THE IMPACT OF FIELD SIZE AND RADIATION QUALITY ON KAP-METER AND CT-CHAMBER RESPONSE

by

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Kerma-area product and kerma-length product are important practical dosimetric quantities used in diagnostic radiology. These quantities are measured by special types of dosimeters which are calibrated in standard radiation qualities established in calibration laboratories. However, in clinical practice the dosimeters are used in different conditions, including the radiation quality and field size. In this paper, energy and field size dependence are studied for both types of dosimeters. One dosimeter of each type is tested. The KAP-meter has shown significant dependence on both radiation quality and field size, while the dependence of the CT-chamber is much less pronounced. Two different approaches can be used to correct for the difference between conditions during calibration and in clinical practice. When the clinical beam is well characterized and energy and field size dependence of the dosimeter are well known, the optimum solution is to apply the adequate correction factor to the measurements, keeping measurement uncertainty as low as possible. If this is not the case, the above limitations must be taken under consideration in the calculation of the expanded uncertainty budget.

Key words: kerma-area product, kerma-length product, energy response, field size, dosimetry, metrology, diagnostic radiology, calibration

INTRODUCTION

Ionizing radiation has been used for medical purposes for over a century. According to the UNSCEAR report, the number of annual medical exposures in the world is measured in billions [1]. Currently, several radiation sources are in widespread use: X-ray units, including mammography units and computed tomography (CT) scanners, open and closed radionuclide sources and accelerators. These sources are used in different medical practices: diagnostic radiology (including the procedures guided by the image obtained by radiation), radiotherapy and nuclear medicine. The safe use of radiation sources for medical purposes is of great concern and the concerns include medical exposure, as well as occupational exposure and the exposure of the general public [1]. Due to the wide variety of source types, medical practices and applications, the instrumentation used for dosimetry in clinical applications is very diverse and so are the calibration procedures, accuracy requirements and operation procedures.

Diagnostic radiology examinations account for more than half of the annual per capita effective dose arising from artificial sources. The number of medical examinations is rising every year and although the effective dose per examination is falling, the collective effective dose is rising. In the last decades, there was a significant increase of the number of CT examinations and CT has become the most important artificial source, accounting for almost half the effective dose resulting from artificial sources [1, 2].

Two physical quantities are used in quality control and radiation protection in diagnostic radiology: air kerma-area product (KAP or P_{KA}) and air kerma-length product (P_{KL}). P_{KA} is used in radiology, fluoroscopy and interventional procedures and P_{KL} is used for CT applications. These quantities are measured by two specially designed dosimeters, KAP-meters and CT-chambers [3]. Due to large dose contributions of diagnostic radiology procedures, the optimization of radiology procedures and quality control are of great importance,

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while the accuracy of measurements performed by KAP-meters and CT-chambers must be as high as possible.

During the clinical use of CT-chambers and KAP-meters many problems may arise, mainly because of the use of dosimeters in conditions significantly different from calibration conditions. Moreover, in many cases differences can result in significant errors in the measured quantities if the appropriate corrections are not applied or if the wrong calibration and correction factors are used. The two most important factors are the energy spectrum and the field size. Several previously published studies found a significant influence of these quantities on KAP-meters' response [4-6]. Studies performed on commercial [7] and custom made [8] CT-chambers found a much smaller dependence of these quantities.

One way to overcome the differences is by performing *in-situ* calibrations [9], provided that the reference dosimeter's energy and field size dependence of response is known and taken into account in calibrations. In this paper, an alternative approach to this problem will be adopted and it will be shown how the correction factors for these influence quantities can be determined, or alternatively, how their influence can be taken into account in the uncertainty budget.

THEORY AND METHODS

Air-kerma area product and air-kerma length product are special dosimetric quantities primarily used in diagnostic radiology. Quantity P_{KA} is used in various medical imaging modalities such as radiography, fluoroscopy, and interventional radiology to estimate organ doses, effective doses, establish diagnostic reference levels and for quality control [4, 10] ; P_{KL} is used for estimating patient doses in computed tomography, establishing dose reference levels, *etc*. [2, 11, 12]. Dosimeters used for measuring these two quantities are usually ionization chambers. In the case of P_{KA}, they are plane parallel transmission chambers, designed to interact with the radiation beam minimally. They can be calibrated to measure incident P_{KA} (used mainly for quality control purposes) and transmitted P_{KA} (used for patient dose estimation) [3]. In this paper, dosimeters of this type will be called KAP-meters. P_{KL} is usually measured by pencil shaped ionization chambers and will be referred to as CT-chambers.

P_{KA} is defined as the air-kerma integral over the irradiated area in X-ray beam in plane perpendicular to beam axis. If air-kerma is denoted by K_a, irradiated area by A and space dimensions by x and y, P_{KA} can be expressed by [3]

$$P_{KA} \quad \int_A K_\alpha \mathrm{d}x\mathrm{d}y \tag{1}$$

P_{KL} is analogously defined as air-kerma integral over the irradiated length. If length is denoted by L, then P_{KL} can be expressed by eq. (2) [3].

$$P_{KL} \quad \int_L K_\alpha \mathrm{d}x \tag{2}$$

In clinical settings, calibrations of KAP-meters can be performed by direct comparison with reference dosimeters of the same type. However, in reference dosimetry laboratories, the reference value of air kerma at the plane of measurement is determined and multiplied by the irradiated area or length at the same plane of measurement to obtain the reference value of P_{KA} or P_{KL}. This calibration method is described in the International Atomic Energy Agency (IAEA) Technical Report Series (TRS) 457 [3]. In standard set-up, focus to detector distance (FDD) is 100 cm. An aperture is positioned at approximately 95 cm from the focus, in order to limit the field size. Aperture dimensions, distance from the focus and dosimeter should be precisely known, because the field size at the plane of measurement is of critical importance for calibrations in terms of P_{KA} or P_{KL}. It is also important that both the aperture and the detector are perpendicular to the beam axis. For 100 mm length CT-chamber calibrations, the recommended aperture length is between 20 mm and 50 mm and the width approximately 2 chamber diameters. For KAP-meters, the aperture should be circular with a 50 mm diameter, or square with dimensions 50 mm × 50 mm [3]. The field size at the plane of measurement is calculated according to IAEA TRS 457 [3].

Due to the difference in application of KAP-meters and CT-chambers, their calibrations are also performed in different radiation qualities. KAP-meters are calibrated in RQR series (IEC standard 61267 [13]) .These qualities correspond to the primary beams used in fluoroscopy and radiography. X-ray tube voltage is between 40 kV and 150 kV and the first half value layer (HVL) between 1.42 mm Al (millimeter of aluminum equivalent) and 6.57 mm Al. On the other hand, CT-chambers are calibrated in RQT series, which corresponds to primary beams in computed tomography [13]. These qualities have a higher mean energy than RQR series qualities and the first HVL are between 6.9 mm Al and 10.1 mm Al. The tube voltage is between 100 kV and 150 kV.

The calibration factor is determined as the ratio of the reference value of a quantity to the instrument's indication corrected for air density and is calculated for different energy qualities and field sizes. The response of the instrument is defined as the inverse of the calibration factor. The energy dependence of the instrument is determined by plotting instrument response versus the different RQR or RQT qualities mean energies. In diagnostic radiology, the first HVL is usually used to characterize the energy spectrum. Dependence on the beam size is determined by plotting instrument response versus beam size [3].

EXPERIMENTAL PROCEDURE

All measurements were performed in the Secondary Standard Dosimetry Laboratory (SSDL) of the Greek Atomic Energy Commission (EEAE). Irradiations were performed using the PANTAK PMC1000 X-ray unit. Reference values of air kerma were measured using the working standard ionization chamber Inovision 96035B, traceable to the primary standard of Physikalisch-Technische Bundesanstalt (PTB). For the purposes of this paper, two instruments were studied: KermaX – plus DDP TinO (IBA Scanditronix model 120-205) KAP-meter and Radcal model 9010 CT chamber.

KAP-meter response

The irradiation scheme for KAP-meter irradiation is given in fig. 1. The scheme is simplified and doesn't show inherent and added filtration of the X-ray unit, apertures (other than A1) and the shutter. Aperture A1 is used to delimit the irradiation field at KAP-meter position. The field size is chosen so that about 50 % of KAP-meter surface is irradiated. The KAP-meter is used in position 2 only when transmitted kerma reference values are determined, in order to simulate beam absorption. The reference point of the KAP-meter was the center of the entrance window for incident kerma calibration and the center of the back window for transmitted kerma calibration. The reference chamber is positioned in the adequate position for incident and transmitted irradiation. The source to chamber distance (SCD) was 1000 mm for incident kerma calibration and 1016 mm for transmitted kerma calibration. The reference value of air kerma was measured at both distances. KAP-meter position 1 was the same in both instances.

The distance between the front side of the aperture and the entrance window of the KAP meter (DCD) was 56.2 mm and the thickness of the aperture was 5 mm. The distance between the aperture and the entrance window of the KAP-meter (d_{inc}) was 51.2 mm and this distance was used to calculate the dimensions of the incident beam. The distance between the aperture and the rear surface of the KAP-meter (d_{trans}) was 67.2 mm, and this distance was used for transmitted air kerma measurements.

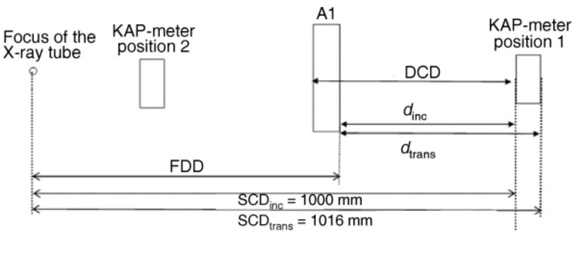

Figure 1. Measurement set-up used during KAP-meter calibrations

Table 1. Properties of the radiation qualities from RQR series used for P_{KA} measurements

Beam quality	Tube voltage [kV]	Current [mA]	Additional tube filtration* [mm]	HVL [mm]
RQR 3	50	20	2.22 Al	1.81Al
RQR 5	70	25	2.70 Al	2.58 Al
RQR 6	80	20	2.85 Al	2.95 Al
RQR 8	100	10	3.20 Al	3.98 Al

* Inherent tube filtration consists of 3 mm Be and 5.2 mm PMMA

Three quadratic apertures with dimensions of 50 mm × 50 mm, 80 mm × 80 mm and 100 mm × 100 mm were used for the evaluation of field size dependence. The field sizes for three different apertures at the position of the chamber were 2780 mm^2, 7110 mm^2, and 11100 mm^2 for incident air kerma and 2870 mm^2, 7340 mm^2, and 11500 mm^2 for transmitted air kerma.

Four RQR series qualities were chosen for P_{KA} measurements: RQR 3, RQR 5, RQR 6, and RQR 8. The qualities were established according to IEC 61267 [13] and their properties as determined by measurements are presented in tab. 1.

CT-chamber response

The set-up used for the determination of the response of the CT-chamber is shown in fig. 2. The scheme was simplified in the same way as for P_{KA} measurements and the aperture A1 limits the irradiated length of the CT-chamber. In this case, the determination of the reference value of air kerma is performed without aperture, so the reference chamber dimensions are not critical.

Three apertures with the length (dimension parallel with the axis of CT chamber) of 20 mm, 30 mm, and 50 mm were used and the irradiated length of the CT chamber was 21.8 mm, 32.7 mm, and 52.6 mm, respectively. Additional measurements were performed without aperture, in which case the nominal active length of the CT-chamber was used in calculations – 100 mm.

Three qualities from the RQT series were used for P_{KL} measurements: RQT 8, RQT 9, and RQT 10. The qualities were established by adding filtration to

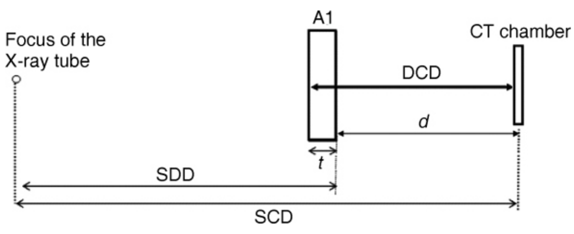

Figure 2. Measurement set-up used during CT-chamber calibrations

Table 2. Properties of the radiation qualities from RQT series used for CT-chamber measurements

Beam quality	Tube voltage [kV]	Current [mA]	Additional tube filtration* [mm]	HVL [mm]
RQT 8	100	20	3.20 Al + 0.20 Cu	7.05 Al
RQT 9	120	20	3.55 Al + 0.25 Cu	8.41 Al
RQT 10	150	15	4.25 Al + 0.30 Cu	10.39 Al

* Inherent tube filtration consists of 3 mm Be and 5.2 mm PMMA

the established RQR qualities, according to IEC 61267 [13] and their properties as determined by measurements are presented in tab. 2.

RESULTS

KAP-meter

KAP-meter energy dependence and dependence on the field size were determined for incident and transmitted radiation beams separately. The KAP-meter response was normalized to a response determined by using RQR 5 radiation quality and a 5 cm 5 cm aperture. Absolute values of the KAP-meter response for reference conditions were 1.020 for incident air kerma and 1.129 for transmitted. Combined and expanded measurement uncertainty ($k = 2$) for KAP-meter calibration was 3.8 %.The response dependence on energy and field size is displayed in fig. 3 for incident air kerma and in fig. 4 for the transmitted air kerma.

The results show similar trends for incident and transmitted air kerma. The response declines with the field size for all investigated radiation qualities and both measurement set-ups. The difference in response for the minimum and maximum field size is between 6 % and 9 %. On the other hand, energy dependence is almost flat between qualities RQR 5 and RQR 8, with the maximum difference being 3.5 %. The difference between RQR 3 and the reference quality is up to 9 %.

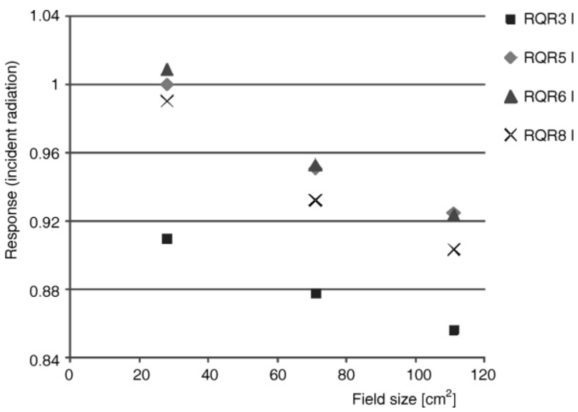

Figure 3. Response of the KAP-meter *vs.* the field size for the incident radiation for different radiation qualities of the RQR series, normalized to the response determined for RQR 5 reference quality

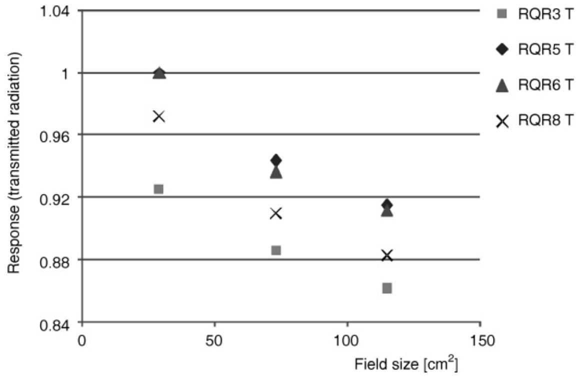

Figure 4. Response of the KAP-meter *vs.* the field size for transmitted radiation for different radiation qualities of the RQR series, normalized to the response determined for RQR 5 reference quality

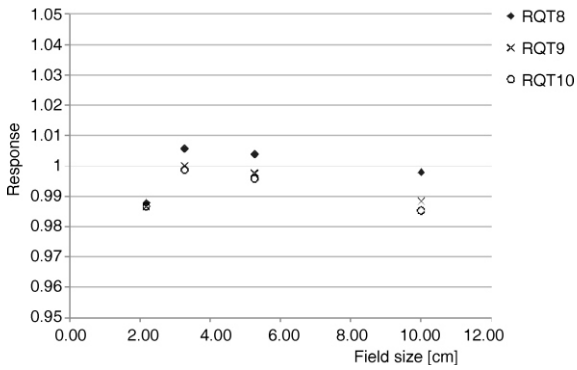

Figure 5. Response of the CT-chamber *vs.* the field size for different radiation qualities from the RQT series, normalized to the response determined for RQT 9 reference quality

CT-chambers

CT-chamber response was determined for 3 radiation qualities and 4 field sizes. The response was normalized to RQT 9 radiation quality, which is the reference quality for the RQT series in diagnostic radiology and 3 cm aperture. The results are shown in fig. 5. Combined and expanded measurement uncertainty ($k = 2$) for CT-chamber calibration was 2.9 %.

Results show that the CT-chamber response decreases monotonously with radiation energy, but the differences are small – less than 1.5 %. The response is also dependent on the field size and the maximum difference occurs between approximately 2 cm and 3 cm – just under 2 %.

DISCUSSIONS

It is evident from the results that there is a significant dependence of the KAP-meter response on radiation quality and field size. The dependence of the CT-chamber is less pronounced, but still needs to be taken into account. If the dependence is ignored and the dosimeters are used in conditions different from calibration conditions, a systematic error will be introduced into measurements and measurement uncertainty would be underestimated.

These problems can be approached in two different ways, depending on the practice and need for accuracy. The first approach is the use of correction factors, the second the expansion of the uncertainty budget.

In order to apply correction factors, a necessary condition is that the radiation quality and field size are known for every measurement that is performed, which is not always the case. Another condition is that the energy dependence and dependence on field size of the dosimeter were determined in a calibration laboratory. The dependence can be presented graphically, as in figs. 3-5, in which case the correction factor can be determined by interpolation for any radiation quality and field size. It is also common to provide tabular representation of these data. In both cases, extrapolation is strongly discouraged, especially on the side of low energies. A problem with this approach is that in some practices (interventional radiology, pediatrics) copper filtration is often used together with aluminum filtration, causing beam hardening. Radiation qualities established in this manner have HVL that are not covered by international standards [14]. Another problem is the measurement uncertainty associated with measuring HVL and field size in clinical conditions, which is often significant.

When low measurement uncertainty is not of critical importance, or when it is difficult to determine radiation quality, or energy (and field size) dependence of the instrument is not known, it is not possible to apply correction factors. However, even if no correction is applied, the effects of radiation energy and field size still exist and must be taken into account. In these cases, it is necessary to expand the uncertainty budget to allow for these influences. Measurement uncertainty can be estimated based on measurements performed in a calibration laboratory, type testing or based on the technical data provided by the manufacturer.

Data represented in figs. 3-5 can be used to estimate measurement uncertainty for P_{KA} and P_{KL} measurements due to the unknown radiation quality and field size. From figs. 3 and 4, it can be seen that the difference between the minimum response and response in reference quality is 9 %. If rectangular probability distribution is assumed, the standard uncertainty is calculated by dividing the interval by 2 and by the coverage factor, which is 1.73 for rectangular distribution. The calculated standard uncertainty is 2.6 %. The same approach is applied to the influence of field size, which yields the same uncertainty. Finally, the combined standard uncertainty of these two influences is 3.7 %.

Measurement uncertainty for P_{KL} measurements can be estimated from fig. 5. In this case, standard uncertainties introduced by radiation quality and field size are 0.43 % and 0.58 %, respectively. The combined standard uncertainty arising from these two influences is 0.72 %. It is important to note that the values for standard uncertainty presented in this paper are valid only for these specific chambers and must be estimated for each chamber type separately.

CONCLUSIONS

The response of instruments used for ionizing radiation measurements in clinical practice often shows a more or less significant dependence on various influence quantities, among which are radiation energy and field size. A significant error might arise if the instruments are used in clinical practice in conditions different from reference conditions during calibration without appropriate corrections. In order to perform corrections, several conditions must be met: actual conditions during clinical use must be known, a calibration factor for reference conditions must be known and applied and correction factors for influence quantities obtained and applied from graphs or tables. If it is not possible to perform corrections, these effects must be taken into account by expanding the measurement uncertainty budget.

In the two examples, it is shown that P_{KA} can be underestimated as much as 16 % and P_{KL} 2 % when commercially available instrumentation is used without applying appropriate corrections.

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AUTHORS' CONTRIBUTIONS

The manuscript was written by M. Z. Živanović and N. Lj. Kržanović, the figures prepared by N. Lj. Kržanović. Measurement set-up was conceived and prepared by A. G. Boziari and the measurements were performed by M. Z. Živanović, N. Lj. Kržanović, Dj. R. Lazarević, and P. A. Konstantinou. All authors analyzed and discussed the results and reviewed the manuscript. The theoretical analysis was carried out by A.G. Boziari and Dj. R. Lazarević.

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УТИЦАЈ ВЕЛИЧИНЕ ПОЉА И КВАЛИТЕТА ЗРАЧЕЊА НА ОДЗИВ КАП-МЕТРА И ЦТ-КОМОРЕ

Производ керме и површине и производ керме и дужине су важне специјалне дозиметријске величине које се користе у дијагностичкој радиологији. Ове величине мере се помоћу специјалних типова дозиметара који се еталонирају у стандардним квалитетима зрачења успостављеним у лабораторијама за еталонирање. У клиничкој пракси услови су различити од услова током еталонирања, укључујући квалитет зрачења и величину поља. У овом раду су проучаване енергетска зависност и зависност од величине поља за оба типа дозиметара. По један дозиметар обе врсте је испитан. КАП-метар је показао значајну зависност одзива и од енергије зрачења и од величине поља, док је зависност одзива ЦТ-коморе много мање изражена. Предложена су два начина да се узму у обзир наведене разлике између клиничких услова и услова током еталонирања. Уколико је клинички сноп окарактерисан и ако је позната енергетска зависност и зависност од величине поља за дозиметар, оптимално решење је да се на мерења примени корекциони фактор. У том случају, повећање мерне несигурности је минимално. Ако не постоји довољно података да се корекција примени, друго решење је да се прошири буџет мерне несигурности.

Кључне речи: производ керме и површине, производ керме и дужине, енергетска зависност, величина поља, дозиметрија, метрологија, дијагностичка радиологија, еталонирање