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Performance of a pencil ionization chamber in various radiation beams

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Abstract

Pencil ionization chambers were recommended for use exclusively in the computed tomography (CT) dosimetry, and, from the start, they were developed only with this application in view. In this work, we studied the behavior of a pencil ionization chamber in various radiation beams with the objective of extending its application. Stability tests were performed, and calibration coefficients were obtained for several standard radiation qualities of the therapeutic and diagnostic levels. The results show that the pencil ionization chamber can be used in several radiation beams other than those used in CT.

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Keywords: Pencil ionization chamber; Calibration; Standard radiation beams

1. Introduction

Pencil ionization chambers were developed for use exclusively in computed tomography (CT) dosimetric measurements. To this end, they have a special design and some particular properties. Externally, these chambers are very similar to a thimble chamber, except they are longer and thinner. The sensitive space of a typical pencil ionization chamber is 10–15 cm long, its external diameter is about 9 mm, and the volume of the sensitive space is about 3 cm³.

A typical characteristic of such chambers is the partial volume response. Therefore, the chamber readings are proportional to the irradiated length, and the instrument readings are usually given in units of dose or exposure times length. This unit allows to easily determine the computed tomography dose index (CTDI), which is the most widely used dose quantity in CT dosimetry (Nagel, 2000). A pencil ionization chamber can be used in free space or inside dosimetric phantoms.

Just a few papers about the proprieties and calibration of pencil ionization chambers have been published. Most of them date from the end of the 1970s and beginning of the 1980s, when these chambers were introduced in the clinical practice (Jucius and Kambic, 1977; Kambic and Wake, 1977; Pavlicek, 1979; Poletti, 1984; Shope et al., 1981; Suzuki and Suzuki, 1978). Recently, Bochud et al. (2001) published a very detailed paper about the calibration procedures for pencil ionization chambers. However, all these papers analyze pencil ionization chambers either in the CT clinical beams per se, or in the standard radiation beams with effective energies close to those of the CT clinical beams. The standard beams recommended by IEC for calibrating pencil ionization chambers are the RQR9 and RQA9 qualities (IEC 61267, 1994).

The aim of this work was to study the performance of a pencil ionization chamber in several radiation beams other than the CT clinical beams or the CT standard calibration beams. It is not very common to use pencil ionization chambers in other radiation beams. This study aims to show that it is possible to extend the applicability of this kind of ionization chambers. It may

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help institutions to make a better use of the ionization chambers that they have. We have chosen the CT ionization chamber for this study because it is, as yet, the only ionization chamber capable of performing CT dosimetric measurements. Therefore, it is essential that the institutions that possess CT machines would have access to these chambers.

2. Materials and methods

A Victoreen pencil ionization chamber, Model 660-6, was coupled to a Victoreen electrometer, Model 660. The sensitive volume of this chamber is 3.2 cm³, the sensitive length is 10 cm, and it is filled with atmospheric air. The physical quantity measured by this chamber is the exposure in air length product, and the electrometer readout is in old units R cm or R cm/min, with a range from 0.01 cm/min (0.001 R cm) to 999 cm/min (99.9 R cm). Because the chamber response is proportional to the irradiated length, all measurements were taken by irradiation of the whole sensitive length of the chamber.

Three X-ray systems, a ⁶⁰Co irradiator, a ¹³⁷Cs irradiator, and a ⁹⁰Sr+⁹⁰Y source were utilized in this work. The first X-rays system was an equipment for diagnostic radiology level, *Medicor Mővek Röntgengyara*, Model *Neo-Diagnomax*, which operates from 40 to 125 kV at the radiographic mode and from 45 to 100 kV at the fluoroscopic mode. Diagnostic qualities defined by IEC 61267 (1994) were used in this system, their parameters are listed in Table 1. The focus-chamber distance in the calibration procedure was 50 cm, and the beam diameter was 10 cm. The reference system for these qualities was a parallel plate ionization chamber with 1 cm³ sensitive volume, *Physikalisch-Technische Werkstätten* (PTW), Model 77334, coupled

Table 1
IEC diagnostic radiology qualities in the *Medicor Mővek Röntgengyara* equipment

Radiation quality	Voltage (kV)	Total filtration (mm Al)	Half-value layer (mm Al)	Effective energy (keV)
<i>Direct beams</i>				
RQR3	52	2.5	1.82	32.0
RQR5	70	2.5	2.45	39.2
RQR7	90	2.5	3.10	46.0
<i>Attenuated beams</i>				
RQA3	52	12.5	4.0	38.8
RQA4	63	18.5	5.7	45.6
RQA5	70	23.5	7.1	51.8
RQA6	80	29.5	8.4	57.9
RQA7	90	32.5	9.1	62.9

to a PTW electrometer, Model UNIDOS 10001. This chamber had been calibrated in air kerma and air kerma rate by PTW and is traceable to *Physikalisch-Technische Bundesanstalt* (PTB), Germany.

The second X-rays system was a low energy system *Rigaku Denki Co. Ltd.* Generator, Type *Geigerflex*, and a *Phillips* tube, Model PW 2184/00. This equipment operated from 20 to 60 kV. Conventional diagnostic radiology qualities defined by the German Norm DIN 6872 Teil 1 (1992) and the mammography qualities similar to those from the *National Institute of Standards and Technology* (NIST) (IAEA TRS 381, 1997) were used in this system. Tables 2 and 3 list parameters of these qualities. In both cases, the focus-chamber distance in the calibration procedure was 100 cm, and the beam diameter was 12 cm. The reference system for the diagnostic radiology qualities was a parallel plate ionization chamber *Nuclear Enterprises* (NE), Model 2536/3B, with an NE electrometer, Model 2560; the sensitive volume was 0.3 cm³. This chamber was calibrated in air kerma by the *National Physical*

Table 2
DIN diagnostic radiology qualities in the *Rigaku Denki* equipment

Radiation quality	Voltage (kV)	Total filtration (mm Al)	Half-value layer (mm Al)	Effective energy (keV)
DN1	31	2	0.64	19.0
DN2	40	4	2.4	28.2
DN3	50	10	4.0	38.9

Table 3
Mammography qualities in the *Rigaku Denki* equipment

Radiation quality	Voltage (kV)	Half-value layer (mm Al)	Effective energy (keV)
<i>Direct beams (total filtration: 0.06 mm Mo)</i>			
RXM20	20	0.28	13.6
RXM23	22.5	0.32	14.8
RXM25	25	0.33	15.1
RXM28	27.5	0.34	15.3
RXM30	30	0.35	15.6
RXM32	32.5	0.37	16.0
RXM35	35	0.38	16.2
<i>Attenuated beams (total filtration: 0.06 mm Mo+2 mm Al)</i>			
RXM20x	20	0.52	18.5
RXM23x	22.5	0.56	18.7
RXM25x	25	0.58	18.8
RXM28x	27.5	0.61	19.0
RXM30x	30	0.67	19.5
RXM32x	32.5	0.72	19.7
RXM35x	35	0.85	21.6
RXM20x	20	0.52	18.5

Laboratory (NPL), UK. The reference system for the mammography qualities was a parallel plate ionization chamber *Radcal Corporation*, Model $10 \times 5-6M$, with a *Radcal Corporation* electrometer, Model 9015; its sensitive volume was 6 cm^3 . This chamber was calibrated in exposure in air. It has a calibration certificate from the *Center for Devices and Radiological Health (CDRH)*, *Food and Drug Administration (FDA)*, USA, and its calibration is traceable to NIST.

The third X-ray system was from *Pantak*, Model HF320, which operates up to 320 kV. In this system, radiotherapy qualities similar to those from *Bureau International des Poids et Mesures (BIPM-01/04, 2001)*, France, were used; their parameters are listed in Table 4. The focus-chamber distance in the calibration procedure was 100 cm, and the beam diameter was 10 cm. The reference system was a cylindrical ionization chamber NE, Model 2505/3 (0.6 cm^3 sensitive volume) with a PTW electrometer, Model UNIDOS 10001. This chamber was calibrated in air kerma by *Laboratório Nacional de Metrologia das Radiações Ionizantes (LNMRI)*, Brazil; the calibration is traceable to BIPM.

The ^{60}Co irradiator was a teletherapy unit from *Keleket Barnes Flexaray*, USA, Model IS, with 0.339 TBq of nominal activity (September 1999). The source-chamber distance at the calibration procedure was 200 cm, and the beam was $20 \times 20 \text{ cm}^2$. The reference system for this quality was the same as for the *Pantak* X-ray system, but with an additional 4-mm-thick PMMA cap to provide electronic equilibrium; it was also calibrated in air kerma.

Table 4
BIPM radiotherapy qualities in the *Pantak* equipment

Voltage (kV)	Additional filtration (mm)	Half-value layer (mm)	Effective energy (keV)
100	1.204 Al	4.027 Al	37.9
135	0.232 Cu	0.494 Cu	66.0
180	0.484 Cu	0.990 Cu	82.2
250	1.570 Cu	2.500 Cu	143.2

Note: The inherent filtration was adjusted to be 2.3 mm Al.

The ^{137}Cs irradiator was a system from *Steuerungstechnik Strahlenschutz GmbH*, Model 0B85, Germany, with nominal activity of 740 GBq (April 1995). The source-chamber distance at the calibration procedure was 131 cm, and the beam diameter was 34 cm. The reference system used for this quality was a spherical ionization chamber with a 1-l sensitive volume, PTW, Model LS-01, with a PTW electrometer, Model UNIDOS 10001. This chamber was calibrated in air kerma, and it has a calibration certificate from PTW traceable to PTB.

The $^{90}\text{Sr} + ^{90}\text{Y}$ source is a part of the beta radiation secondary standard, *Buchler Sekundärnormal*, with a calibration certificate from PTB. It has a nominal activity of 1.85 GBq (February 1981). The source-chamber distance at the calibration procedure was 30 cm, and the beam diameter was 10 cm. The calibration certificate contains absorbed dose rates for various distances.

In all the cases, the ionization chambers were irradiated free in air.

3. Results and discussion

3.1. Repeatability and reproducibility tests

For a test of the repeatability of its response, the pencil ionization chamber was repeatedly exposed to a check source under reproducible conditions. A $^{90}\text{Sr} + ^{90}\text{Y}$ check source (PTW; 11.1 MBq, 1976) was used, and a special acrylic support shown in Fig. 1 was developed for this test. According to IEC 61674 (1997), the maximum acceptable coefficient of variation for the CT specific chambers is 1%. The highest coefficient of variation observed in this test was just 0.32%.

As a reproducibility test, results of multiple repeatability tests performed at different times were compared with each other in order to characterize the long-term stability of the chamber. According to IEC 61674 (1997), the value obtained in each test must not differ from the reference value by more than 3%. As Fig. 2 demonstrates, all deviations were within the acceptable range.

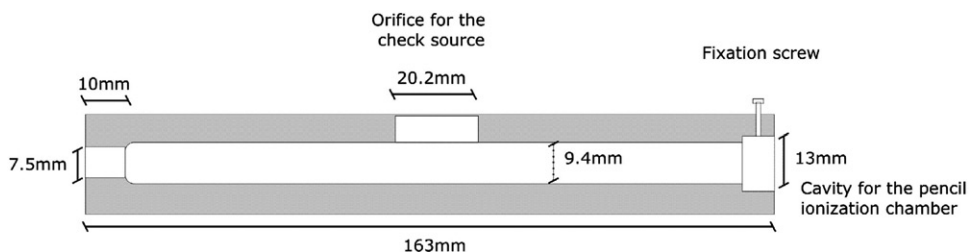


Fig. 1. Acrylic support for repeatability tests of the pencil ionization chamber.

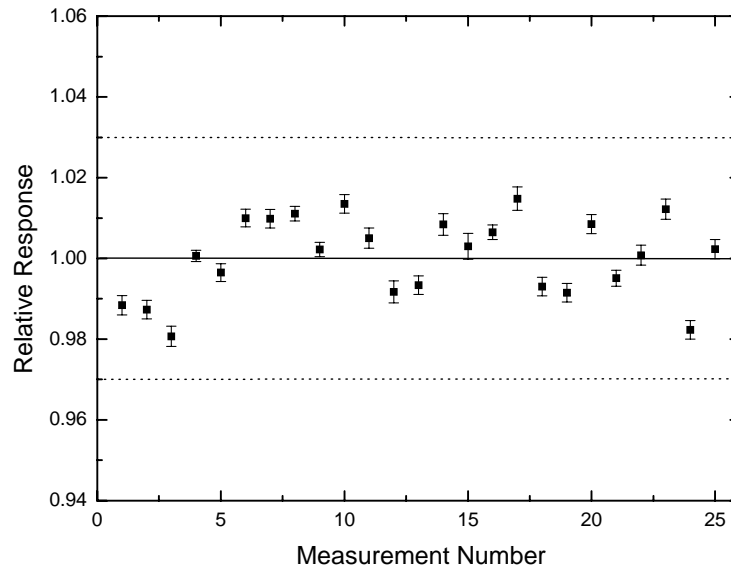


Fig. 2. Results of the reproducibility test of the Victoreen pencil ionization chamber.

Table 5

Calibration coefficients for the Victoreen pencil ionization chamber, Model 660-6, in diagnostic radiology standard beams

Radiation quality	Calibration coefficient (dimensionless)	Energy dependence (%)
RQR3	1.044 ± 0.026	1.3
RQR5	1.058 ± 0.026	
RQR7	1.052 ± 0.024	
RQA3	1.029 ± 0.050	14.5
RQA4	1.126 ± 0.036	
RQA5	1.178 ± 0.040	
RQA6	1.169 ± 0.036	
RQA7	1.173 ± 0.032	
DN1	1.06 ± 0.02	2.9
DN2	1.04 ± 0.03	
DN3	1.03 ± 0.11	

It was not possible to measure the effect of the leakage current in the chamber because of its manual zero adjustment.

3.2. Calibration

Calibration coefficients (Meghzifene and Shortt, 2002) of the pencil ionization chamber were obtained for all the radiation qualities described above, they are listed in Tables 5–8. These coefficients represent ratios of the exposure rate obtained with the corresponding reference system to the exposure rate obtained with the pencil

Table 6

Calibration coefficients for the Victoreen pencil ionization chamber, Model 660-6, in the mammography standard beams

Radiation quality	Calibration coefficient (dimensionless)	Energy dependence (%)
RXM20	1.06 ± 0.09	5.0
RXM23	1.04 ± 0.08	
RXM25	1.03 ± 0.08	
RXM28	1.03 ± 0.08	
RXM30	1.02 ± 0.08	
RXM32	1.02 ± 0.08	
RXM35	1.01 ± 0.08	2.0
RXM20x	0.99 ± 0.11	
RXM23x	1.00 ± 0.10	
RXM25x	0.99 ± 0.09	
RXM28x	1.00 ± 0.09	
RXM30x	1.00 ± 0.09	
RXM32x	1.00 ± 0.09	
RXM35x	1.01 ± 0.09	

ionization chamber. In the cases where the reference systems had been calibrated in air kerma, the conversion factor 114.155 R/Gy (ICRU 47, 1992) applicable to measurements in free air was used. In determining the exposure rates with the pencil ionization chamber, we divided the results of the measurements (corrected for ambient conditions) by the chamber length. The overall uncertainties were computed by combining the Type A and Type B uncertainties; they are presented in the form of 95% confidence intervals. All calibration coefficients

Table 7
Calibration coefficients for the Victoreen pencil ionization chamber, Model 660-6, in radiotherapy standard X radiation beams

Radiation quality	Calibration coefficient (dimensionless)	Energy dependence (%)
BIPM (100 kV)	1.120 ± 0.009	7.4
BIPM (135 kV)	1.093 ± 0.009	
BIPM (180 kV)	1.071 ± 0.007	
BIPM (250 kV)	1.043 ± 0.007	

Table 8
Calibration coefficients for the Victoreen pencil ionization chamber, Model 660-6, in gamma and beta radiation standard beams

Radiation quality	Calibration coefficient (dimensionless)	Energy dependence (%)
^{60}Co	0.94 ± 0.05	6.4
^{137}Cs	1.00 ± 0.07	
^{90}Sr	0.981 ± 0.011	–

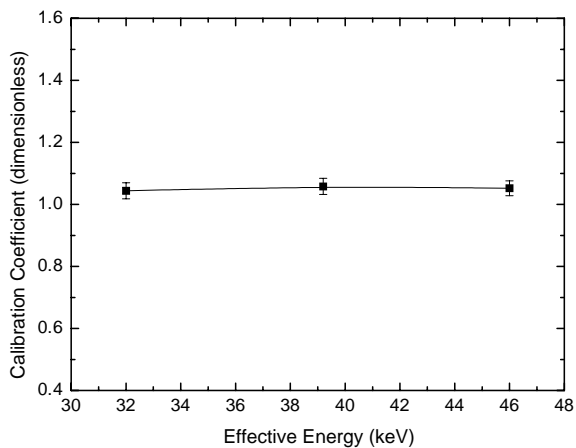


Fig. 3. Energy dependence of the response of the Victoreen pencil ionization chamber. IEC diagnostic radiology qualities, direct beams, in the *Medicor Mövek Röntgengyara* equipment; focus-detector distance 50 cm.

obtained are dimensionless, because the conversion factors from exposure in air into air kerma were excluded from the final results.

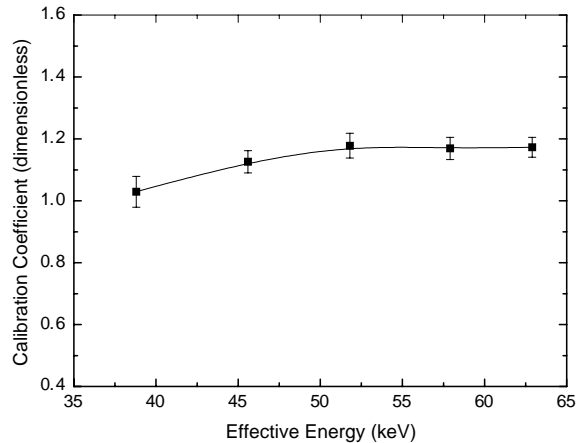


Fig. 4. Energy dependence of the response of the Victoreen pencil ionization chamber. IEC diagnostic radiology qualities, attenuated beams, in the *Medicor Mövek Röntgengyara* equipment; focus-detector distance 50 cm.

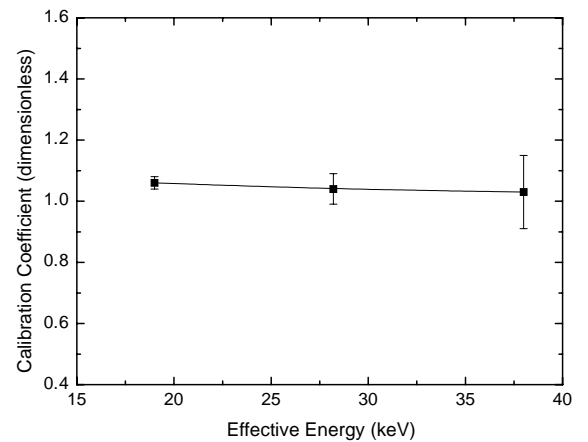


Fig. 5. Energy dependence of the response of the Victoreen pencil ionization chamber. DIN diagnostic radiology qualities in the *Rigaku Denki* equipment; focus-detector distance 100 cm.

As can be seen in Table 5, the uncertainty in the calibration coefficient for the DN3 quality is higher than the uncertainties in the coefficients for the other DIN qualities. This is because the measured air kerma rates for this quality were much lower than the rates for the other DIN qualities.

3.3. Energy dependence

Tables 5–8 also show the energy dependence (the difference between the highest and the lowest calibration coefficients in percent) of the pencil ionization chamber. The energy dependence curves for each group of the

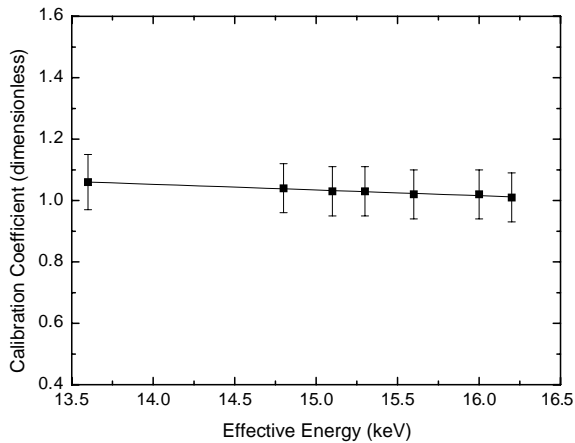


Fig. 6. Energy dependence of the response of the Victoreen pencil ionization chamber. Mammography qualities, direct beams, in the *Rigaku Denki* equipment; focus-detector distance of 100 cm.

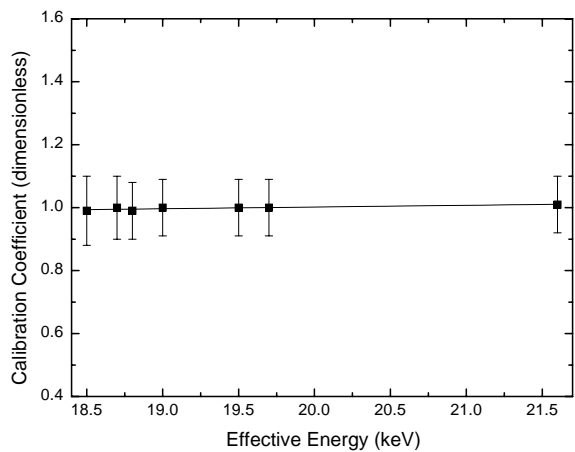


Fig. 7. Energy dependence of the response of the Victoreen pencil ionization chamber. Mammography qualities, attenuated beams, in the *Rigaku Denki* equipment; focus-detector distance 100 cm.

qualities are shown in Figs. 3–8. For beta radiation ($^{90}\text{Sr}+^{90}\text{Y}$), the calibration coefficient is presented in Table 8.

One can see from the figures that the energy dependence is low for all the studied radiation beams. The maximum difference between the chamber measurements and the “real” air kerma length rate was 18%. This demonstrates that the tested pencil ionization chamber can be used in several types of radiation beams, even in those that are not typical of CT. However, a separate calibration is necessary for each quality.

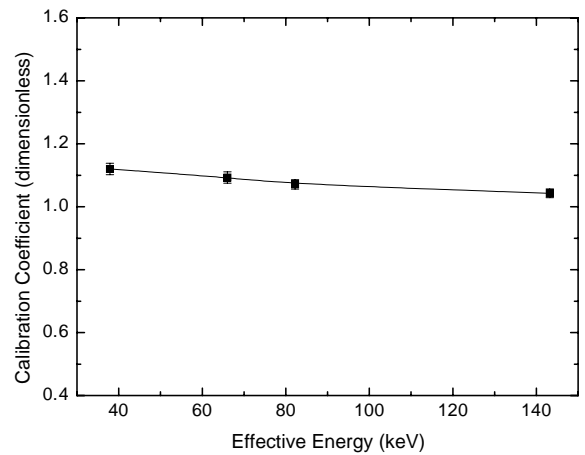


Fig. 8. Energy dependence of the response of the Victoreen pencil ionization chamber. BIPM radiotherapy qualities in the *Pantak* equipment; focus-detector distance 100 cm.

4. Conclusions

Pencil ionization chambers were developed for use only in CT beams. This study shows that their use can be extended to other types of radiation (gamma, X, and beta). This can be helpful, for instance, in situations where one needs to compare dosimetry data for non-CT beams in order to clarify dubious results obtained by other means. However, it is always critically important to make sure that the whole sensitive length of the chamber is irradiated in order to avoid problems due to a partial volume response. All the observed discrepancies between the results produced by the pencil ionization chamber and the reference techniques were within the limits officially regarded as acceptable.

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