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THE INDICATION OF ADSORBED DOSE IN CRITICAL ORGANS BY ENERGY INDEPENDENT PERSONNEL DOSIMETERS

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Abstract—The radiation hazard to a person may be determined by a personnel dosimeter worn on a representative part of the body. According to the ICRP recommendations, the absorbed dose in the critical organs has to be measured. There are different possibilities of estimating an organ dose by a personnel dosimeter. The dose reading can be related to the absorbed dose in the critical organ caused:
—by a homogeneous irradiation incidence,
—by an irradiation incidence with maximum hazard to a person (frontal exposure or exposure from the back).
In routine personnel dosimetry energy-independent dosimeters will be preferred. Experiments showed that a more accurate indication of organ dose will be received by personnel dosimeters with certain energy dependence.

Personnel dosimeters, especially spherical phosphate glass dosimeters, are described which simultaneously indicate the absorbed dose in the bone marrow, gut mucosa, testes, ovaries and lenses of the eye independent of the radiation energy above 50 keV when the dosimeters were exposed at the front of an Alderson phantom.

The possibilities of interpreting an organ dose and the measuring accuracy for personnel dosimeter readings are discussed.

1. INTRODUCTION

NATIONAL and international recommendations demand persons professionally exposed to radiation to wear a personnel dosimeter at a representative part of the body. It is assumed that the dosimeter reading can be related to the possible biological damage.

When a radiation hazard could be expected the absorbed dose in the corresponding critical organ should be determined according to the ICRP recommendations,[1] e.g. in case of a whole body exposure the dose in the gonads or in the bone marrow. The measured value of a personnel dosimeter, however, evidently only indicates the accumulated dose at the location of the dosimeter. According to an accepted opinion, a conversion from surface dose to an organ dose is only possible when in addition to the dose also the radiation energy is known. It is therefore of interest to investigate whether the absorbed dose in the critical organ can be assessed directly in a simple way from the reading of the dosimeter worn at the body surface.

With film dosimeters it is normally not possible to achieve an energy independent indication. The necessity to determine and to consider the effective radiation energy for the dose measurement, however, offers the advantage to determine the absorbed dose in any organ of interest using the proper factors.[2]

The correction factors can be determined experimentally using a suitable phantom, such as an Alderson phantom, for a certain type of film dosimeters. It was demonstrated that the measured dose at the phantom surface is almost proportional to the gonad dose.[3]

On the other hand, a dose can be measured directly without knowledge of the radiation energy by employing ionisation chamber pocket

dosimeters, certain TLD dosimeters and filter compensated phosphate glass dosimeters. Generally an energy independent dosimeter permits only the direct measurements of a single type of absorbed dose, depending on the design and calibration of the dosimeter.

Unfortunately the determination of organ doses is difficult with such dosimeters. Occasionally the energy independent method is regarded as a supplementary technique to the film badge without offering the same possibilities for interpretation.[4] However, the development of suitable energy and directional compensation filters for phosphate glass dosimeters offers the possibility for adapting such dosimeters to the indication of organ doses. It could be shown that a phosphate glass dosimeter permitted the simultaneous measurement of different organ doses in a given range for frontal radiation incidence.[5]

Because of further developments of this technique, it is now possible to determine directly the desired organ dose without prior knowledge of radiation energy using the reading of the personnel dosimeter. As compared with the energy dependent dose recording of the film dosimeter, energy independent dose measurements offer the following advantages:

—Direct dose indication by a single number,
—no complicated assessment of the photon energy or correction factors, resp., for the dose evaluation,
—subsequent choice of the critical organs and determination of the organ dose from a single measured value without considering an energy dependent conversion factor, and, therefore, increased measuring accuracy of the final dose determination.

This principle was previously described in Ref. (6).

Below, the type of dosimeter especially suited for an energy independent organ dose determination, the measuring accuracy achieved by an energy independent method of measurement, and possibilities of interpretation will be shown.

2. APPLICATION OF ENERGY INDEPENDENT PERSONNEL DOSIMETERS FOR ORGAN DOSE DETERMINATION

An energy independent personnel dosimeter for organ dose measurement is required to indicate a measured value at the body surface, which is to show the same energy dependence as the amount of the absorbed dose in the respective critical organ related to an exposure of 1 R (see Fig. 1). Here, a frontal radiation incidence is the basis of the energy absorption in the organ as well as of the exposure of the personnel dosimeter.

On account of their design, air and tissue equivalent quartz fibre dosimeters, TLD and RPL dosimeters as used in routine personnel dosimetry indicate no or only little energy dependence by free air exposure above a quantum energy of about 35 keV.

At the phantom surface, however, such dosimeter shows a more or less high energy dependence of the dose reading depending on its design, wall thickness and the distance to the body surface, which, in the most unfavourable case of a maximum deviation, corresponds to the surface dose.

It will be demonstrated by means of a phosphate glass dosimeter to what extent an energy independent dosimeter indicates an organ dose at the phantom surface when calibrated in free air.

A phosphate glass dosimeter I used in a spherical capsule and approved in routine personnel dosimetry some years ago[7–10] indicates the exposure independent energy within $\pm 8\%$ in the energy range between 45 keV and 1.2 MeV. At the front of an Alderson phantom the same dosimeter yields an energy independent reading of the exposure within 10%, the absorbed dose in the testes is indicated within $\pm 18\%$ almost independent of energy. The absorbed dose in the bone marrow and also in the female gonads, however, is overestimated for quantum radiation of lower energy (see Fig. 2).

Therefore, every energy independent dosimeter calibrated in free air will similarly indicate the exposure and the gonad dose in an almost energy independent way at the surface of the body.

A. R. Jones[3] proved the absorbed dose in all critical organs referred to a free air exposure of 1 R to agree within $\pm 25\%$ in the case of homogeneous radiation incidence (measurements with the rotating phantom) in the energy range above 60 keV. These values are independent of the quantum energy (see Fig. 3).

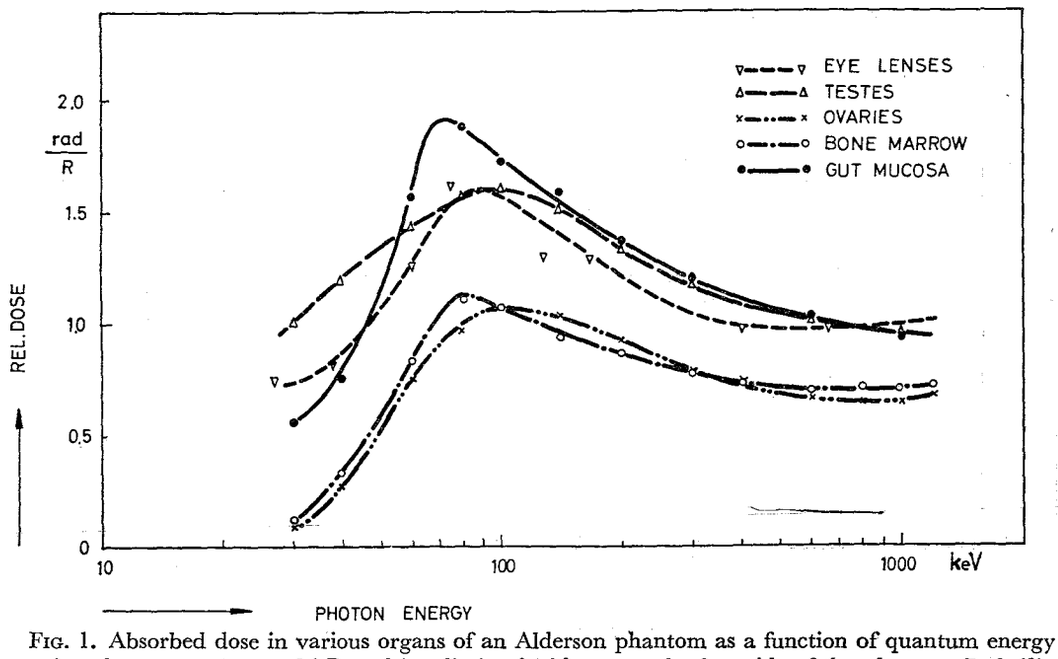

FIG. 1. Absorbed dose in various organs of an Alderson phantom as a function of quantum energy referred to an exposure of 1 R and irradiation incidence on the frontside of the phantom Ref. (3).
testes △— —△ gut mucosa ●——● ovaries ×—·—×
bone marrow ○—·—○ (backside incidence) eye lenses ▽– – –▽.

If the organ dose is based on this simplified definition, the energy independent phosphate glass dosimeter I (calibrated in free air) is assumed to detect the absorbed dose at the front of the phantom in all critical organs of interest in an energy independent way when the radiation is incident from the front half space* (see also Ref. (11)).

In case of homogeneous radiation incidence from the whole space, every energy independent dosimeter (i.e. a LiF dosimeter) will directly indicate the organ dose. For quantum radiation below 50 keV the organ dose will be overestimated.

In the following, the measured values of Fig. 1 serve as the definition of the organ dose (body exposure from the front half-space and maximum absorbed dose in the organ, respectively) (see also Section 4).

* Energy dependence of phosphate glass dosimeter I at the phantom in the energy range of 60 keV to 1.2 MeV for different organs: Testes ±9%, lens of the eye ±15%, gut mucosa ±16%, bone marrow ±18%, ovaries ±20%.

3. A PERSONNEL DOSIMETER FOR ABSORBED DOSE READING IN DIFFERENT ORGANS

In addition to phosphate glass dosimeter I used in routine personnel monitoring, a special compensation filter was developed for organ dose measurements.

Phosphate glass dosimeter II[5] has the same design characteristics as phosphate glass dosimeter I: The phosphate glass is contained in a boron plastic capsule covered with perforated spherical shells of tin. Instead of a 2 mm tin capsule, the phosphate glass dosimeter II is enclosed in a 1.2 mm tin capsule.

When phosphate glass dosimeter II was exposed at the phantom surface, we found an energy dependence of the dosimeter reading referred to the absorbed dose in different organs as given in Fig. 4. Thus, phosphate glass dosimeter II simultaneously indicate the absorbed dose in different organs independent of the energy in the range between 50 keV and 1.2 MeV, viz.

—the absorbed dose in the testes D_t within ±14%,

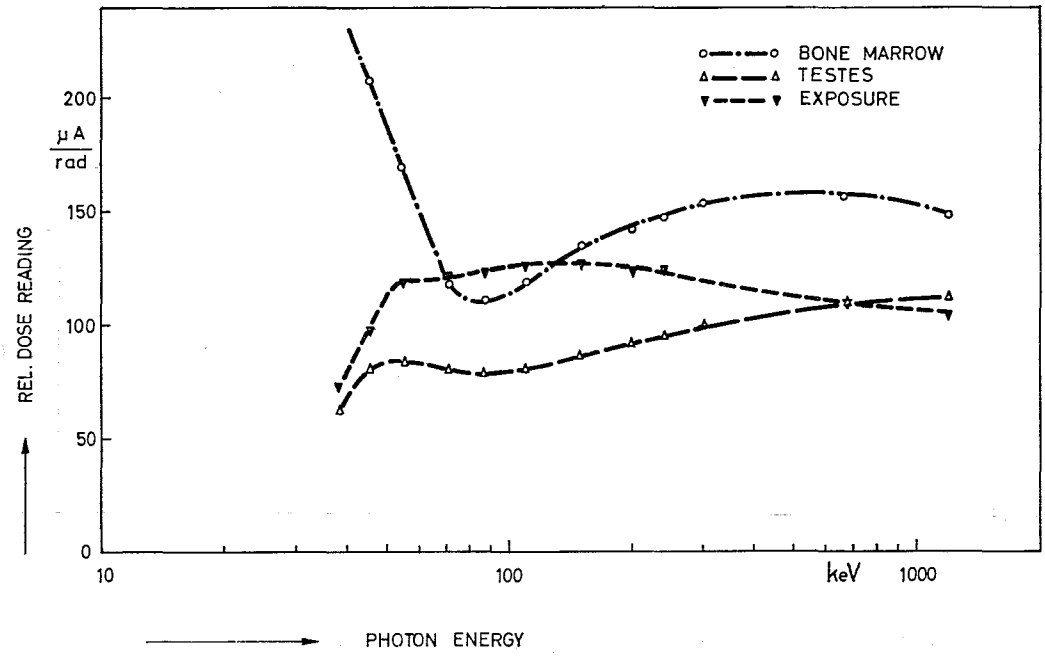

FIG. 2. Dosimeter reading of phosphate glass dosimeter I exposed on the frontside of an Alderson phantom as a function of quantum energy referred to the absorbed dose of 1 rad in different organs and irradiation incidence on the frontside of the phantom

bone marrow ○—·—○ testes △— —△ exposure of 1 R ▲- - - -▲.

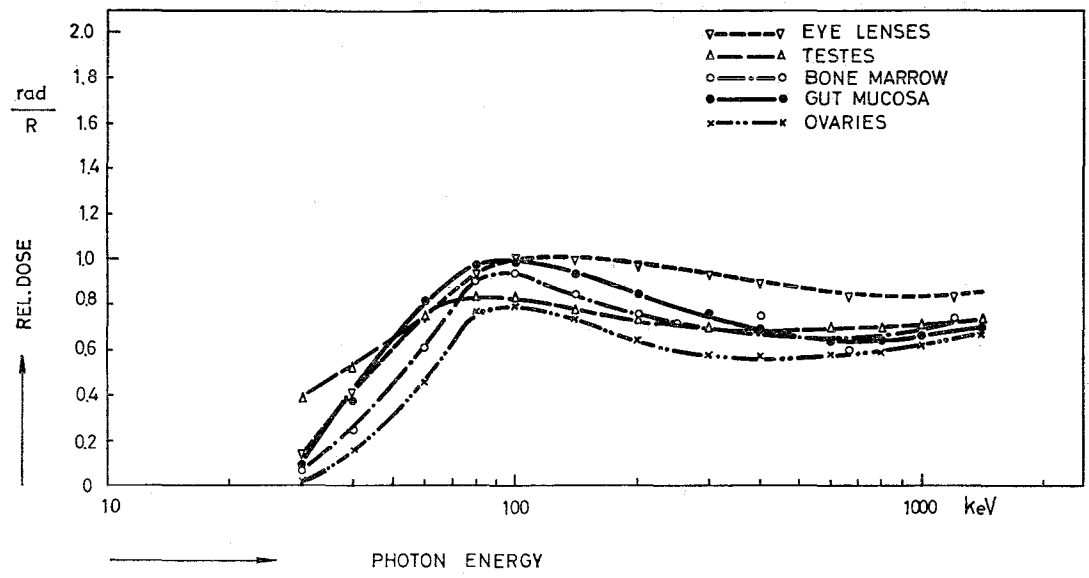

FIG. 3. Absorbed dose in various organs of an Alderson phantom as a function of quantum energy referred to an exposure of 1 R and irradiation from all directions (rotating phantom)

ovaries ×—··—× testes △— —△ bone marrow ○—·—○

gut mucosa ●——● eye lenses ▽- - - -▽.

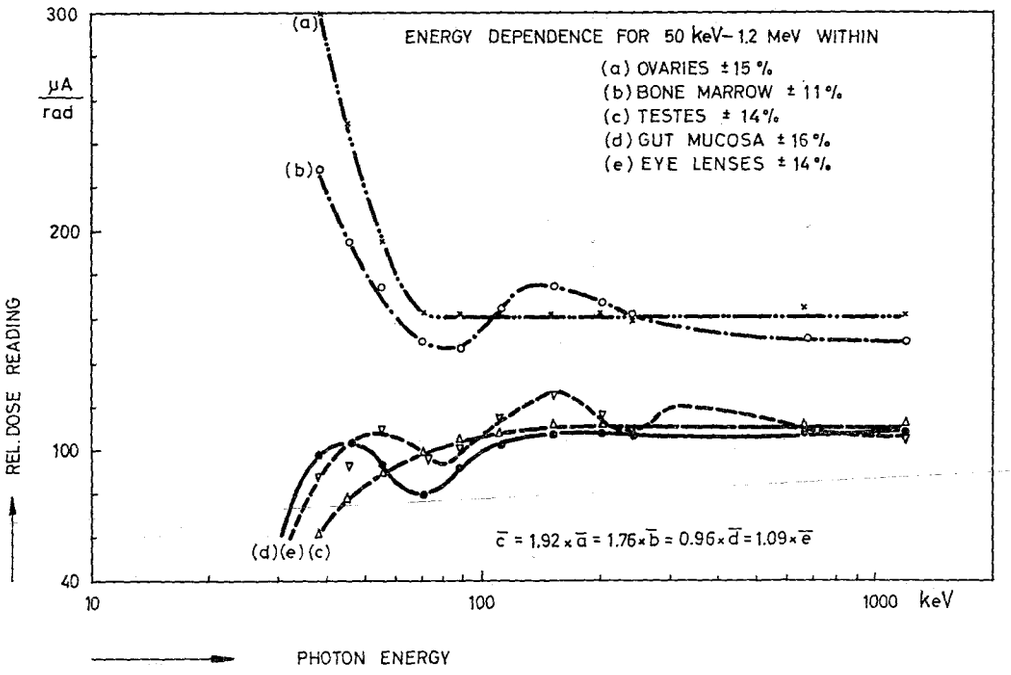

FIG. 4. Dosimeter reading of phosphate glass dosimeter II exposed at the frontside of an Alderson phantom as a function of quantum energy referred to the absorbed dose of 1 rad in different organs and irradiation incidence on the frontside of the phantom for ovaries (a), bone marrow (b), testes (c), gut mucosa (d) and eye lenses (e).

—the absorbed dose in the ovaries D_0 within $\pm 15\%$,
—the absorbed dose in the bone marrow D_b within $\pm 11\%$,
—the absorbed dose in the gut mucosa D_g within $\pm 16\%$,
—the absorbed dose in the lens of the eye D_e within $\pm 14\%$.

Table 1 shows the characteristics of both phosphate glass dosimeters.

An energy independent dosimeter is not the ideal one to indicate accurately an organ dose. A dosimeter indicating all organ doses of interest should be energy dependent to a certain extent.

The absorbed dose D_x of an organ x is directly proportional to the fluorescence intensity F: $D_x = \varepsilon_x(E) \times F$; $\varepsilon_x(E)$ symbolizing the corresponding absorbed dose sensitivity. In the energy range between 50 keV and 1.2 MeV an average value of the absorbed dose sensitivity can be determined experimentally for every organ dose (see Table 2). This average sensitivity is energy independent, with the exception of the measuring error as quoted in Table 1. Hence, the absorbed dose in a desired organ can be calculated from the measured value of phosphate glass dosimeter II with an energy independent conversion factor taken into account.

In routine personnel monitoring the dosimeter reading should be related primarily to the organ most sensitive to radiation, viz. the absorbed dose in the testes D_t. In emergencies (radiation hazard to female persons or acute exposure) the absorbed dose may be converted to other organs as follows:

$$D_b = 0.6 \times D_t$$
$$D_0 = 0.52 \times D_t$$
$$D_g = 1.04 \times D_t$$
$$D_e = 0.92 \times D_t$$

4. DIFFICULTIES OF INTERPRETATION IN ABSORBED DOSE DETERMINATION

The possibilities of an organ dose interpretation are limited by the requirements of the

Table 1. *Organ dose reading with phosphate glass dosimeters*

Dosimeter	Measurement	Energy dependence of dosimeter reading 50 keV – 1.2 MeV
Phosphate glass dosimeter I	Free air exposure	
	Exposure	±8%
	Phantom exposure	
	Exposure	±10%
	Absorbed Dose in:	
	Testes	±18%
	Bone Marrow	(±27%)
Phosphate glass dosimeter II	Free air exposure	
	Exposure	(±23%)
	Phantom exposure	
	Exposure	(±24%)
	Absorbed Dose in:	
	Testes	±14%
	Ovaries	±15%
	Gut Mucosa	±16%
	Bone Marrow	±11%
	Eye Lenses	±14%

Table 2. *Determination of the organ dose from the dosimeter reading (Phosphate Glass Dosimeter* II)

Calibration to organ dose D_x *(rad) from the measuring value* $F(\mu A)$

Absorbed Dose in		
	Testes	$D_t = \varepsilon_t(E) \times F$
	Gut Mucosa	$D_g = \varepsilon_g(E) \times F$
	Bone Marrow	$D_b = \varepsilon_b(E) \times F$
	Ovaries	$D_o = \varepsilon_o(E) \times F$
	Eye Lenses	$D_e = \varepsilon_e(E) \times F$

Average value of absorbed dose sensitivity ε_x(50 keV – 1.2 MeV)

$D_t = \varepsilon_t \times F$	$\varepsilon_t = 0.0102$ rad/μA
$D_g = \varepsilon_g \times F = \frac{\varepsilon_g}{\varepsilon_t} \times D_t$	$\varepsilon_g = 0.0106$ rad/μA
$= 1.04 \times D_t$	
$D_e = 0.92 \times D_t$	$\varepsilon_e = 0.0094$ rad/μA
$D_b = 0.6 \times D_t$	$\varepsilon_b = 0.0061$ rad/μA
$D_o = 0.52 \times D_t$	$\varepsilon_o = 0.0053$ rad/μA

Simultaneous organ dose indication in different organs

Absorbed dose in bone marrow D_b = 0.57 × [Absorbed dose in gut mucosa D_g]
= 0.6 × [Absorbed dose in Testes D_t]
= 1.17 × [Absorbed dose in Ovaries D_o]

$$D_b = 0.57 \times D_g = 0.6 \times D_t = 1.17 \times D_o$$

Critical organs for personnel dosimeters

Routine personnel monitoring: Absorbed dose in gonads (D_t, D_o)
Emergency exposure: Absorbed dose in gut mucosa D_g and bone marrow D_b

definition of an organ dose and by the radiation conditions. These are:

—exposure of the front of the body where the personnel dosimeter is worn,
—homogeneous whole body exposure,
—the definition of the organ dose is based on the radiation incidence corresponding to a maximum absorbed dose in the organ,
—the absorbed dose in the organ is based on a phantom of standard man.

Obviously, these restrictions apply as well to energy dependent measurements. The energy dependent film dosimeter shows more unfavourable measuring properties when radiation conditions deviate but slightly from those of a front exposure. Furthermore, the dose reading of the film dosimeter is very energy and direction dependent, especially for low energy quantum radiation.

On the other hand, the phosphate glass dosimeter is practically direction independent on account of its spherical capsule. An exposure from the front half-space will be indicated correctly, also in the presence of various radiation components.

The values of the absorbed dose in different organs are referred to the radiation incidence leading to the maximum dose absorbed in the respective organ. They were derived experimentally by JONES[3] for different radiation incidences (radiation from front and from behind the phantom as well as for a rotating phantom) by means of an Alderson phantom.

The average value of the absorbed dose in the bone marrow showed less dependence on the radiation incidence. For this organ the maximum dose will be obtained by an irradiation from behind contrary to other organs (exposure from the front).

In this case the radiation incidence with the maximum irradiation effect should guarantee a certain factor also in the presence of different radiation incidences.

The influence of body orientation on the dose reading of a personnel dosimeter as well as on the energy absorbed in the organ restricts the interpretation of an organ dose measurement. This applies to energy independent and energy dependent measurements likewise. Therefore, a representative evidence of the radiation hazard to a person will be created only under conditions of a homogeneous whole body exposure and irradiation from the front. Inhomogeneous exposures may be neglected for small dose readings, but this influence must be considered for high doses, where the additional estimate of the radiation field should provide a correction factor for the personnel dosimeter reading.

An essential improvement of this fact could be achieved with a special dosimeter capsule to be developed, which will yield an correct indication of the dose independent from the body orientation. Such a dosimeter worn at the front of the body indicates the organ dose also for irradiation from behind. Today, the technical realisation of such a personnel dosimeter is feasible with the phosphate glass dosimeter.

5. THE PURPOSE OF ORGAN DOSE MEASUREMENT

Finally, the conditions and the technical prerequisites will be discussed under which an estimate of the organ dose in personnel dosimetry would be favourable.

The phantom measurements by A. R. Jones demonstrate that the absorbed doses per 1 R in different organs may differ by a factor of 2. Therefore, the assessment of a certain organ dose will be of interest only when the total measuring error of the dosimeter is considerably less than this value.

Up to now, only a few results have been published about the order of magnitude of the measuring error in routine personnel dosimetry. In these measurements for comparison one person wore three different dosimeters or two dosimeters of the same type.

The results of these comparison measurements should demonstrate the measuring error to be expected for personnel dosimeters (energy independent phosphate glass dosimeter as described and energy dependent film dosimeter).[9]

Figure 5 indicates the results gained from pairs of dosimeters worn in an isotope laboratory with monthly routine evaluation. 75% of the phosphate glass dosimeter I pairs showed agreement of the dose readings within $\pm 10\%$. With film dosimeter pairs (filter analytical technique*)

* Film dosimeter evaluation by a governmental laboratory in the Federal Republic of Germany.

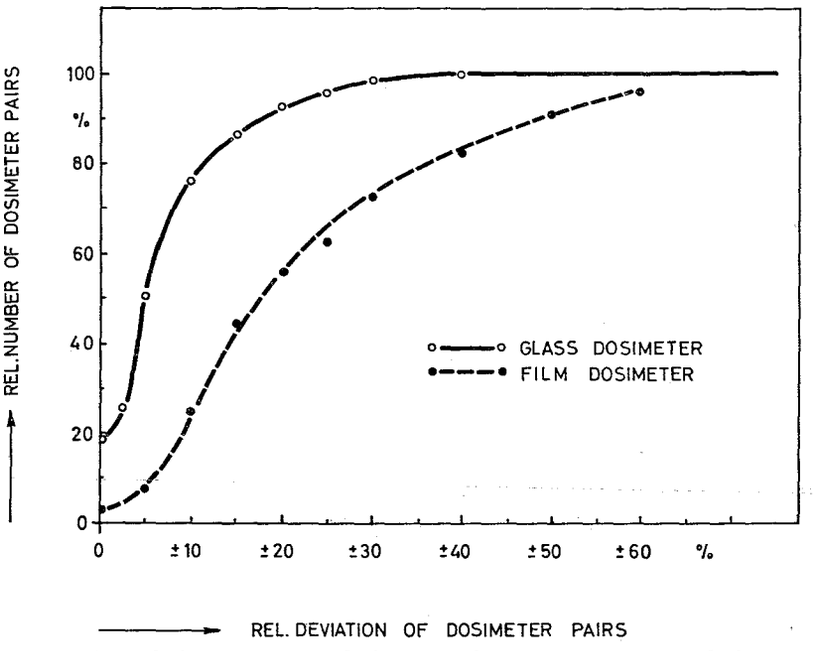

FIG. 5. The relative number of dosimeter pairs of phosphate glass dosimeter I and of film dosimeters worn together by the same person in routine personnel monitoring, found within a given dose reading deviation (63 glass dosimeter pairs and 57 film dosimeter pairs). All film dosimeter pairs were simultaneously worn with glass dosimeter pairs. Dose reading 40 mR to 1 R.

an agreement of the dose readings could only be achieved in 20% of all cases within $\pm 10\%$. Assuming the same extent of inhomogeneous irradiations for both dosimeter types, the agreement of dose readings is an indication of the reproducibility of the measuring accuracy. The fact that the dose reading deviation of film dosimeter pairs is higher than 50% in 44% of all cases must be attributed to the measuring accuracy of the film dosimeter. Similar results were obtained by calibration exposures of the same type of glass and film dosimeter.[12,13]

With a method of measurement involving so many errors, it is therefore not reasonable to convert measured value of the film dosimeter (exposure and surface dose, respectively) into an organ dose by a radiation quality factor (i.e. with additional error influence).

The phosphate glass dosimeter described here guarantees correct and reproducible dose measurement also in the presence of radiation components with different photon energies under conditions of routine personnel monitoring. The small measuring error and the indication of the absorbed dose in different organs, which is energy independent up to $\pm 16\%$, seems to justify the improvement of the present measuring method.

There is no doubt about the significance and suitability of an organ dose indication, especially for dose assessments by governmental agencies. The maximum permissible dose of 3 rem per 13 weeks and 5 rem/year, respectively, for a whole body exposure according to ICRP, is related to an organ dose in all international and national recommendations and rules. Therefore, the organ dose determination will be of significance, especially for exposures reaching those limits.

Legislation is obliged to supervise and, if necessary, prevent any exceeding of the maximum permissible doses. The user of a personnel dose surveillance, however, is interested in exploiting the legally permissible dose values for professionally exposed persons. The best guarantee undoubtedly consists in the direct

measurement of the organ dose as the measuring method with the least measuring inaccuracy.

A phosphate glass dosimeter was used to demonstrate that a reasonable organ dose measurement can be realized technically with an energy independent dosimeter. It has to be left to further discussions in Health Physics dosimetry on the organisation of an appropriate measuring method whether or not an improvement of the present personnel dosimetry method should be considered and to what extent the measuring method suggested here will be introduced and further developed in routine personnel monitoring.

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