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Monitoring the Eye Lens Dose

Statement by the German Commission on Radiological Protection with
Scientific Reasoning

Adopted at the 240th meeting of the German Commission on Radiological Protection on
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Überwachung der Augenlinsendosis

Stellungnahme der Strahlenschutzkommission mit wissenschaftlicher Begründung

This translation is for informational purposes only, and is not a substitute for the official statement. The original version of the statement, published on www.ssk.de, is the only definitive and official version.

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Introduction

The occurrence of lens opacities (cataracts) following exposure to ionising radiation is a known effect which has led to exposure limits being established specifically for the eye lens within the framework of precautionary radiological protection. To exclude deterministic damage (mainly eye lens opacities), the International Commission on Radiological Protection (ICRP) has set specific dose limits for the eye lens (150 mSv/year for occupationally exposed adults and 15 mSv/year for all other persons) (ICRP 1991).

For a long time, cataract formation following exposure to ionising radiation was regarded as a deterministic effect, characterised by a threshold dose (> 500 mSv) below which no detectable effect occurs. However, this view has increasingly been called into question in recent years based on newer studies (see for example (Worgul et al. 2007) and (Chodick et al. 2008)). There are calls for the threshold dose to be set at a much lower level; indeed, it is by no means clear that a threshold dose exists at all. This would mean that lower dose limits for the eye lens should also be considered. The SSK published a Recommendation on this topic in 2009 (SSK 2009). The new ICRP Recommendations published in 2007 left this question unanswered for the time being as the research findings are not yet sufficiently comprehensive. Nonetheless, the debate has raised the question whether, in the practice of occupational radiological protection, more accurate monitoring of eye lens dose should take place and if so, which methods could be applied in this context.

The following statement particularly addresses issues concerning the appropriate dose equivalent quantities for an estimate of the eye lens dose for various types of radiation and considers appropriate monitoring methodologies. It focusses especially on the following questions:

1. Are any new findings available which go beyond the data presented in SSK Volume 43 (SSK 2006) on organ dose for the eye lens, particularly with reference to Sections 3.2.1 and 5.4.3 of this Volume?
2. What are appropriate dose equivalent quantities for a conservative estimate of the organ dose for the eye lens for penetrating radiation and radiation with low penetration depth?
3. Which dose equivalent quantity is particularly appropriate for a conservative estimate of the organ dose for the eye lens for low-energy photon radiation (< 100 keV)?
4. Are there any specific aspects of the dosimetric determination of the organ dose for the eye lens which must be considered?
5. Are there any policy recommendations concerning the need to introduce the dose equivalent quantities $H_p(3)$ and $H_p(0.07)$ (calibration on a slab phantom)?
6. Which protection measures are suitable for the eye lens?

Statement

The available scientific literature only provides conclusive answers to the above questions to a partial extent. In consequence, a number of further studies have been carried out, whose findings are briefly presented in the more detailed Scientific Reasoning annexed to this statement.

Based on these new data analysed in the scientific annex, the following statement is adopted in response to the above questions:

1. The data published in SKK Volume 43 on the organ dose for the eye lens reflect the internationally recognised state of scientific knowledge in 2006. For electrons in particular, these data are based on calculations performed using a very approximate model of the human eye. Therefore, for beta radiation in particular, the conclusions drawn in Section 5.4.3 of this SKK Volume – that for persons occupationally exposed to radiation, monitoring of the skin dose with its limit value of 500 mSv per year also guarantees compliance with the limit value of 150 mSv in any one calendar year for the eye lens dose (provided that the dosimeter is positioned near the eye lens) – can no longer be upheld. This section of the SKK Volume must, therefore, be revised.

For the eye lens dose, dose conversion factors should be used that are based on a more realistic simulation of the human eye and take account of the different sensitivities of areas within the lens to cataract formation following exposure.

For photon radiation fields, Section 3.2.1 of SKK Volume 43 refers only to the relationship of the eye lens dose to the ambient dose equivalent. Given the exposure scenarios being investigated in radiology today, this is not adequate and must be reviewed.

2. Regarding the question of the appropriate dose equivalent quantities for a conservative estimate of the organ dose for the eye lens for penetrating radiation and radiation with low penetration depth, the situation for photons (especially X-ray radiation) and beta radiation must be considered separately.

In photon radiation fields, the personal dose equivalent quantity $H_p(0.07)$ adequately estimates the eye lens dose at energies of < 200 keV; the same applies to $H_p(10)$ at energies > 100 keV. For photon fields, there is therefore no need to introduce the additional personal dose equivalent quantity $H_p(3)$ – and, therefore, possibly also the ambient dose equivalent quantity $H'(3, \Omega)$ – for the specific case of lens monitoring.

For the dose equivalent quantity $H_p(0.07)$, the personal dosimeter used must, however, be calibrated on an ISO water slab phantom (slab phantom), like a whole-body dosimeter, not on an ISO rod phantom as in the case of an extremity dosimeter.

This would entail a change in the practice customarily applied in Germany to date, whereby dosimeters for the personal dose equivalent $H_p(0.07)$ are not calibrated on a slab phantom, nor are design type tests for this type of dosimeter carried out neither are type approvals issued.

For radionuclides with beta radiation that are used in practical applications, the calculated value of the exposed eye lens dose largely depends on which area within the lens is used as the basis for calculating the eye lens dose (mean dose for the entire lens or mean dose in the area of the lens that is sensitive to cataract formation).

It is recommended that efforts be made to achieve international clarification of the question of how the eye lens dose should be calculated – especially if the introduction of a new personal dose equivalent quantity $H_p(3)$ is considered in Germany.

In beta radiation fields and for the sensitive area of the eye lens, the personal dose equivalent $H_p(3)$ estimates the eye lens dose most accurately, although $H_p(0.07)$ also provides a conservative value for the eye lens dose for all radionuclides customarily used. However, for radionuclides with beta energies up to around 1 MeV, a substantial overestimation of the eye lens dose is possible, e.g. by a factor of as much as 280 for the radionuclide Re-186, as electrons with energies of < 0.7 MeV (low-energy electrons) no longer reach the lens of the eye but contribute to $H_p(0.07)$.

If the beta radiation source is positioned at some distance from the lens of the eye, the interaction of the beta radiation with the atmosphere can also lead to a substantial reduction of the eye lens dose. This applies especially to low-energy beta radiation.

3. In the specific case of exposure to x-rays for diagnostic purposes (e.g. in interventional cardiology) and exposure in scattered radiation fields, monitoring of the personal dose $H_p(0.07)$ is sufficient to determine the eye lens dose. Here, the personal dosimeter to be worn must either be calibrated on a slab phantom or, in the case of an extremity dosimeter calibrated on a rod phantom, it must be ensured that the dosimeter also accurately measures backscattered radiation from the phantom. Ascertaining which of the dosimeters currently used legally already fulfil this second requirement is recommended.
4. When determining the eye lens dose by monitoring the dose with a personal dosimeter, the dosimeter must be worn close to the eye or positioned on the body in such a way that it is exposed to approximately the same radiation field as the eye. It must be borne in mind, in this context, that shielding the eye, especially in beta radiation fields, will significantly influence the radiation field at the eye (resulting in a substantial reduction of the eye lens dose).
5. Before introducing the dose equivalent quantities $H_p(0.07)$ for photon radiation with dosimeters calibrated on a slab phantom and $H_p(3)$ for electron radiation in order to determine the eye lens dose, it is recommended that workplace observations (analysis of existing workplace dosimetric data / monitoring of workplace the eye lens dose if no such data are available) be carried out in order to determine whether such introduction is appropriate.
6. Maintaining the maximum possible distance from the radiation source is the first step in keeping the eye lens dose as low as is practically achievable.

In the case of exposure to beta radiation from radionuclides (with a relatively low proportion of photon radiation), the use of protective eyewear can substantially reduce the eye lens dose.

In the case of exposure to scattered radiation fields in diagnostic radiology (photon energy < 150 keV), shielding with lead glass windows or lead glass protective eyewear is recommended, but is far less effective than in beta radiation fields (tenth-value thickness for 50 keV photon / 100 kV X-ray radiation: approx. 1mm lead glass).

Scientific Reasoning

Two types of radiation are particularly significant in relation to eye lens exposure. They are, firstly, beta radiation (electron radiation with low penetration depth) and, secondly, low-energy photon radiation, especially X-ray radiation with tube voltages up to around 150 kV, as used in diagnostic radiology.

Neutron radiation will not be discussed further here in relation to the eye lens dose, as this type of radiation has a very large range in the human body and, therefore, the far lower limit value for the effective dose (annual limit value: 20 mSv for occupationally exposed persons) is reached far more rapidly than a limit value of 150 mSv for the eye lens dose. The same also applies to high-energy photon radiation (e.g. energies > 500 keV), but only if exposure of those body parts which mainly involve head exposure is excluded.

Below, the dose quantities used will be explained briefly first of all, and then the situation with regard to the two types of radiation mentioned above will be considered.

1 Dose quantities

The eye lens is located in the eye behind the cornea and the anterior chamber at a depth of approx. 2 – 4 mm. The eye lens dose is expressed in terms of the organ dose

$$H_{\text{lens}} = w_R D_{\text{lens}},$$

whereby D_{Lens} is the mean energy dose in the eye lens and w_R is the radiation weighting factor which, for photon and electron radiation, has the value 1. The mean eye lens dose is not directly measurable, but calculated as a function of incident radiation using anthropomorphic phantoms. As a rule, conversion coefficients H_{lens}/K_a for photons (K_a air kerma) and H_{lens}/Φ for electrons (Φ electron fluence) are stated for incident monoenergetic radiation, which then enable the organ dose for the eye lens to be calculated from a given spectrum of incident radiation (e.g. ISO radiation qualities for X-ray radiation).

Whereas the data for the eye lens dose contained in ICRP Publication 74 (ICRP 1996) were largely based on calculations performed with the MIRD-type anthropomorphic phantom (Schultz and Zoetelief 1996), new data are now available for photon exposure based on calculations performed with an anthropomorphic voxel phantom (Schlatzl et al. 2007). It is apparent that when performing calculations using the voxel phantom for such a small tissue part as the eye lens, with radiation with relatively low penetration depth (e.g. low-energy photons or electrons < 3 MeV), the calculated mean eye lens dose depends substantially on the voxel size and its position in the area of the lens. Below, therefore, both the data set from ICRP 74 and the data sets for the male (Rex) and female (Regina) voxel phantoms are analysed (for photon exposure, see Table 1).

All these calculations determine the mean value across the entire eye lens as the eye lens dose, as defined in ICRP 103 (ICRP 2008) as the organ dose (equivalent dose). It has been known for some time, however, that different areas of the eye lens vary considerably in terms of their sensitivity to cataract formation following exposure to ionising radiation; in essence, only cells in the area of the anterior lens wall display high sensitivity (see Figure 1).

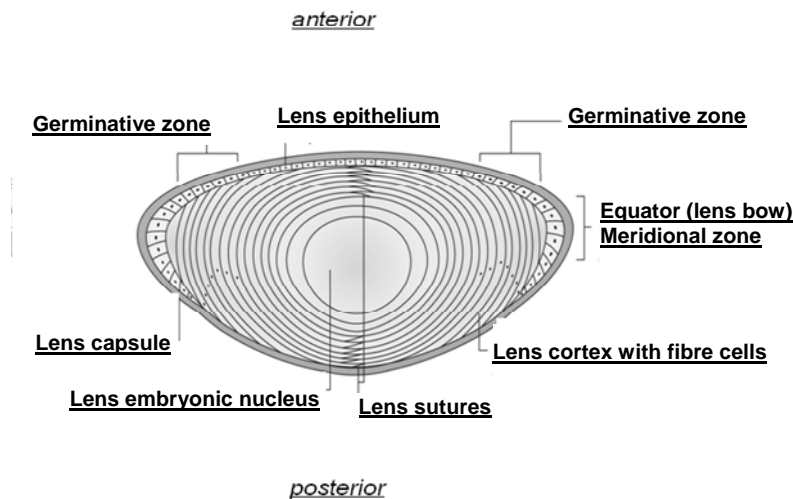


Figure 1: Schematic diagram of the lens, based on (Graw 2003)

For this reason, and due to the very approximate simulation of the geometry of the eye, the calculations mentioned above are beset with considerable uncertainties, particularly in relation to short-range beta radiation. A new publication looks at these very issues and, based on more precise simulation of the eye and lens (see Figure 2), now provides better eye lens dose data for beta radiation (Behrens et al. 2009).

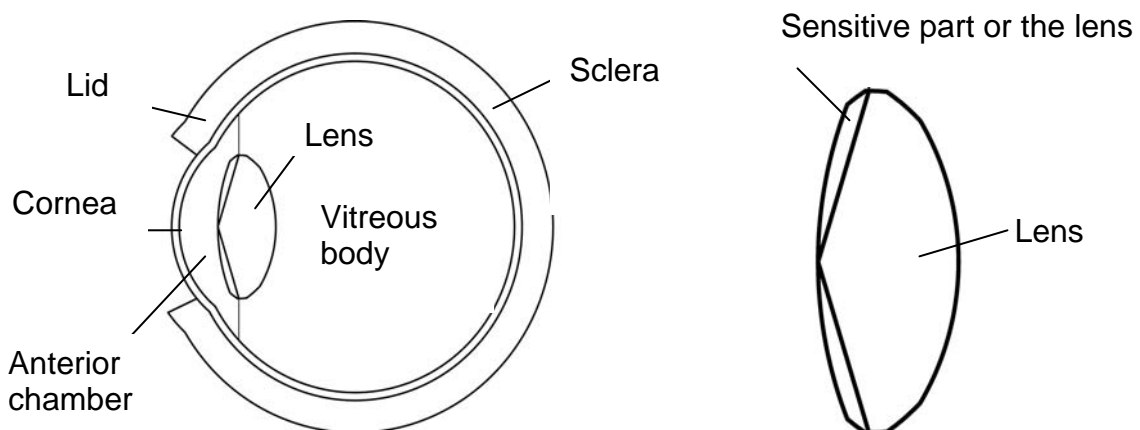


Figure 2: Diagram of the simulation of the eye and lens (Behrens et al. 2009)

In photon radiation fields, the effect of geometry is less pronounced due to the far smaller dose gradients in tissue. In this case, therefore, the above mentioned data from ICRP Publication 74 (ICRP 1996) and the voxel phantoms are used below.

As the eye lens dose is not measurable, the dose equivalent quantities defined for radiological protection are used in order to obtain an estimated value for exposed eye lens dose on the basis of monitoring. The International Commission on Radiation Units and Measurements (ICRU) (ICRU 1985) has, therefore, defined the directional dose equivalent $H'(3, \Omega)$ and the personal dose equivalent $H_p(3)$ specifically for monitoring the eye lens; these relate to the dose equivalent at a 3 mm depth in the ICRU sphere and in the body, respectively. In addition, as ambient dose equivalent quantities, there are the ambient dose equivalent $H^*(10)$ and the directional dose equivalent $H'(0.07, \Omega)$; personal dose equivalent quantities are the personal dose equivalents $H_p(10)$ and $H_p(0.07)$.

However, in Germany, as in many other countries, $H'(3,\Omega)$ and $H_p(3)$ have not been introduced because based on the analysis contained in SSK Volume 43, it was concluded that for monitoring of the eye lens (annual limit value for adults occupationally exposed to radiation = 150 mSv) for exposure to radiation with low penetration depth, the use of the dose equivalent quantities $H'(0.07,\Omega)$ and $H_p(0.07)$, which are mainly used to monitor skin dose (annual limit value = 500 mSv), are sufficient to rule out the possibility of the limit value for the eye lens dose being exceeded. In photon radiation fields of $E > 30$ keV, $H^*(10)$ and $H_p(10)$ provide a conservative estimate of dose (see Sections 3.2.1 and 5.4.3 in (SSK 2006)).

Given that a reduction of the limit value for the eye lens dose cannot be ruled out in future, however, it is important to review whether the dose equivalents $H'(0.07,\Omega)$ and $H_p(0.07)$ and $H^*(10)$ and $H_p(10)$ provide sufficiently accurate estimated values for the eye lens dose or whether the dose equivalents quantities $H'(3,\Omega)$ and $H_p(3)$ are required for this purpose. This is discussed in the following chapters for both relevant types of radiation, i.e. photon and beta radiation. In this context, the respective conversion coefficients are stated for the organ dose for the eye lens and for the dose equivalent quantities; these are compared. α particles do not need to be considered here, as their range in tissue is very small (approx. 0.1 mm per 10 MeV α particles), which means that they cannot reach the lens when emitted by external radiation sources.

In SSK Volume 43, a specific methodology is proposed to determine organ doses, which are not measurable, from externally incident penetrating radiation (photons and neutrons). If measured values are available for the ambient dose equivalent quantity $H^*(10)$, the organ doses sought can be calculated using the conversion coefficients stated in the document – if necessary also with the assistance of corrective factors which take account of the specific position of the radiation source. If measured values are available for the personal dose equivalent, Volume 43 proposes converting these data into $H^*(10)$ values first and then applying the same methodology (see Section 3.1.4). This methodology is also proposed, using the ambient dose equivalent, for the eye lens dose. Only the effective dose and some extremity doses (hands, lower arms, feet, ankles and local skin dose) can be determined directly from the personal dose equivalent quantities. In principle, however, this direct method can also be applied to the eye lens dose if the appropriate dose equivalent quantity, together with a suitable dosimeter, is available.

2 Exposure of the eye lens to photon radiation

Eye lens exposure in persons occupationally exposed to radiation, e.g. in the medical field, in many cases takes the form of exposure to X-ray radiation fields (< 150 kV) commonly used in interventional radiology. A realistic scenario, for example, is the exposure to a scattered radiation field leaving the body of a patient undergoing an examination. Eye lens exposure to monoenergetic photons can also occur when working with radionuclide sources, for example. Both scenarios are considered in more detail below with reference to the appropriate dose equivalent quantities for the determination of eye lens dose. Table 1 shows conversion coefficient data H/K_a (K_a : air kerma) for the organ dose for the eye lens and for various dose equivalent quantities for monoenergetic photon radiation in the 10 keV – 1 MeV range.

The data show that with exposure to high-energy photons (> 200 keV), it can generally be assumed that the dose equivalents $H^*(10)$ and $H_p(10)$ provide a good estimate of the eye lens dose (see also Figure 3).

Table 1: *Conversion coefficients H/K_a (K_a : air kerma) for the organ dose for the eye lens in various anthropomorphic phantoms (MIRD-type phantom (ICRP 1996) and voxel phantoms Rex and Regina (Schlatzl et al. 2007)) and for various dose equivalent quantities for monoenergetic photon radiation with energies ≥ 10 keV. The data for $H_p(0.07)/K_a$ relate to the dose values in a slab and a rod phantom with irradiation from the front (AP).*

Energy (keV)	H_{lens}/K_a in Sv/Gy			$H^*(10)/K_a$	$H_p(10)/K_a$	$H'(0.07,0^\circ)/K_a$	$H_p(0.07)/K_a$	
	AP		AP	in Sv/Gy	in Sv/Gy	in Sv/Gy	in Sv/Gy	
	Rex	Regina	(ICRP 74)		Slab		Slab	Rod
10	0.293	0.047	0.304	0.008	0.009	0.947	0.947	0.950
15	0.725	0.400	0.664	0.26	0.264	0.99	0.98	0.98
20	0.948	0.739	0.912	0.61	0.611	1.05	1.05	1.01
30	1.219	1.158	1.197	1.10	1.112	1.22	1.23	1.06
40	1.362	1.277	1.334	1.47	1.129	1.42	1.44	1.14
60	1.479	1.531	1.492	1.74	1.485	1.59	1.72	1.14
80	1.668	1.548	1.555	1.72	1.624	1.61	1.73	1.16
100	1.756	1.467	1.530	1.65	1.645	1.55	1.67	1.17
150	1.625	1.539	1.425	1.49	1.559	1.42	1.52	1.16
200	1.428	1.327	1.357	1.40	1.463	1.34	1.43	1.15
300	1.243	1.251	1.280	1.31	1.342	1.31	1.34	1.14
500	1.195	1.172	1.199	1.23	1.232	1.23	1.24	
1000	1.154	1.078	1.113	1.17	1.143	1.17	1.17	

With regard to the conversion coefficients for the dose equivalent quantities for photons, the following must be borne in mind: whereas monitoring devices to measure the ambient dose equivalent, $H^*(10)$, and the directional dose equivalent, $H'(0.07,0^\circ)$, are calibrated free in air and the value of the dose equivalent quantity is stated for the reference point in air, personal dosimeters to monitor personal dose equivalents, $H_p(10)$ and $H_p(0.07)$, are worn on the body and calibrated on a phantom. As a result, the radiation field at the site of the personal dosimeter also contains an element of backscatter from the person or the phantom, with the amount depending, for example, on the shape and size of the phantom. The conversion coefficients stated in ICRP 74 and in the standards for H_p therefore always relate to the situation during calibration, i.e. the value of the dose equivalents in the relevant calibration phantom, not to the person wearing the dosimeter. As a rule, however, the difference is relatively small.

In Germany, the personal dose equivalent $H_p(0.07)$ is only used to measure extremity doses, e.g. the local skin dose at a finger. Extremity dosimeters therefore generally take the form of a finger ring dosimeters which are calibrated on an ISO-normed rod phantom. The ISO has also published the relevant conversion coefficients $H_p(0.07)/K_a$ for this phantom (ISO 1999).

In contrast, ICRU in ICRU Report 57 (ICRU 1998), has published conversion coefficients $H_p(0.07)/K_a$ for the calibration of personal dosimeters on a slab phantom. The two data sets differ considerably in respect of energies > 20 keV (see Table 1), whereby the data obtained using the slab phantom provide a much better estimate of eye lens dose.

Table 2 shows the relationship of the organ dose for the eye lens to the dose equivalent quantities $H^*(10)$, $H'(0.07,0^\circ)$, $H_p(10)$ and $H_p(0.07)$ with irradiation from the front (AP).

Table 2: Relationship the of operational quantities $H^*(10)$, $H_p(10)$, $H'(0.07,0^\circ)$, and $H_p(0.07)$ to the organ dose for the eye lens $H_{\text{lens}}^{(1)}$ in monoenergetic photon radiation fields (data from ICRU Report 57 (ICRU 1998) und ISO 4037-3 (ISO 1999)).

Energy (keV)	H_{lens}/K_a In Sv/Gy AP	$H^*(10)/H_{\text{lens}}$	$H_p(10)/H_{\text{lens}}$ Slab phantom AP	$H'(0.07,0^\circ)/H_{\text{lens}}$	$H_p(0.07)/H_{\text{lens}}$ Slab ph. AP Rod ph. AP
10	0.215	0.037	0.042	4.414	4.414 4.428
15	0.596	0.436	0.443	1.660	1.645 1.643
20	0.866	0.704	0.705	1.212	1.206 1.166
30	1.191	0.924	0.934	1.024	1.033 0.890
40	1.324	1.110	1.125	1.060	1.090 0.823
60	1.501	1.160	1.261	1.060	1.144 0.760
80	1.590	1.082	1.197	1.012	1.089 0.729
100	1.584	1.042	1.143	0.978	1.054 0.739
150	1.530	0.974	1.051	0.928	0.992 0.758
200	1.371	1.021	1.088	0.978	1.045 0.839
300	1.258	1.041	1.088	1.041	1.062 0.906
500	1.189	1.035	1.057	1.035	1.047
1000	1.115	1.049	1.047	1.049	1.052

It can be seen in Figure 3 that with external exposure to photons in the energy range > 30 keV and irradiation from the front, the dose equivalent quantities $H^*(10)$ and $H_p(10)$ provide a good conservative estimate of the organ dose for the eye lens, whereas they underestimate the eye lens dose at lower energies.

The operational quantities $H'(0.07,0^\circ)$ and $H_p(0.07)$ (the latter with calibration on an ISO water slab phantom, abbreviated below to “slab phantom”) provide a conservative estimate of the organ dose for the eye lens for the entire photon energy range analysed, but greatly overestimate eye lens dose in the photon energy range < 20 keV.

In contrast, the personal dose equivalent for extremity dosimetry $H_p(0.07)$ (with calibration of the extremity dosimeter on the ISO rod phantom) underestimates the organ dose for the eye lens in the energy range 30 keV – 300 keV by up to 27 %.

⁽¹⁾ The mean value of the eye lens data from ICRU Report 57 (ICRU 1998) and of the data obtained using voxel phantoms Rex and Regina (Schlatl et al. 2007) was taken as the value for the organ dose for the eye lens here (see Table 1).

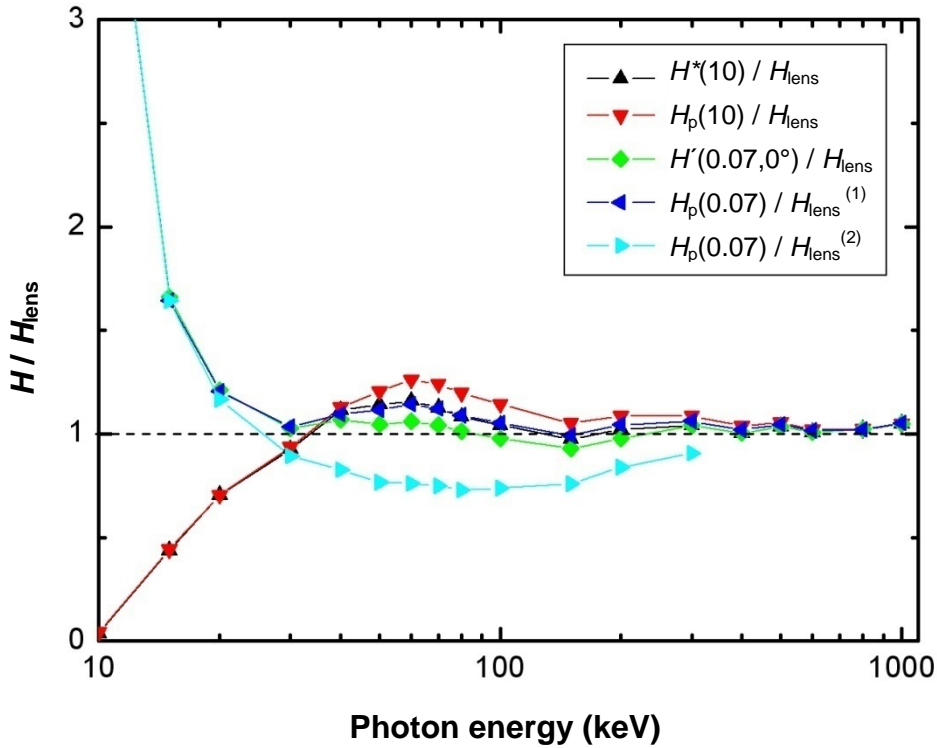


Figure 3: Relationship of the dose equivalent quantities $H^*(10)$, $H_p(10)$, $H'(0.07, 0^\circ)$ and $H_p(0.07)$ to the organ dose for the eye lens H_{lens} (H_{AL}) (mean value of data obtained using the various anthropomorphic phantoms) in monoenergetic photon fields with irradiation from the front (AP) (ICRU 1998).
 (1) $H_p(0.07)$ on a slab phantom,
 (2) $H_p(0.07)$ on a rod phantom.

All the above statements apply to eye exposure from the frontal half-space. In the case of head exposure from behind or from the side, a dosimeter worn on the front side and calibrated on a slab phantom in units of $H_p(10)$ or $H_p(0.07)$ does not correctly estimate the eye lens dose as the calibration phantom (slab phantom) deviates significantly from the shape of a head (Ferrari et al. 2007).

In addition, consideration is given below to the realistic scenario in which, during diagnostic examination using X-rays, exposure to the scattered radiation field leaving the body of the patient undergoing examination occurs.

Here, a scenario is simulated in which X-ray radiation with a field size of 40 cm x 40 cm falls vertically onto an extended flat phantom (in this case a water phantom, which, however, differs only minimally from a tissue phantom in relation to scattered radiation) and a human eye is exposed at a 135° scattering angle.

The fluence spectra of scattered radiation for primary X-ray radiation of 30 kV, 50 kV, 70 kV, 90 kV, 120 kV and 150 kV were calculated by H.-M. Kramer (PTB) (Kramer 2008). The energy absorption coefficients μ_{en}/ρ for the conversion of photon fluence in air kerma were taken from the database of the National Institute of Standards and Technology (NIST) (Hubbell and Seltzer 2009) and the conversion coefficients data provided in Table 1 for the eye lens dose and the dose equivalent quantities were used. For $H_p(10)$ and $H_p(0.07)$, the

conversion coefficients from ICRU Report 57 (ICRU 1998) for the slab phantom were used and for $H_p(3)$, the conversion coefficients were taken from Ferrari et al. (Ferrari et al. 2007).

Figure 4 provides a graphic depiction of the values contained in Table 3. The operational quantity $H_p(3)$ is not shown in Figure 4 because its values differ only minimally from the values for $H_p(0.07)$ here. Tables 3 and 4 as well as Figure 4 also show that in these scattered radiation fields, the operational quantities $H'(0.07,0^\circ)$ and $H_p(0.07)$ (the latter with calibration of the dosimeter on the slab phantom) provide a conservative estimate of the eye lens dose, while the dose equivalent $H_p(10)$, as expected, no longer provides a conservative estimate of the eye lens dose at low photon energies (< 90 kV).

Table 3: Conversion coefficients H/K_a for the lens and various operational quantities for scattered radiation fields from X-ray radiation of various radiation qualities (Kramer 2008)

Tube voltage (kV)	H_{lens}/K_a in Sv/Gy		$H'(10)/K_a$	$H_p(10)/K_a$	$H_p(3)/K_a$	$H'(0.07,0^\circ)/K_a$	$H_p(0.07)/K_a$
	AP	AP	in Sv/Gy	in Sv/Gy	in Sv/Gy	in Sv/Gy	in Sv/Gy
	(Rex, Regina) _{max}	(ICRP 74)					
30	1.007	0.998	0.721	0.726	1.012	1.093	1.092
50	1.152	1.164	0.998	1.008	1.194	1.195	1.204
70	1.239	1.222	1.165	1.185	1.306	1.271	1.294
90	1.299	1.256	1.276	1.312	1.380	1.348	1.364
120	1.353	1.297	1.375	1.428	1.444	1.390	1.431
150	1.401	1.344	1.465	1.536	1.499	1.417	1.494

In photon fields overall, there is therefore no need to additionally introduce the specific operational quantity $H_p(3)$ for the special case of eye lens monitoring. It should be borne in mind, however, that for the operational quantity $H_p(0.07)$, a dosimeter that has been calibrated on a slab phantom should be used. This would entail a change in the practice customarily applied in Germany to date, whereby dosimeters for the operational quantity $H_p(0.07)$ are not calibrated on a slab phantom, nor are design type tests for this type of dosimeters carried out neither are type approvals issued.

It should be noted in this context that an extremity dosimeter calibrated in units of $H_p(0.07)$ on a rod phantom can also provide a conservative estimate of the eye lens dose if the dosimeters response to the backscattered photons from the phantom or the head is at least as large as it is to incident photons from the front. This option has occasionally been used in Germany to determine the eye lens dose using an approved extremity dosimeter attached to the head.

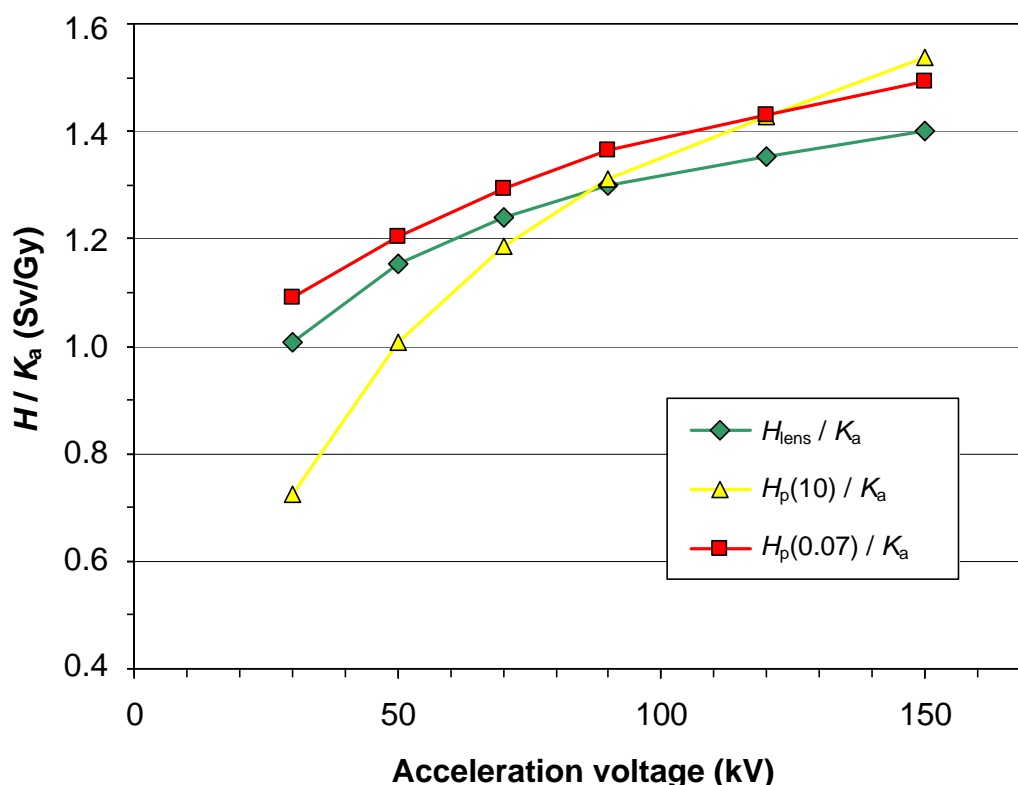


Figure 4: Conversion coefficients H_{lens}/K_a , $H_p(10)/K_a$ and $H_p(0.07)/K_a$ (ISO slab phantom) for scattered radiation fields from X-ray radiation of varying radiation quality with eye exposure from the front (AP) (Kramer 2008).

Table 4: Relationship of conversion coefficients for the various operational quantities to that of the eye lens dose for scattered radiation fields from X-ray radiation of varying radiation quality (Kramer 2008)

Tube voltage (kV)	$H^*(10)/H_{\text{lens}}$ in Sv/Gy	$H_p(10)/H_{\text{lens}}$ in Sv/Gy	$H'(0.07, 0^\circ)/H_{\text{lens}}$ in Sv/Gy	$H_p(0.07)/H_{\text{lens}}$ in Sv/Gy
30	0.716	0.721	1.085	1.084
50	0.866	0.875	1.037	1.045
70	0.940	0.956	1.026	1.044
90	0.982	1.010	1.020	1.050
120	1.016	1.055	1.014	1.058
150	1.046	1.096	1.013	1.066

3 Exposure of the eye lens to beta radiation

Beta particles (electrons) with energies < 3 MeV are a type of radiation with relatively short range in tissue (radiation with low penetration depth) (see Figure 5). With external exposure, the dose transmitted to the tissue is concentrated in the region near the tissue surface. Electrons with energies < 0.7 MeV have a range of < 3 mm and therefore do not contribute to the eye lens dose in practice.

The eye lens is a small tissue part located in the eye and is extremely small in relation to the human body as a whole. As already noted in relation to low-energy photons, the data for the eye lens (eye lens dose, conversion coefficients) depend on the geometry of the eye that is used as a basis for the calculations. The data for the eye lens from ICRU Report 57 originate from F. W. Schultz and J. Zoetelief (Schultz and Zoetelief 1996). New data for the eye lens were compiled by M. Zankl (Zankl 2008) for the reference voxel phantom recommended by the ICRP (see Figure 6). The data show a significant dependence of the conversion coefficients on the phantom selected (Rex or Regina). The two phantoms differ in the voxel structure in the eye area, such that the simulated eye lens is located at different depths. As a consequence, there is considerable variation in the eye lens doses for beta energies < 3 MeV.

The calculations mentioned above always relate to the mean dose across the entire eye lens. This approach was also used for the epidemiological studies (SSK 2009).

In a recently published study by R. Behrens, G. Dietze and M. Zankl (Behrens et al. 2009), the eye is simulated far more realistically and the mean dose in various parts of the eye lens is calculated. Figure 7 shows conversion coefficients for the various areas. For electron energies between 1 MeV and 4 MeV in particular, the resulting differences are significant.

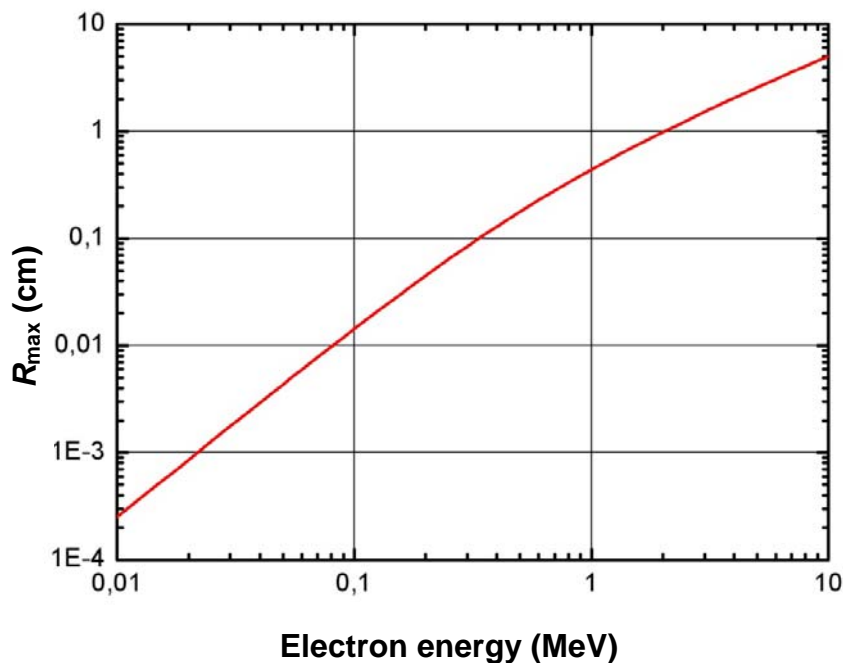


Figure 5: Maximum range R_{max} of electrons in soft tissue as a function of electron energy (Berger et al. 2008).

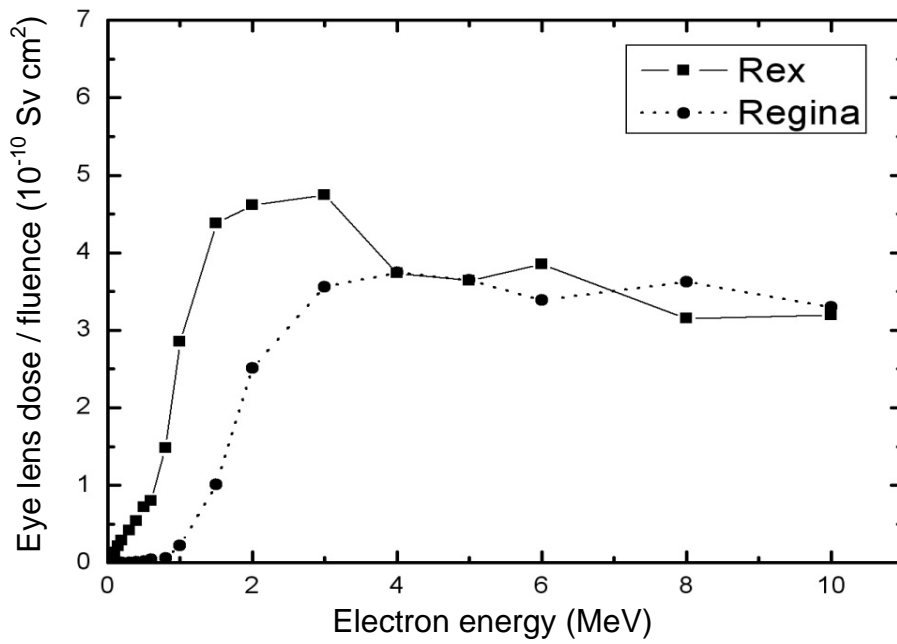


Figure 6: Conversion coefficients H_{lens}/Φ for monoenergetic electrons calculated using the voxel phantoms Rex (solid line) and Regina (broken line). Φ is the fluence of the **vertically incident electrons** (provisional data (Zankl 2008)).

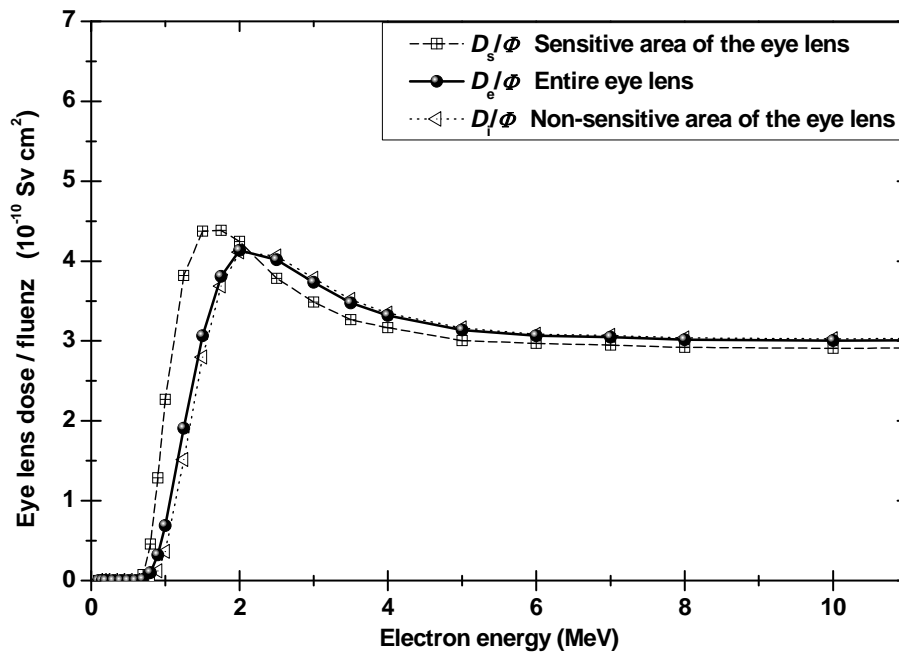


Figure 7: Conversion coefficients $D_{Eye\ lens}/\Phi$ for monoenergetic electrons (equivalent to the value of H_{lens}/Φ) calculated using a realistic model of the eye for various areas of the eye lens (data from (Behrens et al. 2009)). Φ is the fluence of the **vertically incident electrons**.

Figure 8 shows the conversion coefficients for $H'(0.07,0^\circ)$, $H'(3.0^\circ)$ and $H^*(10)$ which characterise the dose equivalent at various depths (0.07 mm, 3 mm and 10 mm) of the ICRU sphere phantom, as well as the data for the eye lens dose from ICRU Report 57 (ICRU 1998).

In radiological protection practice, however, monoenergetic electron radiation is of minor significance. Normally, exposure comes from beta radiation from radionuclides.

Whereas numerous radionuclides only emit beta radiation with energies of less than 1.3 MeV, there are others which emit higher-energy beta radiation (e.g. Rb-88, Zn-62/Cu-62, Ru-106/Rh-106 etc.).

The beta spectra of the radionuclides of Re-186, P-32 and Ru-106/Rh-106 were considered as typical examples ⁽²⁾ (see Figure 9) and mean conversion coefficients were calculated for the organ dose for the eye lens for $H'(0.07, 0^\circ)$ and $H'(3, 0^\circ)$ (see Table 5) (Behrens 2009). These values also take account of the contributions made by the photon emissions from the radionuclides to dose and fluence. For the calculations, point sources were assumed which are located in air on the central axis at a 50 cm distance from the eye lens. The values for $H_p(0.07)$ and $H_p(3)$ scarcely differ from the values for $H'(0.07, 0^\circ)$ and $H'(3, 0^\circ)$, respectively and therefore do not need to be considered here.

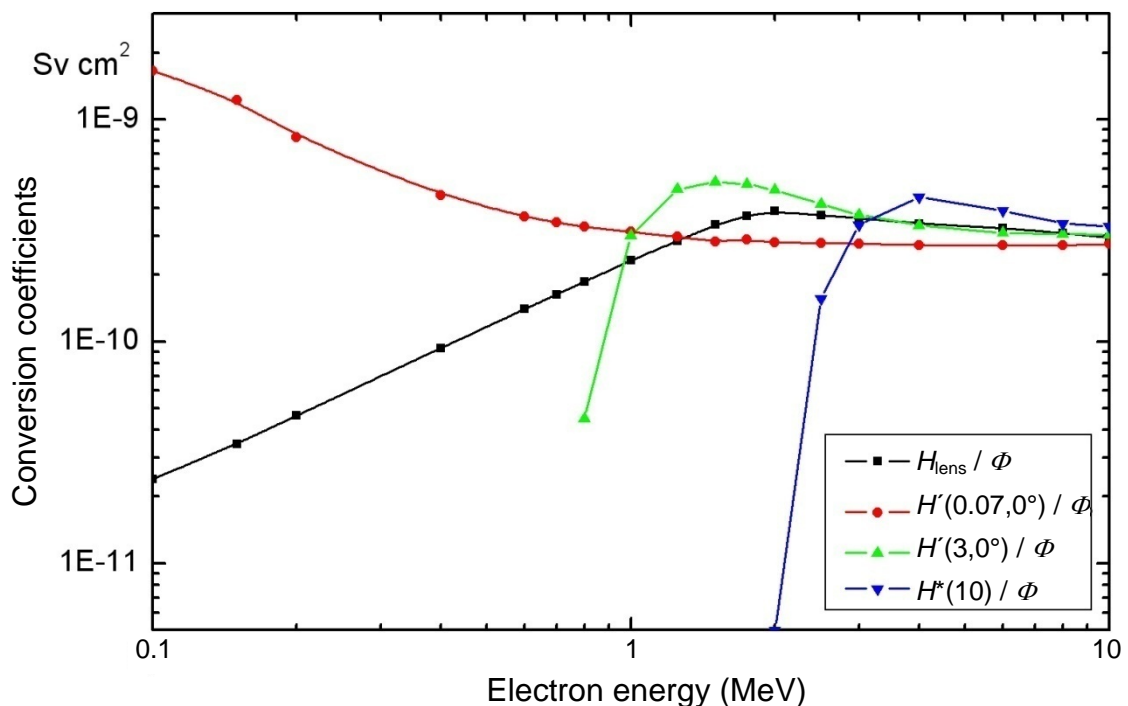


Figure 8: Conversion coefficients H_{lens}/Φ , $H'(0.07, 0^\circ)/\Phi$, $H'(3, 0^\circ)/\Phi$ and $H^*(10)/\Phi$ for monoenergetic electrons. Φ is the fluence of incident electrons (ICRP 1996).

⁽²⁾ Radionuclides with $E_{\text{Beta, max}} < 0.7$ MeV, e.g. I-131, do not need to be considered.

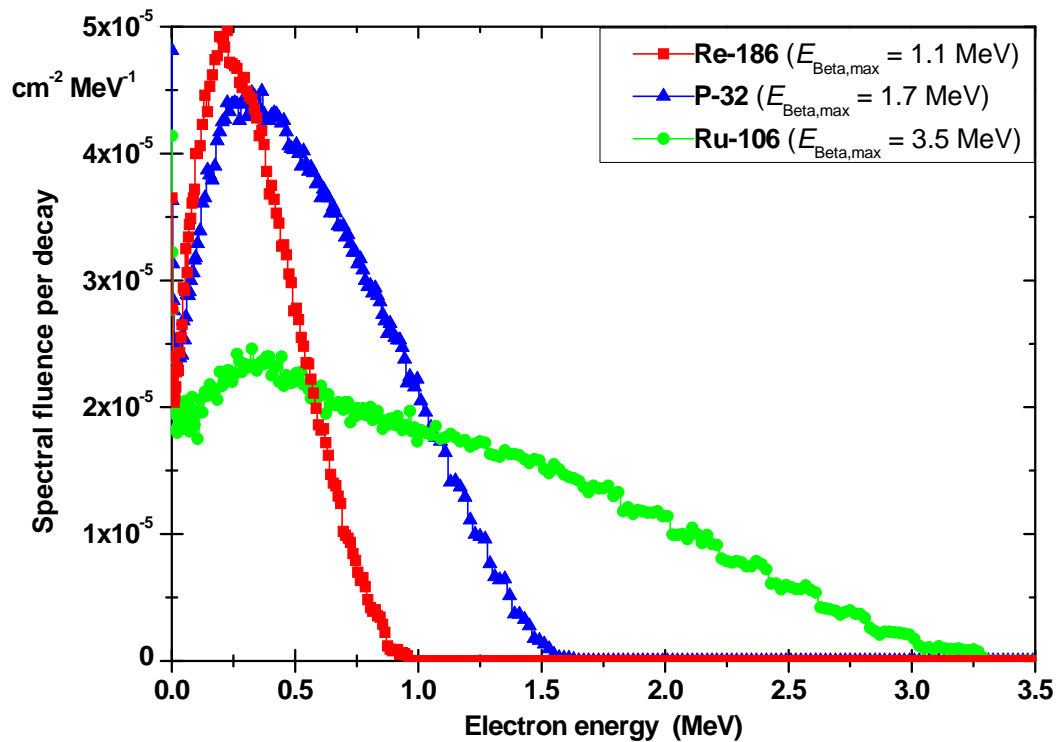


Figure 9: Beta spectra of Re-186, P-32 and Ru-106/Rh-106 (spectra of point sources at a distance of 50 cm in air and calculated using EGSnrc, starting with the theoretical beta spectra of the nuclides (Behrens 2009)).

Table 5: Mean conversion coefficients H/Φ for the eye lens dose (sensitive area) and for various operational quantities for radiation from radionuclides Re-186, P-32, Y-90 and Ru-106/Rh-106 (beta and photon radiation; radionuclide source at a distance of 50 cm in air). Data from (Behrens 2009).

Radionuclides	E_{\max} in MeV	H_{lens}/Φ in Sv cm ²	$H'(0.07, 0^\circ)/\Phi$ in Sv cm ²	$H'(3, 0^\circ)/\Phi$ in Sv cm ²
Re-186	1.1	$1.6 \cdot 10^{-12}$	$4.5 \cdot 10^{-10}$	$1.5 \cdot 10^{-12}$
P-32	1.7	$6.0 \cdot 10^{-11}$	$4.8 \cdot 10^{-10}$	$7.5 \cdot 10^{-11}$
Y-90	2.3	$1.4 \cdot 10^{-10}$	$4.3 \cdot 10^{-10}$	$1.7 \cdot 10^{-10}$
Ru-106/Rh-106	3.5	$1.6 \cdot 10^{-10}$	$3.0 \cdot 10^{-10}$	$1.9 \cdot 10^{-10}$

Obviously, for radionuclides, the mean conversion coefficient for the directional dose equivalent $H'(0.07, 0^\circ)$ is in some cases substantially larger than the mean conversion coefficient for the eye lens dose. This operational quantity, therefore, always provides a conservative estimate of lens dose, but the value of $H'(3.0^\circ)$ matches the value of the eye lens dose (sensitive area) much more precisely than does the value of $H'(0.07, 0^\circ)$. In this context, for the radionuclides analysed, in which the beta radiation contribution to the eye lens dose is considerable, $H'(3.0^\circ)$ is conservatively or approximately equal to the eye lens dose.

Data for $H^*(10)$ and $H_p(10)$ are not provided here as these operational quantities are not appropriate in the relevant beta energy range.

As the radionuclides discussed above can certainly be regarded as representative for radionuclides which emit beta radiation with energies > 0.7 MeV ((Cross et al. 1982), (Cross

et al. 1983)), the directional dose equivalent $H'(0.07, \Omega)$ always provides a conservative estimate of the organ dose for the eye lens in relation to such beta sources. This also applies to the personal dose equivalent $H_p(0.07)$, just as it does to the directional dose equivalent considered, as the conversion coefficients are of equal magnitude.

It can be deduced from Table 5 that the ratio of $H'(0.07, 0^\circ)$ to $H'(3.0^\circ)$ for large beta energies is less than 2. This value is substantially lower than the values stated in SSK Volume 43, Section 5.4.3 for an infinitely extended plane source at 60 cm distance or for exposure from a semi-infinitely extended cloud.

For the case of occupational exposure of the eye to beta radiation, which is considered here, the exposure scenarios described in SSK Volume 43 are not particularly realistic, for the described scenario of an infinitely extended beta radiation source does not play any role. Here, exposure during work with a spatially limited radionuclide source should be the starting point and account should be taken of the real exposure scenario. The data presented in Table 5 consider this.

In any event, based on the new data now available, the argument presented in Section 5.4.3 of SSK Volume 43 (SSK 2006) – that for beta radiation, compliance with the local skin dose limit value of 500 mSv during any calendar year also guarantees compliance with the limit value of 150 mSv during any one calendar year for the eye lens dose for adults occupationally exposed to radiation – can no longer be upheld.

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