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A CONCEPT OF HEALTH PHYSICS DOSIMETRY FOR QUANTUM RADIATION

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Abstract—The concept of Health Physics dosimetry for external quantum radiation, as developed in this paper, started from the basic assumption that the dose reading of personnel dosimeters and area dosimeters shall indicate the radiation hazard to a person to the same extent. Also it will be a requirement for measuring techniques in Health Physics monitoring to assess the quantity absorbed dose instead of the quantity exposure.

Phantom measurements show to what extent the reading of personnel dosimeters deviates from the free-space determined area dose. The possibilities of realizing absorbed dose measurements in free space and in conjunction with a phantom will be discussed.

The new concept of Health Physics dosimetry is characterized by absorbed dose quantity measurement and by different calibration of area dosimeter (free-space irradiation) and personnel dosimeter (phantom irradiation). Dosimeter systems are described which realize the agreement between dosimeter reading of area dosimeters and personnel dosimeters and therefore provide a reasonable interpretation of personnel dosimeter readings.

1. INTRODUCTION

A NEW concept in the methods of absorbed dose determination is developed in the following paper as a basis for discussion. The argument is based on one of the most important questions for health physics measurement technique, i.e. how to interpret the reading of a personnel dosimeter or of an area dosimeter in terms of a meaningful value for personnel radiation exposure.

Conventionally it is attempted to estimate the absorbed dose received by an internal organ of the body from ionization chamber readings[1] and from personnel film badge records, resp.[2] that are calibrated for exposure determination in the unit Roentgen. Based on measurements of body backscattering and depth–dose distribution using a man-phantom, it was shown by the new Harwell film dosimeter[3] that under ideal conditions the exposure may be converted into the organ dose taking into account the direction and energy of the incident radiation and the effective depth of the corresponding organ in the body.

Depth–dose measurements effected by A. R. JONES[4] with LiF dosimeters in a man-phantom show the amount of the dose actually absorbed in an organ related to an exposure of 1 R as a function of the quantum energy. Using personnel film badge values, he stated Roentgen-to-rad-conversion factors for personnel dosimeters as well as for area dosimeters differentiating between environmental, routine and accidental use.[5]

Hence, the estimation of the absorbed organ dose from personnel dosimeter readings may be effected currently only by the use of conversion factors which take into account the energy distribution of the irradiation and the body orientation. The task of determining the absorbed dose in a given critical organ, however, may be solved without knowledge of the energy distribution of the radiation by suitable dosimeters indicating directly the absorbed dose in the corresponding organ.[6]

In the following a new measuring method and suitable dosimeter systems with the stated properties will be described:

The dosimeters are calibrated to read an absorbed dose in a critical organ instead of an exposure.

By an appropriate calibration of personnel dosimeters in connection with a phantom, and of area dosimeters in free space, an agreement of doses given by personnel dosimeters with those by area dosimeters is achieved.

The dosimeter reading is, independent of the radiation energy, at least for frontal incidence of radiation, directly proportional to the absorbed dose in different organs.

2. DOSE MEASUREMENT AS DESCRIPTION OF THE RADIATION HAZARD TO A PERSON

The radiation hazard to a person is primarily dependent on the corresponding energy absorbed in the whole body or in that organ of interest, resp., the damage to which is above all considered. The term "exposure", employing by definition the ionization potential of radiation in air as radiation measurement, cannot be taken as a direct measure of the radiation effect or a radiation damage in the whole body or in a special organ. Describing the radiation effect in an organ, as has soon been recognized also in radiology, requires a dose quantity which corresponds to the energy absorbed at the point of interest in the body.[7–9]

For dose measuring devices used in health physics it is necessary, nevertheless, that the absorbed dose found at the point of interest in the body (e.g. the absorbed dose in the bone marrow) be determined with this device by measurement outside the body. Under these conditions it is the best we can do to carry out health physics measurements with an air-equivalent ionization chamber or a tissue-equivalent ionization chamber, resp. In the necessary conversion of measured exposure to absorbed dose, reference is made to standard tissue (free-space measurement of the kerma in the unit erg/g[13–16]). An absorbed dose determination of this type, however, is of limited practical significance only, since the conversion of the measured exposure to an absorbed dose, especially for quantum radiation below 100 keV, is only practicable with the knowledge of energy distribution, i.e. only under known irradiation conditions. In addition this measurement is of little interest for health physics monitoring as long as it is not possible to consider the influences of body orientation, and the depth of the actual reference organ in the body as well as the change in the radiation field by scattering, absorption, and build-up in the body.

One thinks immediately of designing an instrument that compensates by built-in properties for various influences, in other words, whose dose reading shows the same energy dependence as the energy absorption in the critical organ. Yet, no ionization chamber or any other radiation detector so far has been constructed in such a manner. Nevertheless, it is possible by improved measurement techniques[6,12] e.g. in the new phosphate glass dosimeter cases, but also in GM counters and proportional counters, to change the energy dependence of dose reading in a simple way so that an absorbed dose determination in the organ of interest is possible to a certain extent by free-space measurement or by measurement at the surface of the body without knowledge of the energy distribution.

3. UNSATISFACTORY METHODS OF MEASUREMENT IN AREA AND PERSONNEL DOSIMETRY

Dose and dose rate measuring equipment for health physics monitoring are built and usually calibrated by the manufacturer in a way that they indicate an exposure in the unit "Roentgen". The dosimeter reading, regardless of whether the instrument is used for area or personnel dose measurement, is thus referred to free-space calibration. As personnel dosimeters are worn on the front side of the body, the quantity "exposure" is not measured in this case. Thus a personnel dosimeter measures a dose at the surface of the body not defined more closely which corresponds neither to the exposure in free space nor to the organ or whole body dose, whereas the area dosimeter determines a free-space exposure.

Phantom measurements prove to what extent the reading of the personnel dosimeter may deviate from the "free-space" calibrated quantity. Figure 1 shows the relative reading of a personnel dosimeter at the front side of a phantom related to an exposure for radiation incidence to the front and backside of the phantom. The average distance of the ionization chamber used was about 1 cm from the phantom surface. A personnel dosimeter worn directly

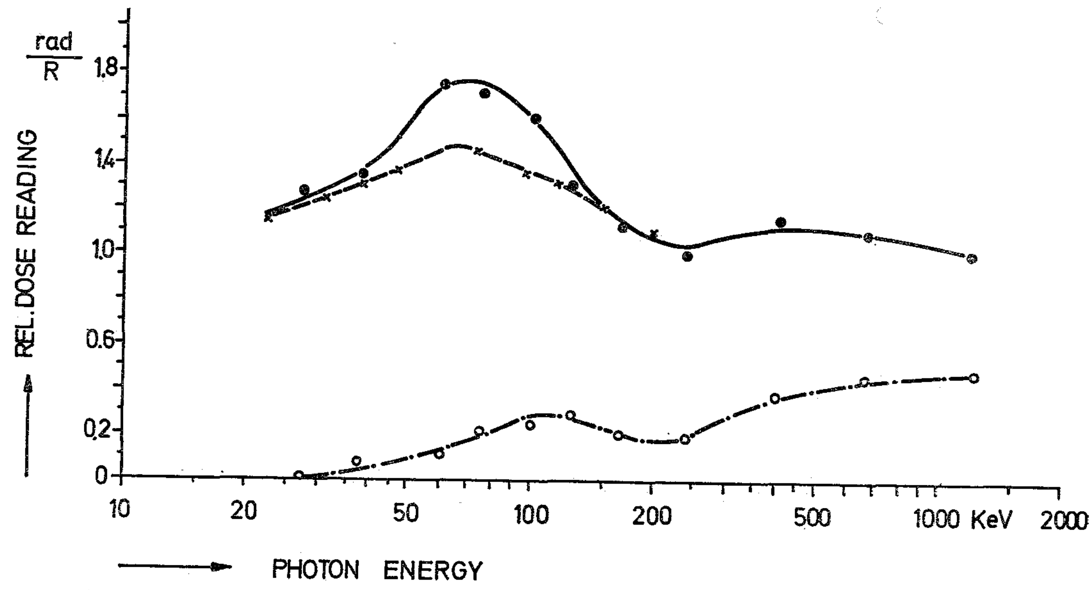


FIG. 1. Relative dose reading of an free-space calibrated personnel dosimeter at the front of an Alderson phantom at an exposure of 1 R as a function of quantum energy
●-●-●-●-●-● dosimeter at phantom surface,[5]
—×—×—× dosimeter at 1 cm distance (all radiation incidence on the front side of the phantom),
—·○—·○—·○ radiation incidence on the backside of the phantom.

on the surface would, however, indicate approximately a surface dose. In case of frontal radiation incidence the reading may be up to 60 per cent higher due to the influence of body back-scattering by quantum energies of about 70 keV compared with a free-space exposure.

This means that in unfavourable cases the personnel dosimeter reading results in a dose of 5 rem instead of the personnel burden of 3 rem calculated according to results of area dose measurements. Phantom measurements reveal furthermore that the absorbed dose may be considerably higher or lower than the exposure depending on the organ of interest (see Table 1).

Therefore correction or conversion factors for certain critical organs depending on the radiation energy were stated for personnel dosimeters as well as for the area dosimeters.

In routine health physics dosimetry it is often not possible to realize this method for lack of knowledge of the energy distribution.

The fact that accurately performed measurements with area dosimeters and personnel dosimeters will result in different dosimeter readings which, in turn, do not at all correspond to the critical organ dose as recommneded by the ICRP, proves that the conventional concept of dose measurement is incomplete for the purposes of radiation protection. In general health physics dosimetry one should start from the basic assumption that the dose reading of a personnel dosimeter agrees with the dose

Table 1. *Average absorbed dose in rad measured for various organs in the Alderson man-phantom referred to an exposure of* 5 R *determined in the free space, radiation incidence on the front side of the phantom, for quantum energies of* 240, 100, 60, *and* 38 keV *according to Ref.* 5

Average energy absorption in the organ	Absorbed dose in rad (exposure 5 R)			
	240 keV	100 keV	60 keV	38 keV
Eye lenses	6.35	8.0	6.25	4.05
Bone marrow	3.35	4.95	3.25	1.18
Testes	6.25	7.9	7.75	5.45
Ovaries	4.1	5.5	3.85	1.03

reading of an area dosimeter and that both measurements will indicate to the same extent the absorbed dose in the organ of interest.

4. PRACTICAL REALIZATION OF A SUITABLE AREA AND PERSONNEL DOSIMETRY BY HEALTH PHYSICS MEASURING TECHNIQUES

4.1 *Choice of an appropriate dose quantity*

There are different possibilities to comply with this obvious dilemma (see Table 2). If the term "exposure" is retained, on the one hand there is the possibility of calibrating the personnel dosimeter in connection with a phantom. Then the energy dependence of the personnel dosimeter reading has to be changed in such a way that the personnel dosimeter indicates on the surface of the body or phantom the value for the free-space dose ("exposure"). Yet this alteration in the present measuring method is ultimately unsatisfactory. In practical health physics work the quantity "exposure" cannot clearly be related to the dose actually absorbed in the body without knowledge of the energy distribution.

Therefore the exposure should not be regarded as a good quantity for describing the radiation hazard to a person and for the actual personnel dose, resp. On the other hand, one may start from the assumption that the personnel dosimeter measures a surface dose as given on the front of the body. Hence, personnel dosimeters would indicate a surface dose in connection with a phantom (in case of an energy-independent reading of the dosimeter). Area dose measuring devices, then, should indicate under free-space conditions a surface dose as given in Fig. 1 for a personnel dosimeter as a function of the quantum energy. In order to realize the same measuring conditions for the personnel dosimeter, area dose measurements could also be performed in connection with a phantom (disadvantages: arising of a direction dependence of the dosimeter system, unduly large measuring arrangement). But even then it would not be an absorbed dose in the interesting critical organ that is measured.

However, in case of a whole body irradiation it is significant and advantageous to define the energy absorption in the critical organ of interest, based on the ICRP recommendations, e.g. bone marrow or gonads, as the actual personnel dose (whole body dose) instead of the surface dose or the absorbed energy in the whole body. The energy absorption in different organs has been measured by means of a man-phantom.[4,5] The absorbed dose in the different organs is

Table 2. Various possibilities of calibrating personnel dosimeters and area dosimeters for health physics monitoring

Dosimeter	Calibration Free space	Calibration Phantom	Measurement
Personnel dosimeter	exposure	—	phantom
Area dosimeter	exposure	—	free space
Personnel dosimeter	exposure	—	phantom
Area dosimeter	exposure	—	phantom
Personnel dosimeter	—	exposure	phantom
Area dosimeter	exposure	—	free space
Personnel dosimeter	—	surface dose	phantom
Area dosimeter	—	surface dose	phantom
Personnel dosimeter	exposure	—	phantom
Area dosimeter	surface dose	—	free space
Personnel dosimeter	—	absorbed dose	phantom
Area dosimeter	absorbed dose	—	free space

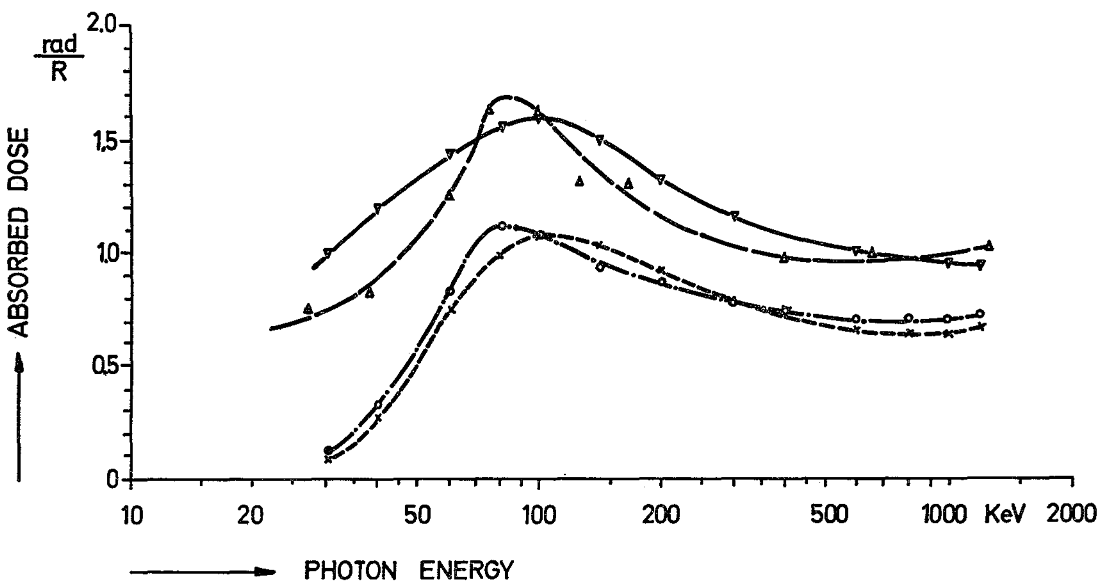


FIG. 2. Absorbed dose in various organs of a phantom as a function of quantum energy referred to an exposure of 1 R and a radiation incidence on the front side of the phantom[5,6]
▽—▽—▽—▽ testes,
×– – –×– – –× ovaries,
△– –△– –△– eye lenses,
–○·–○·–○·– average bone marrow (radiation incidence on the backside of the phantom).

shown in Fig. 2 depending on the quantum energy.

Corresponding to the definition of the "body burden" for internal irradiation the absorbed dose may be related to a normal phantom (e.g. Alderson man-phantom) (see Table 4). Dose measurements (personnel dosimetry, area dosimetry) for external radiation exposure are thus also referred to a standard absorbed dose in the critical organs in an unequivocal way, just as activity measurements (incorporation measurements, air and water monitoring)—for the detection of internal radiation exposure—are independent of an individual interpretation of the measured values. Despite various measuring methods and monitoring applications the radiation hazard to a person could thus be described by an equivalent dose quantity (dose equivalent). The reading of the area dosimeter, calibrated in free space, has to be referred to the absorbed dose in the given organ; the reading of a personnel dosimeter must be calibrated in connection with a phantom (see Table 3), resp.

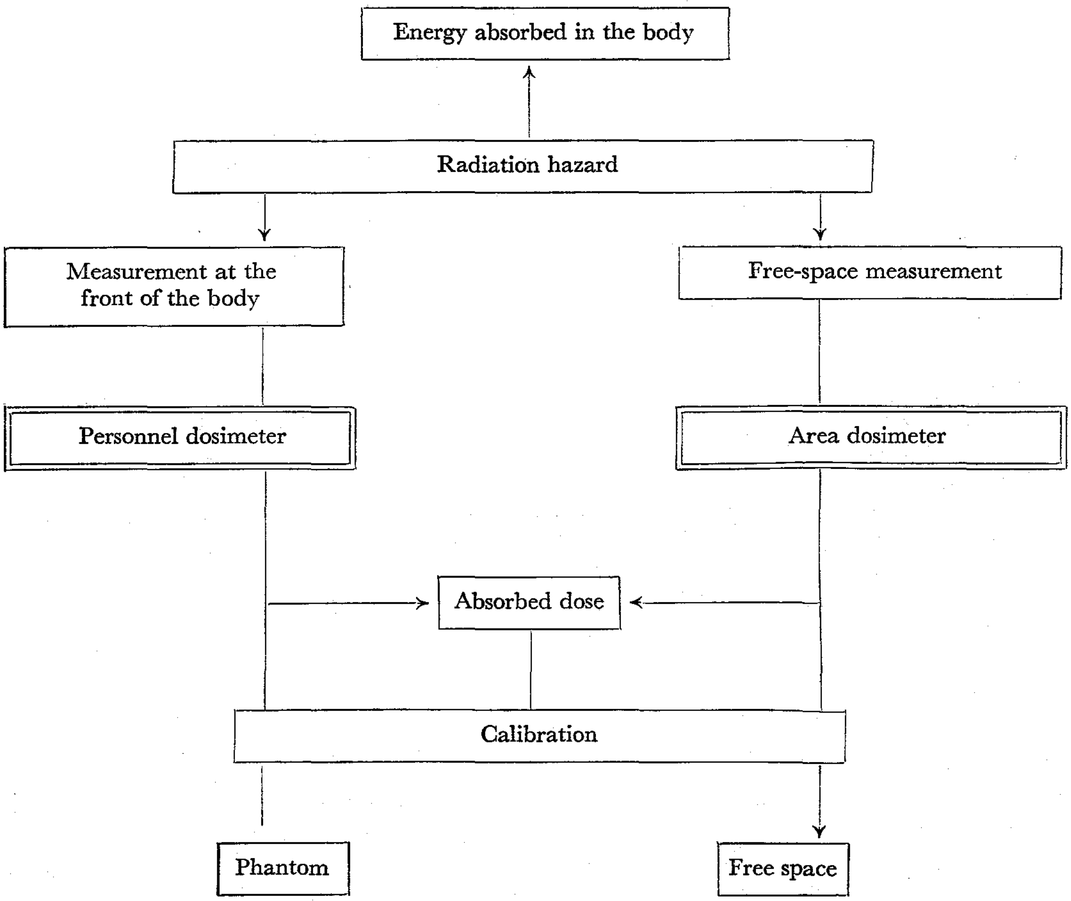
4.2 *Influence of the body orientation*

The reproducibility of the quantity "absorbed dose" measured necessarily by a personnel dosimeter at the surface of the body is twice influenced by the radiation incidence.

In case of a frontal irradiation of the body, a maximum of energy absorption and in case of a backside irradiation of the body a minimum of energy absorption were determined in most of the organs (exception: bone marrow). For the definition of the absorbed dose in a critical organ the influence of body orientation, referred to the radiation source, may be neglected, to a first approximation, if the maximum energy absorption in the organ is assumed.

Furthermore, the original directional dependence of the personnel dosimeter reading and the body orientation related to the radiation incidence will influence the reading of the personnel dosimeter worn at the body. The film badge dosimeters generally used at present will allow only an accurate dose determination in cases of nearly frontal irradiation. In order

Table 3. Calibration of a personnel dosimeter and an area dosimeter which should indicate the radiation hazard to a person to the same extent in health physics measurements



to improve this error which primarily influences the reading fundamentally, it is favourable to use a personnel dosimeter with practically direction independent reading. Personnel dosimeters were described, the dose indication of which is independent from radiation directions in the frontal half-room at the phantom surface.[10,11]

The measurement of the organ dose described here refers primarily to a personnel dosimeter with energy and direction independent dose reading of radiation incidence from the frontal half-room. The absorbed dose refers also to the radiation incidence with a maximum energy absorption in the reference organ in the body.

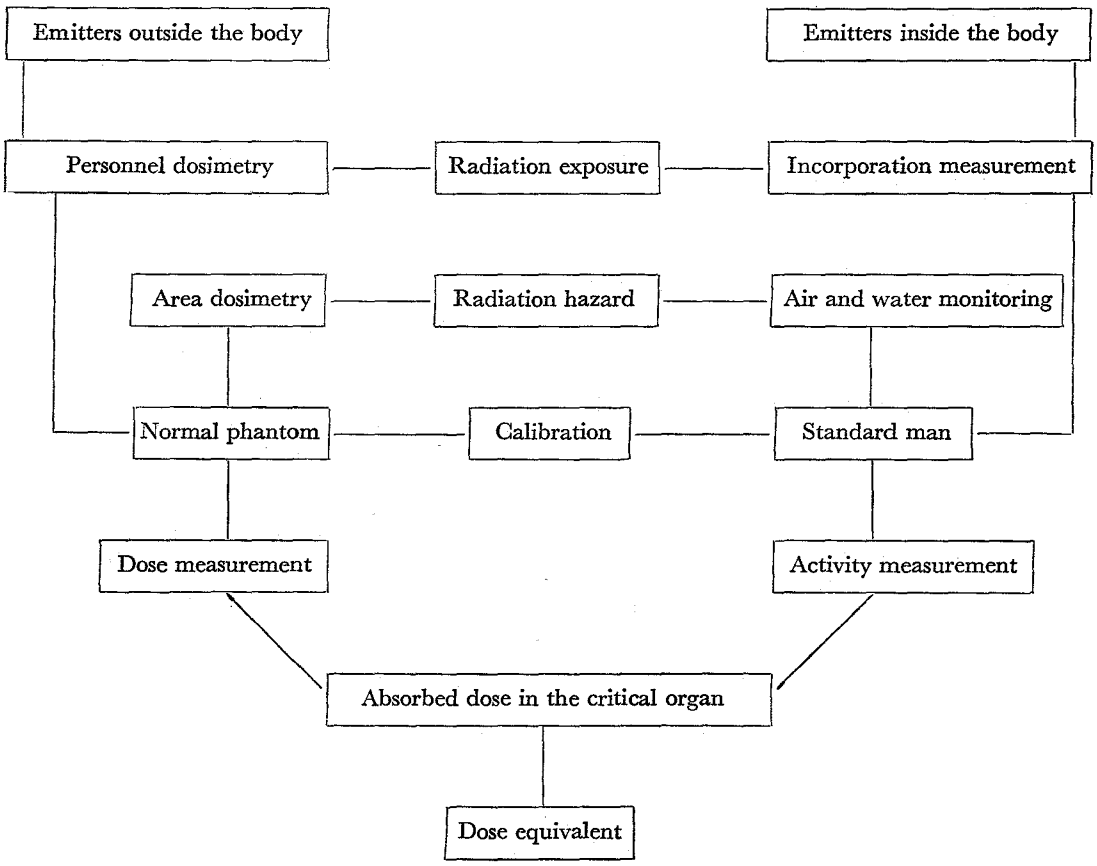
4.3 *Dosimeter systems for the measurement of the absorbed dose*

Area dose measuring devices and personnel dosimeters were constructed, the reading of which is directly proportional over a larger energy range to the absorbed dose in a given organ in case of free-space measurement or at the phantom surface, resp.[6]

The energy dependence of the absorbed dose in an organ is based on the values obtained by A. R. Jones with a man-phantom.[5] Likewise the calibration of the personnel dosimeter was effected in connection with an Alderson man-phantom.

Thus, for area dose measurements the energy dependent reading of a proportional counter

Table 4. Determination of the radiation hazard to or the radiation exposure of a person within health physics monitoring



with Al lining (counter tube "Tol E" by Messrs. Berthold, Wildbad, Western Germany) has been changed by a perforated compensation filter (0.4 mm Sn with 80 per cent covered surface) in such a way that the absorbed dose in the gonads could be measured energy independently in the energy range above 25 keV to 1.2 MeV within ± 7 per cent and the surface dose above 30 keV within ± 16 per cent (reading of the dose rate).

For personnel dose measurements the spherical capsule of a routine phosphate glass dosimeter[10,11] (2 mm Sn with 85 per cent of covered surface) was changed to 1,2 mm Sn. The reading of this new personnel dosimeter calibrated at the phantom surface is directly proportional to the absorbed dose in the organs such as gonads and bone marrow (energy range 45 and 50 keV to 1,2 MeV within ± 15 per cent). The personnel dosimeter reading gives the absorbed dose in the testes, ovaries, and bone marrow, resp., if a uniform correction factor is applied for the different organs covering all radiation energies from 45 keV to 1.2 MeV.

Consequently, for the determination of the absorbed dose, no energy distribution needs to be taken into account, as long as the radiation incidence arrives from the frontal half-room related to the front surface of the phantom. A new personnel dosimeter will, however, be investigated, the dosimeter reading of which is also independent of body orientation.

The dosimeter system described herein shows that an agreement between personnel and area dose measurements can be achieved supposing that in both cases the absorbed dose in the gonads serves as the basis for the organ dose of interest for routine monitoring.

5. CONCLUSIONS

The assumption that the measurements of the area dose as well as the so-called personnel dose in health physics are intended to describe the radiation hazard to or the radiation exposure of a person, resp., to the same degree makes it necessary—owing to the measuring method—to use an absorbed dose or kerma instead of an exposure as basis. The agreement between the dose readings of area dosimeters and personnel dosimeters can be achieved by using different methods of calibration. To realize absorbed dose measurements, the area dosimeter has to be calibrated by a free-space measurement, the personnel dosimeter in connection with a phantom. This is valid, too, for the calibration of neutron dosimeters.[17] The energy dependence of the dose indication must be adapted to the absorbed dose in the organ selected as the critical one for the special case of personnel monitoring. Here, the absorbed dose offers the additional advantage of indicating a real whole body or organ dose, resp., in the quantity "dose equivalent" as recommended by the ICRP.

Personnel dosimeters with indication of an absorbed dose in bone marrow or in the gonads by choice allow, moreover, a significant interpretation of the personnel dosimeter reading as well as an agreement with the dosimeter reading of a suitable calibrated area dose measuring device.

Measuring the absorbed dose instead of the exposure is a technical requirement in health physics today. Furthermore, it is the first prerequisite of a reasonable interpretation of personnel dosimeter readings.

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