2º TEMA

LEONIDAS D. MARINELLI
Director Radiological Physics Division Argonne National Laboratory
Argonne, Illinois, U.S.A.

General technical problems in radiological physics

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Introduction

In the three areas of medicine in which radiological physics is today involved, x-ray diagnosis, radiotherapy, and nuclear medicine, there are certain recurring problems as well as problems which are specific to a particular area. The distinction will not be discussed per se because it will become evident as we shall try to cover each field separately.

I) X-Ray diagnosis

The most widespread medical use of roentgen rays has been and is still for diagnosis. This was also their first use. Toward the end of 1895, Wilhelm Conrad Roentgen persuaded his wife to place her hand on a photographic plate on which he beamed his new rays for 15 minutes. The result was the first radiograph and Roentgen became the first x-ray diagnostician.

Basically, diagnostic techniques involve a properly prepared patient, a radiating source, and the apparatus and materials necessary to record the image resulting from the interactions of the radiation beam and the patient (Figure I).

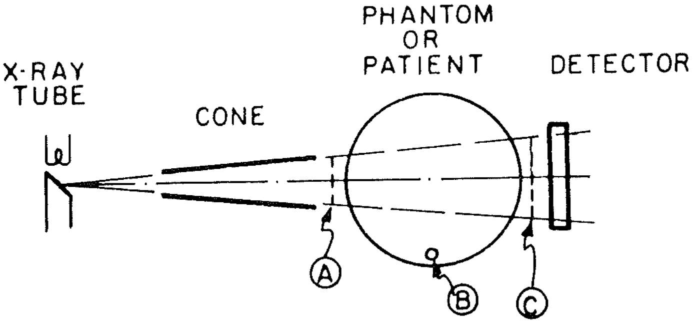

FIG. I. SCHEMATIC ARRANGEMENT FOR DIAGNOSTIC RADIOLOGY

(From H. O. Wyckoff, Ref. (4). Reproduced by courtesy of the author and C. C. Thomas, publisher.)

The development of those portions of the diagnostic techniques involving only the adequate preparation of the patient has been practically the unchallenged domain of the roentgenologist. On other land, the development of the radiation sources has rested with industry without much aid from others; this is probably due to the fact that the commercial demand for diagnostic x-ray apparatus has almost always been large enough to support the cost of the development and research instigated and demanded by the diagnosticians.

This situation has led to the establishment of relatively small, but extremely well-informed groups of electrical engineers and industrial research physicists who have transformed the crude tube of Wilhelm Roentgen into today's variety of diagnostic apparatus. As a rule, these groups have dealt directly with the roentgenologist without too much assistance (or interference) from hospital physicists. A very recent result of this teamwork is the registration of detailed radiographic information onto magnetic tape or similar memory devices in order to selectively retrieve it for more deliberate appraisal via television circuits. Along the same line, diagnosticians have also coded the information carried by the radiographic image onto cards suited to automated selection and correlation by means of commercial business machines.

The trend in everyday diagnostic instrumentation, however, seems to be toward a predominance of electronic accessories aimed at more precise control of the image by phototimers, and pulsed operation of grid tubes aimed at shortening the exposure time, resulting in simultaneous reduction of dose to the patient and of blurring due to motion. The advent of the image intensifier has brought electron optics into the field. Without going into many details it seems that the main advantages resulting from this are reduction of patient's dose and increase in image brightness which in due time have made possible, by allowing constriction of the target size, both amplification of radiographic images and more frequent use of cineradiography.

For improvements in the registration of the image one would have to look into amelioration of some properties of the radiographic film, which has received the consistent attention of only a few major manufacturers throughout the world, and into the fluoroscopic screen which, instead, seems to have been developed practically at random and manufactured by a large number of small firms. A recent advance that promises to increase information in x-ray diagnosis, with a concurrent reduction of dose, is the use of CsI and KI in radiographic intensifying screens (1). These crystals, well-known for their performance in scintillation spectrometry, seem to excel in all the steps leading to conversion of x-ray radiation of diagnostic quality into optimal registration on a photographic film. Thus, compared with the used screen material, $CaWO_4$, they exhibit: a) a higher absorption coefficient, b) twice the luminescent efficiency per unit of photon energy absorbed and, c) better spectral matching with the sensitivity of x-ray films (since the wavelength of the light emitted is around 4300 Å). Whether these materials will ever become practical will depend on the circumvention of some annoying drawbacks, such as hygroscopy of the crystals.

A novel and recent contribution to the general aim of x-ray diagnosis has been the effort of Dr. B. Jacobson to estimate the amount X_i of a chemical element *i* present in a live patient by x-ray spectrophotometry *in vivo* (2). This estimate is based on the solution of a set of n simultaneous equations of the type:

$$I_1 = I_{01} \exp - (\mu_{11} I_1 + \mu_{12} X_2 + \ldots\ldots + \mu_{1n} X_n)$$

associated with the transmitted portion I_1 of photons of total energy I_{01} incident on the mass of material containing element $i = 1,2 \ldots n$. the absorption coefficients of which are designated by μ.

This approach cannot succeed unless the μ's are substantially different; at present this method has shown some measure of success only in the estimate of iodine, hydroxyapatite, and soft tissue. The equations are solved by analog computer methods such as illustrated in the slide (Figure II):

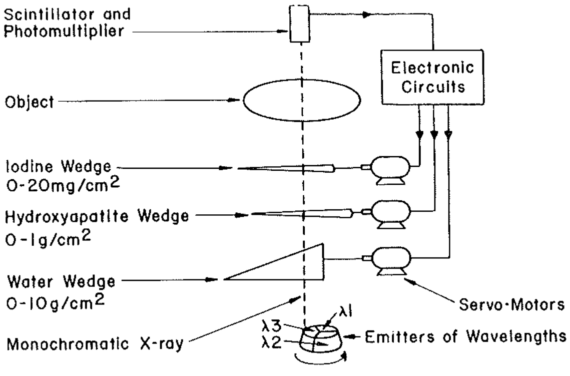

FIG.II. PRINCIPLE OF THE ANALOG COMPUTER

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namely, by interposing the object to be studied beyond three wedges of I^{127}, bone salt, and water in the path of three successive monochromatic x-ray beams originating from a rotating multielement anode and aimed at a properly placed scintillator. The apparatus is set by having the beams cross the wedges at their thickest part; when the object to be measured is interposed, feedback circuits will move the wedges toward their thinner edges until the scintillator registers the pre-set intensity at all wavelengths. By these means the displacement of the wedges will give a measure of the unknown quantities. Some data on bone salt in the metacarpal region which were obtained by these means are shown in Figure III. Although the sensitivities available can keep the absorbed dose within acceptable limits, this technique needs further improvement to become practical; its possibilities when used with roentgenographic contrast media remain to be explored.

Until a decade or so ago, the radiological physicist was rather a stranger in the diagnostic department except for his concern over the protection of the operating personnel; most of his efforts were required in therapy. However, with the widespread concern over the genetic material of mankind, the emphasis turned to the protection of the gonads of the patient. This preoccupation extends to no less than the average gonadal

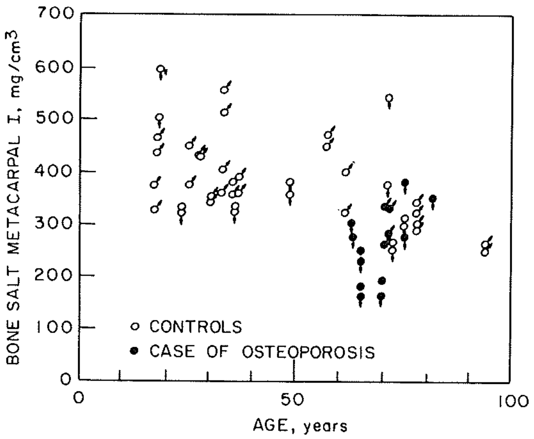

FIG. III. HYDROXYAPATITE VALUE FOR THE METACARPAL BONE OF THE THUMB DECREASES WITH THE AGE. THE VALUES WERE CALCULATED PER UNIT VOLUME OF BONE, INCLUDING THE MARROW.

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dose of the population of an entire country and, to be convincing, some evaluation studies have needed very large population sampling, indeed. The remarkable survey made in England a few years ago required exemplary cooperation throughout the country and special skill and devotion on the part of both the hospital physicists and of the radiological profession (3).

In the U.S.A. there have been two special meetings completely devoted to the reduction of the diagnostic dose to the patient. Although held only three months apart, the overlap in attendance and subject matter was minimal. The written record (4), (5) amply demonstrates the vast and intricate interplay of the disciplines involved in the task of maintaining optimal diagnostic objectives with minimum dose. This is because highest operational efficiency consistent with basic knowledge can be attained only by optimizing *every* step involved in the conveyance of diagnostic information.

In order to keep within the limits of my task, I shall restrict myself to a brief review of the measurements of exposure and absorbed-dose in patients undergoing diagnostic procedures; these measurements require the moderate accuracy and stringent economy that make possible convincing mass surveys.

The measurements of exposure to radiation useful in diagnosis and dermatology was accomplished soon after the implementation of the roentgen by means of standard air-chambers patterned after the basic design of Taylor and Stoneburner (6). Much more recently, very profuse and detailed data on the design and performance of this type of chamber have been given by Ritz (7) and Allisy and Roux (8).

In the early thirties measurements of exposure to low voltage x-rays were made in the clinic not only with thin-walled calibrated thimble chambers but also with the so-called « mesh chamber » originally suggested by Failla (9). The design requirements of this chamber, namely, maintenance of maximal transparency and avoidance of interpenetration of the electric field between the electrodes, was recognized early and properly implemented in practice by the Memorial Hospital group; yet it was not reported in the open literature for many years. Only in 1943 did Quimby and Focht (10) report air, skin, and depth doses from a Chaoul machine by means of a mesh chamber and by an extrapolation chamber (Figure IV)

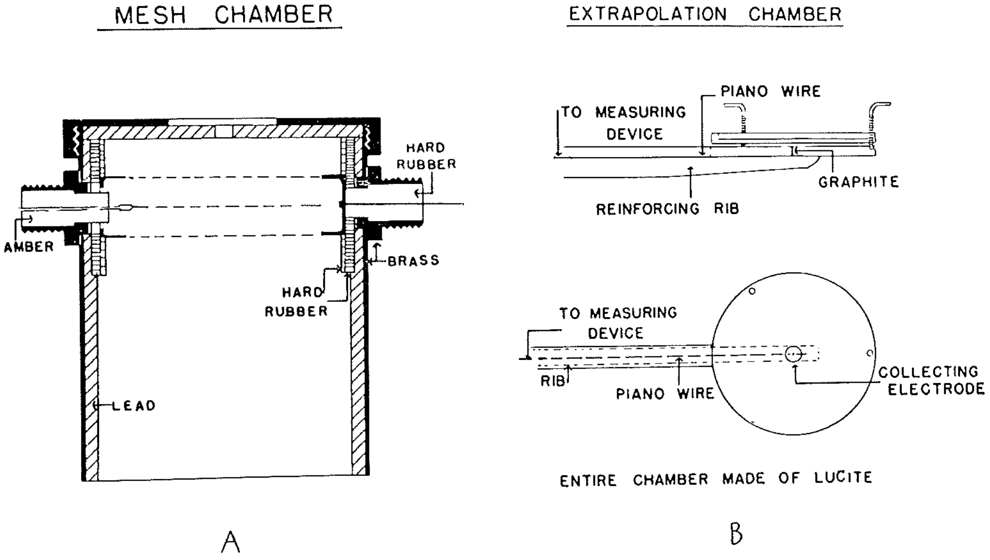

FIG. IV. A, OPEN AIR CHAMBER OF MESH TYPE; B, SMALL EXTRAPOLATION CHAMBER

(From Ref. (10). Reproduced by courtesy of the author and C. C. Thomas, publisher.)

to which a mesh upper electrode was adapted when the absorption of x-ray by a plastic film proved too severe. Since that time more detailed descriptions of the design requirements of mesh chambers have been given by Somerwil (11) and by R. K. Clark (12). To this general category of chambers belongs the recently described « wall-less » chamber of Tranter (13) which is stated to follow the air chamber within a very few percent in the range of 10 to 50 kvp.

The approach to precision by avoiding absorption by the front walls of an ionization chamber, made possible the measurements of air, skin, and depth doses in phantoms (14), (15); it did not solve the problem of measurements *in vivo* at dose-rates and locations of interest to radiation protection; this problem required the development of *rugged* thimble chambers capable of energy independence within the diagnostic region of the spectrum. This did not occur until 1953 when a study by Oosterkamp and Proper appeared in Acta Radiologica (16). In that paper the idea of using an air-filled cavity chamber with a wall of Z lower than air was first proposed as a means of overcoming the high absorption unavoidably associated with wall thicknesses compatible with ruggedness (Figs. V, VI).

Recently a promising design (Fig. VII) has been proposed by Garret and Laughlin (17) who have taken up the original suggestions of Oosterkamp and Proper and added some original points of their own to achieve a satisfactory isotropic and energy independent response from a chamber of modest dimensions (Figs. VIII, IX). Concurrently, the performance of similar chambers of good but somewhat more limited characteristics in energy or directional response have been reported elsewhere.

These designs do represent a significant step forward; however, one must realize that the chamber is also used to measure scattered radiation and it is not basically a standard. Hence the limits of isotropy and energy independence should be established unequivocally with *monochromatic radiation* at *distances relevant* to the use to which these chambers are used. This supplemental information will resolve some of the ambiguities arising in the energy regions of 0.05 mm Al HVL and 2-3 mm Al where the responses clearly show a sharp deviation (Figs. VI and IX). At these energies the « clinical diagnostic » spectrum can be investigated with scintillation spectrometers employing NaI, KI, or CsI, and/or proportional counters using the heavy noble gases.

In the field of radiation protection in diagnostic radiology various other needs have been mentioned in the current lite-

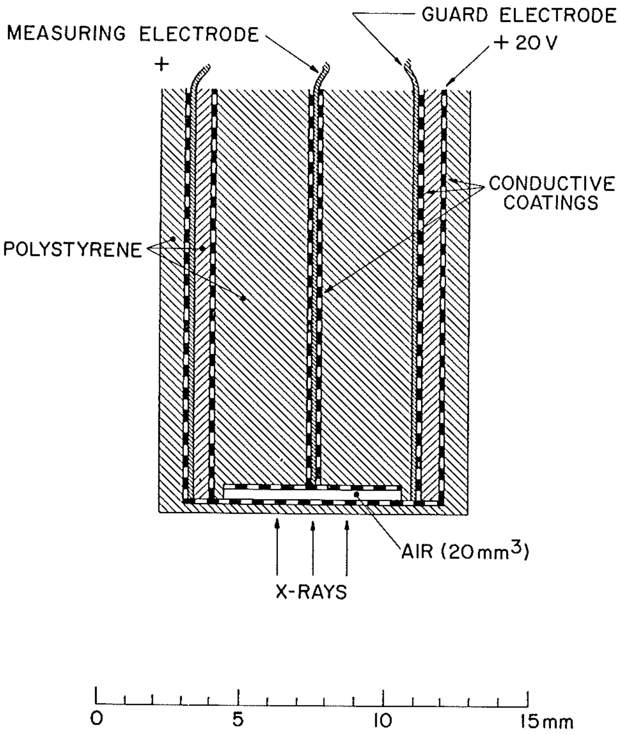

FIG. V. CROSS SECTION OF FLAT IONIZATION CHAMBER

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rature. Some of them have been expressed especially by governmental safety inspectors of diagnostic equipment. They are as follows:

a) convenient methods for the appraisal of screen efficiency;

b) adequate fast response in measuring apparatus to permit correct readings during the typically short times of radiographic and fluoroscopic procedures;

c) personnel dosimeters designed specifically for this energy range;

d) a better understanding of the behavior of irradiated insulators and the elimination of their defects in condenser dosimeter work.

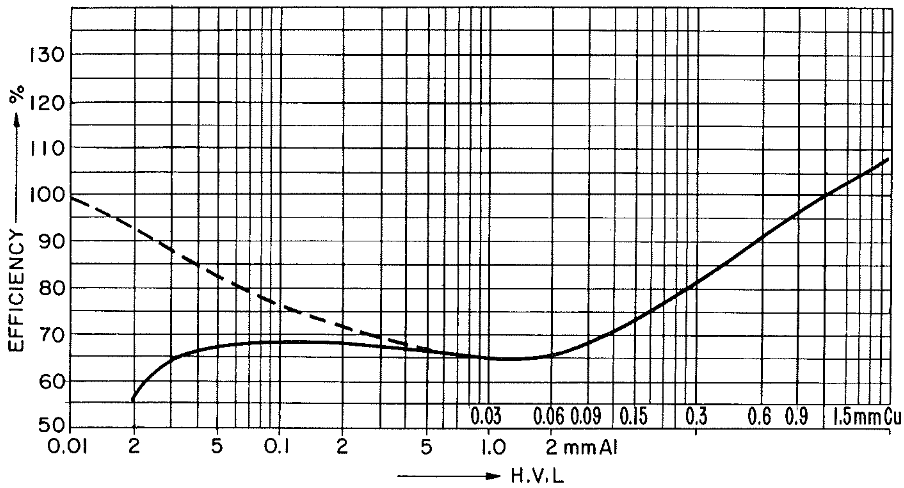

FIG. VI. THE EFFICIENCY OF A FLAT IONIZATION CHAMBER AS A FUNCTION OF H.V.L.

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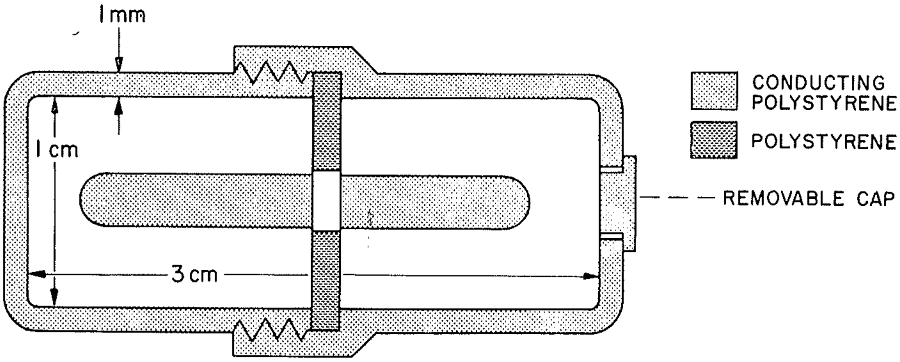

FIG. VII. MEMORIAL DIAGNOSTIC CHAMBER. CROSS-SECTION OF CHAMBER DESIGNED FOR DIAGNOSTIC X-RAY EXPOSURE STUDIES.

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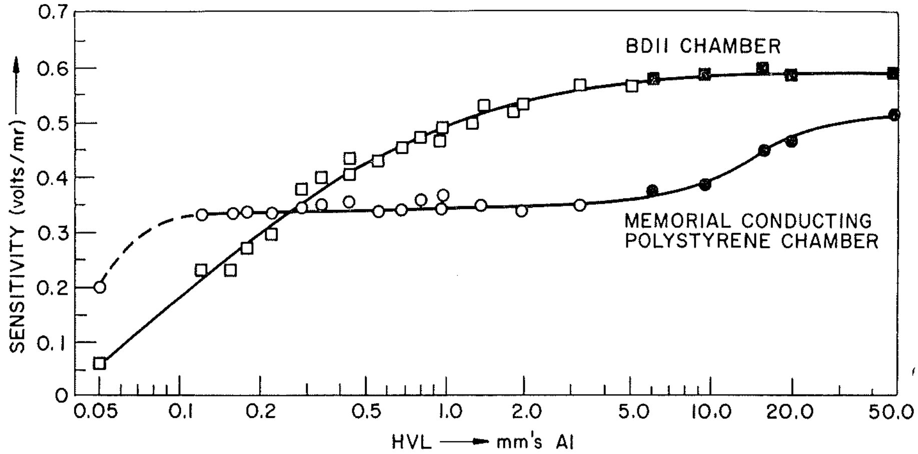

FIG. VIII. ENERGY RESPONSE OF THIMBLE CHAMBERS

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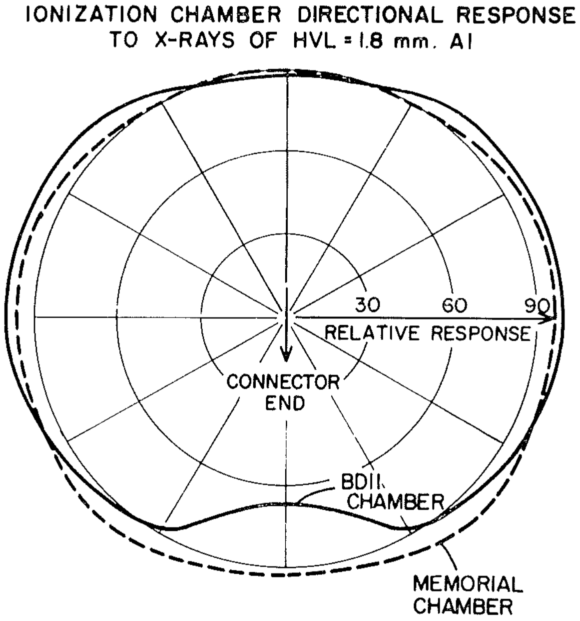

FIG. IX. DIRECTIONAL RESPONSE OF THIMBLE CHAMBERS

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Other problems await also particular solutions in this energy range. One consists in measuring, directly, the *absorbed* diagnostic dose in soft tissues *in vivo,* possibly by an extension of Oosterkamp and Proper's suggestions of a low Z wall chamber filled with tissue gas. A more important problem perhaps consists in measuring, also by direct means, the distributed absorbed dose in bone marrow. This special topic looks rather large today because, correctly or incorrectly, no dose threshold is assumed in the leukemogenic action of radiation.

At present our estimates are still heavily dependent on evaluation of rad to roentgen ratios; these calculations, pioneered and detailed by Spiers, require knowledge of the energy spectra of the secondary electrons crossing the marrow-bone interfaces and knowledge of the dimensions of the cavities comprising the trabecular labyrinth.

Some methods aimed at evaluating the integral doses delivered under typical diagnostic procedures have been described by Grimmett (18), Mayneord *et al* (19), and Rossi (20). The exact role of these measurements in the appraisal of potential leukemogenic action will, of course, remain obscure until the mechanisms involved are clarified. Nevertheless, in the interest of record keeping and of maintaining awareness of the physical agent used, some radiologists have designed ionization chambers, such as shown in Fig. X, which record automatically the total x-ray energy flowing through them on its way to the patient (21).

I sincerely hope that the purpose of this conscientious gatekeeper of photons will be imitated widely outside the field of radiology. Instruments thus conceived should improve the vigilance over, and lead to the reduction of more serious offenses against the public health.

II) Therapy

If Roentgen was unquestionably the first diagnostician, the observer of the first radiobiological effect is much more difficult to identify. Depilation following exposure to x-rays was reported four months after Roentgen's discovery and severe skin burns suffered by a salesman of x-ray machines were described a few months later. Among the early radiobiologists, one can count Henri Becquerel who accidentally discovered the production of erythema on his own skin as a result of having carried a container of the newly-discovered radium in his vest pocket. More systematic were the animal studies of Pierre Curie who collaborated with two medical men, Bouchard and Balthagard; they found that radium destroyed superficial cancers. The first medical case-notes, however, were published in 1904 by Danlos who used the element at the St. Louis Hospital of Paris.

By about 1910, however, it had become obvious that in addition to the study of the biological responses which had just been begun by such pioneers as Bohn, Bergonié and Tribondeau, Dominici, and Perthes, some quantitative approach to radiotherapy was necessary. It was thus that the profession of radiological or hospital physics was born.

The objective of most radiation therapy is the destruction of a tumor with minimal damage to normal structures. It is obvious that to succeed a great deal of care must be exercised in the procedure. Different and, at the same time, rigid requirements have been set for sources of radiation and from spatial source-patient relationships.

Self-contained sources applied within or near the tumor consist usually of radioactive elements, the classical representative of which is Ra^{226}, the well-known daughter of uranium used almost exclusively before 1940. It is in this particular type of therapy that the hospital physicist was first called in to assist in the more or less judicious design of the first moulages conforming with the individual lesion, the first radium teletherapy apparatus, and the first protective containers. Owing to the very high cost of radium in the early twenties, quite a good deal of effort was also devoted, especially in America, to the extraction of radon from radium,

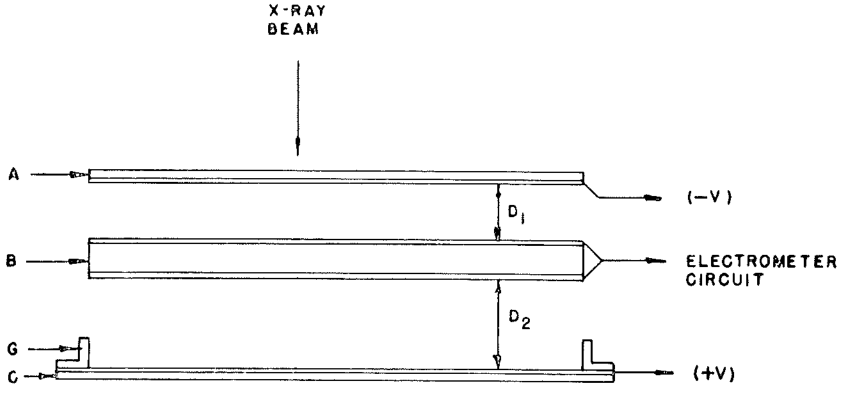

FIG. X CROSS-SECTIONAL SCHEMATIC DIAGRAM OF THE IONIZATION CHAMBER

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and to its proper containment in filtered tubes for intracavitary treatments and in needles of smaller diameter for interstitial therapy.

In the two decades from 1910 to 1930 radiotherapy was actively nourished by radiobiological research in which several radiotherapists participated. Yet, one wonders nowadays just how much of the success in those days depended also on the fact that the early pioneers used radium for the treatment of surface or easily accessible lesions practically in contact with their sources. Under those conditions the influence of the inverse square law limited drastically any accidental overdoses to relatively shallow depths. Moreover, the very high cost of the element limited also the size of the sources and enforced prolonged treatment times even before Regaud's experiments clarified the importance of the time factor in radiation therapy. Also of early vintage are the calculations of the distribution of radiation in interstitial therapy pursued by hospital physicists in various clinics by the use of the inverse square law and of a little known coefficient of absorption. In practice, these deficiencies could not lead to disastrous consequences because the relevant thicknesses rarely exceed a few centimeters; moreover, in many types of treatments, surgical limitations and anatomical configuration dictated the geometrical array of the sources. The exposure, expressed in milligram-hours of radium (or millicuries destroyed of radon), was sufficient to express a method of treatment with a fair record of reproducibility.

With the advent of the powerful but erratic beams of radiation from the early x-ray tubes, however, the probability of accidental overdosage increased. As a consequence, the absolute necessity of achieving meaningful dosimetry became apparent and so did the desire of achieving through it a rational comparison of various methods of treatment and their eventual improvement.

In the years between the definition of the roentgen in x-ray therapy (1928) and the Second World War, a good deal of the physicist's activity was spent in measuring the exposure rate in roentgens from a known radium source under standard condition of filtration and distance.

Because of the high energy photons emitted by radium it was not possible to reach a satisfactory solution based on the use of the parallel plate chamber, which was, and still is, the standard in the range of photon energies below a few tenths of a megavolt; in 1936 these efforts culminated in the clarification and confirmation of the Bragg-Gray criteria governing the now-famous relationship linking the energy D_m released per unit mass in the walls of a cavity to the ionization J_m produced per unit mass of gas in the cavity itself:

$$D_m = J_m W_g \rho_m \qquad (1)$$

In this expression W_g is the energy necessary to produce one pair of ions in the gas and ρ_m is the ratio of the stopping power of the wall material to that of the gas for the ionizing particles crossing the cavity surface.

A discussion of the validity of expression (1) in the evaluation of rads, namely the radiation energy expended in a medium (in units of 100 ergs per gram) will be (or has been) presented by my distinguished colleague, Dr. A. Perussia. Discussion of the most direct, but not the most convenient, method of measurement of absorbed dose, namely calorimetry, (have been) the object of Dr. Dutreix's presentation.

For the moment I shall limit my remarks to the role of dosimetry in the field of radiation therapy. I think we are all agreed that investigations leading to an understanding of the basic phenomena in an ionization device have led to satisfactory and reproducible measurements of absorbed dose. It must be realized, however, that the drive for very high accuracy in dose distribution and radiation measurements in general are being met, not infrequently, with skepticism by very competent therapists who have noted the inconsistency between attainment of meticulous physical measurements of the dose on the one hand and the somewhat cruder clinical appraisal of tumor location on the other.

This criticism would be justified if dosimetric fastidiousness were carried out in the clinic as an end in itself; the comment is not justified, however, if the accuracy is practiced in schools in order to offer the therapist resident the opportunity to appraise the properties of radiation which he will use for the rest of his life and to develop in him the wholesome skepticism and care so necessary to persons who must delegate some aspects of human welfare to the accuracy of instruments.

It must be realized that the basic principles of dosimetry by gas ionization methods have not changed radically to this day but that the variety of the sources in any one institution have very much done so. From the so-called superficial (140 kvp) and deep therapy (200 kvp) machines of the early thirties we do have a respectable range of apparatus to face; namely: Grenz machine (10 kev); plesio-therapy (45 kev); diagnostic equipment (25-100 kvp); medium voltage (140 kvp); conventional or orthovoltage (250-500 kvp); supervoltage roentgen rays (1-2 Mev); linear accelerators (1-70 Mev); betatrons and synchrotrons (15-50 Mev); and teleisotope machines (Co^{60}-Cs^{137}). This list comprises sources of continuous output (constant potential, Van de Graaff generators and teleisotope sources) and others which are pulsed for intervals ranging from 1/120 of a second on down to the microsecond region.

From these sources we may obtain either uniform or very asymmetric spatial emissions; in the latter case very fastidious and very necessary corrections are needed to make the source useful at all. This may be complicated by the fact that the source and the patient may or may not be stationary with respect to each other. An illustration of the different kinds of moving fields in use today is shown in Figure XI.

It is obvious therefore that the variety of therapeutic approaches poses continual challenges to the physicist. His task is still to evaluate the absorbed dose within the body, often in three dimensions when the therapeutic objective of tumor cure demands doses approaching closely the tolerance of the tissues adjacent to the lesion. It has been recognized that these studies have reduced the hazard of radiation injuries that may accrue through unrecognized overlapping in multi-field techniques. What is highly desirable in this respect is the economical attainment of this spatial information with a modicum of accuracy, say 5 or 10 percent. In the very large centers this ideal may be implemented by computer methods fed by a library of depth dose information; in others, if and when attainable, the quantitative evaluation of the luminescence produced by a therapy technique throughout a suitable plastic phantom will be sufficient for the purpose. If I were to name the most informative and convenient method of exploring isodoses in depth following therapeutic techniques, I would not expect harsh criticism if I were to mention the « proper » photographic emulsion, provided that by « proper » I meant the property of absorbing and registering any type of ionizing energy at a rate proportional to that absorbed in an equal volume of water or soft tissue similarly placed.

This desideratum, however, has not been reached; in everyday therapeutic practice we still rely on the ionization chamber which has proved so versatile in skilled hands as to constitute the standard against which other types of detectors are compared, in most — if not all — circumstances. An example of the few limitations of ionization devices is illustrated by considering whether the chambers are to be used *in vivo*. If one were to contemplate the insertion of a dosimeter in a lesion, one would have to think in terms of size of a needle of one or two millimeters in diameter; at this point construction and handling of gas ionization

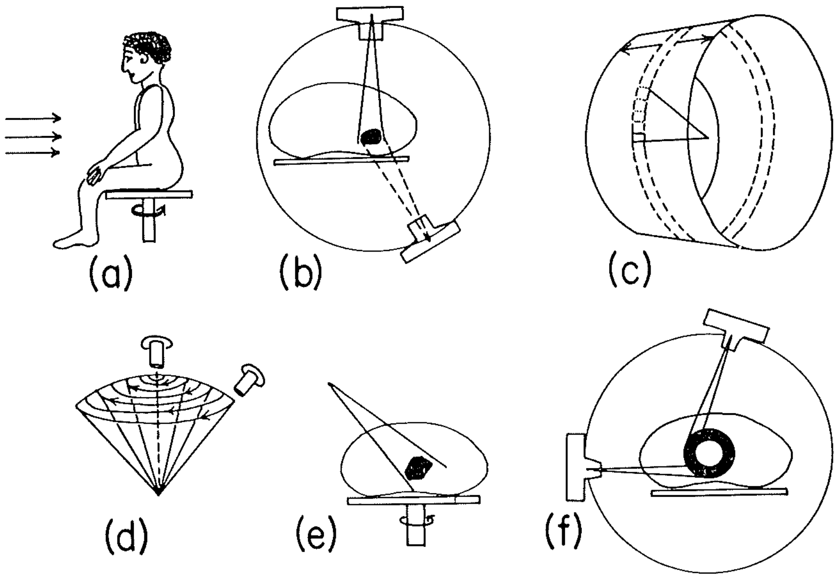

FIG. XI. DIAGRAM ILLUSTRATING THE VARIOUS TYPES OF MOVING FIELD THERAPY

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chambers with high insulation between electrodes becomes impractical for routine purposes. Here the search for convenient methods, especially for those not requiring high skill, has turned to the investigation of the effects of radiation on liquids and solids.

Among liquids the ferrous sulphate dosimeter of Fricke has gained wide recognition in radiation research in general, and, to a more limited extent, in clinical dosimetry. I shall not dwell at length on this and similar chemical dosimeters because they will be discussed by my colleague, Dr. Allisy.

The discovery of measurable radiation effects on the structural properties of many materials has confronted persons interested in dosimetry with too many choices; these have usually been classified by the process which reveals the effect. Some of them have proven convenient in the investigation of radiation damage in solid materials, a field characterized by extremely high exposures to mixed radiations, such as those prevalent in the interior of nuclear reactors.

When information of this sort and the materials in question become available to the radiological physicist two reactions occur: one is total rejection of the method because of the limited control that the physicist can exercise over the properties of these devices; the other is blind acceptance of anything that solid science is likely to offer. If the first attitude may lead to delay in useful applications, the second can lead to a tremendous waste of experimental effort and the publication of inane papers; this can be avoided in most instances, since one knows beforehand that one cannot expect satisfactory dosimetry in predictable energy bands when the atomic number of the materials of the detector is far removed from 7.0 and its active volume is much too large to behave as a small gaseous cavity.

The usefulness of solid state Bragg-Gray devices based on radiation damage has been demonstrated by Ritz and Attix under very stringent conditions (22); they found Mylar films (6μ) satisfactory enough but, unfortunately, useful only from 10^7 to 1.5×10^8 roentgen; damage in larger thicknesses of anthracene did not follow rigorously the ionization in the air cavity.

Of sensitivity compatible with the ranges of exposure used in radiotherapy are the radio-photoluminescent glasses (10-10^5 roentgens) in the form of rods of small dimensions (5-15 mm × 1 mm) (23). These have been used in tissue implants and seem to have gained favor in some radiological departments. Their main advantage over ionization chambers of the condenser type is their ruggedness, smaller size and retention of response to radiation. Although their use is most rewarding in the megavolt region, their shortcomings (which might be minimized in the near future) are definite. These are: a) their Z is relatively high; the suggested corrections brought about by filtration are definitely empirical and have not been demonstrated to apply isotropically, b) in general the response from a batch of rods is likely to be spotty; hence, readings must be constantly checked by the use of several fluorods.

Of great promise, because of their sensitivity and low Z, are the measurements of thermoluminescence available from irradiated LiF (Fig. XII) (for soft tissue) (24) and $CaSO_4$ (for bone mineral) (25). Although the full signal is destroyed by the measurement, use of aliquots permit a permanent record of the reading; moreover, repeated measurements of the phosphorescence have been suggested as feasible (26). Special mention must be made of the small amounts of material needed (a few mg) and the small size of the individual crystals available (a few microns); these properties augur well for their use in real bone trabeculae for the direct measurement of the average dose to the marrow. Thus far, this estimate has been

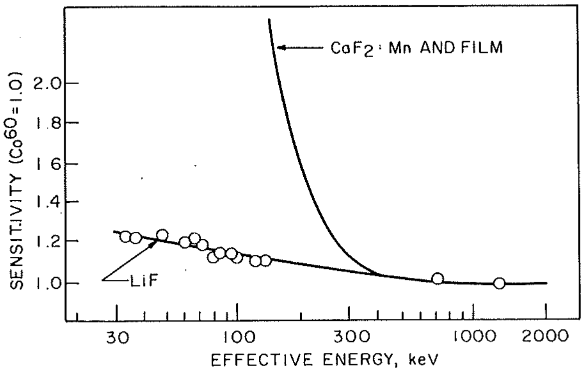

FIG.XII. ENERGY DEPENDENCE OF TLD-100 LiF COMPARED WITH THAT OF OTHER UNSHIELDED DOSIMETERS

(From Ref. (24). Reproduced by the courtesy of the author and publisher.)

attempted only by indirect means, including the use of a biological dosimeter consisting of a phage culture (27) *(vide supra).*

Time does not permit an extended discussion of some applications of these devices; only brief mention can be made of those that should be suited to the spectrometry and dosimetry of β-ray applicators. In principle, the absorbed dose at any one point of a given material can be always calculated with fair accuracy if one knows the energy spectrum of the ionizing particle crossing a small spherical surface surrounding the point. This information can be obtained, over flat surfaces at least, by means of suitably diffused silicon junctions which, according to the depth of the depletion layer (10 to 1000μ) could register the whole energy flow or merely dE/dx. These devices do offer high sensitivity per unit volume and can be used as solid ionization chambers. Their energy response to ionizing particles is practically proportional to energy lost and independent of L.E.T. Recent reviews on the applicability of these methods to dosimetry have been published by Fowler (28) and by Attix and West (29).

Organic scintillators, both liquid and solid, also offer to the investigation the possibility of acquiring spectrometric and dosimetric information; their sensitivity is high, their cost is relatively low, and their shape can be controlled to a certain extent. Since they are not very sturdy instruments, however, and require skillful handling, they cannot generally be considered ideal instruments for routine dosimetry.

Besides using liquid and solid radiation detectors for the estimate of absorbed dose, the radiological physicist should also inquire into the nature of the mechanisms involved in their response, especially when these are evaluated in terms of absorbed energy. Some stimulating facts may ensue, for instance, if one compares radiation-induced luminescence and biological effects one notes that both of them are affected by oxygen and that striking differences exist in the efficiency of their response to radiations of higher L.E.T. Of particular interest are some preliminary findings of Berlman *et al.* of our Laboratory (3): in their investigations of the light emitted by PPO in various solutions under the action of equal energy of α and β radiation, they found (Fig. XIII) that the ratio of luminescence produced by the first to that of the second was correlated to the intrinsic sensitivities of the solutions to radiation chemical damage. These studies were undertaken with the intent of gaining some information on the excitation of atoms and molecules along the ionizing track. What light they may throw, by analogy or otherwise, on the relative biological effects of radiations of different L.E.T. is practically impossible to predict at this time.

Fig. XIII The α/β Ratios from Binary Solutions Composed of Various Solvents with 8 g/l of PPO as the Common Solute

Solvent	mV	α/β Ratio	Gr.
cyclopentane	26.3/54.4	0.052	
hexane	31.9/61.8	0.056	
methyl cyclohexane	37.6/69.7	0.058	
cyclohexane		0.063	14.3
cyclohexene		0.067	
xylene	115.4/142/.7	0.087	11.0
ethyl benzene	103.6/126.6	0.088	9.0
toluene	109.7/131.8	0.090	3.1
styrene	7.8/8.4	0.100	1.6
benzene	101.2/109.3	0.100	1.8
C_6D_6	123.2/115.4	0.115	

(From Ref. (30). Reproduced by courtesy of the author and publisher.)

Nuclear medicine

The most recently developed area in radiological physics is that of nuclear medicine. Although the term has been used in conjunction with the few attempts of external radiotherapy employing a nuclear the reactor as a radiation source, nuclear medicine has come to designate those fields of medical research, diagnosis, and therapy in which radioactive isotopes are given internally.

Of these three areas, research and diagnosis are at present the most active and the most productive. As far as the hospital physicist is concerned, both disciplines require of him the assessment of the distribution of the concentration of a radioelement within the body and its variation with time. The accuracy with which the concentration and/or the localization is required to be known varies considerably; typical examples of the extremes in localization, range from the so-called « hot » or « cold » nodules due to I^{131} localization in the thyroid to the distribution of a colloidal substance, such as Au^{198} or Au^{199}, through the reticulo - endothelial system of the body.

The first attempts to investigate radioisotope distribution *in vivo* by holding a shielded G. M. counter by hand over the body have given way to modern automatic scanning. Evidence of the interest in this technique throughout the world is given by the recent publications of the IAEA, 1959 (31) and of the U.S. AEC, 1962 (32) and the very recent IAEA meeting in Athens last April 20-24. Commensurate in effort and expense, though probably of no comparable usefulness to clinical medicine, have been the simultaneous developments of sensitive methods for assessing the natural potassium content of human beings and the retention of extremely small amounts of radioactive substances which have gained access into their bodies through fallout of radioactive debris. These methods are also being applied today in long-term experimental studies involving slowly changing physiological parameters: as a rule, in these procedures less emphasis is placed on geometrical resolution (33) (34) (35).

It is impossible within the time at my disposal to do much more than outline the functional requirements of a clinical scanning system: they are: a) the registry of the coordinates of a point in a plane; b) a response related to the concentration below the point in question; and finally, c) the presentation of this information to the physician for proper evaluation.

The first task is accomplished by pantographic methods. The second is achieved by the response of a scintillation crystal properly shielded and supplied with a properly designed collimator; to the latter is assigned the double task of allowing the crystal essentially to « look » at one small region at a time and of suppressing the interference of radiation engendered elsewhere. By more or less complicated means, the crystal response is marked graphically in various ways at the coordinates of the point under the collimator. The result is a scintigram for the diagnostic interpretation of which some selection of the total information gathered is usually done by various electronic means.

An ingenious scanning method at this moment reaching commercial outlets is the so-called « static » approach involving no motion of the crystal with respect to the patient. The principle of image information is identical to that of the camera obscura in which a relatively thin crystal takes place of the screen. An obviously dense and high Z shield is supplied with a denser central region through which the pinhole aperture is located (36). The scintillations that occur in the crystal, and their coordinates, are carried over to the scintigram by proper electronic circuits (Fig. XIV). The advantage of this method resides mainly in the higher efficiency and the concurrent benefit of low isotope dosage.

It is well to comment at this point that despite the rapid progress that has been made in the last few years in automatic scanning (37), the demands of the clinics themselves (38) have posed numerous problems of practical nature which are being solved effectively more by careful choice of the radioelements employed than by the alteration of the basic methodology evolved during the last decade.

This trend began with the substitution of one radioisotope of shorter life and emitting gamma rays of lower energy (80-200 kev) for the one which was used initially just because it was easily available. This choice has led to a sharp reduction of the weight and mass of the crystal-shield structure; the practical advantages that ensue are the attainment of better resolution with less expensive collimators (Fig. XV) and the possibility of using several of these to suit the specific anatomical distribution at hand (39).

With the advancing knowledge of biochemical procedures aimed at incorporating radioisotopes in substances which are selectively taken up by various organs in the body, a more recent trend has intervened, namely, first selecting a radioelement with the desirable physical characteristics for optimum scanning and later solving the biochemical problem required by the incorporation of this element in a compound known to localize properly (40).

In the field of research in intermediary metabolism, the activities of the radiological physicist have been many. The results of their laboratory and mathematical studies concerning iodine and strontium metabolism in the human are too well-known to need emphasis here.

In the clinical field, therapeutic applications of radioisotopes do not compare in variety with the diagnostic ones, both the use of I^{131} in the therapy of hyperthyroidism is sufficiently widespread to invite comment. Here the physicist contributes to diagnosis by functional tests with tracer amounts; if I^{131} therapy is indicated, he applies the diagnostic findings to the estimate of the correct absorbed dose. Without his help the evaluation of the correct dose of I^{131} in treatment of hyperthyroidism would have required a much longer time and, under certain circumstances, might have led to erronous conclusions as to the usefulness of the procedure.

The future of internal radioisotope therapy depends critically on the discovery of chemical substances which concentrate in tumor tissue to the virtual exclusion of the rest

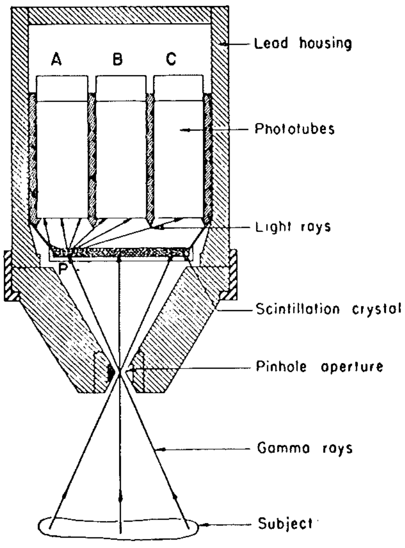

FIG. XIV. SCHEMATIC DIAGRAM OF THE SCINTILLATION CAMERA DUE TO ANGER

(From Ref. (36). Reproduced by courtesy of the author and publisher.)

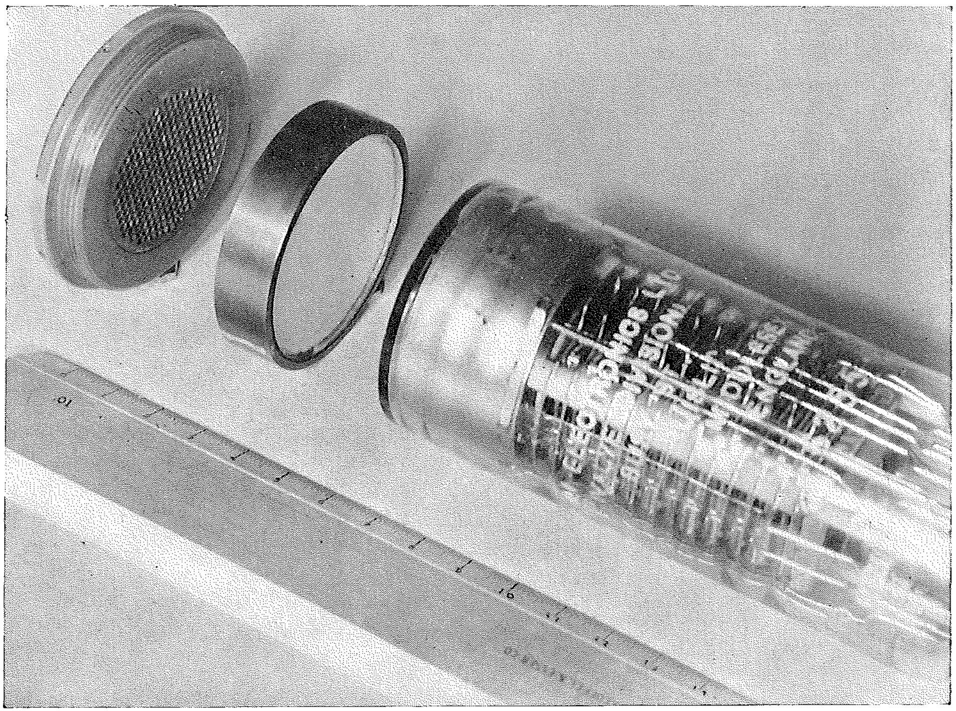

Fig. XV - *Low energy Gamma-ray detector. Collimator thickness* 0.55 *in.; NaI(TI) Crystal is* 1.75 *in.* × 0.25 *in. thick. Lead shield is* 0.25 *in. thick, adequate for* 140 *keV.*

(From Ref. (40). Reproduced by courtesy of the author and publisher.)

of the body. It is difficult to make predictions in this direction, because so much of the chemistry of the body is unknown. It would seem, on the one hand, that the chemical requirements of this type of therapy should be less rigorous than those of chemotherapy because the radio-destruction of the tumor demands only chemical concentration at the site. In chemotherapy, on the other hand, one would guess that additional chemical properties are needed to interfere with tumor metabolism; yet these very properties may be required to enhance specificity in concentration.

Today only certain types of metastatic thyroid cancer benefit in no uncertain terms from this systemic approach owing to the unique affinity of iodine for functional thyroid tissue. Bold and hopeful is the effort of Bale (44) aimed at achieving therapeutic concentrations of radioelements by immunological tagging.

It is perhaps because the success of systemic treatment by radioelements is basically dependent on biochemistry and it is still so limited in the clinic that internal beta-ray dosimetry is attracting so little attention from radiological physicists. Fundamental problems such as determination of beta-ray point source functions and the evaluation of experimental distributions *in situ* by practical means are still unresolved. In certain cases the resolution required suggests the use of photographic emulsions containing grains much smaller than those in use today. In others, such as the dose distribution in red bone marrow residing in trabecular bone containing radioisotopes, the vast photographic information given by autoradiography must be collated in some quantitative fashion by the experimenter. It is obvious that the intricacy of the distribution demands some type of automation. This approach has not been reported for this particular problem, but the radiodiagnostic literature already contains reference to methods analogous to the ones required here but used for the evaluation of information contained in the radiographic image (41) (*Vide supra*).

Problems within the exclusive competence of physicists in this field are the standardization of radioactive sources and the spectrometric evaluation of their purity in everyday clinical practice. In the field of beta-ray dosimetry from external sources, absorbed doses in depth can be evaluated via the extrapolation chamber and scintillation counters when the energy of the radiation is fairly large (42). For very low energy sources such as tritium, C^{14} and S^{35} useful parameters of dosimetric interest can be obtained by mesh chambers (12) and wall-less chambers (43).

Time does not permit consideration of what are perhaps the most complicated dosimetric studies that have faced the radiological physicist since the inception of the profession. These involve accidents due to unscheduled critical excursions of reactors. The interested person is referred to the original reports which are as lengthy and as detailed as required by the complicated situations in which they occurred.

Before leaving the subject it is well to mention that neutron activation analysis of tissue and fluids may well contribute to a better understanding of the metabolism of tracer elements in the body. Thus far, this technique has proven popular with chemists; it has been found definitely useful in tracer analysis of biopsy or autopsy specimens. It remains to be seen whether partial activation of certain portions of the body can facilitate quantitative studies of electrolyte and other mineral transport from certain organs of the body. At first sight this approach seems especially favorable for elements of large activation cross-section and of very short half lives; it is too early to surmise whether it could aid in the selection of a better radiotherapeutic method.

Prophecy in radiological physics, as in any other field of scientific endeavor, has an exceedingly short-lived accuracy; despite this obstacle, I shall conclude this presentation by trying to look quizzically into the future.

The radiological physicist, if he is to play a progressive role in the clinic and in the laboratory, must maintain more than casual contact with fields delving into the effects of ionizing radiation, not only at the histological and biomolecular level but also on the liquid and solid states of inorganic matter. This task will require a greater portion of his time than was the case in the past.

Qualitatively, however, his role may remain unchanged; namely, he is likely to exploit for the immediate benefits of medicine and radiology the discoveries of the future Roentgens, Curies, Rutherfords, and Fermis, who, like these illustrious men, will remain physicists and devote most of their activities to unraveling the mystery of matter and will rarely enter into biomedical problems.

As in the past, the field will be populated also by trainees in the life sciences and medicine who will complement the physicists in their task by contributing the skills and knowledge acquired in medical and biological schools. The result of this collaboration should lead to more rapid, beneficial advances.

An outstanding example of what may come from this reciprocity of scientific interests occurred about 165 years ago not very far from here; for it was in Bologna and in Como that the observations of Galvani, an anatomist, and of Volta, a physicist, led to the idea of the electric current.

APPENDIX

The opportunities for advanced training and study for those interested in radiological physics and/or radiobiology have expanded markedly in the past few years. Undoubtedly the availability of funds in the form of grants and fellowships provided by the Atomic Energy Commission and the Division of Radiological Health of the Public Health Service has given impetus to the creation and strengthening of such programs. For example, as of March 1964, there were 31 educational institutions with graduate curricula in radiological health which have been developed with grant assistance from the Division of Radiological Health (Table I). A list of these institutions is appended, as well as the names of 10 universities participating in the AEC Health Physics program (Table II).

A partial compilation (as of 1961) of institutions awarding degrees in medical physics and the broader field of biophysics along with the primary emphasis of the programs is also attached (Table III). These names were collected by the American Association of Physicists in Medicine. Although there is, of course, duplication among these lists, it is obvious that the number of institutions with programs of interest to those concerned with radiation research in extensive. The wide geographical distribution is also noteworthy.

In considering specific requirements and curricula, it is helpful to refer to the classifications used by the AAPM. The programs listed in Section A of Table III are **in general** more specialized and practically oriented with emphasis directed toward specific radiological (particularly dosimetric) problems. Most of these, it will be noticed, are given within Departments of Radiology at the Medical Schools. The prerequisites usually include a basic college physics background. The courses offered are in such areas as electronics, radiation dosimetry, radiobiology, and radioisotope techniques. The requirements for a Ph. D. are, of course, more stringent and a broader program is required.

The Biophysics Programs listed in Section B of Table III are not as specifically oriented to the study of radiation problems. A basic undergraduate multidisciplinary background is required for admission and in most cases the graduate curriculum is flexibly around the interests of the individual but with the purpose of providing him with a balanced foundation in physics, biology and chemistry. Most of the required courses are those offered by the regular graduate science departments supplemented by one or two survey courses illustrating the various areas in which physical methods are applied to the problems of living systems. In many cases these Biophysics Programs are administred by Committees comprised of representatives of the various disciplines which emphasizes the diversified course of study offered. Ordinarily the choice of an area for thesis investigation is open and flexible but, of course, is influenced by the interests of the members of the Committee. Radiation problems comprise only one area of study and are not necessarily the thesis subject.

With the increasing interest in graduate Biophysics programs more and more institutions are offering undergraduate Biophysics curricula

TABLE I

	Page
University of California	2
University of Cincinnati	4
Colorado State University	6
Columbia University	10
Emory University	12
University of Florida	14
Georgia Institute of Technology	18
Harvard University	20
University of Illinois	22
Iowa State University	24
Johns Hopkins University	26
University of Miami	28
University of Michigan	30
Michigan State University	32
University of Minnesota	36
New York University Medical Center	38
Consolidated University of North Carolina	40
North Dakota State University	42
Northwestern University	44
University of Oklahoma	46
Oregon State University	48
University of Pennsylvania	50
University of Pittsburgh	52
Purdue University	54
Rensselaer Polytechnic Institute	56
Rutgers: The State University	58
Temple University	60
University of Texas	62
University of Washington	64
Washington State University	66
Wayne State University	68

(From booklet entitled « University Curriculums and Fellowships in Radiological Health ». U.S. Department of Health, Education and Welfare, Public Health Service, Division of Radiological Health, March. 2, 1964).

designed to equip the student with all the prerequisites for graduate study. In the absence of such an undergraduate program it is almost impossible for the ordinary physics, chemistry, or zoology major to have all the necessary courses in the fields other than his major. Products of such an undergraduate program are, of course, prime candidates for becoming radiological and health physicists.

The National Laboratories, as foremost employers of persons qualified in radiation studies, have done much in the way of offering courses and facilities for research to encourage interest and competence in this field. The number of opportunities for such studies will undoubtedly continue to increase with the support being provided by the various governmental agencies.

TABLE II

HEALTH PHYSICS PROGRAMS AT PARTICIPATING UNIVERSITIES

University	*Major Departments*	*Area of Emphasis*	*Graduate Degree*
Harvard	Biostatistics Engineering and Applied Physics Industrial Hygiene Physiology Sanitary Engineering	Radiological Engineering	M.S. D.Sc.
Texas A & M	Biology Biology and Nutrition Chemistry Mathematics Nuclear Engineering Physics	Nuclear Engineering	M.S. M.E. Ph.D.
California	Biochemistry Medical Physics Nuclear Engineering Physics Public Health	Biophysics Medical Physics Radiophysical Research	M.S. M.B. Ph.D.

Table II (continued)

University	*Major Departments*	*Area of Emphasis*	*Graduate Degree*
Kansas	Biology Chemistry Mathematics Nuclear Engineering Physics Radiation Biophysics	Biophysics Radiation Chemistry Radiation Biology Tracer Studies	M.S. Ph.D.
Michigan	Engineering Mechanics Environmental Health Industrial Health Nuclear Engineering Physics Zoology	Research Project in related field	M.A. Ph.D. M.P.H. M.E.S.
Puerto Rico	Biology Chemistry Physics	Biology (including Medicine) Chemistry Physics	M.H.P.
Rochester	Chemical Engineering Radiation Biology & Biophysics	Biology Medicine	M.S. Ph.D.
Tennessee	Biology Chemistry Physics	Radiation Physics	M.S. Ph.D.
Washington	Chemistry Fisheries Nuclear Engineering Physics Radiological Sciences Radiology	Radiological Science	M.S. Ph.D.
Vanderbilt	Biology Chemistry Medicine Mathematics Physics and Astronomy	Physics Biophysics	M.A. M.S. Ph.D.

(From booklet entitled « Careers in Health Physics » through United States Atomic Energy Commission Special Fellowships, administered by Oak Ridge Institute of Nuclear Studies, Oak Ridge, Tennessee, October 1963).

TABLE III

UNIVERSITY PROGRAMS IN MEDICAL PHYSICS AND BIOPHYSICS

The institutions which are listed in Sections A and B award degrees in the field of medical physics and biophysics. This list is not complete and is subject to revision. For the guidance of interested parties, the degrees offered and the name of the program director are included. Courses with primary emphasis on Health Physics, for example those in the AEC Health Physics program, are not included. An asterisk (*) indicates mainly radiological physics, and a dagger (/) indicates mainly radiobiology.

Section A. Programs in Medical Physics Including Radiological Physics

Institution	*Location and Department*	*Degree(s)*	*Director*
*Univ. of Califonia (Los Angeles)	Sch. of Medicine, Dept. of Radiology	M.S., Ph.D.	M.A. Greenfield, Ph.D.
*Univ. of Chicago	Sch. of Medicine, Dept. of Radiology	M.S.	R.D. Moseley, Jr., M.D.
*Columbia University	Coll. of Phys. and Surg., Dept. Radiol.	M.S.	H.H. Rossi, Ph.D.
*Emory University	Sch. of Medicine, Dept. of Radiology	M.S., Ph.D.	R.H. Rohrer, Ph.D.
*University of Florida	Coll. of Medicine, Dept. of Radiology	M.S., Ph.D.	J.D. Reeves, M.D.
*Johns Hopkins University	Johns Hopkins Hosp., Dept. Radiology	M.S., Ph.D.	R.H. Morgan, M.D.
Johns Hopkins University	Biomedical Engineering Dept.	Dr. Eng.	S.A. Talbot, Ph.D.
*University of Illinois	Coll. of Medicine, Dept. of Radiology	M.S., Ph.D.	R.A. Harvey, M.D.
*State University of Iowa	Sch. of Medicine, Radiation Research Lab.	M.S., Ph.D.	T.C. Evans, Ph.D.
*University of Kansas	Physics Dept.	M.S., Ph.D.	F. Hoecker, Ph.D.
*Memorial Hospital, New York	Dept. of Biophysics (Cornell Univ.)	M.S., Ph.D.	J.S. Laughlin, Ph.D.
*University of Minnesota	School of Medicine, Dept. of Radiology	M.S., Ph.D.	M. Loken, Ph.D.
*University of Pennsylvania	School of Medicine, Dept. of Radiology	M.S., Ph.D.	J. Hale, Ph.D.
University of Pennsylvania	Moore Sch. of E. Eng., Electromed. Div.	D.Sc.	H.P. Schwan, Ph.D.
*University of Rochester	Sch. of Medicine, Div. of Radiology	M.S., Ph.D.	L. Hempelman, M. D.

TABLE III (continued)

Section A. Programs in Medical Physics Including Radiological Physics

Institution	*Location and Department*	*Degree(s)*	*Director*
*University of Texas (Dallas)	Southwestern Med. Sch., Dept. of Radiology	Ph.D.	F.J. Bonte, M.D.
*University of Toronto	Dept. of Medical Biophysics	M.A., Ph.D.	A.W. Ham, M.B.
University of Utah	School of Medicine	M.S., Ph.D.	T.T. Dougherty, Ph.D.
*Medical College of Virginia	Dept. Radiology	M.S., Ph.D.	R.G. Lester, M.D.
*Stanford University	Sch. of Medicine, Dept. of Radiology	M.S.	H. Kaplan, M.D.
*Washington Univ., St. Louis	Sch. of Medicine, Dept. of Radiology	M.S., Ph.D.	M. Ter-Pogossian, Ph.D.
*University of Wisconsin	Sch. of Medicine, Dept. of Radiology	M.S.	L.W. Paul, M.D.
Section B. Programs in Biophysics Including Radiobiology			
/Bowman-Gray Sch. of Medicine	Dept. Radiology	M.S., Ph.D.	D.J. Pizzarello, Ph.D.
Univ. of California (Berkeley)	Graduate Group in Biophysics	M.A., Ph.D.	R.C. Williams, Ph.D.
Univ. of California (Berkeley)	Donner Lab. of Medical Physics	M.A., Ph.D.	J.H. Lawrence, M.D.
Univ. of California (Los Angeles)	Biophysics Dept.	M.S., Ph.D.	A. Kolin, Ph.D.
California Inst. of Technology	Biophysics Cttee., Div. of Biology	Ph.D. (Biol.)	R.L. Sinsheimer, Ph.D.
University of Chicago	Committee on Biophysics	S.M., Ph.D.	R.E. Zirkle, Ph.D.
University of Colorado	Medical Center, Biophysics Dept.	M.S., Ph.D.	T.T. Puck, Ph.D.
Columbia University	Biophysics Committee	Ph.D.	A. Pollister, Ph.D.
Harvard University	Biophysics Committee	Ph.D.	A.K. Solomon, Ph.D.
University of Illinois	Biophysics Div., Physiology Dept.	Ph.D.	H. von Foerster, Ph.D.
/University of Illinois	Coll. of Medicine, Dept. of Radiology	M.S., Ph.D.	R.A. Harvey, M.D.

TABLE III (continued)

Section B. Programs in Biophysics Including Radiobiology

Institution	*Location and Department*	*Degree(s)*	*Director*
/State University of Iowa	Sch. of Medicine, Radiation Research Lab.	M.S., Ph.D.	T.C. Evans, Ph.D.
Johns Hopkins University	Biophysics Dept.	A.B., Ph.D.	F.D. Carlson, Ph.D.
/Johns Hopkins University	Sch. of Medicine, Dept. of Radiology	M.S., Ph.D.	R.H. Morgan, M.D.
Mass. Institute of Technology	Biophysics Committee	S.M., Ph.D.	I.W. Sizer, Ph.D.
University of Minnesota	Biophysics Committee	M.S., Ph.D.	O.H. Schmitt, Ph.D.
/State University of New York	Upstate Medical Center, Dept. of Radiol.	M.S., Ph.D.	W. Fisher, Ph.D.
Ohio State University	Biophysics Div., Physiology Dept.	M.S., Ph.D.	N.A. Coulter, Jr., Ph.D.
/University of Pennsylvania	Sch. of Medicine, Dept. of Radiology	M.S., Ph.D.	M.L. Mendelsohn, M.D.
University of Pittsburgh	Biophysics Dept.	M.S., Ph.D.	M.A. Lauffer, Ph.D.
/University of Rochester	Div. of Radiology and Biophysics	Ph.D.	J.N. Stannard, Ph.D.
Stanford University	Hansen Biophysics Lab.	Ph.D.	V.W. Burns, Ph.D.
Syracuse University	Biophysics Committee	Ph.D.	S. Goldman, Ph.D.
Univ. Texas (Austin)	Biophysics Committee	Ph.D.	B.S. Jacobson, Ph.D.
/Univ. Texas (Dallas)	Southwestern Med. Sch., Dept. Radiol.	Ph.D.	F.J. Bonte, M.D.
/Univ. Texas (Houston)	M.D. Anderson Hospital, Dept. of Physics	Ph.D.	R.J. Shalek, Ph.D.
/Tulane University	Dept. of Physiology	M.S., Ph.D.	J. Hampton, Ph.D.
Medical College of Virginia	Dept. of Biophysics and Biometry	M.S., Ph.D.	W.T. Ham, Jr., Ph.D.
/Washington Univ., St. Louis	Sch. of Med., Mallinkrodt Inst. Radiol.	M.S., Ph.D.	L.J. Tolmach, Ph.D.
University of Wisconsin	Biophysics Committee	Ph.D.	P. Kaesberg, Ph.D.
/University of Wisconsin	Sch. of Medicine, Dept. of Radiology	M.S.	L.W. Paul, M.D.
Yale University	Biophysics Dept.	Ph.D. B.A., M.S.	R.B. Setlow, Ph.D.

TABLE III (continued)

Section C. Traineeship Programs in Medical Physics

Institution	*Location and Department*	*Degree(s)*	*Director*
*Jefferson Hospital, Philadelphia	Dept. of Radiology		R.O. Gorson, M.S.
Mass. General Hospital, Boston	Physics Research Laboratory		G.L. Brownell, Ph.D.
*Memorial Hosp., New York City	Department of Physics		J.S. Laughlin, Ph.D.
Mayo Clinic, Rochester, Minn.	Section on Biophysics		K.N. Ogle, Ph.D.
*Stanford University, Palo Alto	Dept. Radiology		H.S. Kaplan, M.D.
*M.D. Anderson Hosp., Houston, Tex.	Dept. of Physics		R.J. Shalek, Ph.D.
*Mass. General Hospital, Boston	Dept. Radiology		E.W. Webster, Ph.D.

(From Pamphlet distributed by the American Association of Physicists in Medicine, entitled «The Medical Physicist», October 1961).

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INTERVENTI SULLA RELAZIONE

J. F. FOWLER

May I offer my humble congratulations to Prof. Marinelli for his masterly survey of a huge field? He succeeded in indicating the growing-points for future work in a most stimulating way. I was particularly glad that the mentioned radio-isotope scanning and the gamma cameras, since this subject has been mentioned here very little so far. Physicists are very active in this work, and the problems have statistical aspects which have much in common with those of information content in X-ray diagnostic images.

RISPOSTA DEL RELATORE

L. MARINELLI

I wish to thank Dr. Fowler for his most kind remarks. I must emphasize, however, that due to the lack of time I had to omit almost entirely consideration of the contributions that radiological physicists have made to the quantitative aspects of radiobiology. This intrinsic interest has often led to the transfer of radiological physicists from hospitals and medical schools, but it has steadily enriched the field of radiobiology and, consequently, radiotherapy.

(PAGINA VUOTA NEL TESTO ORIGINALE)

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