Report on revision of the $H_p(3)$ operational quantity implementation, Conversion coefficients, Type test and Calibration procedures

I - Introduction.

The attention devoted in recent years to eye lens dose assessment was increased due to evidences that cataract can be induced by ionizing radiation at dose level lower than previously expected[6,7].
The largest part of the tissues constituting the eye presents radio sensitivity similar to that of the skin; the anterior eye chamber on the other hand presents a higher sensitivity due to the eye lens, also in the range of low radiation doses[13].
A significant number of epidemiological studies[14,6] put in evidence a higher incidence of cataracts in the eye lens, but the mechanism of induction was not completely clarified until now.
Both ICRP and NCRP assumed that the minimum dose necessary to develop cataract is about 2 Gy and 5 Gy for a single or a protracted irradiation respectively[15,16]. Anyway more recent analyses put into evidence excess for doses lower than 0.5 Gy, whilst other sources did not provide information on the existence of a threshold dose[17]. These topics are still matter of debate and ICRP itself, in recent recommendations[8], did not exclude such hypothesis.
For this reason the dose to the eye lens should be evaluated more carefully particularly for people exposed to relevant annual radiation work-load (e.g. for the medical staff in interventional radiology).
To enter in some more detail on the operational quantity, it has to be premised that the monitoring of the eye lens dose has been until now seldom performed and the corresponding conversion coefficients (e.g. $H_p(3)/K_a$ for photons) are not reported on the ICRP and ICRU recommendations. So within the framework of the ORAMED project, WP2 is in charge of critically revising the theoretical fundamentals on which the eye lens operational quantity $H_p(3)$ is based and thereafter the way to calculate it. As a consequence the most suited conversion coefficients from air kerma to personal dose equivalent at 3 mm depth have been determined to design a dosemeter well suited to respond in terms of this operational quantity at interventional cardiology and radiology (IC/IR) workplaces and to specify the calibration and type test procedures for optimizing the radiation performance requirements of this kind of dosemeter. This report presents the third part of this work.

II – Scope

As this report is not a standard, the content does not follow the same rule, there fore it is not included a list a definitions, it is only given in this scope a few basic information on the concepts of dose equivalent, dosimetry system, type testing and calibration, and on the specificity of exposure in IC/IR.

The dose equivalent at 3mm depth, $H_p(3)$ is an operational quantity aimed at estimating the equivalent dose to the eye lens H_{Lens}. This dose equivalent is defined in a phantom made of the 4 elements ICRU tissue. As dose equivalent is not a primary quantity, it cannot be directly measured. In practice, the theoretical value of the dose equivalent is obtained though the application of a conversion coefficient from air kerma to the dose equivalent. Air kerma is measured using absolute dosemeter (that is to say a dosemeter which does require a

calibration in terms of the quantity to be measured). In the case of low and medium photon energy this dosemeter is a free air chamber.

For passive dosemeters, the assessment of doses does not belong only to the dosemeter itself. The doses are evaluated using electronic devices (readers). Therefore a “dosimetry system” includes any devices needed for assessing the doses e.g. dosemeter plus reader plus ancillary equipments. The word “detector” refers only to the sensitive part of the dosemeter.

Before being available on the market, dosimetry systems are type tested according to the relevant EN/IEC or ISO standard to determine their rated ranges of use for all influence quantities. Comparing these rated ranges with those required for a given workplace, one can judge whether they have passed the tests and so if they are suitable for measurements in workplace conditions is guaranteed. It has to be noticed that the type test is not mandatory in all the countries. Failure of any part of the test should be clearly detailed and reasons for the failure considered[1]. To carry out type tests is the responsibility of the manufacturer. All the radiation fields used must be well characterized and traceable to a national standard. As long as the dosimetry system is unchanged, the results of the type test remain valid.

When the dosimetry system is used by dosimetry services, it must be calibrated against a national reference in order to ensure the traceability to the international system of units. This reference calibration of the dosimetry system should be repeated at regular intervals (every 2 or 3 years) depending on the stability of the dosimetry system and the uncertainty budget associated to dose measurements. There should be more frequent periodic checks on the performance of the dosimetry system which may be carried out using non-reference fields and a fixed procedure[1].

The dosemeter which was studied within the frame work of ORAMED is a passive dosimeter based on a thermo luminescent detector (TLD). Therefore this report deals only with the modifications of the requirements of the standards for passive dosimetry. As there were no systematic test of dosimeters based on other detector than TLDs in ORAMED, this work took into account the characteristics of TLDs. Nevertheless, most of the new requirements are so general and based on the specificity of IC/IR exposure so that there might be applied to any passive dosemeter type whatever is the detector.

In most of the cases a dosemeter must be assembled in a holder, ensuring the electronic equilibrium and back scatter properties. For IC/IR application it is advisable to wear the dosemeter at the forehead (at the level of the temple).

The most used high voltage lies between 60 and 110 kVp, the photon spectrum lies from 20 keV to the maximum HV values. Radiations are pulsed beams with very high instantaneous dose rates; usually the X-ray tube can reach 150 kVp.

Medical staff standing generally upright around the patient table, the dosemeter is exposed, except in case of accidental circumstances, to the radiations scattered by the table and the patient.

III - **State of the art.**

1 - Available standards

Type tests are intended to demonstrate the basic performance of the type of the dosemeter. For dosimetry systems based on passive personal dosemeters, to monitor individuals occupationally exposed to external radiation, two International and European standards exist for type testing:

- IEC 62387-1 "Radiation protection instrumentation – Passive integrating dosimetry systems for environmental and personal monitoring – Part 1: General characteristics and performance requirements" [IEC 62387-1].
- ISO 12794 "Nuclear energy – Radiation protection – Individual thermo luminescence dosemeters for extremities and eyes" [ISO 12794].

These standards cover photon and beta radiations, table 1 presents their main features.

A few remarks can be done about these standards:

- Even if the goal of these standards is the same, two slightly different approaches are used. ISO standard are based on the characteristic of the dosemeter itself while IEC standard studies a dosimetry system including other requirements about the reader, the ancillary equipments and the procedures for converting the reading into dose.
- Only the ISO standard takes into account the eye lens dosimetry,
- ISO standard is especially written for TLD based dosemeters while IEC standard include any type of dosemeters.
- None of these standards takes into account the pulsed radiation fields.
- These standards do not address the same type of dosemeters so that they cannot be fully harmonized and the comparison between the test results can require an exhaustive analysis

It follows that since the ISO standard 12794 is the only one to account for eye lens dosimetry and is specially studied for TLD based dosemeters. It is therefore more suitable to start from this standard to define the type test procedure. As it is mentioned in the introduction of ISO 12794, this international standard should be used in conjunction with IEC 61066 (which has been replaced by 62387-1) to look at additional requirements relative to additivity and to the reader (electromagnetic compatibility, mechanics and software) could be added later on the basis of IEC standards.

Table 1: Comparison of the main requirements of ISO and IEC standards for passive photon dosimetry (adapted from reference 2).

(Influence) quantity	ISO 12794	IEC 62387-1
Type of detector and type of dosemeter	TLD, Extremity and eyes	all passive; whole body
Radiation energy	(15 keV to 3 MeV) 0,5 ≤ response ≤ 1.5	any energy (80 keV to 1.25 MeV) and angle: 0.71 ≤ response ≤ 1.67
Angle of incidence (0 to 60°)	at 60 +/-5 keV: 0.85 ≤response≤ 1.15	
Linearity	1 mSv to 1 Sv: 0.9 ≤ response ≤ 1.1	0.1 mSv to 1 Sv: 0.91 ≤ response ≤ 1.11
Coefficient of Variation	reproducibility: 10% batch homogeneity: 15%	from 15% (< 0.1 mSv) to 5% (> 1.1 mSv)
Environmental conditions and others	temperature up to +40°C and humidity up to 90%: 0.9 ≤ response ≤ 1.1 light exposure: 0.9 ≤ response ≤ 1.1	temp.:-10°C to +40°C, humidity 40% to 90%, fading, light, reader stability and power supply combined: 0.83 ≤ response≤ 1.25
Additivity (1)	no requirement	0.91 ≤ response ≤ 1.11
Electromagnetic Compatibility		IEC 61000-6-2 deviation (2) limited
Mechanics		IEC 60068-2-32 deviation (2) limited
Software		WELMEC Guide 7.2 (3)

(1) Additivity of measured values for different irradiation conditions.
(2) Deviation is an additional indication which is due to the influence quantity, e.g. to additional or lost pulses as a result of EMC.
(3) A guide to software requirements from the European Corporation in Legal Metrology, recommended for application all over Europe.

2 - Wearing conditions at the workplace.

- Collective and individual protective materials (glasses, table curtain, ceiling shielding) can be used to decrease radiation exposures. Thus:
  - ✓ The X-rays spectrum and the dose equivalent rates depend on the use of protections. For instance it was reported that the dose equivalent rate to the eye lens is divided by a factor of 100 when protective leaded glasses are worn and ceiling shield is used.
  - ✓ The main part of the radiation field to which the medical staff is exposed should be due to the scattered radiation coming from the patient. The table curtain is used to avoid exposures to the primary beam when the X-rays generator is located under the patient table. Thus, in such a case, the angle of incidence of the radiation field does not change significantly during interventions if the medical staff and the X-rays generator do not move significantly. The X-ray tube can be moved around the patient during the intervention so that the table curtain is less efficient and a part of the radiation fields is not scattered by the patient. A ceiling shielding can be used to screen off a part of the radiations scattered by the patient and/or the direct beam when the X-ray generator is located above the patient. Therefore depending on the use of protections, the angle of incidence of the radiation varies.

- In any case, it is advisable that the dosemeter measures the X-rays to which the eye lens is exposed; this means wearing the dosemeter in contact with the skin and close to eye lens to account for the different shape of the head and the backscattered radiation.

Taking into account the above remarks, to measure the largest exposure the dosemeter should be worn (at the level of the temple) on the side of the head facing the X-ray tube.

3 - Consequences on the dosemeter type test and calibration procedures:

- The dosemeter must be calibrated in conditions as closest as possible to the wearing condition, so for calibration and type test, the dosemeter must be put in contact with the surface of a phantom to account for the backscattered radiations.

- Because doses can be very low when protection (collective and individual) are used the sensitivity of the dosemeter system must be sufficient for measuring the shielded X-ray DOSE.

- The angular response of the dosemeter is a critical parameter for measuring $H_p(3)$. The consequence of the position of the X-ray tube and the medical staff around the patient table is that the radiation fields could be restricted to a particular solid angle. The limits of this solid angle is not well known in advance, it depends on the position of the medical staff around the patient table, the X-ray tube and the use of collective protection. In such a case one cannot rely on an average response over a large distribution of angles to limit the influence of an over or under response for a particular angle. Therefore, a more drastic requirement for the angle response than the one proposed in the IEC standard might be introduced.

4 - Performance requirement for energy response

Taking into account that the exposures of the medical staff in IC/IR can be high, a more drastic criterion than +-50% as mentioned in table 1 could be used.

Taking as an example a dosemeter based on FLi TLD, an over response in terms of dose equivalent is noted for low energies below 100 keV. This range of over response of FLi being the energy domain of IC/IR, this over response could lead to an over estimation of the dose equivalents. In case of exposures close to the dose limits this over estimation is not bearable. To avoid this, one could choose a more drastic criterion for the variation of the energy response on the whole energy range mentioned in table 1. One could also set a more drastic criterion to a reduced part of the energy range, the one covering the field of IC/IR from 15 to 150 keV. In this last case one would introduce a particular energy range for the dosemeters used in IC/IR. It should be noted that this difficulty is not specific to the eye lens dosimetry, it is also the case for whole body and extremity dosimetry in IC/IR.

It must be taken into account that such a more drastic requirement for the angle and/or energy responses could be too difficult to fulfil.

IV - Type test procedure

For the passive dosemeters for the eye lens dosimetry, the following table that described the influence quantities and their associated criteria, taken from ISO 12794 (Individual thermo luminescence dosemeters for extremity and eyes) is examined.

Table 2: Performance requirements for extremity and eye dosemeters

No.	Performance characteristic	Class of dosemeter	Performance requirements	Test required [a]
1	Batch homogeneity	R/D	The coefficient of variation of the evaluated value for n dosemeters shall not exceed 15 % for a dose of 10 mSv or less	Q
2	Reproducibility	R	The coefficient of variation of the evaluated value for n dosemeters shall not exceed 10 % for each dosemeter separately for a dose of 10 mSv or less	Q
		D	No requirement	
3	Linearity	R/D	The response shall not vary by more than 10 % over the dose equivalent range 1 mSv to 1 Sv	T
4	Stability of dosemeters under various climatic conditions	R/D	The evaluated values of dosemeters irradiated either at the beginning or at the end of a storage period shall not differ from the conventional true value by more than 5 % for 30 d storage under standard test conditions, or 10 % for 48 h storage at 40 °C and 90 % relative humidity	T
5	Detection threshold	R/D	The detection threshold shall not exceed 1 mSv	T
6	Self- irradiation	R/D	After a storage period of 60 days, the zero point shall not exceed 2mSv	T
7	Residue	R	After irradiation with a conventional true value of 100 mSv, the detection threshold limit shall not be exceeded and the response shall remain within the requirement for linearity at a dose level of 2 mSv	T
8	Effect of light exposure on the dosemeter	R/D	As a result of exposure to 1 000 $W \cdot m^{-2}$ equivalent to bright sunlight (295 nm to 769 nm) for 1 d, the zero point shall not change by more than 1 mSv and, for exposure during one week, the evaluated value shall not differ from the evaluated value of a dosemeter kept in the dark by more than 10 %	T
9	Isotropy (photons)	R/D	When irradiated with photons of (60 ± 5) keV, the mean value of the response at angles of incidence of 0°, 20°, 40° and 60° from normal shall not differ from the corresponding response for normal incidence by more than 15 %	T
10	Energy response (photons)	R/D	When irradiated with photons in the energy range 15 keV to 3 MeV, response shall not vary by more than ± 50 %	T
11	Energy response (beta radiation)	R/D	When irradiated with beta radiation in the energy range (E_{max}) 0,5 MeV to 3 MeV, the response shall not vary by more than ± 50 %	T

[a] T: Type.
Q: Quality control.

Two kinds of performance requirements are identified: type tests and quality control tests. Type tests are intended to demonstrate the basic performance of the type of the dosemeter and quality control tests are intended to verify the performance of a specific production or delivery batch of dosemeters. Since IEC standards do not introduce such a distinction, we will deal with both aspects in the following.

Among the characteristics listed in table 2 some are not entirely transposable for the dosimetry in IC/IR:

- point 11 is out of the field of this study,
- points 5, 6, 8, 9 and 10 have to be changed following the information discussed above.

1 - Detection threshold

The sensitivity of the dosemeter system should be sufficient for measuring the X-rays shielded by the protective material, so **a 10 µSv per period** (1 or 3 months) detection threshold might be relevant. Such a very low threshold is very difficult to measure compared to the natural background. This natural background for cosmic and telluric component is about 0.8 mSv (average value in France), thus per month it represents about 70 µSv; accounting for the factor of 2 of uncertainty acceptable at low doses the threshold could be 140 µSv. On the other hand, taking into account the limit of exposure corresponding to 150 mSv /year in terms of H_{lens} , for a measurement (wearing) period of 1 month for a worker directly exposed to radiation the maximum is 3.75 mSv (3/10 of the maximum effective dose is the limit of the category A workers so 150 /10 x 3 / 12); a detection threshold at about one tenth of this maximum should be advisable so 375 µSv. So a detection threshold of **0.1 mSv** as proposed in the IEC standard could to small. A threshold between 140 and 375 µSv, let **0.2 mSv** could be a good compromise solution. Such a lower threshold has consequences on the line 6 of the table 2. The sensitivity to self irradiation should be reduced down to 200 µSv.

2 - Linearity

For this test the requirements of both standards ISO and IEC are equivalents (**+/-10%**), only the dose equivalent range differs. Taking into account the lower detection threshold, the linearity domain should be extended to lower doses. The range should be 2**00 µSv to 1 Sv**.

3 - Performance requirements for energy response

The ISO 12794 standard was published to meet the needs in a range of energy (15 keV - 3 MeV) broader than that met in IC/IR. For the dosemeters based on the TLD of the FLi type, the criterion of +-50% can be achieved, taking into account the over response in terms of dose equivalent for weak energies lower than 100 keV. In the case of exposure to radiation in industry, it is generally retained as probable assumption that the worker can be exposed to a broad spectrum covering most of the energy range between 15 keV and 3 MeV and most of the angles so that, an average even an over estimation of 50% on part of the energy domain does not generate a too important over estimation of the dose. However, the over-response of FLi type TLD is significant at energy range met in IC/IR workplaces. Therefore, this over-response could generate an important over estimation of the doses. Taking into account that the exposures of the medical staff in IC/IR can be high, a criterion more drastic than +-50% should be used. Taking example on the data of reference 1 for the values of assessed annual dose values at or near the dose limit, the maximum variation could be **+/-20%** or in a more general probabilistic approach the 95 % confidence interval should not exceed 0.67 to 1.5 ,i.e. about 40% (with a coverage factor of 2).

Remarks:

1- One has to keep in mind that in the energy domain of the IC/IR, $H_p(3)$ over estimates D_{Lens} up to 13 % (see figure here after[(4)])
2- The radiation qualities proposed by both IEC and ISO standard only rely on those of ISO 4037 standard. The “narrow” radiation qualities shall be used namely N-15, N-20, N-30, N-40, N-60, N-80, N-100, N-150.

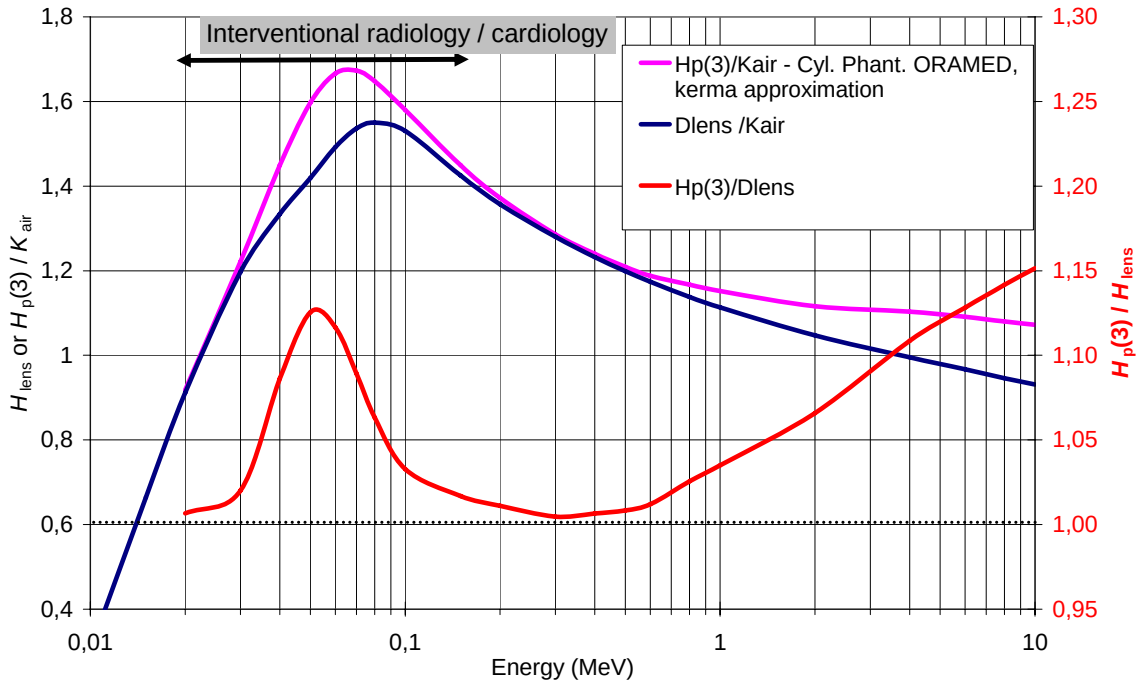

Figure 1: Comparison of $H_p(3)$ and Dlens

If it proves to be impossible for a dosemeter to respect the criterion in terms of energy response, then it can become necessary to carry out a specific calibration for the use in IC/IR by means of a reference beam with energy lower than 150 keV. The chapter "calibration" of this report will deal with this issue. In such a case, and exclusively in the case of IC/IR, the energy domain can be restricted to 20-150 keV with a maximum variation of the energy response of **+/-30%.**

4 - Performance requirements for angle response

The requirement for isotropy proposed in the IEC standard is not enough drastic taking into account the particular issue of IC/IR exposure. So for isotropy, we would remain on the criteria of the ISO standard, that is to say: "the mean value of the response at angle of incidence 0°, 20°, 40° and 60° from the normal shall not differ from the corresponding response for the normal incidence by more than 20**%** when irradiated with photons of 60 keV". If the domain of angle is extended to 75°, taking into account the difficulty of the measurements at such an angle, the criterion can be relaxed to 30% without jeopardizing the quality of the measurements.

5 - Additivity of the indicated value

This requirement has been introduced in the IEC standard 62387-1 for dosimetry system using more than one detector to evaluate the indicated value. If the algorithm used to evaluate the indicated value is either a linear combination of the signals or a linear optimization of them, this requirement is fulfilled and no tests are required (the algorithm is an additive one). Looking at this standard, one can read:

"*It shall be assured that the indicated value is additive for mixed irradiations. Mixed irradiation means that a dosemeter is irradiated with two (or more) portions of dose equivalent with different radiation qualities. The difference in the radiation qualities can be*

- *a difference in the dose values, and / or*
- *a difference in the value of one specific influence quantity (for example different energy and angle of radiation incidence), or*
- *a different type of radiation if the dosimetry is tested with respect to more than one type of radiation (for example type test for photon and beta radiation).*

Requirement for a): the relative response of the mixed irradiation has to be within the range required for the non-linearity.
Requirement for b): the relative response of the mixed irradiation has to be within the range required for the specific influence quantity."

The requirement for c) is not relevant for the use in IC/IR where only one type of radiation is met. Requirement a) and b) have to be fulfilled.

6 - Other requirements

IEC standard gives requirements on the reader, namely stability, ambient temperature, light exposure, primary power supply, electromagnetic disturbances… Additional requirements are also given in IEC standard about the mechanical performance of the dosemeter, there have to be fulfilled. These requirements are not copied in this report but have to be fulfilled.

7 - Number of measurements to evaluate the results of a test.

Both IEC and ISO standards agreed on the fact that the choice of the number of measurements or the sample size has to be chosen in such a way that the confidence interval obtained for each mean, $\bar{x}$, for a confidence level of 95% lies either within the upper and lower limits of variation, x_u and x_l, of the measured value permitted in the test (test passed) or outside these limits (test failed). This rule is given by the following equation: $x_l + I < \bar{x} < x_u - I$

For dosimetry requirements ISO recommends starting with 10 measurements whereas IEC often proposes at least 6 measurements.

If one of the permitted limits of variation, x_u or x_l, lies within the confidence interval of the mean the number of measurements or the sample size can be increased to reduce the width 2 I of the confidence interval of the mean. IEC mentioned an upper limit of 25 measurements, and propose that if this number is already reached one can give up the former equation to use the following one: $x_l < \bar{x} < x_u$

8 – Batch homogeneity and reproducibility

The criterion is given in terms of coefficient of variation, ISO and IEC standard proposed 2 different approaches see table 1, both are relevant.

V - Calibration

Up to now, radiation qualities recommended for the photons calibration purposes are those of the ISO 4037 standard. They must be traceable to a national reference. In most of the cases, for industry needs, routine calibrations are performed using ^{137}Cs or ^{60}Co. In the particular case of the IC/IR, if it is proven to be impossible for a dosemeter to respect the criterion in terms of energy response, it can then become necessary to carry out a specific calibration for the use in IC/IR. In such a case one could use a reference beam with energy lower than 150 keV rather than using ^{137}Cs or ^{60}Co. It is then useful to choose a quality close to that which will be met at the workplace. This choice has to be done by the calibration laboratory in accordance with the end user. A few radiation qualities, which could be use for calibration, are presented hereafter. Among the possibilities, the standard ISO 4037 presents a list of qualities for broad energy spectra (see table and figure below).

Table 3: Characteristics of a W60 to W150 (wide-spectrum series of ISO 4037)

Mean energy, $\overline{E}$ keV	Resolution, R_E % (keV)	Tube potential [1] kV	Additional filtration [2] mm Sn	Additional filtration [2] mm Cu	1st HVL Cu mm	2nd HVL Cu mm
45	48 (29)	60		0,3	0,18	0,21
57	55 (44)	80		0,5	0,35	0,44
79	51 (56)	110		2,0	0,96	1,11
104	56 (84)	150	1,0		1,86	2,10

[1] The tube potential is measured under load.

[2] The total filtration consists, in each case, of the additional filtration plus inherent filtration, adjusted to 4 mm of aluminium.

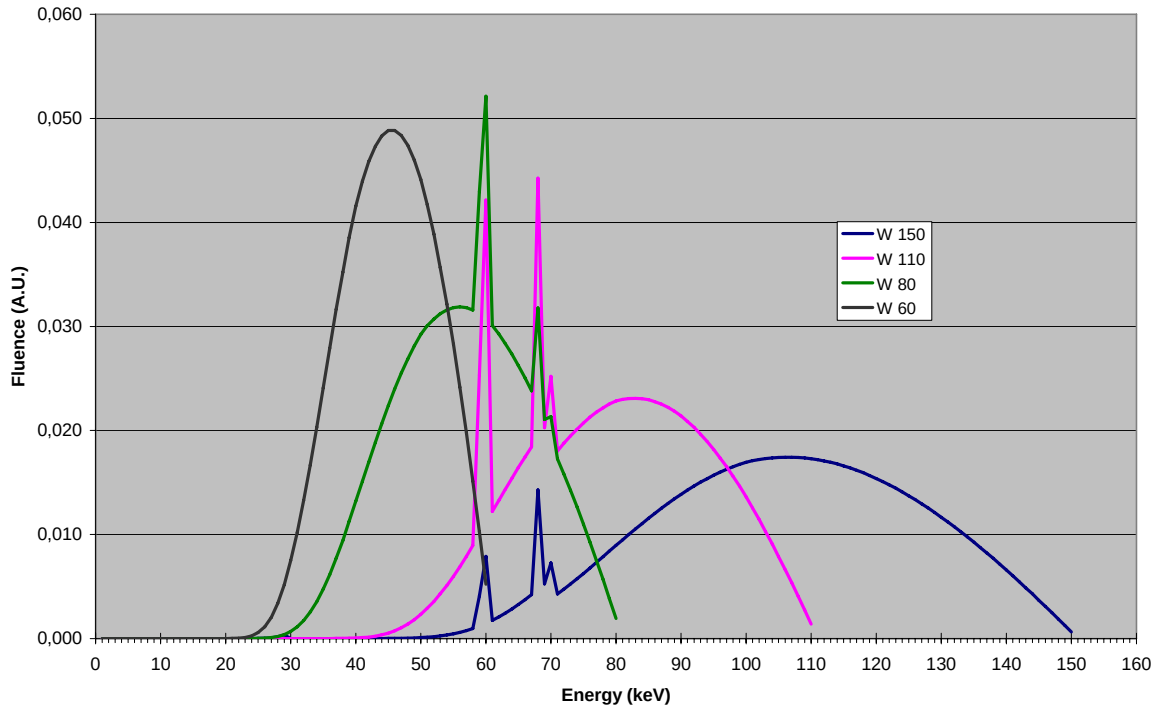

Figure 2: Spectra for a few radiation fields (wide-spectrum series of ISO 4037)

Nevertheless, the total filtration of the spectra is quite large and the energy distribution, characterized by the resolution, is smaller than the one of the spectra met in IC/IR. To account for that, it would be possible to use the radiation qualities of the IEC 61267 standard « medical diagnostic X-ray equipment – Radiation conditions for use in the determination of characteristics » (see table 5 here after)

Table 4: Conversion coefficient from air kerma to dose equivalent at 3 mm depth
for a few W qualities taken from ISO 4037
Monte Carlo calculations (PENELOPE Code), standard uncertainties better than 0.3%

	Angle (degree)	W 60	W 80	W 110	W 150
(Sv/Gy)	0	1.47	1.58	1.65	1.57
	20	1.46	1.58	1.63	1.54
	45	1.42	1.53	1.60	1.54
	60	1.34	1.47	1.54	1.50
	75	1.20	1.34	1.45	1.40
	90	0.87	1.02	1.15	1.17

Table 5 - Characterization of Standard radiation qualities RQR 2 to RQR 10

Standard RADIATION QUALITY	Approximate X-RAY TUBE VOLTAGE	Nominal first HVL	Nominal value of the HOMOGENEITY COEFFICIENT
Characterization	kV	Aluminium (mm)	
RQR 2	40	1.42	0.81
RQR 3	50	1.78	0.76
RQR 4	60	2.10	0.73
RQR 5	70	2.46	0.70
RQR 6	80	2.81	0.67
RQR 7	90	3.20	0.65
RQR 8	100	3.59	0.64
RQR 9	120	4.37	0.63
RQR 10	150	5.62	0.63

Remark: Homogeneity coefficient is the ratio of the first and second HVL.

Table 6: mean energy and resolution for 3 RQR qualities at LNHB

	RQR 4	RQR 7	RQR 9
Inherent filtration (mm Al)	2.2		
Additional flitration (mm Al)	0.52	0.80	1.19
Mean energy (keV)	37	48	57
Resolution % (keV)	73 (27)	67 (32)	77 (44)

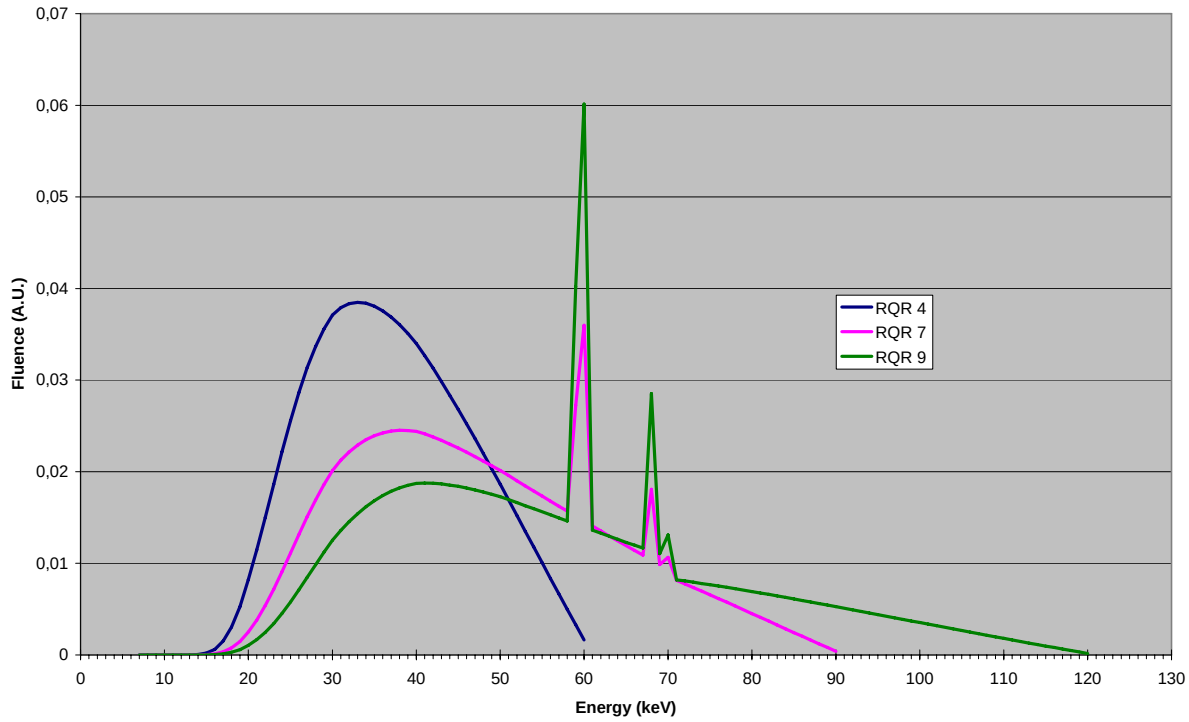

Figure 3: spectra of RQR radiation field described in IEC 61267

In order to make a comparison with the results of table 4, the table 7 here after gives the conversion coefficients, $h_{p,K}(3) = H_p(3)/K_{air}$, from air kerma to dose equivalent at 3 mm depth for different qualities.

Table 7: Conversion coefficient from air kerma to dose equivalent at 3 mm depth
Monte Carlo calculations (PENELOPE Code), standard uncertainties better than 0.3%

	Angle (degree)	RQR4	RQR7	RQR9	N30	N80	N120	70 kV
(Sv/Gy)	0	1.239	1.376	1.461	1.019	1.665	1.588	1.495
	20	1.229	1.373	1.452	1.009	1.659	1.584	1.484
	45	1.179	1.326	1.406	0.955	1.599	1.554	1.429
	60	1.108	1.253	1.347	0.875	1.546	1.516	1.367
	75	0.953	1.107	1.210	0.698	1.420	1.424	1.231
	90	0.599	0.768	0.884	0.336	1.118	1.167	0.900

It is also possible to use radiation beams specially designed to mimic the specific radiation fields scattered by the patient[5] as the one used during the CONRAD project (Table 8). Previous studies[5] have shown that the spectra of the photons scattered by the patient is shifted toward the lower energies of 5 to 10 keV depending on the measurement points at the level of the chest or of the hip of the surgeon and that its HVL remains close to the one of the initial spectrum emitted by the X-ray tube.

Table 8: Beam parameters used for the CONRAD project

Initial spectrum	Tube voltage (kVp)	70
	Total filtration	4.5 mm Al + 0.2 mm Cu
	Mean energy (keV)	48
	Resolution % (keV)	60 (29)
Scattered spectrum	Mean energy (keV)	42
	Resolution % (keV)	52 (22)

The ISO standard also recommends, if another phantom has not been agreed with the dosemeter manufacturer, to use the ISO slab phantom for testing the dosemeters intended to measure $H_p(3)$ (see chapter 7 paragraph 2 ISO 12794). Within the framework of ORAMED project, the WP 2 has proposed, starting form the phantom used for measuring the CDTI for scanner exposures, a new phantom. It is a square section, right cylinder with a diameter of 20 cm water filled with 0.5 cm lateral wall thickness. This shape has the advantage to be closer to the shape and the dimension of the head. For the calibration, the longitudinal axis of this phantom is perpendicular to the axis of the radiation beam. The beam crosses the phantom along the diameter at the middle height. The centre of the detector must be on this axis, the dosemeter being fixed at the surface of the phantom.

This geometry allows, within the framework of systematic study of the angular response of a dosemeter in a parallel radiation fields, to irradiate the dosemeter for all the incident angles simultaneously. All the calculations presented in this report were done using this phantom.

VI - Conclusion

This report is not a new standard; it refers to existing standards and tries to adapt the existing requirements to the particular case of the eyes lens dosimetry in IC/IR. The starting point was the only one standard dealing with eye lens dosimetry with TLDs (ISO 12794). Taking into account this particular use, it has been proposed to change a few requirements and to add other few taken from IEC standard.
For most of the tests, because TDLs are passive detectors, continuous radiation fields can be used for a part of the tests instead of pulsed radiation fields like those met at workplace.

Annex

Description of the narrow series beam of the ISO 4037 standard, N-15, N-20, N-30, N-40, N-60, N-80, N-100, N-150, to be used for the type testing.

The spectra are given as eye guide they have been calculated with the Xcomp5 software using the filtration parameter given in ISO 4037 standard (see table A1). Conversion coefficients are taken from reference 10. They have been calculated using MCNP 4C.

Table A1 – Characteristics of narrow-spectrum series (taken from ISO 4037)

Mean energy, $\overline{E}$	**Resolution,** R_E	**Tube potential** [1]	**Additional filtration** [2] mm			**1st HVL** [4]	**2nd HVL** [4]
keV	%	kV	Sn	Cu	Al	mm	mm
12	33	15			0,5 [3]	0,14 Al	0,16 Al
16	34	20			1,0 [3]	0,32 Al	0,37 Al
20	33	25			2,0 [3]	0,66 Al	0,73 Al
24	32	30			4,0 [3]	1,15 Al	1,30 Al
33	30	40		0,21		0,084 Cu	0,091 Cu
48	36	60		0,6		0,24 Cu	0,26 Cu
65	32	80		2,0		0,58 Cu	0,62 Cu
83	28	100		5,0		1,11 Cu	1,17 Cu
100	27	120	1,0	5,0		1,71 Cu	1,77 Cu
118	37	150	2,5			2,36 Cu	2,47 Cu

[1] The tube potential is measured under load.

[2] Except for the five lowest energies, where recommended inherent filtration is 1 mm Be, the total filtration consists of the additional filtration plus the inherent filtration, adjusted to 4 mm of aluminium.

[3] The recommended inherent filtration is 1 mm Be, but other values may be used provided that the mean energy is within ± 5 % and the resolution is within ± 15 % of the values given in the table.

[4] The HVLs are measured at 1 m from the focal spot.

Table A2 : Conversion coefficient from air kerma to dose equivalent at 3 mm depth (10)

	Angle (degree)	N10	N15	N20	N30	N40	N60	N120	N150
(Sv/Gy)	0	0.058	0.39	0.65	0.99	1.28	1.55	1.59	1.52
	20	0.051	0.38	0.64	0.97	1.26	1.56	1.57	1.50
	45	0.026	0.29	0.55	0.91	1.21	1.53	1.55	1.49
	60	0.010	0.20	0.46	0.84	1.14	1.42	1.51	1.47
	75	0.003	0.12	0.35	0.77	1.08	1.36	1.46	1.44
	90	-	0.05	0.21	0.60	0.91	1.24	1.35	1.32

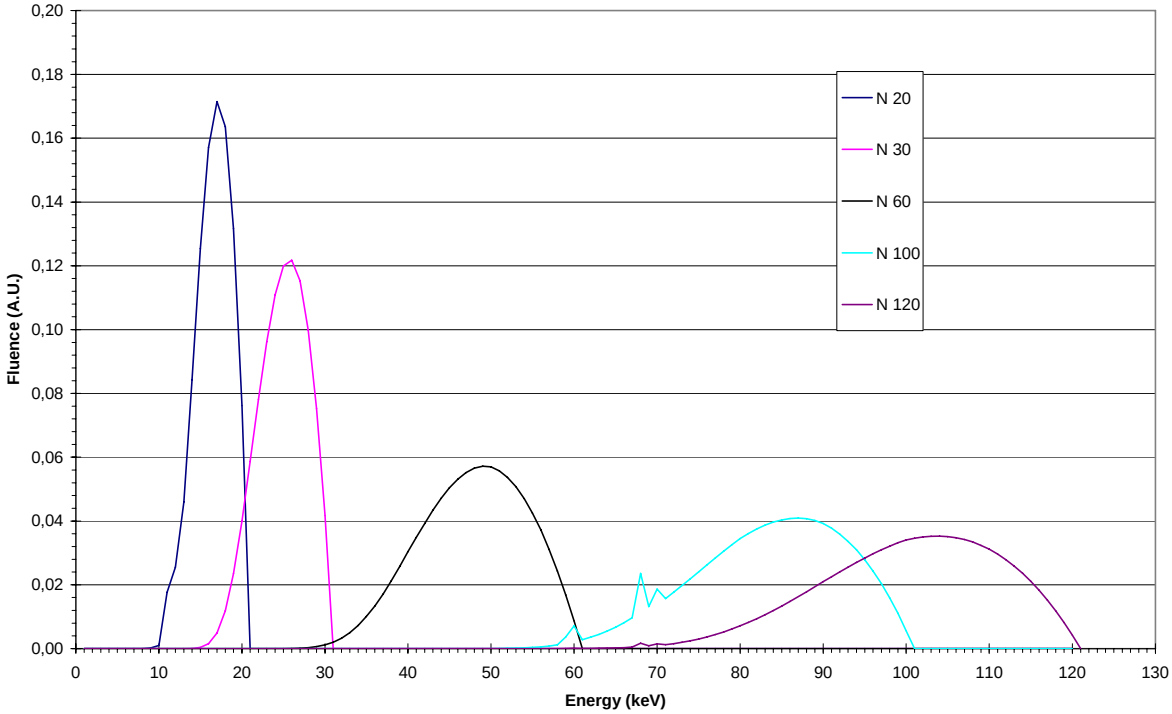

Figure A1: Spectra of narrow spectrum series described in ISO 4037

Bibliography

1 European Commission, Technical Recommendations for Monitoring Individuals Exposed to External Radiation, Radiation Protection No 160

2 IEC 62387-1 Radiation protection instrumentation – Passive integrating dosimetry systems for environmental and personal monitoring – Part 1: General characteristics and performance requirements [IEC 62387-1].

3 ISO 12794 Nuclear energy – Radiation protection – Individual thermoluminescence dosemeters for extremities and eyes [ISO 12794].

4 Bordy J.M., Gualdrini G., Daures J. and Mariotti F., Principle for the design of radiation protection dosemeters for operational and protection quantities, Radiat. Prot. Dosim. To be published

5 Bordy J.M., Daures J., Denoziere M., Gouriou J., Itié C., Struelens L., Donadile L. and Schultz F., Design of a realistic calibration field for diagnostic radiology (Medical staff dosimetry), Proceedings of the international workshop on uncertainty assessment in computational dosimetry. A comparison of approaches. ISBN 978-3-9805741-9-8 :

6 Worgul B.V., Kundiyev Y. I., Sergiyenko N.M., Chumak V.V., Vitte, P.M., Medvedovsky, C., Bakhanova, E.V., Junk, A.K., Kyrychenko, O.Y., Musijachenko, N.V., Shylo, S.A., Vitte, O.P., Xu, S., Xuef, X. and Shore, R.E., Cataracts among Chernobyl Clean-up Workers: Implications Regarding Permissible Eye Exposures. Radiation Research 167, 233-243, 2007

7 Behrens R, Dietze G, Zankl M., Dose conversion coefficients for electron exposure of the human eye lens. Phys. Med. Biol. 54 (2009).

8 International Commission on Radiological Protection, Recommendation 2007 of ICRP (2008).

9 ENEA RT/2009/1/BAS, ORAMED project eye-Lens dosimetry, a new Monte Carlo approach to define the operation quantity Hp(3), Marioti F., Gualdrini G., ISSN/0393-3016, Bologna, Italy (2009)

10 CEA-R-6235, Conversion coefficients from air kerma to personal dose equivalent Hp(3) for eye-lens dosimetry, Daures J., Gouriou J., Bordy J.M., ISSN-0429-3460, Saclay, France (2009)

11 Briesmeister, J.F. (Ed) MCNP – A General Monte Carlo N-Particle Transport code Version 4C, Oak ridge National Laboratory. LANL Manual LA-13709-M version 4B Los Alamos (2000)

12 Salvat F., Fernandez M.F. and Sempau J., PENELOPE 2006: A Code System for Monte Carlo Simulation of Electron and Photon Transport

13 Biagini, C., "Radiobiologia e Radioprotezione", ISBN 88-299-1463-0, Piccin Nuova Libreria S.p.A. – Padova, 1999.

14 Chodick G et al, "Risk of cataract after exposure to low doses of ionizing radiation: a 20-year prospective cohort study among US radiologic technologists" Am. J. Epidemiol. 168 620–31, 2008.

15 International Commission on Radiological Protection. 1990 Recommendations of the International Commission on Radiological Protection. Oxford, United Kingdom: Pergamon Press, 1991. (ICRP publication 60).

16 National Council on Radiation Protection and Measurements. Limitation of exposure to ionizing radiation. Bethesda, MD: National Council on Radiation Protection and Measurements, 1993. (NCRP report 116).

17 Nakashima E, Neriishi K, Minamoto A. A reanalysis of atomic-bomb cataract data, 2000–2002: a threshold analysis. Health Phys 2006;90:154–60.