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X and gamma reference radiation for calibrating dosemeters and doserate meters and for determining their response as a function of photon energy —

Part 4:
Calibration of area and personal dosemeters in low energy X reference radiation fields

Rayonnements X et gamma de référence pour l'étalonnage des dosimètres et des débitmètres et pour la détermination de leur réponse en fonction de l'énergie des photons —

Partie 4: Étalonnage des dosimètres de zone (ou d'ambiance) et individuels dans des champs de référence X de faible énergie

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Foreword

ISO (the International Organization for Standardization) is a worldwide federation of national standards bodies

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ISO 4037-4 was prepared by Technical Committee ISO/TC 85, *Nuclear energy*, Subcommittee SC 2, *Radiation protection*.

ISO 4037 consists of the following parts, under the general title *X and gamma reference radiation for calibrating dosemeters and doserate meters and for determining their response as a function of photon energy*:

— *Part 1: Radiation characteristics and production methods*

— *Part 2: Dosimetry for radiation protection over the energy ranges from 8 keV to 1,3 MeV and 4 MeV to 9 MeV*

— *Part 3: Calibration of area and personal dosemeters and the measurement of their response as a function of energy and angle of incidence*

— *Part 4: Calibration of area and personal dosemeters in low energy X reference radiation fields*

Introduction

This part of ISO 4037 is closely related to the three other parts of ISO 4037. The first, ISO 4037-1, describes the methods of production and characterisation of the photon reference radiations. The second, ISO 4037-2, describes the dosimetry of the reference radiations and the third, ISO 4037-3, describes procedures for calibrating and determining the response of dosemeters and doserate meters in terms of the International Commission on Radiation Units and Measurements (ICRU) operational quantities [1, 2, 3] for radiation protection purposes.

This part of ISO 4037 is the fourth part of the series, and it describes special procedures for low energy X reference radiation fields. In ISO 4037-3, all the dose quantities used are based on the air kerma K_a free in air. Either K_a is the selected measuring quantity, or one of the dose-equivalent quantities $H'(0,07)$, $H_p(0,07)$, $H_p(10)$ and $H^*(10)$ is determined using conversion coefficients from air kerma K_a to the appropriate dose-equivalent quantity. For the dose-equivalent quantities $H'(0,07)$ and $H_p(0,07)$, this procedure is associated with only a small additional uncertainty, because the conversion coefficients depend only slightly on the photon energy and angle of radiation incidence for the ranges given in ISO 4037-3. Therefore, for these dose-equivalent quantities, no special attention is given for the low energy X reference radiation fields. For the two other dose-equivalent quantities $H_p(10)$, and $H^*(10)$, this is different. For them, the use of conversion coefficients can be associated with large additional uncertainties if low energy X reference radiation fields are considered; see the remark already given in these cases in ISO 4037-3. This is because the conversion coefficients depend strongly on the photon energy and the angle of radiation incidence. For nominally the same radiation quality as defined in ISO 4037-1, the conversion coefficients can differ by several tens of percent. A detailed description of all the measurements and methods necessary to avoid these additional uncertainties is given by Ankerhold *et al.* [4, 5] and by Behrens [6].

NOTE For irradiation of the whole body, $H_p(10)$ and $H^*(10)$ are relevant for radiation protection, as long as they are closer to their limit than $H'(0,07)$ and $H_p(0,07)$. This is the case down to about 15 keV.

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X and gamma reference radiation for calibrating dosemeters and doserate meters and for determining their response as a function of photon energy —

Part 4:
Calibration of area and personal dosemeters in low energy X reference radiation fields

1 Scope

This part of ISO 4037 gives guidelines on additional aspects of the characterization of low energy photon radiations. This part of ISO 4037 also describes procedures for calibration and determination of the response of area and personal dose(rate)meters as a function of photon energy and angle of incidence. This part of ISO 4037 concentrates on the accurate determination of conversion coefficients from air kerma to $H_\mathrm{p}(10)$ and $H^*(10)$ for the spectra of low energy photon radiations. As an alternative to the use of conversion coefficients, the direct calibration in terms of these quantities by means of appropriate reference instruments is described.

2 Normative references

The following referenced documents are indispensable for the application of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

ISO 4037-1:1996, *X and gamma reference radiation for calibrating dosemeters and doserate meters and for determining their response as a function of photon energy — Part 1: Radiation characteristics and production methods*

ISO 4037-2:1997, *X and gamma reference radiation for calibrating dosemeters and doserate meters and for determining their response as a function of photon energy — Part 2: Dosimetry for radiation protection over the energy ranges from 8 keV to 1,3 MeV and 4 MeV to 9 MeV*

ISO 4037-3:1999, *X and gamma reference radiation for calibrating dosemeters and doserate meters and for determining their response as a function of photon energy — Part 3: Calibration of area and personal dosemeters and the measurement of their response as a function of energy and angle of incidence*

BIPM, IEC, IFCC, ISO, IUPAC, IUPAP, OIML, *Guide to the Expression of Uncertainty in Measurement*, 1995

ICRU Report 51:1993, *Quantities and Units in Radiation Protection Dosimetry*, International Commission on Radiation Units and Measurements, Bethesda, Maryland 20814, USA

3 Terms and definitions

For the purposes of this document, the terms and definitions given in ISO 4037-3 and the following apply.

3.1
low energy X-ray reference radiation
all radiation qualities as specified in ISO 4037-1 and ISO 4037-3 with nominal tube potentials up to and including 30 kV

NOTE These radiation qualities are all continuous reference filtered radiations and fluorescence radiations.

3.2
spectral fluence
distribution of fluence Φ with respect to photon energy E

$$\Phi_E = \frac{\mathrm{d}\Phi}{\mathrm{d}E}$$

3.3
spectral air kerma
distribution of air kerma, K_a with respect to photon energy E

$$\left(K_\mathrm{a}\right)_E = \frac{\mathrm{d}K_\mathrm{a}}{\mathrm{d}E}$$

3.4
pulse height spectrum
dN/dQ
distribution of number of pulses N with respect to charge Q generated in the detector

3.5
spectral-fluence response function
function $R(E, Q)$ describing the relationship between spectral-fluence Φ_E and the pulse height spectrum, dN/dQ

$$\frac{\mathrm{d}N}{\mathrm{d}Q} = \int_{E_0}^{E_\mathrm{max}} R(E,Q)\cdot\Phi_\mathrm{E}\ \mathrm{d}E$$

3.6
unfolding
determination of the spectral-fluence Φ_E from the (measured) pulse height spectrum, dN/dQ

3.7
spectral-fluence response matrix
matrix where each column represents the response function $R(E, Q)$ for photons with energy E

4 Symbols (and abbreviated terms)

The symbols (and abbreviated terms) used are given in Table 1.

Table 1 — Symbols (and abbreviated terms)

Symbol	Meaning	Unit
ρ	air density	kg/m^3
ρ_0	air density under reference conditions: ρ_0 = 1,1974 kg/m^3	kg/m^3
ρ_{irr}	air density prevailing during irradiation	kg/m^3
ρ_{con}	air density prevailing during determination of the conventionally true value of the measurand	kg/m^3
ρ_{cal}	air density prevailing during calibration of the instrument	kg/m^3
ρ_{MC}	air density prevailing during calibration of the monitor chamber	kg/m^3
ρ_{spec}	air density prevailing during the spectral measurements	kg/m^3
$\Delta\rho$	change of air density	kg/m^3
α	angle of radiation incidence to the normal of the phantom surface	° (degree)
$\Delta\alpha$	change of angle of radiation incidence	° (degree)
U	tube potential	V
ΔU	change in tube potential	V
T	air temperature	K
T_0	air temperature under reference conditions: T_0 = 293,15 K (equivalent to 20 °C)	K
r	relative air humidity	—
r_0	relative air humidity under reference conditions: r_0 = 0,65 (equivalent to 65 %)	—
p	air pressure	kPa
p_0	air pressure under reference conditions: p_0 = 101,3 kPa	kPa
m_d	gradient of the gradient $m(d_{air})$	m^2/kg
$m(d_{air})$	gradient for distance d_{air}	m^3/kg
m(1,0 m)	gradient for distance 1,0 m	m^3/kg
K_a	air kerma free in air	Gy
$k(\rho, M)$	air density correction factor for measurand M	—
$H_p(10)$	personal dose-equivalent at 10 mm depth	Sv
$H_p(0{,}07)$	personal dose-equivalent at 0,07 mm depth	Sv
$H^*(10)$	ambient dose-equivalent at 10 mm depth	Sv
$H'(0{,}07)$	directional dose-equivalent at 0,07 mm depth	Sv
$h_{p,K}(10, \alpha)$	conversion coefficient from K_a to $H_p(10)$ for angle of radiation incidence α	Sv/Gy
$h^*_K(10)$	conversion coefficient from K_a to $H^*(10)$	Sv/Gy
E	photon energy	eV
d_{MC}	distance from the beam exit window of the X-ray tube to the monitor chamber	m
d_{air}	distance from the beam exit window of the X-ray tube to the point of test	m
$\Phi_E(E)$	spectral fluence at the photon energy E	m^{-2}·eV^{-1}
N	number of pulses generated in the detector	—
Q	charge Q generated in the detector by one photon	C
$R(E, Q)$	response function	m^2·C^{-1}

5 General procedures for calibrating and determining response

All criteria and procedures in Parts 1 to 3 of ISO 4037 are based on the measuring quantity air kerma, K_a, free in air. Either K_a is the selected measuring quantity or one of the dose-equivalent quantities $H'(0{,}07)$, $H_p(0{,}07)$, $H_p(10)$ and $H^*(10)$ is determined using conversion coefficients from air kerma K_a to it. K_a is measured using a secondary standard or other appropriate instruments exactly calibrated. For the dose-equivalent quantities $H'(0{,}07)$ and $H_p(0{,}07)$, this procedure is associated with only a small additional uncertainty, because, for the ranges given in ISO 4037-3, the conversion coefficients depend only slightly on the photon energy and the angle of radiation incidence. Therefore, the only correction given for them for the low energy X reference radiation fields, in addition to Parts 1 to 3 of ISO 4037, is the air density correction and the same applies to the air kerma K_a free in air. For the two other dose-equivalent quantities $H_p(10)$ and $H^*(10)$, this is different. For them, the use of conversion coefficients can be associated with large additional uncertainties if low energy X reference radiation fields are considered, see the remarks already given in these cases in ISO 4037-3:1999 in Tables 9 to 11, 28 to 30 and 32. This is because the conversion coefficients $h_{pK}(10, \alpha)$ and $h^*_K(10)$ depend strongly on the photon energy, and $h_{pK}(10, \alpha)$ depends in addition on the angle of radiation incidence. For nominally the same radiation quality as defined in ISO 4037-1, the conversion coefficients can differ by several tens of percent.

There are two possible approaches to overcome this deficiency. For method I, a spectrometer is used to measure the spectrum of the radiation quality under consideration. From this spectrum, the exact conversion coefficient can be calculated and applied to the measured value of air kerma, K_a, free in air. For method II, a special standard chamber for $H_p(10)$ or $H^*(10)$ is used. This chamber must have, for these quantities, a similarly small variation in response with energy and, for $H_p(10)$, in-addition angle dependence of the response as required for the standard instrument for air kerma K_a free in air in ISO 4037-2:1997, 4.3.

This part of ISO 4037 defines the conditions that must be met to use one of the two methods and the experimental steps to be used for the selected method. If a monitor chamber (see ISO 4037-2:1997, 8.2) is used as a transfer device, additional corrections must be applied for differences in the air density prevailing during calibration of the monitor chamber and during calibration of the instrument under test. This part of ISO 4037 does not give advice on the construction of the instruments necessary for both methods. Examples for the instruments and the experimental steps for both methods are given by Ankerhold *et al.* [4, 5], Behrens [6] and Duftschmid *et al*. [7].

6 Characterization and production of low energy X-ray reference radiations

6.1 General

This clause specifies the characteristics by which a laboratory can produce the reference filtered X radiations given in ISO 4037-1 for the given purposes. For various influence quantities, data are given on the change which causes a change of the measurand of 2 %. These data shall either be interpreted as limits for the deviation from its nominal value or, where possible, as a criterion for the necessity of corrections.

The requirements given in ISO 4037-1:1996, 4.1.2, paragraph 5 (mean energies within ± 5 % and resolution within ± 15 % of the values given in Tables 3, 4 and 5 of ISO 4037-1) must not be used for the quantities $H_p(10)$ or $H^*(10)$ for low energy reference radiations, as they are not sufficient in these cases and shall be replaced by the requirements in this clause.

6.2 Tube potential

This subclause is relevant for methods I and II. The dose-equivalent quantities $H_p(10)$ and $H^*(10)$ are, for low energy X radiation, more sensitive to the tube potential than the air kerma, K_a, free in air. Table 2 gives values for the change of tube potential that cause a change in the value of the conversion coefficient of 2 %, if all other parameters are unchanged. For methods I and II, the requirements on the absolute value of the tube potential (given in ISO 4037-1:1996, 4.2.2) of ± 2 % are sufficient, but the change in tube voltage must not exceed the limits given in Table 2.

NOTE All calculations in this subclause are based on the following assumptions. Firstly, for the purpose of calculating changes of the value of the conversion coefficient to the dose-equivalent quantity, $H_p(10)$ or $H^*(10)$, for a given radiation quality, the respective conversion coefficient can be replaced by the monoenergetic one for the mean energy. Secondly, the relative change of tube potential and the relative change of the mean energy are equal to each other.

Table 2 — Change of tube potential that causes a change in the value of the conversion coefficients of 2 % for radiation qualities with nominal tube potentials up to and including 30 keV

Radiation quality [a]	Tube potential U kV	Mean energy [b] keV	ΔU causing a change of 2 % of the conversion coefficient V		$\Delta U/U$ causing a change of 2 % of the conversion coefficient %	
			$h_{p,K}(10, 0°)$ $h^*_K(10)$	$h_{p,K}(10, 60°)$	$h_{p,K}(10, 0°)$ $h^*_K(10)$	$h_{p,K}(10, 60°)$
L-10	10	9,2	12	5,4	0,12	0,054
L-20	20	17,4	150	79	0,74	0,40
L-30	30	26,7	450	320	1,5	1,1
N-10	10	8,9	10	5,6	0,1	0,056
N-15	15	12,7	41	22	0,28	0,15
N-20	20	16,5	130	67	0,63	0,33
N-25	25	20,4	250	150	0,99	0,61
N-30	30	24,7	450	300	1,5	0,99
H-10	10	8,7	9	4,6	0,09	0,046
H-20	20	14,0	83	41	0,41	0,21
H-30	30	20,1	300	180	1,0	0,59

[a] See Table 1 of ISO 4037-3:1999.

[b] Values were taken from reference [8] in the Bibliography for a distance of 2,5 m, a typical distance for calibrations with respect to $H_p(10)$ performed on an ISO water slab phantom.

6.3 Field uniformity and scattered radiation

This subclause is relevant for methods I and II. The cross-sectional area of the reference-radiation beam should be sufficient to completely irradiate area dosemeters and doserate meters, or the phantom used for the calibration of personal dosemeters. The variation of the air kerma rate over the beam area shall be less than 5 %, and the contribution of scattered radiation to the total air kerma rate shall be less than 5 % (see ISO 4037-1:1996, 4.5). Test 1 of ISO 4037-1:1996, 4.5.3.1 shall not be performed, because the corrections for air attenuation are large and can only be performed if the spectral fluence is known.

6.4 Spectral fluence and conversion coefficients

This subclause is relevant for method I only. For every radiation quality, the knowledge of the spectral fluence is necessary to determine the conversion coefficient from air kerma to the measurand under consideration for the X-ray facility used. In informative Annex B, an example for the determination of the spectral fluence is given. The spectral fluence is converted to a spectral air kerma by folding the spectral fluence with the monoenergetic fluence to air-kerma conversion coefficients. This spectral air kerma is then folded with the monoenergetic conversion coefficients for the respective measurand (see ISO 4037-3) to get the spectral $H_p(10)$ or $H^*(10)$ distribution which is then integrated to get the actual conversion coefficient. The conversion coefficients obtained are valid only for the air density, ρ_{spec}, prevailing during the spectral measurements.

7 Dosimetry of low energy reference radiations

7.1 General

The instruments to be used shall be standard instruments as given in Subclause 4.1 of ISO 4037-2:1997. The general procedures in Clause 5 of ISO 4037-2 and, where appropriate, the procedures applicable to ionization chambers in Clause 6 of ISO 4037-2:1997, shall be followed. Subclause 7.2.1 is relevant for method I and subclause 7.2.2 for method II.

7.2 Operation of the standard instruments

7.2.1 Instruments for the measurement of air kerma

This subclause is relevant for method I only. ISO 4037-2 gives detailed guidelines on the operation of the instruments to be used for the measurement of the air kerma, K_a, free in air. These guidelines shall be followed.

7.2.2 Instruments for the measurement of the dose-equivalent quantities defined in ICRU 51

7.2.2.1 General

This subclause is relevant for method II only. The instruments to be used for the measurement of the reference radiation shall be a secondary standard or other appropriate instruments. Generally, this comprises an ionization chamber assembly and a measuring assembly. The detailed guidelines given in ISO 4037-2 for instruments to be used for the measurement of the air kerma, K_a, free in air are transferred here for instruments for the measurands considered in this part of ISO 4037.

7.2.2.2 Calibration

The standard instrument shall be calibrated for the range of energies and for the measurands that are intended to be used.

7.2.2.3 Energy dependence of the response of the instrument

Above a mean energy (see ISO 4037-1) of 30 keV, the ratio of the maximum to minimum response of the instrument shall not exceed 1,2 over the energy range for which the standard instrument is to be used. For mean energies between 8 keV and 30 keV, the limit of this ratio shall not exceed 1,3.

Whenever practical, the reference radiations used to calibrate the secondary standard instrument should be the same as those used for the calibration of radiation protection instruments.

7.2.2.4 Stability check facility

Where appropriate, a radioactive check source may be used to verify the satisfactory operation of the instrument prior to periods of use.

8 Calibration and determination of the response as a function of photon energy and angle of radiation incidence

8.1 General

The general methods given in ISO 4037-3 shall be followed. For an unsealed standard ionization chamber, this includes corrections for air temperature, pressure and humidity according to ISO 4037-2:1997, 6.7.3.

In this clause, additional requirements and advice on the selection of calibration method are given. Moreover, for the dose-equivalent quantity $H_p(10)$, limits are given for the adjustment of the angle of incidence.

8.2 Selection of calibration method

This subclause gives information, additional to ISO 4037-2, on the choice of dosimetric method, which can be used for determination of the conventionally true value of the dose quantities of interest. As explained in Clause 5, two methods are possible to determine the conventionally true value of the dose quantities of interest.

Method I, using spectrometry and reference instruments for K_a, is recommended for those laboratories, which need to achieve an uncertainty of the conventionally true value of about 4 % (k = 2) or less.

Method II, using secondary standard instruments which directly measure dose-equivalent quantities, is recommended for all other laboratories. The achievable uncertainty is between 4 % and 6 % (k = 2) depending on the radiation quality.

The time period, starting from the determination of the conventionally true value of the measurand until the calibration of the instrument under test and the determination of its response as a function of photon energy and angle of radiation incidence, has to be considered, because the stability of certain parameters over this period must be maintained.

8.3 Calibration by using reference instruments for K_a

8.3.1 General

This subclause is relevant for method I only. Within the long time period (typically one month or more), from the determination of the conversion coefficient (see 6.4) to the measurement of the conventionally true value of the air kerma and the calibration of the instrument, the requirements concerning tube potential of 6.2 must be followed. In addition, the air density at all measuring events shall be constant within the limits given in Table 3, otherwise the appropriate corrections given shall be applied.

The additional corrections for the use of a monitor chamber as a transfer device are given.

As an example, Table 3 gives values for the percentage change of air density that cause a change in the value of the air kerma, K_a, and the conversion coefficients $h_{p,K}(10, 0°)$, $h^*_K(10)$ and $h_{p,K}(10, 60°)$ of 2 % at 2,5 m distance between the point of test and the focus, and for 0° and 60° radiation incidence. These conditions are representative for calibrations with respect to $H_p(10)$ performed on a ISO water slab phantom (see ISO 4037-3).

8.3.2 Conventionally true value of the measurand air kerma

Within the short time period (typically one or a few hours) from the measurement of the conventionally true value of the air kerma to the calibration of the instrument, the air density must not change by more than the limits given in Table 3. Normally, this is the case and no correction is necessary. In the other few cases, the correction method given in Annex A shall be applied as follows. If ρ_{con} is the air density prevailing during determination of the conventionally true value of the air kerma K_a and if ρ_{cal} is that during calibration of the instrument, then the conventionally true value of K_a during calibration is

$$K_a(\rho_{cal}) = \frac{k(\rho_{cal}, K_a)}{k(\rho_{con}, K_a)} K_a(\rho_{con}). \tag{1}$$

For the air density correction factor $k(\rho, K_a)$ for the quantity air kerma K_a see Equation (A.2) in Annex A.

If a monitor chamber is used as a transfer device for the measuring quantity air kerma K_a then the difference of the air density prevailing during the calibration of the monitor chamber, and the air density prevailing during the calibration of the instrument, shall be within the limits given in Table 3. Otherwise the correction method given in Annex A shall be applied as follows. If the monitor chamber is mounted at a distance d_{MC} from the beam exit window, ρ_{MC} is the air density prevailing during calibration of the monitor chamber and if ρ_{cal} is that during calibration of the instrument at distance d_{air}, then the conventionally true value of K_a during calibration is (for the air density correction factor $k_{MC}(\rho, K_a)$ see Equation (A.5) in Annex A):

$$K_a(\rho_{cal}) = \frac{k(\rho_{cal}, K_a)}{k_{MC}(\rho_{MC}, K_a)} K_a(\rho_{MC}) \tag{2}$$

Table 3 — Percentage change of air density that causes a change in the value of the air kerma K_a and the conversion coefficients $h_{p,K}(10, 0°)$ or $h^*_K(10)$ and $h_{p,K}(10, 60°)$ of 2 % at 2,5 m distance between the point of test and the focus of the X-ray tube and 0°and 60° radiation incidence

(This distance is typical for calibrations with respect to $H_p(10)$ performed on an ISO water slab phantom.)

Radiation quality [a]	Tube potential U kV	$\Delta\rho/\rho$ for 2,5 m distance causing a change of 2 % of the value of		
		K_a %	$h_{p,K}(10, 0°)$, $h^*_K(10)$ %	$h_{p,K}(10, 60°)$ %
L-10	10	0,9	6,3	4,8
L-20	20	5,3	> 20	> 20
L-30	30	14	> 20	> 20
N-10	10	0,8	3,5	2,9
N-15	15	2,1	9,2	6,9
N-20	20	4,3	> 20	18
N-25	25	8,0	> 20	> 20
N-30	30	12	> 20	> 20
H-10	10	0,7	2,4	2,0
H-20	20	1,9	3,7	3,2
H-30	30	4,4	11	9,1

[a] See Table 1 of ISO 4037-3:1999.

8.3.3 Conventionally true value of the measurands dose-equivalent quantities $H_p(0,07)$ and $H'(0,07)$

The determination of the conventionally true value of the dose-equivalent quantities $H_p(0,07)$ and $H'(0,07)$ is based on the determination of the conventionally true value of the air kerma K_a plus the application of a conversion coefficient. The conversion coefficients given in ISO 4037-3 for the dose-equivalent quantities $H_p(0,07)$ and $H'(0,07)$ shall be applied. Using the conventionally true value of the air kerma K_a as determined in 8.3.2 leads to

$$H_p(0,07;\rho_{cal}) = h_{p,K}(0,07)\, K_a(\rho_{cal}) \tag{3}$$

$$H'(0,07;\rho_{cal}) = h'_K(0,07)\, K_a(\rho_{cal}) \tag{4}$$

8.3.4 Conventionally true value of the measurands dose-equivalent quantities $H_p(10)$ and $H^*(10)$

8.3.4.1 Corrections of $h_{p,K}(10, \alpha)$ and $h^*_K(10)$ for air density

If the air density ρ_{cal} prevailing during calibration of the instrument differs from the air density ρ_{spec} prevailing during the determination of the conversion coefficient using spectrometry (see 6.4) by more than the limits given in Table 3, then, in addition to the correction of the air kerma K_a, the correction method given in Annex A shall also be applied to the conversion coefficients $h_{p,K}(10, \alpha)$ or $h^*_K(10)$ as follows:

$$h_{p,K}(10,\alpha,\rho_{cal}) = \frac{k\left(\rho_{cal}, h_{p,K}(10,\alpha)\right)}{k\left(\rho_{spec}, h_{p,K}(10,\alpha)\right)} h_{p,K}(10,\alpha,\rho_{spec}) \text{, and} \quad (5)$$

$$h_K^*(10,\rho_{cal}) = \frac{k\left(\rho_{cal}, h_K^*(10)\right)}{k\left(\rho_{spec}, h_K^*(10)\right)} h_K^*(10,\rho_{spec}) \quad (6)$$

For the air density correction factors $k(\rho, h_{p,K}(10,\alpha))$ and $k(\rho, h^*_K(10))$ for the conversion coefficients $h_{p,K}(10,\alpha)$ and $h^*_K(10)$, see A.2.

8.3.4.2 Evaluation of the effect of angle of radiation incidence α for $H_p(10)$

For a given value of K_a and parallel radiation incidence, the conventionally true value of the dose-equivalent quantity $H_p(10)$ is changed if the angle of radiation incidence is changed; this is not the case for the dose-equivalent quantity $H^*(10)$. Table 4 gives, for unidirectional radiation values, the change of the angle of radiation incidence that cause a change in the value of the dose-equivalent quantity $H_p(10)$ of 2 %. The angle of radiation incidence shall be within the limits given in Table 4, otherwise the enhanced uncertainty must be considered.

NOTE 1 All the calculations in this clause are based on the following assumption. For the purpose of calculating changes of the value of the dose-equivalent quantity $H_p(10)$ for a given radiation quality, the respective conversion coefficient can be replaced by the monoenergetic one for the mean energy.

NOTE 2 The adjustment of the angle of radiation incidence α needs two steps, firstly the adjustment of 0° incidence and secondly a rotation of the device through angle α. If the uncertainty of the second step is lower than that of the first step, then two measurements at two angles of radiation incidence of + α and − α are recommended. The mean value of the two measured values is taken as the value for the angle of radiation incidence α which will (to the first order) compensate the error of the adjustment of 0° incidence.

Table 4 — Change $\Delta\alpha$ of the angle of radiation incidence α that causes a change of $H_p(10)$ of 2 %

Radiation quality [a]	**Mean energy** [b]	**$\Delta\alpha$ in deg causing a change of $H_p(10)$ of 2 % for angle of incidence of**					
	keV	0°	15°	30°	45°	60°	75°
L-10	9,2	2,0	0,93	0,38	0,17	0,016	$(8{,}8 \times 10^{-6})$[c]
L-20	17,4	10	4,8	1,9	0,90	0,41	0,083
L-30	26,7	16	10	4,2	1,9	0,83	0,33
N-10	8,9	1,8	0,85	0,34	0,15	0,011	$(2{,}7 \times 10^{-6})$[c]
N-15	12,4	4,4	2,0	0,81	0,40	0,17	0,0078
N-20	16,4	10	4,2	1,7	0,79	0,36	0,066
N-25	20,4	17	7,1	2,6	1,2	0,54	0,15
N-30	24,7	15	9,3	3,7	1,7	0,75	0,28
H-10	8,6	1,6	0,80	0,31	0,13	0,0087	$(1{,}2 \times 10^{-6})$[c]
H-20	14,0	6,4	2,6	1,0	0,52	0,24	0,021
H-30	20,1	17	6,9	2,5	1,2	0,53	0,14

[a] See Table 1 of ISO 4037-3:1999.

[b] Values were taken from reference [8] in the Bibliography for a distance of 2,5 m, a typical distance for calibrations with respect to $H_p(10)$ performed on an ISO water slab phantom.

[c] Not achievable in practice.

8.3.4.3 Determination of the conventionally true value of $H_p(10)$ and $H^*(10)$

The determination of the conventionally true value of the dose-equivalent quantities $H_p(10)$ or $H^*(10)$ is based on the determination of the conventionally true value of the air kerma K_a plus the application of a conversion coefficient. Using the conventionally true value of the air kerma K_a as determined in 8.3.2 leads to

$$H_p(10;\rho_{cal}) = h_{p,K}(10,\alpha,\rho_{cal})\,K_a(\rho_{cal}),\ \text{and} \tag{7}$$

$$H^*(10;\rho_{cal}) = h_K^*(10,\rho_{cal})\,K_a(\rho_{cal})\,. \tag{8}$$

Equations (5) and (6) are used to determine the conversion coefficients.

8.3.5 Performing the calibration

The calibration is done according to ISO 4037-3 using the conventionally true values determined above.

8.4 Calibration by using reference instruments which measure the ICRU dose-equivalent quantities

8.4.1 General

This subclause is relevant for method II only. Within the time period of typically 1 h from the measurement of the conventionally true value of the ICRU dose-equivalent quantities to the calibration of the instrument, the requirements concerning tube potential of 6.2 must be followed. In addition, the air density shall be stable within the limits given in Table 5, otherwise the corrections given shall be applied.

The additional corrections for the use of a monitor chamber as a transfer device are given.

As an example, Table 5 gives values for the percentage change of air density that cause a change in the value of the dose-equivalent quantities $H_p(10, 0°)$ or $H^*(10)$ and $H_p(10, 60°)$ of 2 % at 2,5 m distance of the point of test from the focus and for 0° and 60° radiation incidence. These conditions are representative for calibrations with respect to $H_p(10)$ performed on a ISO water slab phantom.

8.4.2 Conventionally true value of the measurands dose-equivalent quantities $H_p(10)$ and $H^*(10)$

8.4.2.1 Correction of $H_p(10)$ and $H^*(10)$ for air density

Within the short time period (typically one or a few hours) from the measurement of the conventionally true value of $H_p(10)$ or $H^*(10)$ to the calibration of the instrument, the air density must not change by more than the limits given in Table 5. Normally, this is the case and no correction is necessary. In the other few cases, the correction method given in Annex A shall be applied as follows. If ρ_{con} is the air density prevailing during determination of the conventionally true value of $H_p(10)$ or $H^*(10)$ and if ρ_{cal} is that during calibration of the instrument, then the conventionally true value of $H_p(10)$ or $H^*(10)$ during calibration is

$$H_p(10,\rho_{cal}) = \frac{k\left(\rho_{cal}, H_p(10)\right)}{k\left(\rho_{con}, H_p(10)\right)}\,H_p(10,\rho_{con}) \tag{9}$$

$$H^*(10,\rho_{cal}) = \frac{k\left(\rho_{cal}, H^*(10)\right)}{k\left(\rho_{con}, H^*(10)\right)}\,H^*(10,\rho_{con}) \tag{10}$$

For the air density correction factors $k(\rho, H_p(10))$ and $k(\rho, H^*(10))$ for the quantities $H_p(10)$ and $H^*(10)$, see A.2.

Table 5 — Percentage change of air density that causes a change in the value of $H_p(10, 0°)$ or $H^*(10)$ and $H_p(10, 60°)$ of 2 % at 2,5 m distance of the point of test from the focus and 0° and 60° radiation incidence

(This distance is typical for calibrations with respect to $H_p(10)$ performed on an ISO water slab phantom.)

Radiation quality[a]	Tube potential U kV	$\Delta\rho/\rho$ for 2,5 m distance causing a change of 2 % of the value of	
		$H_p(10, 0°)$ or $H^*(10)$ %	$H_p(10, 60°)$ %
L-10	10	1,1	1,2
L-20	20	5,9	6,2
L-30	30	15	15
N-10	10	1,1	1,2
N-15	15	2,8	3,1
N-20	20	5,2	5,7
N-25	25	8,3	8,8
N-30	30	12	13
H-10	10	1,1	1,2
H-20	20	4,0	4,9
H-30	30	7,3	8,7

[a] See Table 1 of ISO 4037-3:1999.

If a monitor chamber is used as a transfer device for the measuring quantity $H_p(10)$ or $H^*(10)$, then the difference of the air density prevailing during the calibration of the monitor chamber and the air density prevailing during the calibration of the instrument shall be within the limits given in Table 5. Otherwise, the correction method given in the Annex A shall be applied as follows. If the monitor chamber is mounted at a distance d_{MC} from the beam exit window, ρ_{MC} is the air density prevailing during calibration of the monitor chamber and ρ_{cal} is that during calibration of the instrument at the distance d_{air}, then the conventionally true value of $H_p(10)$ or $H^*(10)$ during calibration is

$$H_p(10, \rho_{cal}) = \frac{k(\rho_{cal}, H_p(10))}{k_{MC}(\rho_{MC}, H_p(10))} H_p(10, \rho_{MC}), \text{ or} \quad (11)$$

$$H^*(10, \rho_{cal}) = \frac{k(\rho_{cal}, H^*(10))}{k_{MC}(\rho_{MC}, H^*(10))} H^*(10, \rho_{MC}). \quad (12)$$

For the air density correction factors $k(\rho, H_p(10))$, $k_{MC}(\rho, H_p(10))$, $k_{MC}(\rho, H^*(10))$ and $k(\rho, H^*(10))$ for the quantities $H_p(10)$ and $H^*(10)$, see A.2.

8.4.2.2 Adjustment of angle of radiation incidence α for $H_p(10)$

The value of the dose-equivalent quantity $H_p(10)$ depends on the angle of radiation incidence, this is not the case for the dose-equivalent quantity $H^*(10)$. Table 4 (see 8.3.4.2) gives, for unidirectional radiation values, the change of the angle of radiation incidence that cause a change in the value of the dose-equivalent quantity $H_p(10)$ of 2 %. The angle of radiation incidence shall be within the limits given in Table 4, otherwise the enhanced uncertainty must be considered.

8.4.2.3 Determination of the conventionally true value of $H_p(10)$ and $H^*(10)$

The conventionally true values of $H_p(10)$ or $H^*(10)$ are given by Equations (9) and (10) or (11) and (12) without any additional corrections.

8.4.3 Performing the calibration

The calibration is done according to ISO 4037-3 using the conventionally true values determined above.

8.5 Statement of uncertainty

This subclause is relevant to methods I and II. Where only one method is affected by a particular point, this is mentioned. The guidelines given in ISO 4037-3:1999, 7.2 shall be followed and the component uncertainties given there shall be used. In addition to or replacing given component uncertainties, the following ones given as relative standard uncertainties (1 s or $k = 1$) shall be taken into account. These values are only approximate values and should not be taken directly. The uncertainties need to be evaluated by each laboratory for their facilities.

a) Uncertainty resulting from changes of the tube voltage: usually less than 2 % or corrected, should be assessed by the test laboratory.

b) Uncertainty due to changes in air density: usually less than 2 % or corrected, should be assessed by the test laboratory.

c) Uncertainty of the conversion coefficients, method I only: usually 1,5 %, should be assessed by the test laboratory.

d) Uncertainty of the conventionally true value of $H_p(10)$ or $H^*(10)$, method II only: usually 2,5 %, should be given in the calibration certificate.

e) Uncertainty due to adjustment of the angle of incidence, $H_p(10)$ only: usually less than 2 %, should be assessed by the test laboratory.

Annex A
(normative)

Correction for air density

A.1 General

Corrections for air density are given for all quantities defined in 10 mm depth in tissue for nominal tube potentials equal to or greater than 10 kV to less than or equal to 30 kV.

A.2 Method for air density correction

The climatic conditions, given by the air temperature T, the air pressure p and the relative humidity r, affect the value of the air kerma K_a, of the conversion coefficients $h_{p,K}(10, \alpha)$ and $h^*_K(10)$ from air kerma K_a to the dose-equivalent quantities $H_p(10)$ and $H^*(10)$ and of their product, the dose-equivalent quantities $H_p(10)$ and $H^*(10)$ themselves, even if all other conditions of the irradiation facility are constant. The effect is due to the absorption of the photon radiation on the way from the beam exit window of the X-ray tube to the point of test and to the change of this absorption with photon energy. All influences increase with increasing air path. The absorption depends only on the air density ρ. For temperatures between 15 °C and 25 °C, ρ is given by the following formula, see Drake and Böhm [9] with modifications for new reference values given in reference [4] in the Bibliography:

$$\rho = \rho_0 \left[1{,}005\,699 \, \frac{p}{p_0} - \frac{1}{175{,}7} \times \frac{r}{r_0} \left(\frac{T}{T_0} \right)^{17{,}97} \right] \frac{T_0}{T} \tag{A.1}$$

where

p is the air pressure, p_0 = 101,3 kPa;

T is the air temperature, T_0 = 293,15 K (equivalent to 20 °C);

r is the relative air humidity, r_0 = 0,65 (equivalent to 65 %);

ρ_0 is the air density for reference conditions, ρ_0 = 1,197 4 kg/m^3.

NOTE A change of the air density of 1 % is equivalent to a change of the air pressure from 100 kPa to 101 kPa if temperature and humidity are unchanged, or to a change of the temperature from 293 K to 296 K if air pressure and humidity are unchanged. The air pressure changes under normal conditions and altitudes below 1000 m by about – 20 % to + 10 %.

The correction of each of the above-mentioned quantities for air density is performed as follows: For the air kerma K_a, taken as an example, the air density correction factor, $k(\rho, K_a)$, which is the quotient of the value of the measurand at the air density ρ and the value of the measurand at the air density at reference conditions, ρ_0, is calculated according to

$$k(\rho, K_a) = \frac{K_a(\rho)}{K_a(\rho_0)} . \tag{A.2}$$

The value under irradiation conditions is then obtained from the value at reference conditions according to

$$K_a(\rho_{irr}) = k(\rho_{irr}, K_a) \;\; K_a(\rho_0) \tag{A.3}$$

ρ_{irr} being the density of air during irradiation.

A linear approximation to the air density in the range from $\rho = 0{,}96$ kg/m^3 to $\rho = 1{,}32$ kg/m^3 of the correction factor leads to

$$k(\rho) = 1 + m(d_{air})\ (\rho - \rho_0) \qquad (A.4)$$

where d_{air} is the distance from the beam exit window to the reference point.

If a monitor chamber at a distance d_{MC} from the beam exit window is used as a transfer device, then the correction must only be applied to the air path from the monitor chamber to the reference point. This leads to

$$k_{MC}(\rho, K_a) = 1 + m(d_{air})(\rho - \rho_0)\left(1 - \frac{d_{MC}}{d_{air}}\right) \qquad (A.5)$$

The gradients, $m(d_{air})$, are different for different air paths, d_{air}. For $d_{air} = 1{,}0$ m to $d_{air} = 3{,}0$ m, $m(d_{air})$ can be approximated by a linear fit, too:

$$m(d_{air}) = m(1{,}0\ \text{m}) + (d_{air} - 1{,}0\ \text{m})\ m_d \qquad (A.6)$$

The uncertainty of the linear approximations using $m(1{,}0\ \text{m})$ and m_d compared with the values determined directly according to 8.4.2.1 is less than or equal to 1 % in the range of air density from $\rho = 1{,}10$ kg/m^3 to $\rho = 1{,}27$ kg/m^3. Inclusion of the uncertainties of the calculations themselves leads to an overall uncertainty for the corrections, $|k(\rho)-1|$, of about 5 %, this in turn resulting in an overall uncertainty for the correction factors, $k(\rho)$, of about 2 %.

In A.3, values for these two parameters, $m(1{,}0\ \text{m})$ and m_d, are given for K_a and the conversion coefficients $h_{p,K}(10, \alpha)$ and $h^*_K(10)$, and in A.4 for $H_p(10)$ and $H^*(10)$.

A.3 Air density correction parameters for K_a, $h_{p,K}(10, \alpha)$ and $h^*_K(10)$

Tables A.1 and A.2 give, as an example, values for the two parameters $m(1{,}0\ \text{m})$ and m_d, for the quantity K_a and the conversion coefficients $h_{p,K}(10, \alpha)$ and $h^*_K(10)$. The data may be slightly different from one X-ray facility to another, but the differences can be neglected for the range of air density from $\rho = 1{,}10$ kg/m^3 to $\rho = 1{,}27$ kg/m^3.

A.4 Air density correction parameters for $H_p(10)$ and $H^*(10)$

Tables A.3 and A.4 give, as an example, values for the two parameters $m(1{,}0\ \text{m})$ and m_d, for the quantities $H_p(10)$ and $H^*(10)$. The data may be slightly different from one X-ray facility to another, but the differences can be neglected for the range of air density from $\rho = 1{,}10$ kg/m^3 to $\rho = 1{,}27$ kg/m^3.

