A POCKET DOSEMETER, WITH BUILT-IN CHARGER, FOR X-RADIATION AND GAMMA RADIATION

by N. WARMOLTZ and P. P. M. SCHAMPERS.

The accumulated dose of γ-radiation and X-radiation to which a person has been exposed is commonly determined by means of a miniature ionization chamber combined with an electroscope charged to some hundreds of volts, which can conveniently be carried in the pocket.

In this type of instrument the radiation causes discharge of the system according to the dosage; this can be read from the electroscope by means of a microscope provided for the purpose; Thanks to new developments in glass technology, however, it is now possible to make these dosemeters completely vacuum-tight and able to withstand higher voltages, which increases the deflection and so permit the microscope to be dispensed with. Moreover, it is found that this construction is well suited to the incorporation of an electrostatic charger in the same instrument; this does away with the need of batteries and enables the meter to be used under any conditions, even under water.

Ionizing radiations

Effect upon living tissue

Owing to the present large-scale production of artificial radioactive substances, ionizing radiations other than the familiar X-rays are being produced. For example, γ-rays are now being generated on a wide scale and at intensities which at one time would have been considered incredibly high: hence the problems relating to the effect of these radiations upon living organisms are demanding more and more attention.

In view of these developments, the measurement of the dosages to which people are exposed is a subject of considerable importance. Before entering into the details of this subject, however, we will briefly recall the manner in which these radiations affect biological matter and the methods adopted to establish a measure of the irradiation dose based on these biological effects.

Charged particles, e.g. α-rays, β-rays, protons and fission products, cause direct ionization and also excitation and dissociation of molecules. In matter, they proceed along a certain path depending, amongst other things, upon the energy, mass and charge of the incident particle and the nature of the particular material through which it passes. The depths of penetration of these particles with the energies nowadays prevalent are relatively small, ranging from some fractions of a millimetre to a few centimetres in the case of very hard β-radiation.

On the other hand, X-ray and γ-ray quanta (photons) cause very little direct ionization, but the fast electrons released by these quanta have, like β-radiation, a very high ionizing power, and so cause secondary ionization, excitation and dissociation.

For these electromagnetic quanta the probability of absorption is considerably less than for the first-mentioned particles, so that, in general, the rays pass right through the object, though attenuated by scatter and absorption. To illustrate this point, 1 MeV γ-radiation in water has a linear coefficient of absorption of 0.07 cm⁻¹: in other words, this radiation is reduced to about \( \frac{1}{3} \) of its original intensity in penetrating a barrier of water about 14 cm thick.

Fast neutrons, being uncharged, ionize indirectly by transferring a considerable proportion of their energy to any light-weight nuclei with which they happen to collide, so enabling these nuclei to produce ions in the tissue. Slow neutrons cannot do this, but in certain substances readily produce nuclear reactions whereby ionizing particles are released. The penetrating power of fast neutrons is very high in heavy substances, but decreases with the weight of the atoms constituting the material.

Dosimetry

To study the effect of radiation upon biological matter we require in the first place a measure of the radiation. Let us now consider the manner in which such a measure is established.

The processes initiated by radiation in biological tissue are very complex as may be deduced from the fact they involve such subsidiary effects as the
above-mentioned ionization, excitation and dissociation; in fact, there can be no doubt that our concept of these processes as a whole is still incomplete. However, it has been found in the course of many investigations that the quantity of energy absorbed may be employed as a measure of the effects produced by radiation, for example, the destructive effect upon tissue. Since direct measurement of the energy absorbed by a particular tissue is usually impracticable, it is necessary to find some other means of obtaining this information. An associated quantity suitable for direct measurement is the ionization caused by the radiation in a given volume of air (or other gas).

Since the mean energy to form one ion pair in air is known (32.5 eV), the energy absorbed in the air can then be computed. To ascertain from this the amount of energy absorbed in a particular tissue, it is necessary to take into account the nature of the tissue and that of the radiation, and the geometry of the object and of the beam.

The energy absorbed by a particular tissue can be computed for a wide range of wavelengths of X-rays and \( \gamma \)-rays by multiplying the corresponding value in air by the ratio of the respective X-ray absorption factors of the two absorbers. The unit of dosage employed for X-radiation and \( \gamma \)-radiation is the röntgen: one röntgen of X-radiation or \( \gamma \)-radiation is such that it produces in 0.001293 gram of air (1 cc at 1 atm. and 0 °C) ions of either sign carrying 1 e.s.u. of charge. The amount of energy absorbed by air from one röntgen \( (r) \) is 84 ergs per gram.

It is particularly necessary to bear in mind that, in general, the value in röntgens is merely a measure of the X-ray irradiation at a particular point, as evaluated in terms of the ionization caused by such irradiation assuming that there is air at that point. This applies irrespective of the real nature of the matter constituting the point concerned. However, throughout a wide range of wavelengths the röntgen-evaluation is likewise a measure of the effect produced by the radiation. It is found that the amount of energy absorbed per röntgen varies very little as between different biological tissues; for the most important muscle, and other tissues, the energy absorption at nearly all wavelengths is 80 to 100 ergs per gram per röntgen.

However, for relatively soft radiation some tissues absorb considerably less energy (e.g. up to 50 ergs per gram per röntgen in the case of fat) and others considerably more (roughly, up to 500 ergs per gram per röntgen).

Basically, the equipment employed to measure radiation in röntgens comprises an air-filled chamber containing two electrodes between which a voltage is applied, and a sensitive instrument for the measurement, either direct or indirect, of the ionization current.

For \( \beta \)-particles and other radiations which cannot conveniently be measured in röntgens and to which the formal definition of this unit is not strictly applicable, another quantity has been introduced, i.e. the "absorbed dosage", the unit of which is the "rad". The "absorbed dosage" may be defined as the amount of energy transferred from an ionizing radiation to a particular point in a given substance per unit mass by ionizing particles. One rad is equivalent to an absorbed dosage of 100 ergs per gram; X-radiation can also be evaluated in terms of the rad.

Although in general the effect of a particular radiation upon organic tissue depends upon the dosage as measured in röntgens or rads, equal rad-dosages of different radiations do not always produce exactly the same biological effect. Owing to the complexity of the process it is impossible to assign this difference direct to any particular cause, but there is little doubt that it arises from spatial variations in ion density. For example, where an \( \alpha \)-particle and a \( \beta \)-particle cause the same overall ionization, the one will produce along its relatively shorter path a much greater concentration of ions than the other. Again, fission products and recoil nuclei of neutrons likewise produce very heavy ion-concentrations as compared with \( \beta \)-particles, or with X-rays and \( \gamma \)-rays. This relative concentration of the ionization sometimes enhances, and sometimes diminishes the biological effect.

Accordingly, another unit has been introduced, viz. the "rem". A dosage in rads equals the same dosage in rads multiplied by a factor representing the relative biological effect appropriate to the particular case. As a rule, tolerance dosages are expressed in terms of the number of rads per week. According to definition, the relative biological effect of X-radiation and \( \gamma \)-radiation is unity; hence the tolerance evaluated in rads equals the tolerance in rads. We have already seen that in certain (usually unimportant) circumstances, the energy absorbed per röntgen by particular tissues may vary quite appreciably above or below 1 rad; however, for purposes of protection against X-radiation and \( \gamma \)-radiation, where the precise maximum tolerance dose is not always known, this possible variation is ignored and 1 röntgen is considered equivalent to one rad.

The measurement of X-radiation and \( \gamma \)-radiation can also be accomplished by means of a suitable Geiger-Müller counter, crystal counter or scintillation counter, and the result expressed in terms of the number of particles so recorded per unit area and per unit time. Provided that the sensitivity of the particular counter and the energy distribution of the radiation are known, the dosage in röntgens can then be computed.

1) For a more detailed account of these effects and of the exact method of measurement, see the article by W. J. Oosterkamp in Appl. sci. Res. B3, 100, 1953 and B3, 477, 1954.

Another widely-used method of dosimetry is that based upon the blackening of a photographic plate. Again, the discoloration or fluorescence of certain crystals and glasses has lately been adopted as a measure of large dosages.

Tolerance dose

It has long been evident that exposure to X-radiation or γ-radiation causes varying degrees of damage to living organisms. The effects increase in severity with the dose, ranging from small changes inaccessible to direct observation, and slight and temporary variations in the blood count, to grave, possibly fatal, injuries to essential organs. Similar effects are produced by corpuscular radiations, the least penetrating of which, although affecting only the skin and the subcutaneous tissue, may nevertheless give rise to serious consequences.

The increasing use of radioactive substances and ionizing radiations in science and technology calls for the provision of a survey of tolerance dosages. Accordingly, the International Commission on Radiological Protection has recommended certain maximum limits for the radiation doses which may be considered tolerable in the event of life-long irradiation of the entire body (Table I).

### Table I. Tolerance dose for irradiation of the entire body.

<table>
<thead>
<tr>
<th>Radiation Type</th>
<th>X-radiation or γ-radiation</th>
<th>Other ionizing radiation</th>
</tr>
</thead>
<tbody>
<tr>
<td>In the blood-forming organs, sex organs and the eyes</td>
<td>0.3 r or rad per week</td>
<td>0.3 rem per week</td>
</tr>
<tr>
<td>In the base layer of the epidermis</td>
<td>0.6 r or rad per week</td>
<td>0.6 rem per week</td>
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</tbody>
</table>

For irradiation confined to the hands and forearms, the feet and ankles, or the head and neck, 1.5 r per week is permissible, provided that in the last case the eyes are protected so that the dose received by them does not exceed 0.3 r per week.

Since α- or β-radiations and protons can usually be prevented from reaching the body by quite simple methods (e.g. gloves), the above tolerances are important first and foremost in work involving X-radiation, γ-radiation and neutrons; on the other hand, substances emitting α-radiation are particularly dangerous when assimilated through the nose or mouth.

All the tolerances are specified in terms of the dosage per week. It is held to be immaterial whether the dose absorbed during this period results from a brief irradiation at a high dosage rate, or from a continuous irradiation at a low one. The effect of the radiation upon living tissue is cumulative, but partial recovery takes place in the course of time.

To complete this survey, Table II shows the approximate effects of a large short-period dose of γ-radiation under conditions of total body irradiation.

### Table II. Effect of a heavy short-period dose of γ-radiation.

<table>
<thead>
<tr>
<th>Dose</th>
<th>Effect</th>
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<tbody>
<tr>
<td>0-25 r</td>
<td>no perceptible injury.</td>
</tr>
<tr>
<td>25-50 r</td>
<td>changes in the blood count, no serious injury.</td>
</tr>
<tr>
<td>50-100 r</td>
<td>changes in the blood cells, some injury.</td>
</tr>
<tr>
<td>100-200 r</td>
<td>serious injury.</td>
</tr>
<tr>
<td>200-400 r</td>
<td>very grave injury, possibly fatal.</td>
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</tbody>
</table>

Pocket dosemeters for personal protection

In order to avoid the danger of exceeding the tolerance doses defined above, a person working in the presence of ionizing radiations must acquire, with the aid of one of the usual instruments for measuring dosage rate, an appreciation of the situation in which he works and hence an assurance that in normal circumstances he will not absorb more than the permissible weekly dose. Since he cannot continuously measure the dosage rate prevailing wherever he happens to be throughout the day, and since this rate usually varies at every moment, it is desirable that the worker be provided with a pocket dosemeter from which he can read, at the end of a day or week, the total dose absorbed during that time. This also ensures that any incidental and transient increase in intensity will be measured as well.

Where the particular radiation employed is confined to a narrow beam, special precautions are necessary to ensure that this beam cannot strike any part of the body without also striking the dosemeter.

Dosemeters of the type usually employed include a very thoroughly insulated electrometer system, which is charged from a battery or some other source of about 200 V; the deflection of this meter is read with the aid of a small microscope. The electrometer system is encased in a conductive housing, which also constitutes the ionization chamber containing air at a pressure of 1 atm. The number of ions formed in this chamber per second by the incident radiation corresponds to the dosage rate, and the total number of ions so formed during the particular period of observation governs the discharge of the system. As a rule, the displacement of the electrometer leaves is proportional to this total, and the dosage can be read from the scale of a microscope calibrated in röntgens.
One of the existing types of dosemeter has a sensitivity of 0.5 r full scale deflection; the variation in the reading of this meter in the absence of radiation is only 1 to 2% per 24 hours. Heavier doses are measured by means of dosemeters incorporating well-insulated capacitors, which increase the full scale deflection reading to 100 r. A diagram of such a meter is shown in fig. 1.

A simple charging device incorporated in the instrument would enable the latter to be used as a dose-rate meter, from which the time required for a discharge covering a certain number of scale divisions can be determined by counting. Although by no means comparable in quality with the instruments usually employed for this purpose, the above combination would constitute a very simple and inexpensive dose-rate meter. A meter of this type giving a full scale reading of 0.2 r would permit a dosage rate of 72 röntgens per hour to be measured quite easily in a matter of 10 seconds, again, a rate as low as 2 r per hour could be measured with the same instrument in 1 minute by utilising only about 20% of the scale. Higher dosage rates, up to the order of several hundred röntgens per hour, could also be measured with the same instrument. However, to facilitate the task of reading the dosage rate at frequent intervals and under all manner of conditions, it is desirable to find some means of dispensing with the microscope.

With the idea of effecting these improvements C.C. and T. Lauritsen have designed a simple pocket dosemeter with its own charger 3).

This dosemeter is essentially an electrostatic meter, with the pointer mounted in bearings. It incorporates a charger operating on the principle of friction between two solids, and is approximately the size of a cigarette packet. Although moisture-proof, this instrument is not vacuum-tight, and so contains air at a pressure of 1 atm. It can be used either as a dosemeter, or as a dosage-rate meter.

A new design

A new dosemeter has been designed (fig. 2) based on the above considerations but having a vacuum-tight chamber. This allows complete freedom of choice as to the type and pressure of the gas contained in the ionization chamber, and so permits the attainment of a wide variety of sensitivities. Other advantages of this instrument are that it is inexpensive and can conveniently be carried in the pocket.

The electroscope-system employed comprises two identical, rectangular conductive foils. The material used, besides being easy to trim and mount, is such that it neither sags appreciably under its own weight, nor vibrates unduly when in vacuum. The elasticity of this material must of course be consistent with a reasonable deflection of the system at moderate voltages. One end of the two foils (or leaves) is attached to an efficient insulator in the form of a rod or tube (fig. 3). It will be seen that the system as a whole bears a very close resemblance to the old gold-leaf electroscope; in the uncharged condition the leaves are parallel to each other. The electroscope system is housed in an oblong bulb of oval cross-section, made of glass having good conducting properties. This is to prevent the accu-

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Theometer is mounted on the end of the charger incorporated in the instrument. The charger is a glass tube some millimetres in diameter and a few centimetres long containing a drop of mercury. When shaken to and fro in the tube, this mercury acquires a charge, which is transferred direct to a contact wire. Also included in the instrument is a switch, which, when in a certain position, establishes electrical contact between the wire in the charger and the sensitive system. When open, the switch is locked to the wall of the bulb by a small magnet, so that the latter can be filled with a suitable gas and used, as already described, as an ionization chamber.

The bulb is enclosed in an aluminium or plastic case, which also contains the operating mechanism for the magnetically operated switch mentioned above. Two apertures, one on each side of the case and exactly opposite each other, are provided for reading the electrometer. The electrometer leaves themselves act as the pointers for this reading. A frosted plate on which a scale may be engraved, is fitted in the rear aperture. The scale can alternatively be inserted at the front, but in some models a large cylindrical lens of plastic is fitted in the front aperture. This facilitates reading generally, but also enables the meter to be read from a distance, for example when placed on a laboratory bench as part of an experiment which must be remotely controlled. In normal use the instrument is fixed in the waistcoat or breast pocket by means of a strong clip provided at the back.

To charge the dosemeter, the magnetic switch is pressed down and, if necessary, the flat back of the instrument tapped lightly on the hand to detach the switch from the wall of the bulb, so that it will drop onto the contact connected to the system. The position of the switch is readily visible. Next, the electrometer is shaken fairly vigorously lengthwise and at an angle of 45° to the horizontal, with the window end held lower than the switch end. The leaves will then be seen to diverge; when they have reached the limit of deflection, the magnet is pushed towards the window, the meter being held in the same slanting position throughout this process.

Once charged, the instrument may be employed either as a dosemeter or as a dosage-rate meter; the variation in deflection during periods when the meter is not exposed to radiation is less than 1% per 24 hours. Shaking-tests have shown that, provided suitable materials are employed, the mercury-drop charger will continue to function almost indefinitely (i.e. after more than 1 million chargings) without any decrease in the voltage generated. During these tests, the complete instrument was shaken very vigorously to test its robustness; this is a quality usually difficult to produce in chargers operating in the principle of friction between two solids, and is important for an instrument which is to be carried in the pocket.

The sensitivity of an ionization chamber is governed primarily by the volume, nature and pressure of the gas filling, and to a lesser extent by the material constituting the wall of the chamber. A suitable choice of all these variables makes it possible to make radiation meters of this type in three distinct and widely different grades of sensitivity, all three being little dependent on the wavelength of the measured radiation. The most sensitive type, tested with the $\gamma$-radiation emitted by cobalt 60 (about 1.2 MeV), gives full scale deflection for a dosage of 0.2 röntgens. The sensitivity is not affected by any decrease in the hardness of the radiation until the energy drops to 300 keV; below this energy, the sensitivity increases until, at 150 keV, it reaches a maximum which is twice as high as the value at 1 MeV. (fig. 4). A further decrease in hardness to 75 keV restores the sensitivity to its original level; any further softening of the radiation is accompanied by a decrease in sensitivity owing to absorption by the bulb. However, at 50 keV the sensitivity is still about 60% of the original value.

This relatively greater sensitivity to soft radiation...
arises from the fact that it is impossible to employ in the dosemeter materials entirely equivalent to air; hence photo-electric X-ray absorption affects the measurements quite appreciably even at 100 - 200 keV.

The most sensitive model just described is designed primarily with a view to the protection of laboratory workers; a weekly tolerance dosage of 0.3 r is well within its range.

In the second model, full scale deflection corresponds to 70 röntgens; it will be seen from fig. 4 that the sensitivity of this particular instrument is governed only very slightly by the wavelength of the incident radiation; the maximum at 150 keV represents a mere 15% increase in sensitivity. This virtual independence of wavelength is obtained by employing a separate, built-in ionization chamber.

The third model covers dosages up to 250 röntgens at full scale deflection. The sensitivity is higher by a factor of about 2 at the maximum than at 1 MeV. By reason of the low pressure and high field intensity employed, the ion current in this model reaches saturation relatively slowly; this may be an advantage, particularly in the measurement of flash dosages. Model three can be adapted for the measurement of still higher dosages.

All these models are insulated so thoroughly that the discharge per month in the absence of radiation is at most one or two percent.

Other applications

Consider now the electrometer without the charger, as shown in fig. 5. As in the instrument already described, the whole of the bulb, other than the long neck to which the system is sealed, is made of glass having good conducting properties. The neck has good insulating properties, and is coated with a water-repellant material which enables the system to retain its charge for a long time. Being vacuum-tight, the instrument is not affected by humidity in the surrounding atmosphere. The sensitivity is 2.5 kV at a full scale deflection of 10 scale divisions. A considerable reduction of the sensitivity can be effected by employing thicker leaves. To determine whether an object is charged, it is only necessary to hold the instrument against or near to the object. The electroscope is easily fixed in an apparatus at any point where a measurement of voltage is required. It is therefore very suitable for use in schools and for demonstration purposes: an enlarged image of the system can be very simply projected on to a screen. The charging unit (fig. 6) can also be used individually in demonstrations. The long glass tube containing the drop of mercury and a sealed-in contact is best suited to this purpose; it is capable of generating 3 kV. By shaking the charger vigorously, it is possible to produce a current of some tenths of a μA. The other type of charger, fitted with a flexible connection, is suitable for charging the fountain-pen type of pocket dosimeter.

Summary. Following a brief recapitulation of the effects of ionizing radiations upon biological tissue, the principles of dosimetry, tolerance dosages and the effects of intense irradiation are considered. After descriptions of existing types of pocket dosimeter a more detailed account is given of a new design which incorporates a self-charger and which dispenses with a microscope. This instrument is fully enclosed in a vacuum-tight bulb of conductive glass, which, in turn, is housed in an aluminum case. Full scale deflections corresponding to dosages of 0.2 r, 70 r, 250 r, or more, can be obtained by adopting suitable dimensions for the instrument and by varying the gas pressure. The discharge in the absence of radiation is considerably less than 1% per 24 hours. The charger is a glass tube containing a drop of mercury, which during the charging process, is connected to the sensitive system by means of a magnetic switch. Charging is effected by shaking the instrument several times, with the electrometer system facing downwards. Attention also is drawn to the suitability of the individual electroscope and charger systems for demonstration purposes.
ABSTRACTS OF RECENT SCIENTIFIC PUBLICATIONS OF N.V. PHILIPS' GLOEILAMPENFABRIEKEN

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From measurements at 6 Mc/s it is concluded that no extra noise is generated in a ring of NbN when this ring is brought into a superconducting state, even when a persisting current of about 100 A is excited.


Polycrystalline mixed crystals of (La,Sr)CoO$_3$ have been prepared. Perovskite structure is found for all compositions. Ferromagnetism is observed for medium Sr concentrations. Curves are given for the saturation magnetization, the paramagnetic Curie temperature, and the effective paramagnetic moment as a function of composition. It is suggested that the ferromagnetism observed is caused essentially by a positive Co$^{3+}$-Co$^{4+}$ interaction. The sign of the exchange interaction is discussed in connection with the theory of Anderson and Polder, and the theory of Zener.


An apparatus is described for polymerizing monomers in bulk up to a pressure of 10 000 atmospheres, in which the polymerizing substance can be heated and the temperature of the substance measured. Styrene shows an explosive reaction at 10 000 atmospheres and at about 70 °C. Indene polymerizes slowly when heated at 10 000 atmospheres and shows an explosive reaction at 175 °C. Both compounds give a solid polymer. Croton aldehyde heated at 10 000 atmospheres gives a brittle, high-melting polymer. Coumarone and some chlorinated ethylenes carbonize when heated at 10 000 atmospheres. Butyaldehyde polymerizes to a solid product which rapidly reverts to the monomer.


The hydrolysis of methylene diurea giving urea and monomethylolurea was found to be a monomolecular reaction. The rate of the reaction is directly proportional to the hydrogen ion concentration in the pH range measured (3-5) and independent of the buffer concentration. The activation energy appears to be 19.5 kcal/mole. Generally, the reaction of an amidomethylol group with an amide group leading to the formation of a methylene bridge between urea fragments, will be a reversible reaction. The rates of both the forward and the reverse reactions are proportional to the hydrogen ion concentration.


The reaction between monomethylolurea and methylene diurea appears to be bimolecular, and the rate constants were found to be directly proportional to the concentration of the hydrogen ions. An influence of the buffer concentration was not observed. The activation energy was found to be 15 kcal/mole.


The reaction of methylene diurea with formaldehyde shows a close resemblance to the previously studied reaction of urea and formaldehyde (see these abstracts, No. 2046) i.e. the reaction proved to be bimolecular and the rates were found to be directly proportional to the concentration of hydrogen ions; an influence of the buffer concentration on the rate was also observed. Obviously the reaction is subject to general acid and/or base catalysis. The activation energy appeared to be about 15 kcal/mole. The values for the rate constants were almost the same as were found for the reaction between urea and formaldehyde.