analog-to-digital converter of the analyzer. Signal integration over very long periods is possible with this technique and background subtraction offers no problem. There is of course some uncertainty due to noise at the low-energy end of the spectrum, but because the

low-energy pulses are weighted by a smaller factor than those higher up the energy scale, this difficulty is not so great as might at first appear.

A feature of great interest is that it is possible in principle to find the actual, as distinct from the relative, energy deposition in the phosphor without relying on any other standardizing instrument, provided the energy-deposition corresponding with a given pulse-height is known. Now the energy scale can be determined with considerable accuracy by passing electrons of known energies into the phosphor and in one of our dosemeters we have provided a thin window through which conversion electrons can be admitted for this purpose. It is worth remarking that distortion of the pulse-height spectrum by the light-guide or by phosphor boundary effects (Blum, 1962) which makes the electron spectrum hard to interpret, does not affect the issue here, since it is the spectrum of energy-losses within the phosphor, however brought about, that concerns us and the initial energy-distribution of theelectrons themselves is of no interest.

The pulse method can be used only in low-intensity fields, since the electronic circuits otherwise overload, and it would therefore appear that absolute determination of the energy-deposition could not be extended into the high-flux range. In fact, one of our dosimeters has been provided with interchangeable multiplier mounts, one containing a preamplifier for pulse-counting at low intensities, the other incorporating a dynode supply chain suitable for electrometric work in high fluxes, where comparison with NBS-calibrated ion-chambers is easy. If the measuring ranges can be made to overlap, which seems feasible, interesting possibilities of internal cross-checking arise.

We have not pursued this method of evaluating energy-deposition, which in principle needs no calibration by ionization or calorimetric methods, with any vigor, but we believe that this singular and often-overlooked advantage of the scintillation technique deserves attention.

The scatter-radius function

We are using these dosimeters to study percentage depth doses in strictly mono-energetic beams from high-energy gamma-emitters. By working with mono-energetic radiation (which can also be obtained at extremely high energy, though at low intensity, in the form of de-excitation gammas) we hope to predict the results which would be obtained with generators of any known continuous spectral output; by using a single energy we can also both calculate and measure the zero-area depth-doses, which are of some importance, as we shall see. Only with scintillation dosimeters is it possible to reach the necessary sensitivities.

In the course of this work we have had occasion to re-examine the variation of scatter intensity with field size. Since Dr. Glover will present (Session 5) a new treatment of scatter in some detail, I shall only briefly describe our work on this topic, carried out in collaboration with Dr. Fred Schmidt of Emory University. The amount S(r) of scattered radiation at the center of a circular field, per unit of primary radiation arriving there, depends on the field radius r. The r-dependence is represented by the so-called scatter-radius function which has been formulated in many ways, of which the best-known is Meredith and Neary's (1944). The scatter-radius relation is important because, if it is known, isodose shapes can be calculated (as was done in preparing the IAEA isodose compendium) and so also can the total energy absorption, or integral dose, in the irradiated body. For this last purpose we need to know the saturation scater at the center of a very large field, a quantity represented in the Meredith-Neary formulation by a certain constant ". Published "-values, however, are available over quite a limited range of energies, and generally are in very poor agreement - partly because they are not all based on the same depth-dose figures and partly (it seemed to us) because the Meredith-Neary formulation is not perfect, though quite adequate for clinical use. Not only because of this slight departure from perfection, but more importantly because

the Meredith-Neary representation involves Bessel functions, which are not always easy to manipulate, Dr. Schmidt and I thought it worth-while to examine once again the problem of representing S(r) analytically.

At first sight, investigation of the scatter-radius functions seems unimportant when the photon energy is high, since it is well known that the percentage depth dose is a slowly varying function of field area in this energy region. But though relatively small by orthovoltage standards, the area-dependence can by no means be entirely neglected in the megavolt range. At 4 MV, for example, the depth dose in a 100 cm^2 field si about 20% larger than in a field of 10 cm^2 area, and at 8 MV there is an increase of more than 10% for the same change in field size, so that even at these energies the scatter-radius function repays study.

We began at low energies, calculating S(r) for a variety of r from published depth-dose tables. We applied to the S(r) values so obtained a curve-fitting technique, involving a moderately complex computer program, developed by Turner and others (1961). A simple expression:

$$S(r) = \alpha - \beta e^{-\gamma r}$$

where α, β and γ are constants whose values depend on the depth and on the quantum energy, gave an excellent fit. An expression of this type was one of the possibilities rejected at an early stage by Meredith and Neary, who of course had no computer techniques available to them. A typical result is shown in Fig. 3. The values of α and β agree to one part in approximately 2,500; this is equivalent to saying that the computer predicts zero scatter at zero field radius, which is the correct physical result, although no S(r) values were supplied to the computer for $r < 2.25$ cm. The excellence of fit is dramatically illustrated by plotting $[\alpha - S(r)]$, which equals $\alpha e^{-\gamma r}$ if $\alpha = \beta$, against r on semilogarithmic paper, when a perfect straight line (not shown) is obtained. Our method predicts a linear dependence of S(r) on r at $r = 0$ and thus removes the small downward concavity

evident in the Meredith-Neary scheme at small r. We are now engaged in the laborious task of fitting all available sets of data and we shall report on this work soon. The α-values (corresponding with the M's of the Meredith-Neary schema) so far obtained by us are bigger than those reported by other groups and it will be interesting to atteppt an experimental verification of this prediction.

Our principal efforts have been in the comparatively low-energy region because it is there that lateral energy-escape complicates the calculation of energy absorption, but we have tried the method up to cobalt-60 energies where it works equally well. Beyond that energy, central-axis depth doses for zero area are not available and values of S(r) for manipulation by the computer cannot be calculated. We hope that studies with mono-energetic radiations will eventually eliminate this problem, but we have also tried another approach: The curve of depth-dose versus radius looks quite similar in shape to a plot of S(r) versus r and it therefore occurred to us to apply our curve-fitting technique to the depth dose values themselves. If the fit is good, extrapolation to zero radius becomes possible, and S(r) can then be calculated just as at lower energies. We first tried the method at photon energies where the zero-area depth dose was known experimentally. The computer extrapolation to zero radius agreed to within 1% with the experimental data in these cases. We are now examining a large number of data sets by this method and if the existing standard of accuracy is maintained, we propose to use the technique for calculating zero-area depth doses, and hence S(r), up to the highest energies for which data are available. It will be interesting to see if our results agree with Dr. Glover's.

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References

Belcher, E. H., 1953a, Proc. Roy. Soc., A216, 90

Belcher, E. H., 1953b, Brit. J. Radiol., 26, 455

Belcher, E. H., and Geilinger, J. E., 1957, Brit. J. Radiol., 30, 103

Blum, P., 1962, Radiation Res., 16, 626

Herbert, R. J. T., 1956, Brit. J. Radiol., 29, 345

Meredith, W. J., and Neary, G. J., 1944a, Brit. J. Radiol., 17, 75

Meredith, W. J., and Neary, G. J., 1944b, Brit. J. Radiol., 17, 126

Moriuchi, S., and Miyanaga, I., 1966, Health Phys., 12, 541

O'Foghludha, F., 1954, Phys. Med.,Biol., 9, 155

Turner, M. E., Monroe, R. J., and Lucas, H. L., 1961, Biometrics, 17, 120

APPENDIX 3

DISTRIBUTED NEUTRON SOURCES

Introduction:

For neutron dosimetry studies it would be desirable to have a neutron source that is distributed uniformly over fairly large volumes of simple geometry. One technique that has been suggested for achieving this is to mix a gamma ray emitter in solution with a substance that has a high photoneutron cross section. Two possibilities immediately present themselves: (1) deuterium and an isotope with gamma ray energy above the 2.2 MeV threshold and (2) beryllium and an isotope with gamma ray energy above the 1.62 MeV threshold. Some preliminary investigations have been done on the first possibility, a combination of heavy water and sodium-24. These investigations will be reported here.

Theory:

The simpliest case is to consider a point source of a gamma ray emitter in an infinite medium of heavy water and to calculate the neutron flux at the source point from photoneutron interactions throughout the medium. The uncollided gamma ray flux at a distance r from a source of strength S gamma rays/second is

$$\frac{S}{4\pi r^2} e^{-\mu r} \quad \text{photons/cm}^2\text{-sec},$$

where μ is the total attenuation coefficient. The neutron production rate at this point is

$$\frac{SN\sigma dv}{4\pi r^2} e^{-\mu r} \quad \text{neutrons/sec}$$

where N is the density of deuterium atoms - atoms/cm^3

σ is the photoneutron cross section - cm^2

dv is an element of volume.

The uncollided fast neutron flux at the source point is then

$$\Phi_o = \int \frac{SN\sigma e^{-\mu r}}{4\pi r^2} \quad \frac{e^{-\sigma_r r}}{4\pi r^2} \, dv \qquad \text{neutrons/cm}^2\text{-sec}$$

where σ_r is the macroscopic fast neutron removal cross (units of cm^{-1}) and the integration is over all space. The volume element can be written as $dv = 4\pi r^2 dr$ and the expression reduces to

$$\Phi_o = \frac{SN\sigma}{4\pi} \int_o^\infty \frac{e^{-(\mu+\sigma_r)r} \, dr}{r^2}$$

This integral is not defined at the lower limit, however, this does not bother us because in practice we cannot make a measurement of the neutron flux in an infinite medium at the source location. A more practical situation is to place the detector and the source side by side at a distance d from a container of heavy water. If the container is large enough to be considered a semi-infinite medium the flux density at the detector becomes

$$\Phi_d = \frac{SN\sigma}{8\pi} \int_d^\infty \frac{e^{-(\mu+\sigma_r)r} \, dr}{r^2}$$

where the factor 1/2 has been introduced since we are no longer concerned with an infinite medium. If the substitution $y = \frac{r}{d}$ is made in the integral

$$\Phi_d = \frac{SN\sigma}{8\pi d} \int_1^\infty \frac{e^{-d(\mu+\sigma_r)y}}{y^2} \, dy$$

$$= \frac{SN\sigma}{8\pi d} E_2 \left[d(\mu+\sigma_r) \right]$$

where E_2 is the second order exponential integral.

Experiment

A source of Na-24 was made and placed at a distance of about 4 centimeters from a curved side of a cylindrical drum of D_2O. The drum measured 23 inches in diameter. A BF_3 neutron detector was placed at the same distance from the drum but separated from the gamma ray source by 3 inches of lead. Counts were taken with the BF_3 tube bare, which will detect predominantly thermal neutrons, and covered by a cadmium coated paraffin sleeve, which will make the detector sensitive to fast neutrons.

The source was an aluminum capsule that was irradiated for one hour in the flux trap of the University of Virginia Reactor operating at one megawatt. The neutron reactions in aluminum are the (n,γ) leading to a 2.3 minute aluminum isotope, the (n,p) leading to a 9.5 minute magnesium isotope, and the (n,α) which produces the 15 hour sodium-24. This isotope decays by emission of a 2.78 and a 1.37 MeV gamma ray in cascade. Thus, all disintegrations produce one gamma ray with energy above the deuterium (γ,n) threshold. The aluminum sample cooled for a day allowing the shorter half life activities to decay. The exposure rate was then measured to be 400 mR/hr at one foot from the sample. The rule of thumb formula,

$$\text{Dose at one foot} = 6CE,$$

gives a gamma ray source strength of C = 16 mCi, which is equivalent to

$$S = 5.9 \times 10^8 \text{ gamma rays/sec.}$$

The paraffin covered BF_3 detector was calibrated by exposing it at a distance of one meter from a one Curie plutonium-beryllium neutron source. The net count rate (background subtracted) was 14.2 counts/sec. The source emits 1.7×10^6 neutrons/sec which gives a flux density of 13.5 neutrons/cm^2-sec at one meter. Thus, the detector gives 1.05 counts/sec for each neutron/cm^2-sec incident on it.

The detector was separated from the Na-24 source by three inches of lead and placed so that the detector and the source were each about four centimeters from the heavy water drum. Background counts were taken by retaining the source detector geometry but removing the heavy water. The results which are averages of several counts are reported in Table 1.

TABLE 1

Condition	Counts/Minute	Neutron Flux Density Neuts/cm^2-sec
Bare Detector	233	
Background	100	
Pa. Covered Detector	520	64
Background	133	

One thing immediately obvious is that the number of counts from thermal neutrons is considerably lower than those from fast neutrons. The detector was not calibrated for thermal neutrons so a direct flux comparison cannot be made, however, assuming that the count rate-to-flux conversion factor would be about the same, the fast neutron flux density is about four times the thermal.

To calculate the response refer to the equation

$$\Phi_d = \frac{SN\sigma}{8\pi d} E_2 \left| d(\mu+\sigma_r) \right| .$$

The values

$$S = 5.9 \times 10^8 \text{ gamma rays/sec}$$

$N = 6.01 \times 10^{22}$ atoms/cm^3

$\sigma = 1\text{mb} = 10^{-27}$ cm^2

$\mu = 0.04$ cm^{-1}

$\sigma_r = 0.08$ cm^{-1} (2.76b)

$d = 4$ cm

$E_2 = (.48) = 0.33$

gives a calculated flux of

$\Phi_d = 116$ neutrons/cm^2-sec.

This value is about twice the measured value, however the discrepancy is not too surprising as the following approximations have been made.

(1) The calculations were done for a point source and a semi-infinite plane of D_2O but in the experiment the heavy water was in a cylindrical can. This difference would over estimate the calculations.

(2) The source was not a point source but a cylindrical tube of aluminum about eight inches long. Thus, the true distance from the source to the heavy water would be greater than 4 centimeters. Further, the source was placed in a lead pig with the open end toward the D_2O. Thus, the part of the source furtherest from the front end would be partially shielded. These effects would decrease the effective source strength used in the calculations and thus decrease the calculated value.

(3) The gamma ray source strength was not measured accurately and may be in error by as much as 50%.

(4) The calculation includes only uncollided gamma rays and neutrons.

Conclusions

It has been shown that the concept of making a distributed neutron source by producing Na-24 sources and placing them in and near heavy water will produce measurable neutron flux densities and doses. It is proposed to extend this work to geometries in which the neutron source distribution can be calculated and can be adjusted. An example might be a cylindrical tank of heavy water with tubes parallel to the axis at various radial positions. These tubes would be filled with Na-24 of such concentrations to achieve a desired neutron production distribution. As in the present experiment Na-24 can be produced in alumirum wires to facilitate handling of the gamma ray sources. In simple geometries the neutron distributions can be calculated using neutron transport codes presently available for the University of Virginia Computer.

APPENDIX 4

Technics developed (2–4) at the Massachusetts Institute of Technology, National Institutes of Health, and Stanford University School of Medicine are essentially the ones currently being used for treatment of large areas. In these treatments, typical daily doses involve an incident electronic charge of about 10^{-9} coulombs per square centimeter. To deliver such a dose in one minute would require a current of 1.7×10^{-11} amps/cm^2; in 10 nanoseconds a current of 0.1 amps/cm^2 is required.

For treatment of less extensive superficial tumors a method has been developed to obtain uniformity over an area of 700 cm^2. A low atomic number absorber shaped like the hub and spokes of a wagon wheel and placed midway between the exit window of the accelerator tube and the patient has been used to reduce electron flux in the central part of the beam so that the dose distribution with the aid of air scattering is quite uniform over a circle 30 cm in diameter. The energy of the electrons has not been degraded by use of scattering foils, and the x-ray background has been kept to a low level. Various monitoring devices have been used and considered which could be automated to switch off the electron beam at preselected dose levels. This method, for electron therapy with a linear accelerator, has been used by Dr. Martin Levene at the Peter Bent Brigham Hospital.

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REFERENCES

1. BRAAMS, R.: Superficial Radiation Therapy of Large Skin Areas. Dermatologica 117: 204–214, October 1958.
2. SMEDAL, M. I., JOHNSTON, D. O., SALZMAN, F. A., TRUMP, J. G., AND WRIGHT, K. A.: Ten Year Experience with Low Megavolt Electron Therapy. Am. J. Roentgenol. 88: 215–228, August 1962.
3. KARZMARK, C. J., LOEVINGER, R., STEELE, R. E., AND WEISSBLUTH, M.: A Technique for Large-Field, Superficial Electron Therapy. Radiology 74: 633–643, April 1960.
4. HORWITZ, H., AND HAYBITTLE, J. L.: Whole Body Superficial Irradiation with Strontium 90 Beta Rays. Brit. J. Radiol. 33: 440–446, July 1960.

Beta-Ray Extracorporeal Irradiators Affording Complete Patient Mobility[1]

F. O'FOGHLUDHA, Ph.D., and JAMES S. WOLF, M.D.

Several beta-ray applicators (shunts) have been constructed permitting continuous extracorporeal irradiation of human blood, without impairing subject mobility. Mean blood doses of up to 320 rads/day have been reached in patients of 5-liter blood volume with no more than 200 mCi ^{90}Sr and with negligible radiation hazard to staff and visitors.

High efficiency of energy transfer has been achieved by relying on beta-emitters, by using blood-bearing tubing with very thin walls, and by close apposition of the tubes to the beta sources; further improvement in mean dose has been brought about by increasing the ratio r/V, where r is the volume of blood instantaneously irradiated and V is the total blood volume.

Use of beta rather than gamma irradiation reduces the external hazard considerably. In one of the shunts now described, the bremsstrahlung hazard is minimized by encapsulation of the beta-emitting material (in this case, ^{90}Sr) in aluminum rather than the conventional silver. This shunt is in the form of a wrist-borne bracelet to which ^{90}Sr sources can be attached in a matter of seconds after blood has begun to flow in the shunt. Shunts have also been made with ^{90}Y and ^{32}P, the latter of which has the considerable advantage of a short half-life, which causes mechanical damage to the shunt to have less catastrophic effects. The most recent shunt consists of a box-like container whose walls are made of PVC in which ^{32}P has been chemically incorporated. The blood flows directly over the PVC, resulting in an extremely high energy transfer, while the low-Z matrix material ensures minimum bremsstrahlung.

For all shunts, mean doses were measured with the Balkwell-Adams modification of the Fricke dosimeter. The G-value measured by us for this system was 62 mols/100 eV. Dosimetric results are consistent and indicate that mean dose rates of some 500 rads/day can be easily achieved without serious external hazard and without encumbering the patient with heavy shielding.

[1] From the Lahey Clinic and M.I.T. High Voltage Research Laboratory, Cambridge, Mass. Presented at the Fifty-third Scientific Assembly and Annual Meeting of the Radiological Society of North America, Chicago, Ill., Nov. 26–Dec. 1, 1967.

LiF Depth-Dose Measurements[1]

W. R. HENDEE, Ph.D., R. GOLDEN, M.S.,[2] C. E. GARCIGA, M.D., D. B. GILBERT,[3] and G. S. IBBOTT[4]

The import of LiF dose measurements at depths within phantoms and patients depends upon their agreement with traditional ionization chamber measurements. The lack of correlative depth-dose studies utilizing both measurement technics is surprising, since increased response of LiF at low photon energies (1) may provide inaccurate dose measurements in degraded photon beams. Ionization chamber and LiF dose measurements at depths within phantoms exposed to orthovoltage x-ray and ^{60}Co radiation have been compared in our laboratory.

Cobalt-60 depth doses measured with TLD-100 LiF agree well (±1 per cent) with ionization chamber measurements. A single exposure to LiF within

[1] From the Departments of Radiology and Surgery, Medical College of Virginia, Richmond, Va. Presented at the Fifty-third Scientific Assembly and Annual Meeting of the Radiological Society of North America, Chicago, Ill., Nov. 26–Dec. 1, 1967.

APPENDIX 5

MULTI-RADIOACTIVE TRACER UPTAKE ANALYSIS UTILIZING ON-LINE COMPUTER TECHNIQUES,
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The possibility of utilizing radioactive tracer techniques to study a number of metabolic functions (e.g. thyroid, cardiac, and renal function) during extended manned space flight is being considered. Short-lived radioisotopes will be used to tag various materials. These materials could then be injected in or ingested by the astronaut. Measurements of the distribution of the tagged material as a function of time is carried out using a gamma ray scintillation spectrometer.

The information desired is related to the biological changes and thus the physical processes which tend to degrade the information (i.e. degradation of the spectrum by the detection system, half-life decay of the radioisotope, the effects of scattered radiation, and separation of the various radioisotopes in a mixture) must be compensated for in order to obtain such information. Further the information is required in a short period of time after measurement, since this system could be used to monitor these various metabolic functions.

The on-line computer system (which compensates for the various physical degradation processes enumerated above) has been developed for the analysis of the spectra obtained utilizing the scintillation spectrometer. The technique also shows great promise for application to other clinical problems. The computer technique has been successfully applied to a number of uptake problems and the results obtained on a number of patients will be presented.