Doses monitoring in radiology: calibration of air kerma-area product (P_{KA}) meters*

Monitoração de doses em radiologia: a calibração de medidores do produto kerma-área (P_{KA})

Ricardo Andrade Terini[1], Maria Carolina de Santana Campelo[2], José Neres de Almeida Jr.[3], Silvio Bruni Herdade[4], Marco Aurélio Guedes Pereira[5]

Abstract **Objective:** The authors have sought to study the calibration of a clinical P_{KA} meter (Diamentor E2) and a calibrator for clinical meters (PDC) in the Laboratory of Ionizing Radiation Metrology at Instituto de Energia e Ambiente – Universidade de São Paulo. **Materials and Methods:** Different qualities of both incident and transmitted beams were utilized in conditions similar to a clinical setting, analyzing the influence from the reference dosimeter, from the distance between meters, from the filtration and from the average beam energy. Calibrations were performed directly against a standard 30 cm^3 cylindrical chamber or a parallel-plate monitor chamber, and indirectly against the PDC meter. **Results:** The lowest energy dependence was observed for transmitted beams. The cross calibration between the Diamentor E2 and the PDC meters, and the PDC presented the greatest propagation of uncertainties. **Conclusion:** The calibration coefficient of the PDC meter showed to be more stable with voltage, while the Diamentor E2 calibration coefficient was more variable. On the other hand, the PDC meter presented greater uncertainty in readings (5.0%) than with the use of the monitor chamber (3.5%) as a reference.

Keywords: Kerma; Meters; Calibration; Dosimetry; Radiology; X-rays.

Resumo **Objetivo:** Neste trabalho buscou-se estudar a calibração de um medidor clínico de P_{KA} (Diamentor E2) e um calibrador para medidores clínicos (PDC) no Laboratório de Metrologia das Radiações Ionizantes do Instituto de Energia e Ambiente da Universidade de São Paulo. **Materiais e Métodos:** Diferentes qualidades de feixes incidentes e transmitidos foram utilizadas, em condições semelhantes às clínicas, analisando-se a influência do dosímetro de referência, da distância entre medidores, da filtração e da energia média do feixe. Foram feitas calibrações contra uma câmara cilíndrica de 30 cm^3 ou uma câmara monitora de placas paralelas, e indiretamente contra o PDC. **Resultados:** Observou-se menor dependência energética para feixes transmitidos; a calibração cruzada entre Diamentor E2 e PDC apresentou as maiores incertezas propagadas. **Conclusão:** O coeficiente de calibração do medidor PDC mostra-se mais estável com a tensão, enquanto o coeficiente para o Diamentor E2 varia mais. O PDC apresentou maior incerteza nas leituras (5,0%) do que quando se utilizou a câmara monitora (3,5%) como referência.

Unitermos: Kerma; Medidores; Calibração; Dosimetria; Radiologia; Raios X.

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INTRODUCTION

When radiosurgical or radiological procedures are performed, it is of utmost importance to utilize techniques that ensure the best image quality, contributing for the correct diagnosis or for the accuracy of surgical procedures. At the same time, however, it is necessary to monitor the radiation dose delivered to the patient in order to avoid immediate and future risks induced by the radiological procedures[1]. By means of a kerma-area product (P_{KA}) meter or a dose-area product (DAP) meter[2], it is possible to perform an evaluation of the air kerma integrated over the area to be irradiated, as well as, based on appropriate conversion factors[3,4], to estimate the effective dose or energy transmitted to the patient quantities, related to the risk caused by radiation.

In Brazil, although there is no regulation enforcing the utilization of such devices, it is common to utilize imported x-ray emitting apparatuses equipped with a P_{KA} meter coupled after the collimator of the x-ray tube, which may be either fixed or detachable. During the procedure, such device provides the P_{KA} values with which the technicians and physicians have to deal with. Other systems estimate the values for P_{KA} based on the equipment operational parameters. Thus, the correct evaluation of such readings is of utmost importance in

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order to ensure appropriate protection against radiation, both for the patient and the technical/medical team, which are subjected to scattered or even direct radiation during the procedures.

The kerma-area product

The quantity P_{KA}, expressed in Gy.m^2, is defined[5] as the integral of air kerma (K_a) over an area A, in an area (dxdy) of a plane perpendicular to the central axis of the x-ray beam, multiplied by the area A of the beam in the same plane (equation 1):

$$P_{KA} = \int_A K_a(x,y)\, dxdy \qquad (1)$$

Its main advantage is that its value, by definition, is independent from the distance to the tube focus (because, for a given solid angle, the K_a value is proportional to the inverse square of the distance, and the beam area varies with the square of the distance), if the air attenuation is not considered. In practice, this occurs within the uncertainty margin. Thus, P_{KA} may be measured at any plane between the collimator and the patient.

For the measurement of P_{KA}, a parallel plate ionization chamber with sufficient area to comprise the entire x-ray beam is placed at the tube's exit, after the collimator, to monitor total patient exposure. The chamber is transparent to visible light and its response is proportional to the total quantity of energy directed to the patient during the radiological procedure. The irradiated area is delimited by the collimator behind the chamber. If the beam intensity (in terms of K_a) is integrated over the area of the chamber crossed by the x-ray beam, the P_{KA} value is obtained.

The calibration of P_{KA} meters

At any measurement, the meter must be appropriately calibrated in order to provide reliable readings. The calibration of P_{KA} meters can be done in clinical environment, at the very x-ray unit where it is utilized or at a standard dosimetry laboratory[1], in those cases where it can be detached from the x-ray apparatus. Recent studies demonstrated that the obtained results and uncertainties are strongly related to the characteristics of the standard beams, the measurement geometry and to the method of calibration. Significant differences between the qualities of the clinical beams and those utilized in the calibration may reduce the reliability and increase uncertainties[6].

As the P_{KA} meter chamber is in general attached to the x-ray tube collimator, being a part of the mechanical arrangement of the emitting equipment, in most of times the chamber-electrometer system cannot be calibrated in a laboratory, but only *in loco*.

Thus, the calibration of the transmission ionization chamber + electrometer set is usually done in the examination room of the institution, based on the P_{KA} value obtained from K_a measurements by means of a reference ionization chamber, and of the irradiated area A on a film exposed at nearly the same distance of the chamber. The product of such values is compared with the reading from the clinical P_{KA} meter in determined conditions and then the calibration coefficients can then be calculated[7]. Thus, the reading from the reference values is not immediate, as the film has to be developed.

For such cases, a recently developed alternative is the patient dose calibrator (PDC) (Radcal Co.), a commercial portable equipment which provides readings of P_{KA} and K_a values, and which can, in addition, be calibrated in a laboratory and taken to the field to verify the calibration of clinical P_{KA} meters. Recent studies report, for the PDC, lower energy dependence than conventional clinical P_{KA} meters[8,9]. Additionally, the equipment entry surface has markings which make easier the incidence area delimitation of the radiation beam, by relying on the light beam from the clinical equipment collimators, thus films are not necessary anymore.

Objectives

The present study was aimed at analyzing the behavior of P_{KA} meters in different calibration conditions, as well as the quantities of influence on their accuracy and on the uncertainties, thus opening the possibility of creating such type of calibration service in the Laboratório de Metrologia das Radiações Ionizantes (LMRI) of Instituto de Energia e Ambiente da Universidade de São Paulo (IEE-USP), in order to support clinical institutions and professionals involved in the utilization of such type of equipment. The study reports the measurements performed and the analysis of the respective results comprising laboratory calibration tests of a clinical P_{KA} meter and of a PDC calibrator in previously characterized standard beams, with qualities similar to those clinically utilized. The application of a calibrated PDC meter in the verification of the calibration of clinical meters in hospital environment is also included.

MATERIALS AND METHODS

Equipment utilized

The radiation emitting source was an industrial Philips x-ray apparatus (Yxlon International X-Ray GmbH) with constant potential (maximum voltage of 320 kV), with a MCN 323 fixed tungsten anode tube (22° angle) and beryllium window, with a MGC40 controller, internal voltage divider and digital display, together with a set of lead and steel radiation field definers. The voltage was monitored by means of a digital Tektronix TDS 5104 oscilloscope with a LabVIEW (National Instruments) software. For the monitoring of environmental conditions, a Fluke model 1529 temperature meter and a model RPM4 pressure meter were utilized. For the characterization of the standard x-ray beams, lead (Pb) collimators with known area and 99.99% purity aluminum (Al) and 99.5% purity copper (Cu) filters were utilized.

In the measurements made at the LMRI of IEE-USP, the calibration of the following two P_{KA} meters was analyzed: 1) a PTW, model Diamentor E2 (DE2) clinical meter; 2) a Radcal model PDC meter. Both meters were calibrated against a standard 30 cm^3 cylindrical PTW ionization chamber model 23361, calibrated at Instituto de Radioproteção e Dosimetria/Comissão Nacional de Energia Nuclear (IRD/CNEN), or a PTW TN 34014 transmission monitoring chamber, each one of them connected to a PTW UNIDOS electrometer, also utilizing a lead collimator as the reference aperture for P_{KA} determination. Measurements have been made with standard beams of the RQR series[10], in addition to others with fixed Al or Al + Cu filtration, similar to clinically utilized qualities[11], utilizing tube voltages determined as per the practical peak voltage (PPV) parameter [12–15].

The PDC meter is designed as a calibrator of clinical P_{KA} meters. Thus, cross-calibrations of the DE2 clinical meter were also performed in lab with reference to the PDC meter[16], as well as calibration tests with clinical meters in apparatuses of Hospital Israelita Albert Einstein (HIAE), São Paulo, SP, Brazil.

Measurement of the PPV quantity

The PPV quantity was defined in papers of investigators from Physikalisch Technische Bundesanstalt (PTB), Braunschweig, Germany[12], and introduced for practical utilization by the IEC 61676[13] standard, as an electrical quantity unequivocally defined and more strongly related to the imaging contrast than other parameters most frequently utilized in calibration, maintenance and quality control of x-ray apparatuses, such as $kVp_{average}$ or $kVp_{absolute}$. Currently, PPV is recommended by International Electrotechnical Commission (IEC)[10], International Atomic Energy Agency (IAEA)[1] and International Commission on Radiation Units and Measurements (ICRU)[14] as a standard of voltage applied to radiodiagnosis tubes, in the characterization of x-ray beams to be utilized in the calibration of dosimeters and non-invasive kVp meters.

The utilization of standardized beams allows for the comparison between results from different laboratories, reproducibility analysis and greater reliability in the calibration results. The IEE-USP is accredited by Instituto Nacional de Metrologia, Qualidade e Tecnologia (Inmetro) for calibration tests of kVp meters and dosimeters.

The PPV is electrically determined[1,13] from the acquisition (preferably done with an invasive meter) of the waveform of the voltage applied to the x-ray tube during exposure, by means of the equation 2:

$$\hat{U} = \frac{\sum_{1}^{N} \omega_i . U_i}{\sum_{1}^{N} \omega_i} \qquad (2)$$

where: $\hat{U}$ is the PPV value, U_i represents the instantaneous values of the voltage applied to the tube acquired in N samplings comprising the waveform, and $\omega_i\,(U_i)$ represents the values of polynomials defined in the references 11 e 12, weighting each U_i value. In a previous issue of this journal, Terini et al.[15] analyzed the measurement of PPV in the radiological practice.

The determination of PPV requires the acquisition of the voltage waveform. In the constant potential equipment utilized at LMRI, the voltage values were directly acquired from the internal voltage divider. Such a divider was previously calibrated by comparison with the end-point value of the x-ray spectra produced by the system, measured, on their turn, by an Amptek, Inc. cadmium telluride (CdTe) detector, as per the experimental and statistical method described by Terini et al.[17]. A computer code developed by means of the LabVIEW software allowed for the acquisition of data from the voltage dividers and the calculation of the reference quantities associated with the voltage waveform: $kVp_{absolute}$, $kVp_{average}$, PPV, exposure time and ripple.

Calibration of the PTW DE2 meter

Measurement conditions (beam qualities and standard dosimeters) utilized in the calibration of the DE2 meter are shown on Table 1[18].

For incident beams, the geometry adopted in the calibration of the DE2 meter is shown on Figure 1A. For the determination of the standard P_{KA} value, the value of the air kerma rate (K_a) measured with the standard chamber was multiplied by the area (A) of the reference collimator aperture (diameter of 8.32 cm), making the correction of the focus-collimator distance (93.5 cm) relative to the focus-detector distance (99.5 cm). In such a case, data collection was done for beams of the RQR[10] series (Table 1, item 1), and then replacing the 30 cm^3 chamber by the clinical DE2 meter (Figure 1A).

Subsequently, corrections were also made for environmental conditions (temperature and pressure) (k_{TP}), for beam intensity variations, by comparison with the readings from the monitor chamber. The calculation of the calibration coefficients (N_{PKA}) was performed as per equation 3, by means of the ratio between the calculated reference P_{KA} value ($P_{KA,ref}$) and the value read on the P_{KA} meter under testing ($P_{KA,DE2}$).

$$N_{P_{K,A}} = \frac{P_{KA,ref}}{P_{KA,DE2}} = \frac{K_{ar,ref}.A}{P_{KA,DE2}} = \frac{M_{ref}.k_{TP}.f_c.k_Q}{P_{KA,DE2}} \cdot \left(\frac{D_{fd}}{D_{fc}}\right)^2 \qquad (3)$$

where: M_{ref}, f_c and k_Q are, respectively, the reading (already corrected for beam variations), the calibration factor and correction factor for the reference chamber beam quality.

Then, by using the tandem method[19,20] for transmitted beams, the DE2 meter was placed at 33.5 cm and the standard chamber at 99.5 cm from the focus (Figure 1B). In such a geometry, readings from the meters were simultaneously performed. Besides the RQR series, measurements were performed for transmitted beams with fixed 3 mmAl filtration (Table 1, items 2.a and 2.b).

In another series, DE2 meter was also calibrated by utilizing the PTW monitor chamber as a new reference (Table 1, item 2.c) after its previous calibration against the 30 cm^3 standard chamber. In such a case, the geometry was selected in such a way that a single beam integrally crossed the DE2 meter and also the monitor chamber placed at 99.5 cm from the focal spot[21].

The same previously mentioned corrections were performed in all the measurements.

Table 1 Calibration conditions utilized with the PTW DE2 meter.

1	*Incident* beam, RQR series, against 30 cm^3 chamber
2	Beam *transmitted* through the DE2 meter itself
2.a	*RQR series against the 30 cm^3 chamber*
2.b	With 3 mmAl fixed filtration against 30 cm^3 chamber
2.c	With 3 mmAl fixed filtration against monitor chamber
2.d	With 3 mmAl fixed filtration against PDC meter
2.e	With 3 mmAl + 0.1 mmCu fixed filtration against PDC
2.f	With 4 mmAl + 0.2 mmCu fixed filtration against PDC
2.g	With fixed 1.5 mmAL + 0.9 mmCu filtration, against PDC
2.h	RQR series against PDC
3	*Transmitted* beams, with 3 mmAl fixed filtration, for two distances between chamber and meter

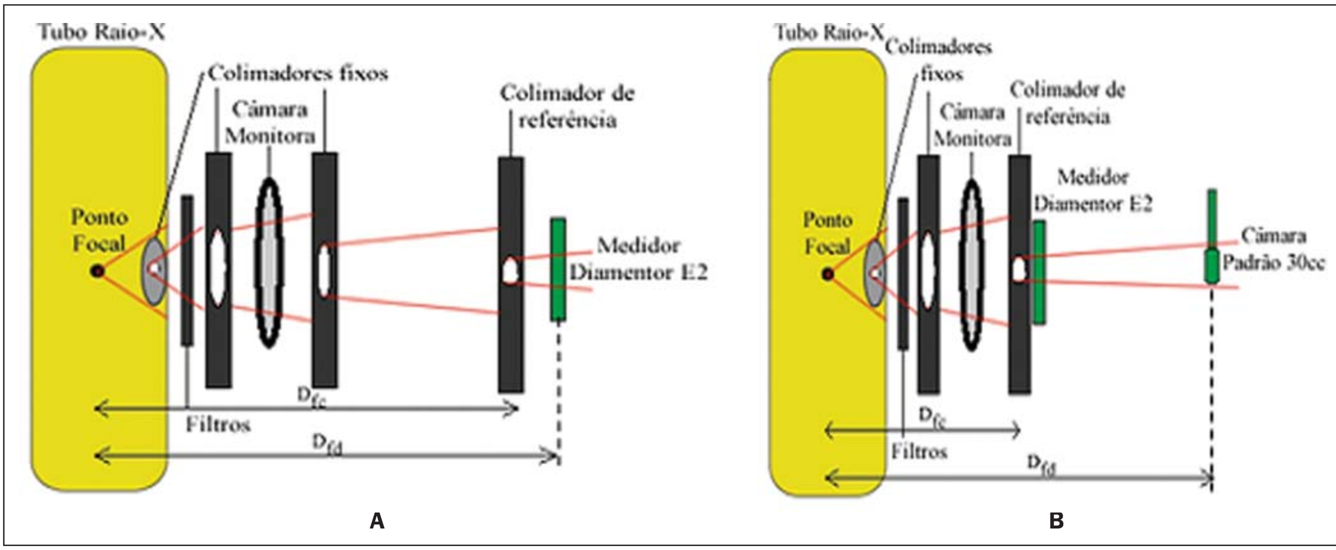

Figure 1. Geometry utilized to calibrate the PTW DE2 meter (**A**) by the substitution method against the standard 30 cm^3 chamber, for *incident* beams , and (**B**) by a tandem type method for beams *transmitted* by the meter. The additional filtration for the RQR series was previously determined. Dfc is the focus-collimator distance (93.5 cm on **A** and 33.5 cm on(**B**) and Dfd is the focus-detector distance (99.5 cm).

Calibration of the PDC meter

The PDC meter was preliminarily calibrated based on the guidance established on the IAEA document TRS 457[(1)], against the reference PTW 30 cm^3 ionization chamber, utilizing the same previous setup, with the Pb collimator with known reference area at 8.5 cm from the detectors testing point (Figure 2A).

PDC calibration was carried out by the substitution method, utilizing previously characterized standard incident beams of the RQR series and beams with fixed Al and Cu filtration (Table 1, items 2.d to 2.h). The PDC and the reference chamber were alternately positioned at 100 cm from the x-ray tube focus, as shown on Figures 1A and 1B. For the measurement of K_a, the mean K_a values read from the reference chamber were corrected for normal air density.

Calibration of the DE2 meter *vs.* PDC meter

With the PDC meter, the calibrations of the DE2 meter became similar to cross calibrations, as the PDC is designed to be previously calibrated in a laboratory and then utilized in the calibration of clinical meters, as in the case of the DE2 meter.

Thus, measurements of the DE2 meter calibration against the PDC were performed for RQR beams and with other fixed filtrations recommended by the EURAMET[(11)] Project (Table 1, items 2.e to 2.g) for inter-comparison. In all cases, simultaneous readings from both meters were done (Figure 2B), applying the appropriate corrections and determining the DE2 meter calibration coefficients as a function of PDC, according to equation 2.

In order to verify the influence of the distance on P_{KA} values, other measurements were performed for two different separations between the focus and the collimator (65.5 cm and 42.3 cm).

In all cases, combined standard uncertainties were determined in an attempt to identify the contribution of each factor to the total uncertainty. Based on the collected data, it was also possible to analyze the variation of the results with the voltage applied to the tube and with the values of half-value layer (HVL) or semi-reducing layer,

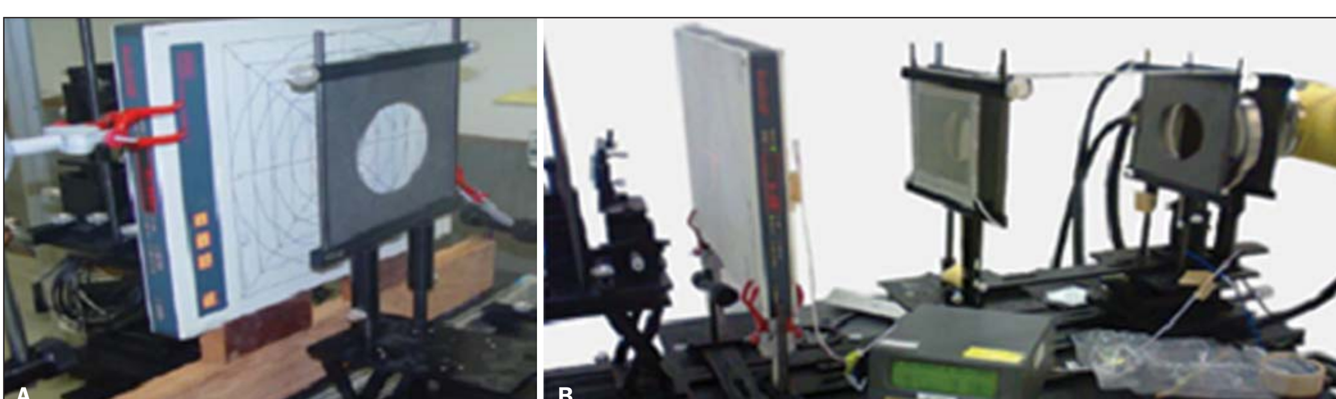

Figure 2. A: Experimental assembly in laboratory for PDC meter calibration for incident beams, utilizing the 30 cm^3 chamber as reference. **B:** Assembly for calibration of the DE2 meter against the previously calibrated PDC meter, for beams transmitted through the DE2 meter.

as well as the effectiveness of the tandem method[18].

Verification of the calibration of a P_{KA} meter in a clinical environment

For comparison, and as an application of the calibrated PDC meter in a clinical environment, the verification of a fixed P_{KA} meter (Scanditronix-IBA) calibration was made on a Philips Omni x-ray apparatus at HIAE[9]. The PDC, placed on the table in the examination room, was positioned at 80.5 cm distance from the x-ray tube focus. One should observe that, although such a distance does not coincide with the PDC calibration distance, the P_{KA} product, in this limit (as checked), is independent from the mentioned distance.

All measurements were performed for exposure times of 200 ms in radiographic mode. P_{KA} values were determined with both meters being simultaneously irradiated, in two measurement series, as follows:

1) varying the tube voltage from 50 to 120 kV, with fixed current-time product of 50 mAs, for three sizes of radiation fields (15 × 15; 20 × 20; and 25 × 25 cm^2);

2) varying the current-time product in the range from 2 to 100 mAs, with fixed tube voltage of 81 kV and field size of 20 × 20 cm^2, in order to verify the measurements linearity.

Calibration coefficients with respective uncertainties were determined for the clinical P_{KA} meter, taking into consideration the PDC calibration performed in the laboratory.

Some nominal characteristics of the P_{KA} meters utilized in the present study are: nominal accuracy (k = 2) (DE2: 0.01%; PDC: 10%; IBA: 7%), resolution (DE2: 0.01 $\mu Gy.m^2$ and 0.01 $\mu Gy.m^2/s$; PDC: 1 $\mu Gy.m^2/min$ and 0.01 $\mu Gy.m^2$; IBA: 0.1 $\mu Gy.m^2$).

RESULTS

Results from the PTW Diamentor E2 meter calibration

Table 2 shows the results from the previous characterization of the standard RQR beams[10] utilized during the calibrations, by indicating the PPV and 1st HVL (HVL_1), homogeneity coefficient ($h = HVL_1/HVL_2$), besides the determined additional filtration.

The following results refer to the calibrations performed on the DE2 meter, taking as reference: 1) the 30 cm^3 PTW chamber, for incident and transmitted through the meter beams from RQR beams (Table 3 and Figure 3) or with fixed filtration (Table 4); 2) the PTW monitor chamber previously calibrated against the 30 cm^3 standard chamber (Figure 4) for beams with 3 mmAl fixed filtration; 3) the Radcal PDC meter previously calibrated against the same standard chamber (Table 5)[22]. Lines on the charts are just for visual guidance.

Results from the calibration utilizing the PDC meter

Table 5 presents the results of the Radcal PDC meter calibration against the

Table 2 Results from the characterization of the RQR series standard beams[10], indicating the adjusted voltage and current values, the determined additional filtration, as well as the kerma rate values ($M_{c,ref}$), HVL_1 and h coefficient determined for each beam. The uncertainties (for k = 1) of the determined values are shown in parentheses beside the values, affecting the last significant digit(s) at right.

RQR	kVp_{mean} (kV)	PPV (kV)	Current (mA)	$M_{c,ref}$ (Gy/h)	HVL_1 (mmAl)	h	Aditional filtration (mmAl)
2	39.2(3)	40.0(1)	14.3	0.89(2)	1.4(1)	0.81(7)	2.176(5)
3	49.4(3)	50.0(1)	12.0	1.41(4)	1.8(1)	0.75(7)	2.174(5)
4	59.6(4)	60.0(1)	11.5	1.91(4)	2.2(1)	0.72(7)	2.334(5)
5	69.4(4)	70.0(1)	13.2	2.71(6)	2.6(1)	0.71(5)	2.583(5)
6	79.6(5)	80.0(2)	11.5	2.99(6)	3.0(1)	0.67(5)	2.684(5)
7	89.8(5)	90.1(2)	10.2	3.27(7)	3.5(2)	0.68(5)	2.792(5)
8	99.6(6)	99.9(2)	11.5	4.25(9)	4.0(2)	0.67(5)	2.967(5)
9	119.6(7)	119.9(3)	12.5	6.03(13)	5.1(2)	0.68(5)	3.353(5)
10	150.2(9)	149.9(2)	11.0	7.64(17)	6.5(3)	0.70(5)	3.695(5)

Table 3 Determined P_{KA} values and DE2 meter calibration coefficients ($N_{PKA,DE2}$) in relation to the 30 cm^3 PTW chamber, for incident and transmitted beams of the RQR series. The uncertainties presented in parentheses, for the values measured with the E2 detector, are type A only.

	Incident beams			Transmitted beams		
RQR	$P_{KA,DE2}$ ($\mu Gy.m^2/s$)	$P_{KA,ref}$ ($\mu Gy.m^2/s$)	$N_{PKA,DE2}$	$P_{KA,DE2}$ ($\mu Gy.m^2/s$)	$P_{KA,ref}$ ($\mu Gy.m^2/s$)	$N_{PKA,DE2}$
2	1.01(6)	1.48(5)	**1.46(9)**	8.04(8)	9.16(25)	**1.14(4)**
3	1.88(6)	2.51(8)	**1.34(6)**	15.39(7)	16.52(44)	**1.07(4)**
4	2.63(6)	3.24(10)	**1.23(5)**	20.66(7)	21.09(25)	**1.02(3)**
5	3.93(5)	4.60(14)	**1.17(4)**	30.54(9)	30.51(81)	**1.00(3)**
6	4.43(6)	5.09(15)	**1.15(4)**	34.20(8)	34.01(88)	**0.99(3)**
7	4.91(7)	5.55(17)	**1.13(4)**	37.60(12)	37.44(97)	**1.00(3)**
8	6.19(3)	6.90(21)	**1.11(4)**	46.88(11)	47.0(13)	**1.00(3)**
9	9.22(9)	10.22(31)	**1.11(4)**	72.63(13)	74.2(19)	**1.02(3)**
10	11.47(9)	12.94(40)	**1.13(4)**	86.22(14)	91.7(24)	**1.06(4)**

Table 4 Calibration coefficients of the DE2 meter ($N_{PKA,DE2}$) against the 30 cm^3 chamber, for incident and transmitted beams of the RQR series, and transmitted beams with 3 mmAl fixed filtration, for comparison.

PPV (kV)	$N_{PKA,DE2}$ incident RQR	$N_{PKA,DE2}$ transmitted RQR	$N_{PKA,DE2}$ transmitted 3 mmAl
40	1.46(9)	1.14(4)	1.13(4)
50	1.34(6)	1.07(4)	1.06(4)
60	1.23(5)	1.02(3)	1.01(3)
70	1.17(4)	1.00(3)	0.99(3)
80	1.15(4)	0.99(3)	0.99(3)
90	1.13(4)	1.00(3)	0.99(3)
100	1.11(3)	1.00(3)	1.00(3)
120	1.11(4)	1.02(3)	1.02(3)
150	1.13(4)	1.06(4)	1.06(4)

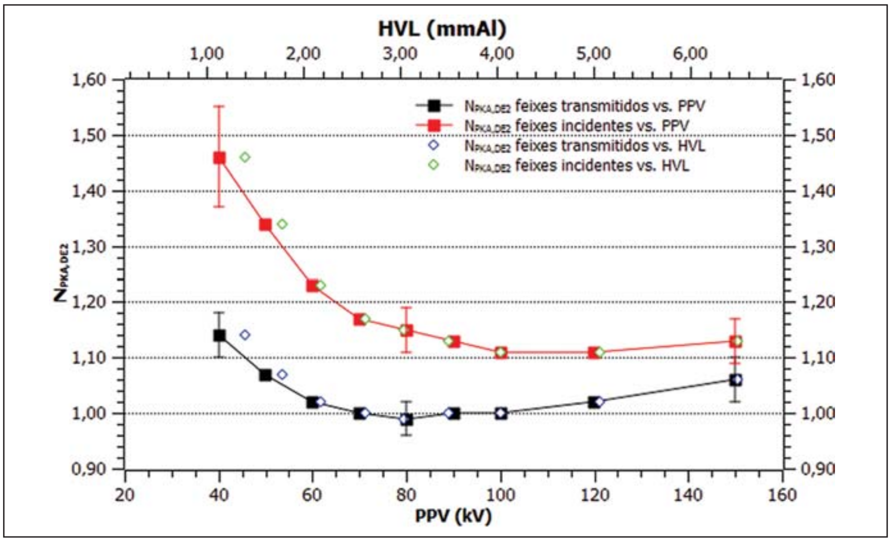

Figure 3. Energy dependence of the DE2 meter calibration for incident and transmitted beams of the RQR series (Table 4), measured against the standard 30 cm^3 chamber, as a function of PPV and of the 1st HVL.

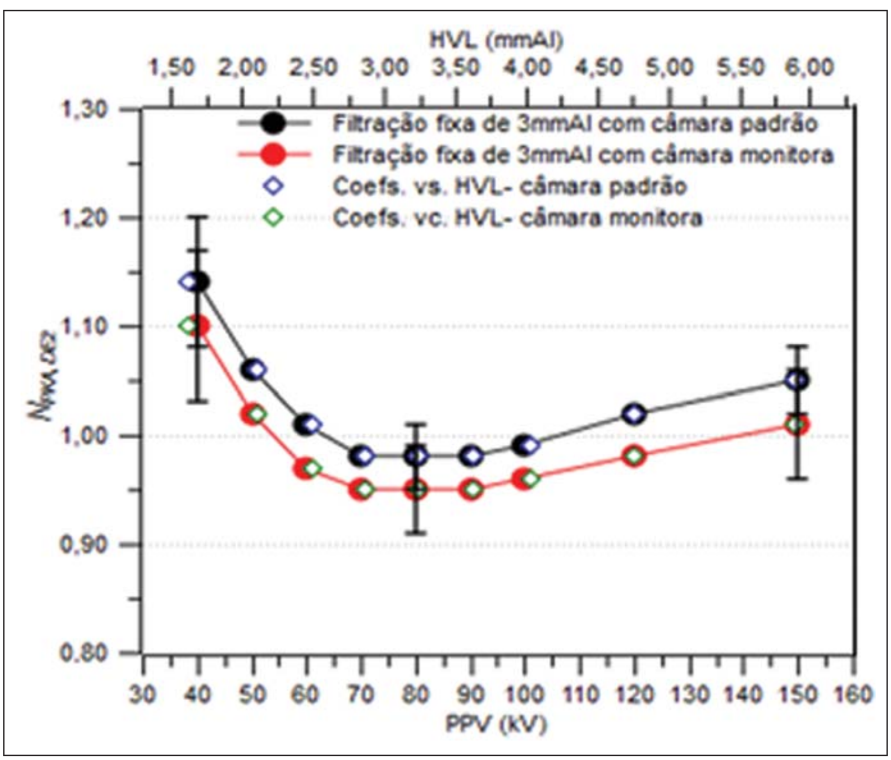

Figure 4. DE2 meter calibration coefficients for beams with 3 mmAl fixed filtration, utilizing as reference the PTW 30 cm^3 chamber (black circles) or the PTW monitor chamber (red circles), both as a function of the PPV and HVL.

30 cm^3 standard chamber, for beams *transmitted* through the chamber of the DE2 meter, as well as the calibration coefficients of the DE2 meter, against the previously calibrated PDC, for RQR beams and beams with some fixed Al and Cu filtrations.

Table 6 shows an example of the sources (in percentage values) involved in the uncertainty of the calibration coefficients. The uncertainties are always presented for k = 1.

Dependence of the DE2 meter calibration with distance

Figure 5 presents the results from the analysis of the variation of the DE2 meter calibration coefficients for two distances to the reference chamber.

Results from a P_{KA} meter calibration in clinical environment against the PDC meter

Table 7 shows the results obtained from the measurements performed at HIAE to verify the calibration ("cross" calibration) of a Scanditronix-IBA[(9)] meter, by comparison with the previously calibrated PDC meter. The P_{KA} values shown on the Table for the clinical meter were not corrected for air density, as both temperature and pressure were not monitored on the site.

Additionally, in order to analyze the PDC response linearity and compare it with that of the clinical meter, a $P_{KA} \times$ mAs chart was built (Figure 6), adjusting a straight line for each data set, by means of the minimum squares method. The uncertainties of all results are shown for the coverage factor k = 1.

DISCUSSION

Based on Table 3 and on Figure 3, it is possible to observe that the PTW DE2 meter presents lower energy dependence with beams transmitted through it than with incident beams, coherently with the geometry where it is clinically utilized. Additionally, as shown on Table 4, the energy dependence of the meter for transmitted RQR standard beams is similar to that obtained with 3 mmAl fixed filtration beams utilized in practice.

On the other hand, Figure 4 shows that the calibration coefficients for this meter, as the monitor chamber is taken as reference, are systematically lower than those with the 30 cm^3 chamber. This fact seems to indicate that, in such cases, the beams that reach the reference meters are different. In fact, one verifies that only the central portion of the x-ray beam reaches the cylindrical chamber, while in the other selected geometry, the same beam that crosses the DE2 meter also reaches the monitor chamber.

Also, based on Figure 5, one verifies that within the range of tested distances, there was no significant variation in the meter calibration coefficients.

In the analysis of "cross" calibration for different field sizes in clinical situation, it

Table 5 PDC calibration coefficients against the 30 cm^3 reference chamber, for (upper Table) beams of the RQR series and beams with fixed filtrations recommended by the EURAMET[11] Project (see Table 1), transmitted through the DE2 meter chamber, and (lower Table) cross calibration coefficients of the DE2 meter against the calibrated PDC meter.

PPV (kV)	$N_{PKA,PDC-ref}$ RQR	$N_{PKA,PDC-ref}$ 1,5 mmAl + 0,9 mmCu	$N_{PKA,PDC-ref}$ 4 mmAl + 0,2 mmCu	$N_{PKA,PDC-ref}$ 3 mmAl + 0,1 mmCu
50	1.03(6)	1.36(8)	1.15(7)	1.09(7)
80	1.01(6)	0.99(6)	1.04(6)	1.06(6)
100	0.99(6)	0.95(6)	1.01(6)	1.04(6)
120	0.98(6)	0.93(5)	1.00(6)	1.04(6)
PPV (kV)	$N_{PKA,DE2-PDC}$ RQR	$N_{PKA,DE2-PDC}$ 1,5 mmAl + 0,9 mmCu	$N_{PKA,DE2-PDC}$ 4 mmAl + 0,2 mmCu	$N_{PKA,DE2-PDC}$ 3 mmAl + 0,1 mmCu
50	1.08(6)	0.86(6)	1.00(6)	1.01(6)
80	1.01(6)	0.94(6)	0.93(6)	0.96(6)
100	1.00(6)	1.04(6)	0.98(6)	1.00(6)
120	1.03(6)	1.12(7)	1.03(6)	1.05(6)

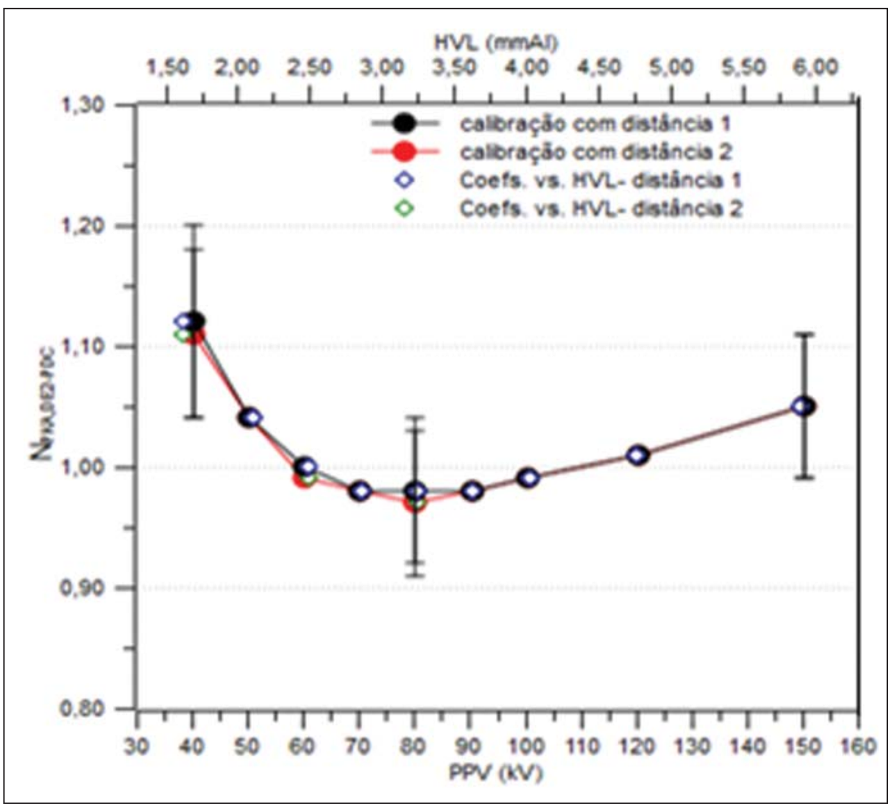

Figure 5. Results of the DE2 meter calibration against the calibrated PDC meter, for beams with 3 mmAl fixed filtration, at two different distances (65.5 cm and 42.3 cm) between focus and P_{KA} meter, ($N_{PKA,DE2-PDC}$ vs. PPV, HVL).

is possible to observe (Table 7) that the analyzed meter presented variations from –6% to +16% in relation to the standard (PDC) for all fields. For the largest field, the meter presented slightly smaller energy dependence.

Finally, Figure 6 demonstrates the degree of linearity of both meters (PDC and IBA clinical meter) within the analyzed range in clinical situation.

CONCLUSION

Measurements performed in the several calibration modes of the P_{KA} meters comprise a great part of the clinical applications of such equipment and aim at comparing its behavior for incident beams and transmitted beams which reach the patient, besides analyzing cross calibrations (as performed in hospitals) and direct calibrations performed in laboratory.

Initially, with a view on analyzing the effect of the incident beams on the device, the DE2 meter was calibrated in laboratory by the substitution method against the 30 cm^3 chamber. The results on Table 4 show that the energy dependence of the calibration coefficient ($N_{PKA,DE2}$) is greater for the initial voltages (40 to 60 kV). As the beams *transmitted* through the meter, both from the RQR series and fixed filtration beams (Table 4) are analyzed, one observes that the calibration coefficient $N_{PKA,DE2}$ presented more stable values than for incident beams (being practically constant from 60 to 120 kV). Additionally, in such cases, DE2 meter coefficients for RQR beams and those with fixed 3 mmAl filtration were similar. For example, for 60 kV and incident beams, the result was 1.23(5), while with transmitted beams, they were 1.02(3) (RQR series) and 1.01(3) (3 mmAl filtration).

On the other hand, Figure 4 shows that, as the calibration reference is modified, different calibration coefficients may be obtained as a function of the difference between the beam that crosses the P_{KA} meter and that which crosses the standard ionization chamber. Thus, it is necessary to verify which situation is closer to that utilized in the clinical practice.

In the investigation of the quantities of influence on the calibration results, Figure 5 shows the values obtained for different distances between the focus, P_{KA} meter and reference collimator. For each distance, the area of the beam which will reach the reference chamber is modified. In the investigated range, however, different areas had no significant impact on the calibration results in such a way that the meter can be utilized, at least within the investigated distance limits.

In the measurements with the PDC, beams with different fixed filtrations were utilized and, after its previous calibration, the cross calibration of the DE2 meter against the PDC meter was performed, and the characteristics of both meters could be

Table 6 Components of uncertainty (k = 1) of the DE2 P_{KA} meter calibration coefficients for 80kV voltage. Beam codes as per Table 1.

Component*	1	2.h	2.c	2.b	2.g
1	0.5%	–	–	0.5%	–
2	3.0%	–	–	3.0%	–
3	–	5.0%	5.0%	–	5.0%
4	–	6.0%	–	–	6.0%
5	0.01%	0.01%	0.01%	0.01%	0.01%
6	2.0%	2.0%	2.0%	2.0%	2.0%
7	1.3%	1.3%	1.3%	1.3%	1.3%
8	0.15%	–	0.07%	0.15%	–
9	0.15%	0.07%	0.07%	0.15%	0.07%
10	–	–	3.5%	–	–
Total relative uncertainty	**3.9%**	**8.2%**	**6.2%**	**3.9%**	**8.2%**

* Standard uncertainty components: 1. standard ionization chamber calibration coefficient; 2. reading of the air kerma meter; 3. reading of the PDC P_{KA} meter; 4. PDC calibration coefficient against the 30 cm^3 standard chamber; 5. reading of the DE2 P_{KA} meter; 6. correction for the inverse square of distance; 7. reference collimator aperture size; 8. correction factor for standard air density for the reference chamber ($k_{TP,ref}$); 9. correction factor for standard air density for the P_{KA} DE2 meter ($k_{TP,DE2}$.); 10. calibration coefficient of the monitor chamber against the 30 cm^3 standard chamber ($N_{mon\text{-}ref}$).

Table 7 P_{KA} values read from the clinical meter at HIAE and values determined with the PDC (after calibration), for three radiation fields and some voltage values. IBA meter calibration coefficients are also presented ($N_{PKA,med\text{-}PDC}$), traceable to the reference chamber of the IEE-USP LMRI.

Series	Voltage (kV)	$P_{KA,IBA}$ (µGy.m^2)	$P_{KA,PDC}$ (µGy.m^2)	$N_{PKA,med\text{-}PDC}$ (para P_{KA})
1 (25 × 25 cm^2 field)	50	48.0(17)	52.6(46)	1.10(10)
	60	78.5(27)	77.5(58)	0.99(8)
	70	111.2(39)	112.2(83)	1.01(8)
	80	145.0(51)	152(11)	1.05(9)
	90	183.6(64)	198(14)	1.08(9)
	100	222.5(78)	250(18)	1.12(9)
	110	262.8(92)	296(21)	1.13(9)
	120	345(25)	305(23)	1.13(9)
2 (20 × 20 cm^2 field)	50	23.3(8)	22.0(22)	0.94(10)
	60	37.6(13)	38.3(30)	1.02(9)
	70	70.7(25)	54.8(41)	1.02(9)
	80	70.7(25)	75.5(56)	1.07(9)
	90	89.1(31)	97.9(72)	1.10(9)
	100	108.0(38)	123(90)	1.14(9)
	110	128.1(45)	147(11)	1.15(9)
	120	155.1(54)	170(17)	1.10(9)
3 (15 × 15 cm^2 field)	50	13.1(5)	13.8(16)	1.05(13)
	60	21.1(7)	20.7(19)	0.98(9)
	70	30,0(11)	31.0(25)	1.03(9)
	80	39.9(14)	42.7(33)	1.07(9)
	90	50.6(18)	55.5(42)	1.10(9)
	100	61.2(21)	69.7(52)	1.14(9)
	110	72.0(25)	82.9(61)	1.16(9)
	120	84.0(29)	96.2(71)	1.15(9)

observed. The PDC calibration coefficient (Table 5) tends to be more stable with the voltage (above 80 kV), but the DE2 calibration coefficients present more fluctuations, particularly at higher voltages. This seems to occur due to the composition of the ionization chamber of the clinical meters, which rely on some components with higher atomic numbers in order to reach the desired transparency.

The importance of conforming the radiation beams utilized in the calibrations with those applied in the clinical practice becomes noticeable as data on Table 5 are observed. Beams with different filtrations, utilized in different radiological procedures, produce significantly different calibration coefficients for the DE2 detector, and the difference increases with the thickness of additional filtration.

At the same time, Table 6 demonstrates that the component which most affects the calibration uncertainty is the very reading of the calibrated instruments and the calibration coefficients of the reference chamber. As regards temperature and pressure, at the first measurements an Oregon meter was utilized, with a participation of 0.15%. Such participation decreased to 0.07% as the Oregon meter was replaced by a Fluke meter. The PDC device presented a greater nominal uncertainty in the readings (5.0%) than with the utilization of the monitor chamber (3.5%). The participation of this portion, when the DE2-PDC cross calibration is performed, is higher, since the uncertainties propagate.

From the data on Tables 5 and 7, one observes a smaller energy dependence of the PDC (+4% to –3%) as compared with the DE2 meter (+14% to –2%) and with the tested clinical P_{KA} meter (–2% to +16%), with the calibration factors of the latter presenting a tendency to increase with the tube voltage, in all evaluated field areas.

On the other hand, both the PDC and the analyzed clinical P_{KA} meter present an excellent linearity within the investigated intensity range (up to 700 µGy.m^2, with R ≈ 1) (Figure 6).

Uncertainties inherent to P_{KA} meters calibration are typically high, but the accuracy of the conventional calibration method (which utilizes ionization chamber + film) may, in fact, be improved by utilizing a P_{KA} meter calibrator, such as the PDC as clinical reference, provided it has previously been calibrated in a standard laboratory, in such a way it can be utilized in cross calibrations of other P_{KA} meters. It is obvious that whenever the calibration of the clinical meter can be directly made in laboratory, the accuracy will tend to be higher.

In the European Community, the utilization of the P_{KA} meters has been mandatory from several years[(23)]. In Brazil, there are still no regulation regarding this issue,

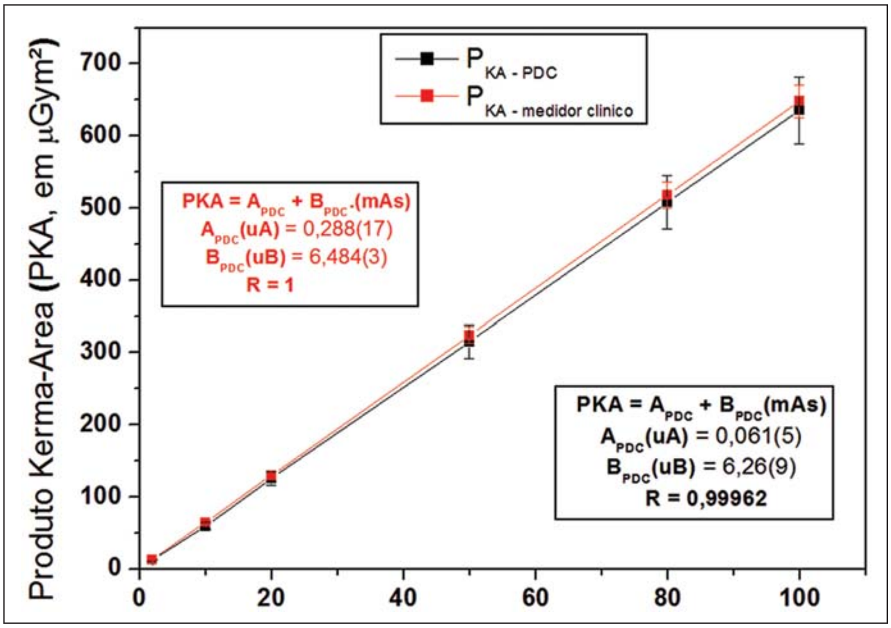

Figure 6. Variation of P_{KA} values as a function of the current-time product (mAs), for the PDC and the clinical IBA meter (linearity curve).

and currently only a limited number of institutions have such devices installed in their x-ray systems. Also, few studies on the subject are found in the literature. On the other hand, IAEA has been emphasizing the P_{KA} quantity for the improvement of dose monitoring, considering the high number of reports on radiological accidents caused by inappropriate procedures.

The utilization of P_{KA} meters is an excellent alternative for monitoring of doses on patients in clinical procedures, by clinical and technical teams; however, such meters must be periodically calibrated, which is normally a responsibility of a medical physicist. One of the objectives of the present study has been to study the calibration of such type of instrument, both in laboratory and in a clinical environment with a view on raising the awareness on this matter in the country and the implementation of such service in the LMRI of IEE-USP.

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