Dosimetric standard for continuous X-rays radiation fields of low and medium-energies (< 300 kV)

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Abstract

This work presents the methodology used for the setup of the dosimetric standard at the Laboratoire National Henri Becquerel (**LNHB**) for the continuous X-rays irradiation field of medium-energies (100 kV to 250 kV) in term of air-kerma rate. Principle of measurements and characteristics of the standard are described. Additionally, a first assessment of global uncertainty budget on the value of air-kerma rate taking into account several correction factors and a first estimate of that of a calibration are developed.

Résumé

Ce travail présente la méthodologie suivie lors de la mise en place des références dosimétriques au LNHB (Laboratoire National Henri Becquerel) pour les faisceaux de rayons X continus de moyennes énergies (100 kV à 250 kV) en terme de débit de kerma dans l'air. Le principe de la mesure, ainsi que les caractéristiques du détecteur (instrument absolu) permettant d'obtenir les références nationales, sont décrits ci-dessous. De plus, un premier bilan de l'incertitude globale sur la valeur du débit de kerma dans l'air prenant en compte de nombreux facteurs de correction, ainsi qu'une première estimation de celui d'un étalonnage, sont développés.

Introduction

X-ray radiations induce erythemas and leukaemias. The .I.C.R.P. (International Commission of Radiological Protection) enacted the first recommendations to protect against the effects of the ionizing radiations. The recommendations were modified along the years and are today the roots of the **96/29 Euratom directive** which ensures the protection of the public and the workers [1]. The **97/43 Euratom directive** is particularly applied in the medical field for irradiations of patients to optimize benefit-to-risk ratios [2].

The application of these directives transcribed in the French legislation, set rules for maintenance, internal and external quality control of the machines, written procedures and a metrological traceability.

The LNHB, french national laboratory for metrology of ionizing radiations, has to deliver to secondary accredited laboratories, or directly to users, dosimetric standards for continuous X-rays of low and medium-energies.

This paper gives a description of these X-rays beams, as well as the air-kerma rate standard.

I Materials and method

I.1 Radiation qualities

The continuous X-ray beams of low and medium-energies are produced by an industrial generator with its X-ray tube and can go up to 320 kV. The beams are defined by the generating potential of the tube and by the total filtration. The quality beams is characterized by the Half-Value Layer (HVL) [3] [4] and the air-kerma rate. This HVL is the thickness of an additional copper or aluminium filter (depending of the beam) of high purity (less than 0.01 % of impurities) which decreases the air-kerma rate by a factor of 2. The uncertainty on the HVL is around 0.80 % (one standard deviation).

The reference point is at 1.20 m of the focus tube. At this distance the beam diameter is 14 cm with less than 0.6% of inhomogeneity. The irradiation beam dose rate has a stability of about 0.1 % over several hours (≈3h). The measuring device is placed in a temperature controlled room (20° C ± 0.5° C and 50 % HR).

I.2 Principle of the detector (absolute instrument)

The low and medium-energy X-ray beams are characterized in term of air-kerma rate and measured with a free-air ionization chamber [5].

The kerma (**K**inetic **E**nergy **R**eleased in **MA**tter) is the quotient (1) of the sum of the initial kinetic energies of all the charged ionizing particles released by non charged particles dE_{tr} in the air mass dm .

$$K_{air} = \frac{dE_{tr}}{dm} \quad (1)$$

It is defined at point *P* located at the center of the inner side of the diaphragm (figure 1) and is expressed in Gray ($1\text{Gy} = 1\text{J.kg}^{-1}$).

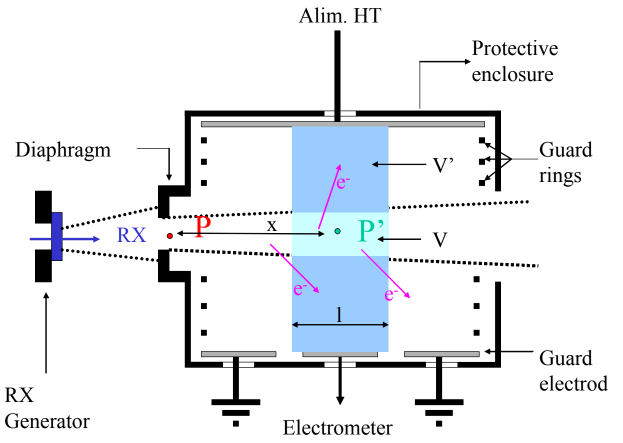

Figure 1: schematic plan of a free-air ionization chamber standard

The free-air ionization chamber is an absolute instrument (known collection volume *V*).

The application of a potential difference between the electrodes makes it possible to collect the charges created by the interaction of the beam with the air. The guard rings connected to a resistances bridge guarantee the uniformity of the electric field over the interaction volume *V*.

This chamber is placed in a lead enclosure to protect it from scattered radiations.

I.3 Determination of the air-kerma rate

The equation to calculate the air-kerma rate is:

$$\dot{K}_{\text{air}} = \frac{I}{\rho_{\text{air}} \cdot V} \cdot \frac{W_{\text{air}}}{\text{e}} \cdot \frac{1}{1-\text{g}} \cdot \prod k_{\text{i}} \quad (2)$$

with:

I: Ionization current measured with the free-air ionization chamber and expressed in A;

$\rho_{\text{air}} = 1.20479\ \text{kg.m}^{-3}$, density of dry air (20° C and 1013.25 hPa);

V: Detection Volume in cm^3;

$W_{\text{air}}/\text{e} = 33.97\ \text{J.C}^{-1}$, average energy necessary to create an electron-ion pair in dry air, per unit of the electron charge [6];

g: is the fraction of the initial electron energy lost by Bremsstrahlung production in air. This value is negligible for X-rays of low and medium-energies [7];

$\prod k_{\text{i}}$: Product of correction factors taking into account the characteristics of the detector (electrodes polarization, scattered photons, recombination of the charges, etc…) and the environmental conditions of the measurement (temperature, pressure and hygrometry).

I.4 Determination of correction factors

As indicated by equation (2), the air-kerma rate is corrected by several correction factors. Some are determined experimentally; and the others by using simulations.

- The experimentally determined factors are:

- **Recombination factor k_s**: corrects for the loss between the number of produced charges and the number of collected charges due to the recombination of the charges.

- **Attenuation factor in the air k_a**: corrects for air attenuation between P (located at the inner side of the diaphragm) and the P' (located in the middle of the volume V), (figure 1).

- **Polarization factor k_{pol}**: takes into account the dissymmetry of ion collection.

- **Transmission factor k_l**: corrects for the transmission through the matter around the diaphragm.

- **Transmission factor k_p**: corrects for the transmission through the walls.

- The factors determined by software simulation based on the finite elements method are:

- **Distortion factor k_d**: takes into account the possible distortion of the electric field inside the chamber which can induce an error in the determination of the volume *V* [8].

- The factors determined by Monte-Carlo simulations are:

- **Factor for electron loss k_e**: to evaluate the loss of ionization due to electrons which dissipate part their energy out side the volume *V'*.

- **Factor for scattered photons k_{sc}**: corrects for the charges due to secondary photons in *V'*.

II Results

II.1 Standard radiation qualities (100 kV and 250 kV)

Table 1 gives two examples of radiation qualities (100 kV and 250 kV) according to the recommendations of the CCEMRI [4]. The X-ray tube has a tungsten anode and an inherent aluminium filtration of 3.2 mm.

Generating potential (kV)	100	250
Additional Al filtration (mm)	0.318	-
Additional Cu filtration (mm)	-	1.641
Al HVL (mm)	4.044	-
Cu HVL (mm)	-	2.484
$(\mu/\rho)_{\text{air}}$ (cm²/g)	0.280	0.155
Air-kerma rate (mGy/s)	0.51	0.49

Table 1: characteristics of LNHB standard radiation qualities 100 kV and 250 kV

II.2 Details of the free-air ionization chamber WK06

The LNHB standard (WK06) is suitable for X-ray beams between 100 kV to 250 kV (figure 2). Table 2 describes some of the principal characteristics.

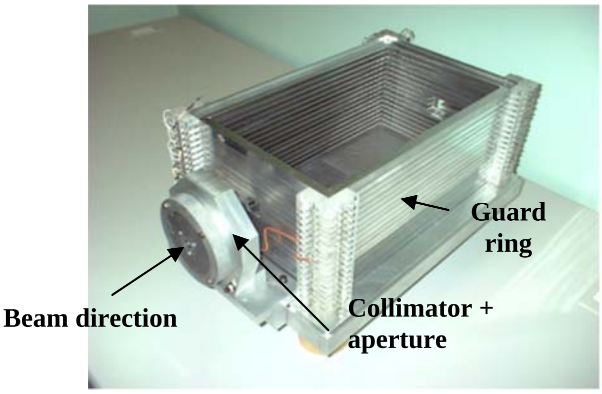

Figure 2: View of the WK06 free-air ionization chamber

Standard WK06	
Aperture diameter (cm)	1.0074
Air path length PP' (cm)	**31.8**
Collecting width (cm)	23.1
Electrode separation (cm)	18.0
Collecting length (cm)	6.0004
Measuring volume (cm^3)	**4.7827**
bias voltage (V)	5000

Table 2: Main characteristics of the standard WK06

The collecting Volume (V) is geometrically defined by the diameter of the beam, itself dependent on the diameter of the aperture diaphragm, and by the collecting electrode width (l).

It is necessary to add two half-spaces corresponding to half of the intersection with the beam of the volume perpendicular to the electrodes and situated between the collecting electrode and the guard electrode. This volume was measured with an uncertainty of 0.05 %.

The PP' distance (figure 1) is selected to ensure the electronic equilibrium.

II.3 Simulation by Monte-Carlo method

Computer codes simulating the radiation-matter interactions and based on the Monte-Carlo method were used to create a numerical model of WK06.

MCNP code version 4C [9], was used to check the detector design (fluorescence inside the volume V, collimation of the aperture, etc…) and to consider simplifications with the numerical model which allows to increase simulation speed.

Another code PENELOPE [10] was used to calculate the correction factors k_e (electron loss) and k_{sc} (scattered photons).

II.4 Correction factors and their associated uncertainties for 100 kV and 250 kV

The characteristic correction factors of the detector are given for each radiation quality. These values and their associated uncertainties are listed in table 3.

Although the correction factor of hygrometry k_h is taken equal to 0,998 as long as the Relative Humidity (HR) is included between 20 and 80 % at 20° C [11] [12].

However, the signal-to-noise ratio is around 1000 for the weakest currents of ionization (pA).

The product of all these factors results in a total correction of around 1 % of the value of the air-kerma rate.

Correction Factors	Generating potential		Relative uncertainty	
	100kV	250kV	Type A	Type B
k_{sc}	0,9942	0,9968	-	0,07%
k_e	1.0001	1.0065	-	0.10%
k_s	1.0006	1.0006	-	0.03%
k_{pol}	0.9994	0.9994	0.05%	-
k_a	1.0108	1.0060	-	0.10%
k_d	1.0000	1.0000	-	0.10%
k_l	0.9999	0.9999	-	0.01%
k_p	1.0000	0.9998	-	0.01%
k_h	0.9980	0.9980	-	0.03%
Total	1.0009	1.0061	**0.05%**	**0.19%**

Table 3: Correction factors for the LNHB standard for 2 quality beams and their associated uncertainties

II.5 Air-kerma rate

The I.3 paragraph describes the relation to calculate the air-kerma rate. For two radiation qualities (100 kV and 250 kV), the values are respectively 0,52 and 0,53 mGy.s^{-1} (Table 1) for ionization currents $I_{100kV} \approx 55$ pA and $I_{250kV} \approx 88$ pA.

Measurement of the ionization current, dimensional measurements (volume of detection), physical constants (W_{air}/e, ρ_{air}…), and various correction factors quoted previously, take part in the assessment of uncertainties budget.

Table 4 gives the uncertainty budget of the air-kerma rate at one standard deviation. It is equal to 0.31 % (at one standard deviation).

	Relative uncertainty	
	Type A	Type B
Volume		0.05%
Positioning	-	0.10%
Ionization current	0.07%	0.11%
Correction factor k_T	-	0.04%
Correction factor k_P	-	0.04%
Correction factors k_i	0.09%	0.19%
Physical Constants (W_{air}/e and ρ_{air})	-	0.15%
Air-kerma rate	0.12%	0.29%
Quadratic sum	**0.32%**	

Table 4: Uncertainties on the air-kerma rate

III Application

III.1 Calibration of a transfer instruments

The calibration coefficient in air-kerma denoted (N_K) is given by the following relation:

$$N_K = \frac{\dot{K}}{I_{tr}} \quad (3)$$

Where $\dot{K}$ is the air-kerma rate determined by the standard according to the relation (2) and I_{tr} is the ionization current measured by the transfer instrument with its associated electronics. This current is corrected with k_T and k_P to tally with the standard conditions of measurements (T=293.15 K, P=1013.25 and 50 % HR).

III.2 Uncertainty associated with the calibration coefficient: example

Table 5 gives the uncertainty established for the calibration of an ionization chamber (NE2571 type). It is equal to 0.35% (at one standard deviation).

	Relative uncertainty	
	Type A	Type B
Standard air-kerma rate	0.12%	0.29%
Positioning of transfer chamber	-	0.10%
Ionization current I_{tr}	0.07%	0.11%
Correction factor k_T	-	0.04%
Correction factor k_P	-	0.04%
N_K	0.23%	0.33%
Quadratic sum	**0.41%**	

Table 5: Uncertainties for the calibration of a transfer chamber

IV Discussion and prospects

The primary air-kerma rate values of the LNHB for the continuous X-rays beams of medium-energies have uncertainty levels similar to the foreign counterpart laboratories.

In order to reduce the uncertainty, it would be necessary to improve the magnitude of these components. The air-kerma rate uncertainty comes mainly from W_{air}/e, measure current and product of correction factors.

To reduce uncertainty on W_{air}/e (0.15 %) requires a fundamental study on the physical parameter such as W_{air}. In the same way, the limit on the measuring accuracy of the current (0.15 %) depends on the capacitor uncertainty values.

The level of precision reached at the laboratory is ten times lower than the user's needs (for radiation protection) [13]. Nevertheless, to measure the air-kerma rate of curietherapy radionuclide which requires a calibration in X-rays beams, it is important to reduce these uncertainties.

In the continuity of this work, the LNHB develops a second standard which will be adapted to the continuous X-rays beams for low-energies from 10 kV to 60 kV.

Conclusion

The LNHB has established a primary standard for air-kerma rate in the continuous X-rays radiation of medium-energies. Forthcoming international comparisons are planned in the current of the year 2007.

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