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ORIGINAL ARTICLE

Calibration of reference KAP-meters at SSDL and cross calibration of clinical KAP-meters

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Abstract

Introduction. In the summer of 2007 the secondary standard dosimetry laboratory (SSDL) in Norway established a calibration service for reference air-kerma product meter (KAP-meter). The air-kerma area product, P_{KA}, is a dosimetric quantity that can be directly related to the patient dose and used for risk assessment associated with different x-ray examinations. The calibration of reference KAP-meters at the SSDL gives important information on parameters influencing the calibration factor for different types of KAP-meters. The use of reference KAP-meters calibrated at the SSDL is an easy and reliable way to calibrate or verify the P_{KA} indicated by the x-ray equipment out in the clinics. *Material and methods.* Twelve KAP-meters were calibrated at the SSDL by use of the substitution method at five diagnostic radiation qualities (RQRs). *Results.* The calibration factors varied from 0.94 to 1.18. The energy response of the individual KAP-meters varied by a total of 20% between the different RQRs and the typical chamber transmission factors ranged from 0.78 to 0.91. *Discussion.* It is important to use a calibrated reference KAP-meter and a harmonised calibration method in the P_{KA} calibration in hospitals. The obtained uncertainty in the P_{KA} readings is comparable with other calibration methods if the information in the calibration certificate is correct used, corrections are made and proper positioning of the KAP-chamber is performed. This will ensure a reliable estimate of the patient dose and a proper optimisation of conventional x-ray examinations and interventional procedures.

The air-kerma area product, P_{KA}, is a dosimetric quantity that can be directly related to the patient dose and used for risk assessment associated with different x-ray examinations. P_{KA} is defined as the integral of air-kerma, $K_{c,air}$, over the area, A, of the x-ray beam in a plane perpendicular to the beam axis [1,2], thus:

$$P_{KA} = \int_A K_{c,air} dA$$

P_{KA} has the unit Gym^2 and can be directly measured by use of a KAP-meter placed in the radiation beam. A KAP-meter is an electrometer with a plane parallel transparent ion chamber with an active area of typical 15 cm × 15 cm. The P_{KA} measurement is approximately independent of the distance from the x-ray tube focus, as long as the radiation beam does not extend outside the chamber area [3].

P_{KA} is the recommended quantity for use in the establishment of diagnostic reference levels (DRLs) [4] for conventional x-ray examinations and is also a good indicator for when threshold doses for deterministic effects are reached in interventional x-ray procedures. Most modern x-ray equipment provides the operator with the total P_{KA} from the examination or procedure. This P_{KA} is either obtained from P_{KA} measurements from a built-in KAP-meter or calculated by use of a software algorithm. To get a reliable estimate of the patient dose, it is essential that the P_{KA} measurement is proper calibrated.

A reference KAP-meter is a useful measuring device to perform cross calibration of KAP-meters or the determined P_{KA} provided by the x-ray units locally at the hospital. The reference KAP-meter must be calibrated and traceable to a secondary standard dosimetry laboratory (SSDL) [2]. Prior to use in cross calibration of KAP-meters, care has to be taken. Most manufactures deliver KAP-meters that are calibrated to give the P_{KA} on the outgoing side of the KAP-chamber. KAP-meters calibrated in this way are suitable for use in patient dose measurement by attaching it to the housing of the x-ray tube. For use in calibration purposes, the reference KAP-

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meter has to be calibrated to give the P_{KA} on the incoming side of the KAP-meter [2]. The difference between these two calibration factors is simply the transmission factor of the KAP-chamber. By using the wrong calibrating factor, a systematic error is introduced in the measurement. The calibration certificate of the KAP-meter should therefore provide the user with both of these calibration factors. One calibration factor that gives the P_{KA} on the incoming side of the KAP-chamber for calibration purposes and one that gives the P_{KA} on the outgoing side of the KAP-chamber for measurements of patient dose.

The aim of this work was to describe the calibration of KAP-meters at the Norwegian SSDL and focus on the different calibration factors provided in the calibration certificate. The different components contributing to the uncertainty in the calibration factors are presented and discussed. The importance of using a calibrated reference KAP-meter and harmonizing the calibration methods in clinics will also be discussed.

Material and methods

A calibration service for KAP-meters, traceable to Physikalisch-Technische Bundesanstalt (PTB, the German primary standard dosimetry laboratory), was established at the Norwegian SSDL during the summer 2007. The calibration method is based upon the same principles as used at PTB. The calibration setup at the Norwegian SSDL consists of the following elements: 1) an x-ray tube, 2) a rotating filter wheel fitted with different filter thicknesses, 3) a lead collimator of 50 mm $\times$ 50 mm to define the radiation field size incident on the KAP-meter, 4) the KAP-chamber, 5) a movable housing for precise KAP-chamber positioning and 6) a monitor ion chamber to check the stability of the dose rate during the KAP-chamber substitution (Capintec, type PM-30), see Figure 1. The centre of the KAP-chamber and the exit side of the collimator was placed at a distance of 100 cm and 95 cm from the focus of the x-ray tube, respectively.

The KAP-meter was calibrated at five well defined radiation qualities (RQRs) defined by IEC 61267 [5], given in Table I. The desired radiation quality was obtained by employing the required combination of tube voltage and additional filtration.

Prior to the calibration, the homogeneity of the KAP-chamber area was investigated for radiation quality RQR 5. The homogeneity was investigated by measuring P_{KA} for the same well defined radiation field size in five different positions on the chamber area. The primary position was in the centre of the chamber and the other four was shifted 2.5 cm in vertical and horizontal direction.

The reference KAP-meter calibration was performed using the substitution method. This means that the reference KAP-meter to be calibrated and the SSDLs secondary standard KAP-meter [6] was alternating measuring the P_{KA} in the x-ray beam under controlled conditions. The reference KAP-meter calibration factor incident on the KAP-camber, defined as N_{KA}, was given by the ratio of the "true" P_{KA} given by the secondary standard and the reference KAP-meter reading. The transmission factor, T, for the reference KAP-meter was calculated from measurements performed with the monitoring ion chamber, with and without the reference KAP-chamber in the x-ray beam. The product of N_{KA} and T gives the calibration factor for the outgoing side of the KAP-meter.

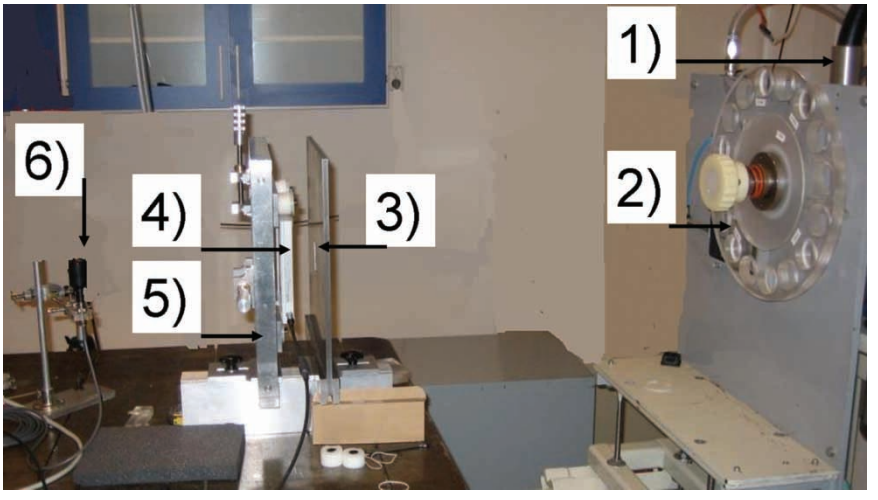

Figure 1. Calibration setup at the Norwegian SSDL. 1) x-ray tube, 2) rotating filter wheel, 3) 50 mm $\times$ 50 mm collimator, 4) the KAP-chamber, 5) movable housing for KAP-meter positioning and 6) monitor ion chamber.

For each radiation quality the incoming calibration factor and the corresponding transmission factor for the KAP-meter was measured. In accordance with the IAEA, RQR 5 was chosen as the reference radiation quality [2]. The calibration certificate give the incoming N_{KA} for RQR 5 together with the quality correction factor, k_Q, (normalized to RQR 5) and transmission factors for all five radiation qualities.

The overall uncertainty in the calibration factor established at the SSDL is depending on the uncertainty in each component of all the input parameters and estimated according to the Guide of Uncertainty in Measurements [7].

Results

Totally 12 KAP-meters were calibrated at the Norwegian SSDL during summer 2007. Two manufacturers with several different models of KAP-meters, all common at Norwegian hospitals, were represented in these calibrations. The homogeneity of all the KAP-meter was within $\pm 3\%$.

The energy dependence in the calibration factor and the transmission factor for the 12 KAP-meters is shown in Figures 2 and 3.

The majority of the KAP-meters followed the energy response curve normally obtained for KAP-meters [3,8]. A deviation from the normal energy response was observed for two of the KAP-meters at the three highest RQRs. Both of these KAP-meters were of the type VacuTec 70157. The observed deviation is not directly linked to the KAP-meter type, since one similar KAP-meter also showed the normal energy response. The energy response of the individual KAP-meters vary by a total of 20% between the different RQRs, but for the most common RQRs used in diagnostic (70 to 150 kV) the energy response only vary by 6%, except for the two KAP-meters mentioned above having 12% variation.

Table I. The five radiation qualities used in the SSDL calibration of KAP-meters.

Standard radiation quality	X-ray tube voltage kV	First HVL mm Al
RQR 2	40	1.42
RQR 5	70	2.58
RQR 8	100	3.97
RQR 9	120	5.00
RQR 10	150	6.57

All the KAP-meters showed energy dependence in the transmission factor, with an increasing transmission with increasing energy in the radiation quality, see Figure 3. Typical transmission factors ranged from 0.78 to 0.91 depending on the radiation quality and type of KAP-meter. KAP-meters of the same type showed comparable transmission factors. One of the PTW KAP-meters, PTW 34015, showed a lower transmission factor. This KAP-chamber is constructed differently from the other PTW chambers. It has an additional point detector in the middle of the chamber area for air-kerma measurement.

Table II summaries the incoming calibration factor, N_{KA}, transmission factor, T, and the product of N_{KA} and T (the outgoing calibration factor) at RQR 5 for all the KAP-meters. As can be seen, eight of the KAP-meters are by the manufactures calibrated to give the P_{KA} on the outgoing side of the KAP-chamber with a deviation of $\pm 3\%$. Three of the KAP-meters are calibrated to give the P_{KA} on the entrance side of the KAP-chamber, with a deviation of about $\pm 5\%$. The deviation in the calibration of one of the KAP-meters was so large that it was not possible to figure

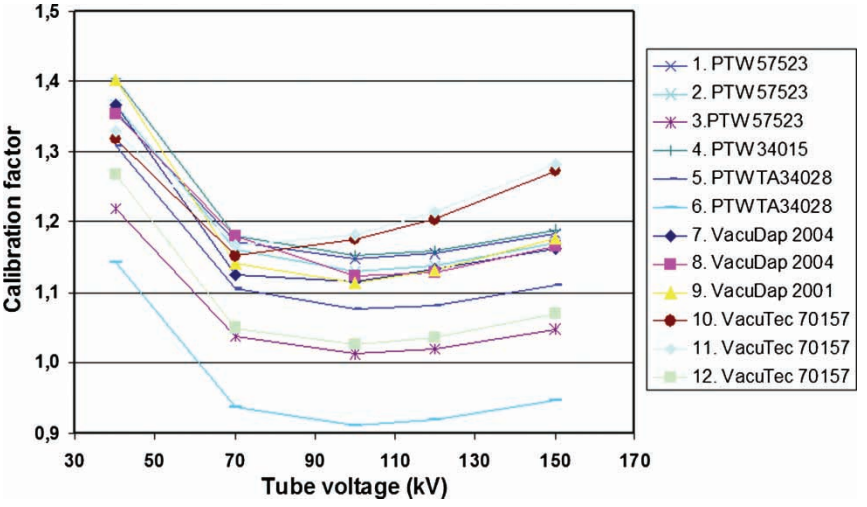

Figure 2. The incoming calibration factor, N_{KA}, as function of radiation quality.

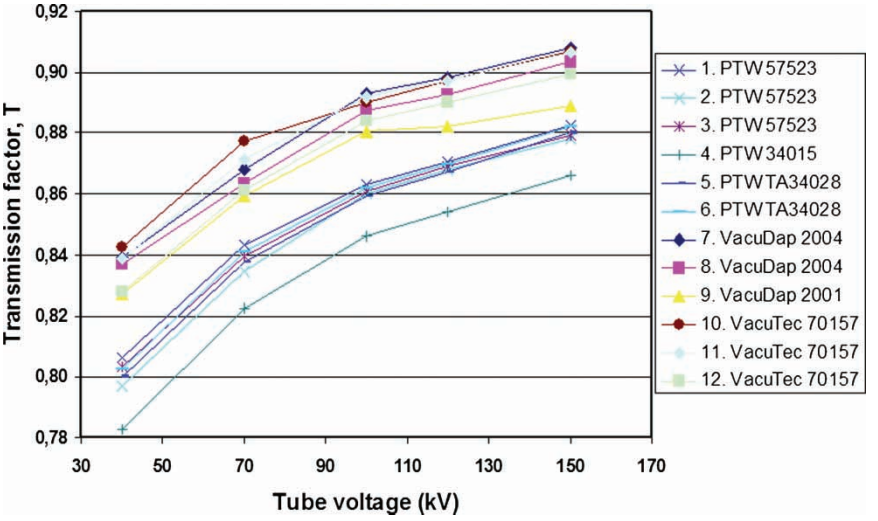

Figure 3. The chamber transmission factor as function of radiation quality.

out if it was calibrated for the incoming or outgoing side of the chamber. The manufactures different settings of the KAP-meters explained much of the variation observed in the incoming N_{KA} among the calibrated meters.

The overall uncertainty in the incoming calibration factor N_{KA} provided by the SSDL was $\pm 4\%$ ($k = 2$ or 95% confidence level). The contributing factors to the uncertainty are given in Table III. The main contributions to the combined uncertainty were coming from the primary calibration of the secondary standard KAP-meter and the stability of both meters.

Discussion

The use of a secondary standard KAP-meter as the national standard for the realisation of the P_{KA} at the SSDL is an effective method to calibrate reference KAP-meters. An alternative method for calibration of KAP-meters is based on measurements of the air-kerma in the reference plane and determination of the P_{KA} by calculating the area in the same plane [9]. The accuracy of these two calibration setups are the same since the uncertainty related to these two setups are comparable.

When using reference KAP-meters in calibration or dose measurements it is important to know their characteristics to achieve the correct results. The calibration of reference KAP-meters at SSDL has given important information on homogeneity over the chamber-area, energy dependence and the transmission through the chamber for different types of KAP-meters. The homogeneity test of the individual KAP-meters show that positioning of the x-ray field in the centre of the chamber is not that critical. To achieve the lowest uncertainty the small homogeneity error ($< 3\%$) should be corrected for, otherwise it should be included in the uncertainty budget giving a slightly higher uncertainty. All the calibrated KAP-meters showed the expected energy dependence [3], see Figure 2. To reduce the uncertainty of the P_{KA} measurement in the clinic, this energy dependence should be corrected for. Unfortunately, this correction is often difficult to perform in practise, due to not complete knowledge of the x-ray beam quality used together with the fact that the radiation quality may change during the examination. The latter is especially important for complex interventional procedures. If not corrected for, the energy dependence should be included in the uncertainty budget and will again result in a higher total uncertainty of the measured P_{KA} [3].

KAP-meter calibrations at the national SSDL revealed that reference KAP-meters in use at Norwegian hospitals are not consistent in their way of indicating P_{KA}. As illustrated in Table II, some KAP-meters indicate the P_{KA} on the incoming side

Table II. The incoming calibration factor (N_{KA}), transmission factor (T) and the outgoing calibration factor ($N_{KA} \times T$) at the reference radiation quality RQR 5 from the SSDL calibration of all the KAP-meters.

DAP-meter	1	2	3	4	5	6	7	8	9	10	11	12
N_{ka}	1.17	1.16	1.04	1.18	1.10	0.94	1.13	1.18	1.14	1.15	1.17	1.05
T	0.84	0.83	0.84	0.82	0.84	0.84	0.87	0.86	0.86	0.88	0.87	0.86
N_{ka}xT	0.99	0.97	0.87	0.97	0.93	0.79	0.98	1.02	0.98	1.01	1.02	0.90

Table III. Uncertainty budget for the calibration of KAP-meter at the Norwegian SSDL.

No.	Uncertainty components	Estimated relative standard deviation, u_i (%)
1	X-ray output stability	0.2
2	Differences in energy spectra of radiation beams between PSDL and SSDL	0.1
3	Field inhomogeneity	0.2
4	Uncertainty in calibration factor reported by PSDL	0.8
5	Constancy of calibration factor	0.5
6	Measurement with secondary standard KAP-meter	1.1
7	Measurement with reference KAP-meter	1.1
	Combined uncertainty	1.9
	Expanded uncertainty (k = 2)	3.8

of the chamber while others indicate the P_{KA} on the outgoing side of the chamber. As mentioned earlier, the use of the KAP-meter is depending on which P_{KA} the meter indicates. KAP-meters indicating the outgoing P_{KA} are suitable for patient dose measurements while those indicating the incoming P_{KA} are suitable for calibration purposes. Wrong use of the KAP-meter will introduce a systematic error of 10 to 20% in the P_{KA} measurements, due to if the transmission in the KAP-chamber is included or not. An independent calibration at the national SSDL is therefore useful to provide the user with a calibration certificate containing the necessary information to ensure a correct use of the KAP-meter at the hospitals.

The use of reference KAP-meters calibrated at the SSDL is an easy way to verify the P_{KA} indicated by the x-ray equipment out in the clinics. If the x-ray equipment is fitted with a built-in KAP-meter it is important to determine if it is the outgoing or incoming P_{KA} that is provided to the user. For equipment having undercouch configuration, this verification will also reveal if the indicated P_{KA} takes into account the absorption in the patient couch or not. If the verification reveals that the indicated P_{KA} are outside the given tolerance limit set by the hospital, action should be taken. This can be solved by either correcting the P_{KA} reading by a calibration factor, which will give the lowest uncertainty, or adjust it to be inside the tolerance giving some higher uncertainty.

The use of a reference KAP-meter for calibration or verification purposes is associated with different uncertainty levels depending on how it is used in the clinic. Table IV list the dominating factors that contribute to the total uncertainty of the calibration of P_{KA} locally at the hospitals. Two uncertainty budgets for the on-site calibration are included in the table to illustrate how efficient different actions are to reduce the total uncertainty of the calibration. The uncertainty estimates are mainly taken from the IAEA Code of Practice for medical diagnostic x-ray [2]. As can be seen, if no corrections are carried out the total uncertainty of the calibration will be approximately $\pm 25\%$. This uncertainty could be reduced to about $\pm 7\%$ if some corrections are carried out. Scattered radiation from couch, phantom (if used) and attenuation in couch are the dominating uncertainty factors. The uncertainty will be substantial reduced by careful positioning of KAP-chamber relative to couch or phantom and taking into account the absorption in the couch (undercouch configuration). On x-ray units performing examinations with defined radiation qualities the uncertainty due to the energy dependence in the KAP-meter can be reduced by choosing the quality correction factor, k_Q, for the actual radiation quality. If the beam quality is not well known an increased uncertainty in the P_{KA} must be expected. The environmental uncertainty contribution can be reduced using the well known temperature and pressure correction factor, k_{TP}, for ion chambers. All of these considerations should be done by a qualified medical physicist.

Table IV. Uncertainty components in calibration of KAP-meters or calculated P_{KA} indication on x-ray units in clinic.

No.	Influencing factor	Estimated relative standard deviation, u_i (%)	
		Light correct.	No correct.
1	Uncertainty in reference KAP-meter calibration factor reported by SSDL	2.0	3.0
2	Radiation quality (energy dependence of KAP-meter)	1.5	4.6
3	Environmental condition (pressure, temperature, humidity)	2.2	5.6
4	Scattered radiation, field size, couch attenuation	1.5	10
	Combined uncertainty for the x-ray unit's P_{KA}	3.7	13
	Expanded uncertainty (k = 2)	7.3	25

To obtain the lowest uncertainty in the daily P_{KA} measurements at the clinics a calibration factor should be estimated and used manually to correct the P_{KA} reading. This will introduce a new element in the dose assessment procedure. If a higher uncertainty is accepted, this extra element can be avoided by introducing a tolerance limit for the P_{KA} reading. The reading on the x-ray unit is then used as long as it is inside this tolerance. If the verification shows that the reading is outside tolerance, adjustment has to be made. Based on the achievable uncertainties in the calibration, see Table IV, a tolerance limit set to $\pm 10\%$, will give acceptable uncertainties in the daily P_{KA} measurements.

It is important that a calibrated reference KAP-meter is used in the calibration or verification of the P_{KA} reading on the x-ray units. This traceable calibration will ensure that it is the correct measured quantity from the clinics that contributes to determination of the national diagnostic reference levels. The use of a calibrated reference KAP-meter is also important to get a reliable estimate of the patient dose and a proper optimisation of conventional x-ray examinations and interventional procedures. To get representative and comparable P_{KA} measurements it is important to harmonise the calibration [10] or verification procedures of patient-dose measurement in clinics.

A study carried out among a representative set of clinics showed a great variation in the indicated P_{KA} from the x-ray units (28 units) [11]. Most of these clinics had not calibrated or verified the built-in KAP-meters or the calculated P_{KA} from the x-ray units, mainly because they trusted the adjustment of the P_{KA} indicator done by the manufacturer or service engineers. The knowledge in the clinics on how to perform a calibration or verification of the P_{KA} reading from the x-ray unit was limited. This shows the importance of using a calibrated reference KAP-meter, and that the on-site calibration methods used at the clinics are harmonized in a national guideline.

Declaration of interest: The authors report no conflict of interest. The authors are responsible for the content and writing of the paper.

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