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Comparison of air kerma area product and air kerma meter calibrations for X-ray radiation qualities used in diagnostic radiology.

Report on the EURAMET project #1177, identified in the BIPM key comparison database (KCDB) as EURAMET RI(I) – S9

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(m) *Dutch Metrology Institute (**VSL**), The Netherlands*
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(s) *Slovak Institute of Metrology, (**SIM)**, Slovakia*
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Abstract

The EURAMET #1177 project, identified as EURAMET.RI(I)-S9 comparison, was the first EURAMET wide scale supplementary comparison in the field of diagnostic radiology for air kerma area product, P_{KA}, and air kerma, K. It was conducted with the goal of testing the measurement and calibration capabilities for P_{KA} and K, as well as of supporting the relevant CMCs of the participating laboratories..

Two commercial KAP meters and an ionization chamber were selected as transfer instruments and circulated between the 22 European participants. The measurements were performed from April 2011 until July 2012.

The stability and the performance of the transfer instruments were tested by the pilot laboratory (IRCL/GAEC-EIM) and few other laboratories as well. The test results revealed that the energy (radiation quality), Q, irradiation area, A, and air kerma rate, $\dot{K}$, dependences of response of the transfer KAP meters influence the comparison of the results when different measurement conditions were pertained and therefore, appropriate correction factors were obtained and applied to the reported calibration results of the laboratories, when necessary.

The comparison reference values (CRVs) for each instrument were determined as the weighted mean of the calibration coefficients of the three participating primary laboratories. The relative standard uncertainty of the CRVs were in the range of (0.4 - 1.6) % depending on the transfer instruments and beam qualities. The comparison result as the ratio of the corrected calibration coefficient of participant and the respective CRV, and its uncertainty were calculated for all beam qualities and transfer instruments. The informative degrees of equivalence (DoE) were calculated for the refrence RQR 5 beam quality. In case of air kema area product measurements the results for the RADCAL PDC KAP meter were used.

The 216 KAP meter calibration results of the two different transfer instruments in terms of air kerma area product were consistent within 5 % except 40 results of 8 participants.

The 103 air kerma calibration results were consistent within 1.7 %, except 10 results of 4 participants.

Contents

1. Introduction

Few key and supplementary comparisons in dosimetry at diagnostic radiology (DR) level have been conducted and published yet. In the first comparison, performed under the EUROMET #364 project (2000), a few European primary standard dosimetry laboratories (PSDL) compared their primary air kerma standards for a selected set of X ray qualities used for calibration in DR, including mammography [1]. The EURAMET project #526 (2001-2003), identified as EUROMET.RI(I)-S4 comparison involved a wide variety of available mammography ionization chambers and beam qualities [2]. The BIPM mammography key comparison was established in 2007. Five PSDLs have published results in the data base BIPM.RI(I)-K7. The EURAMET project #1221 (2012) identified as EURAMET.RI(I)-S10, referred to the PTB and IAEA bilateral comparison of the air kerma standards for x-radiation qualities used in general diagnostic radiology and mammography [3]. The BIPM.RI(I)-S1 (2012) supplementary comparison concerned the comparison of the air-kerma standards of the IAEA and the BIPM in the mammography x-ray range from 25 kV to 35 kV [4]. Finally, some international DR research projects also included comparison of dosimeters in clinical and calibration laboratory beams [5, 6, 7, 8, 9].

Considering the lack of robust traceability of the air kerma (K_a), air kerma area product (P_{KA}) and air kerma length, and uncertainty budgets for the different calibration methods, a comparison at the DR level was considered important and desirable. It would enable the PSDL, SSDLs and other dosimetry laboratories to test their dosimetry measurement standards and support their calibration and measurement capabilities (CMC).

For this need, the EURAMET #1177 project, identified as EURAMET RI(I)-S9 comparison, was proposed and conducted. It was carried out in conjunction with two other similar comparison programs, scheduled under different organizations and projects as follows:

(a) EURADOS project (EURADOS WG 12, SG 3: Technical aspects on DAP calibration and CT calibration), where laboratories from 5 countries participated (ES, IT, FI, EL and PL), and
(b) IAEA Coordinated Research Program (CRP E2.10.08), Activity 3, focusing on the comparison of air kerma area product (KAP) meter calibration procedures carried out by the participating calibration laboratories in four countries (CZ, FI, EL, RS)

It is worth mentioning that a few laboratories participated in more than one of these three projects.

Two KAP meters, the IBA Kerma X-plus DDP TinO (referred as KERMA-X hereafter) and the Radcal PDC (referred as PDC hereafter) and one diagnostic ionization chamber, type Exradin Magna A650 (referred as MAGNA hereafter), were selected as transfer instruments and circulated between the participants. The comparison parameters were their calibration coefficients in terms of air kerma area product, N_{PKA}, and air kerma, N_K. Details on the transfer instruments, calibration quantities and beam qualities are presented in section 3.

For the EURAMET project, calibrations only at standard radiation beam qualities, i.e. at RQR reference X-ray beam qualities [10], were requested and used for the analysis of results. This was decided in order to maintain the traceability of the measurements and to use the results for supporting the CMC claims of the laboratories published in the BIPM CMC database. Although calibrations for KERMA-X were requested both for incident and transmitted radiation [11], the results were analysed only for calibrations at incident radiation.

For the EURADOS and IAEA projects, besides calibrations at standard beam qualities, calibrations also at non-standard beam qualities, selected to resemble the clinical beam qualities, were requested but only on a voluntary basis; i.e. if the laboratory could provide also these calibrations, it was accepted as a partner in this extra comparison. The primary purpose of the comparison at non-standard beam qualities was to study the feasibility of the suggested qualities for calibration, both for incident and transmitted beams; the results will be reported elsewhere and will not be discussed more in this report.

Upon an open call between participants, a specific working group (WG) was established to support the coordinator in data evaluation and drafting the report:

- Costas J. Hourdakis, IRCL/GAEC-EIM, Greece, coordinator of the EURAMET project #1177 and IAEA CRP E2.10.08 Activity 3,
- Hannu Jarvinen, STUK, FInland, coordinator of the EURADOS WG 12 SG 3
- Josiane Daures, LNHB-LNE, Franc, member from a PSDL
- Istvan Csete, IAEA, convenor of the EURAMET TC-IR Working Group on CMCs and Comparisons

2. Participating laboratories

2.1 General data

Twenty two (22) laboratories (PSDLs and SSDLs) participated in this EURAMET #1177 comparison (Table 1):

EUARAMET members and associates : SCK-CEN/LNK Belgian Nuclear Research Centre* (BE), CMI (CZ), PTB (DE), SIS (DK), STUK (FI), LNE-LNHB (FR), IRCL/GAEC-EIM (EL), MKEH (HU), IAEA, GR (IS), VSL (NL), NRPA (NO), ITN (PT), IFIN-HH (RO), SSM (SE), SIM (SK) and JSI (SI).
(* SCK-CEN/LNK became a member of EURAMET in 2013, during the project reporting phase)

Not being EURAMET members : SURO National Radiation Protection Institute (CZ), UPC Universitat Politècnica de Catalunya (ES), IRP-DOS Istituto di Radioprotezione (IT), NIOM Nofer Institute of Occupational Medicine (PL), VINCA Institute of Nuclear Science, Radiation and Environmental Protection Laboratory (RS).

The ICRL/GAEC-EIM, Greece (EL) as the pilot laboratory was responsible for the overall coordination of the comparison and the analysis and the reporting of the results.

Table 1. *List of participating laboratories to the EURAMET 1177 1177 comparison ([a] Not EURAMET member, [b] Participation through the IAEA CRP).*

	Country, Code	**Institute code used in this report**	**Institute**	**Contact Person(s)**	**ADDRESS**	**e-mail address**
1	Belgium, BE	SCK•CEN	Belgian Nuclear Research Centre (SCK•CEN)	Liviu-Cristian Mihailescu	Boeretang 200, Mol 2400, Belgium	lmihaile@sckcen.be fvanhave@sckcen.be
2	Czech Republic, CZ	CMI	Czech Metrology Institute (CMI)	Vladimir Sochor	Okruzni 31, Post Code 638 00, Brno, Czech Republic	vsochor@cmi.cz
3	Czech Republic, CZ	SURO [a,b]	"SURO" National Radiation Protection Institute (SURO)	Leos Novak	Batroskova 289, 140 00 Prague 4 Czech Republic	leos.novac@suro.cz
4	Denmark, DK	SIS	National Institute of Radiation Protection (SIS)	Kurt Meier Pedersen	Knapholm 7 DK-2730 Herlev, Denmark	kmp@sis.dk
5	Finland, FI	STUK	Radiation and Nuclear Safety Authority (STUK)	Antti Kosunen, Paula Toroi	P.O.Box 14, Laippatie 4, FI-00881 Helsinki Finland	paula.toroi@stuk.fi antti.kosunen@stuk.fi
6	France, FR	LNE-LNHB	Laboratoire National Henri Becquerel/Commissariat à l'Energie Atomique (LNE-LNHB)	Josiane Daures, Marc Denoziere	LNHB P.C. 111, FR-91191 Gif sur Yvette cedex, CEA/SACLAY, France	josiane.daures@cea.fr marc.denoziere@cea.fr
7	Germany, DE	PTB	Physikalisch-Technische Bundesanstalt (PTB)	Ludwig Büermann	Bundesallee 100 38116 Braunschweig, Gernany	Ludwig.Bueermann@ptb.de
8	Greece, EL	IRCL/GAEC-EIM	Ionizing Radiation Calibration Laboratory, Greek Atomic Enegy Commission (IRCL/GAEC-EIM)	Costas J. Hourdakis	Patr. Grigoriou & Neapoleos, Agia Paraskevi 15310 Athens Attiki, Greece	khour@gaec.gr arboziar@gaec.gr
9	Hungary, HU	MKEH	Hungarian Trade Licensing Office (MKEH)	István Csete	H 1124 Budapest, Hungary, Németvölgyi ut. 37-39. 1534 Budapest, P.O.Box. 919	cseteis@mkeh.hu
10	IAEA	IAEA	International Atomic Energy Agency, (IAEA)	Ahmed Megzifene Istvan Csete	PO Box 100, 1400 Vienna, Austria	a.meghzifene@iaea.org I.csete@iaea.org
11	Iceland, IS	GR	Icelandic Radiation Safety Authority / Geislavarnir ríkisins (GR)	Guðlaugur Einarsson	Rauðarárstíg 10, IS-150 Reykjavík, Island	ge@gr.is

12	Italy, IT	IRP-DOS [a]	Istituto di Radioprotezione (IRP-DOS, ENEA)	Paolo Ferrari	Via dei colli 16, 40136 Bologna (BO) Italy	Paolo.ferrari@enea.it
13	Netherlands, NL	VSL	Dutch Metrology Institute (VSL)	Jacco de Pooter	P.O.Box 654, 2600 AR Delft, The Netherlands	jdPooter@vsl.nl
14	Norway, NO	NRPA	Norwegian Radiation Protection Authority (NRPA)	Hans Bjerke	P.O.Box 55 NO-1332 Osteras, Norway	hans.bjerke@nrpa.no
15	Poland, PL	NIOM [a]	Nofer Institute of Occupational Medicine (NIOM)	Marcin Brodecki	SSDL, Radiation Protection Dept, Nofer Institute for Occupational Medicine, Sw. Teresy 8, str, 91-348 Lodz	marbrod@imp.lodz.pl
16	Portugal, PT	ITN-LMRI	Nuclear and Technology Institute, Metrology Laboratory for Ionising Radiation and Radiocativity (ITN-LMRI)	João Cardoso	Estrada Nacional 10, 2686-953 Sacavém, Portugal	jcardoso@itn.pt
17	Romania, RO	IFIN-HH	Horia Hulubei National Institute of R&D for Physics and Nuclear Engineering (IFIN-HH)	Sorin BERCEA	30 Reactorului st., Magurele, jud. Ilfov, P.O. Box MG-6, RO-077125, Romania	Bercea@ifin.nipne.ro bercea@nipne.ro
18	Serbia, RS	VINCA [a,b]	"VINCA" Institute of Nuclear Science, Radiation and Environmental Protection Laboratory (VINCA)	Olivera Ciraj-Bjelac	M.P.Alasa 12-14, Vinca, Belgrade (P.O. Box 522, 11001 Belgrade), Serbia	ociraj@vinca.rs
19	Slovakia, SK	SIM	Slovak Institute of Metrology, SIM	Jaroslav Compel	Karloveská 63, 842 55 Bratislava 4, Slovakia	compel@smu.gov.sk
20	Slovenia, SI	JSI	Jozef Stefan Institute (JSI)	Denis Glavič-Cindro	Jamova 39 1000 Ljubljana, Slovenia	Denis.cindro@jsi.sl
21	Spain, ES	UPC [a]	Universitat Politècnica de Catalunya, (UPC)	Merce Ginjaume	Diagonal 647, Pavello C, 08028, Barcelona, Spain	merce.ginjaume@upc.es
22	Sweden, SE	SSM	Swedish Radiation Safety Authority (SSM)	Jan-Erik Grindborg, Linda Persson	Solna strandväg 122, SE-171 54 Solna, Sweden	Jan-Erik.Grindborg@ssm.se

2.2 Calibrating conditions

2.2.1 X-ray systems

The X-ray systems used for calibration by the participating laboratories are shown in Table 2 and Fig. 1. Eighteen (18) of those were therapy / industrial type X-ray systems running in continuous mode and were equipped with X-ray tubes with stationary tungsten (W) anodes (targets). The X-ray tube exit window varied between the systems, as 1 mm Be, 4 mm Be and 7 mm Be were reported. The other four (4) X-ray systems concerned radiography systems with rotational tungsten (W) anodes (targets) operating in radiography mode (for short exposure times) or in fluoroscopy mode.

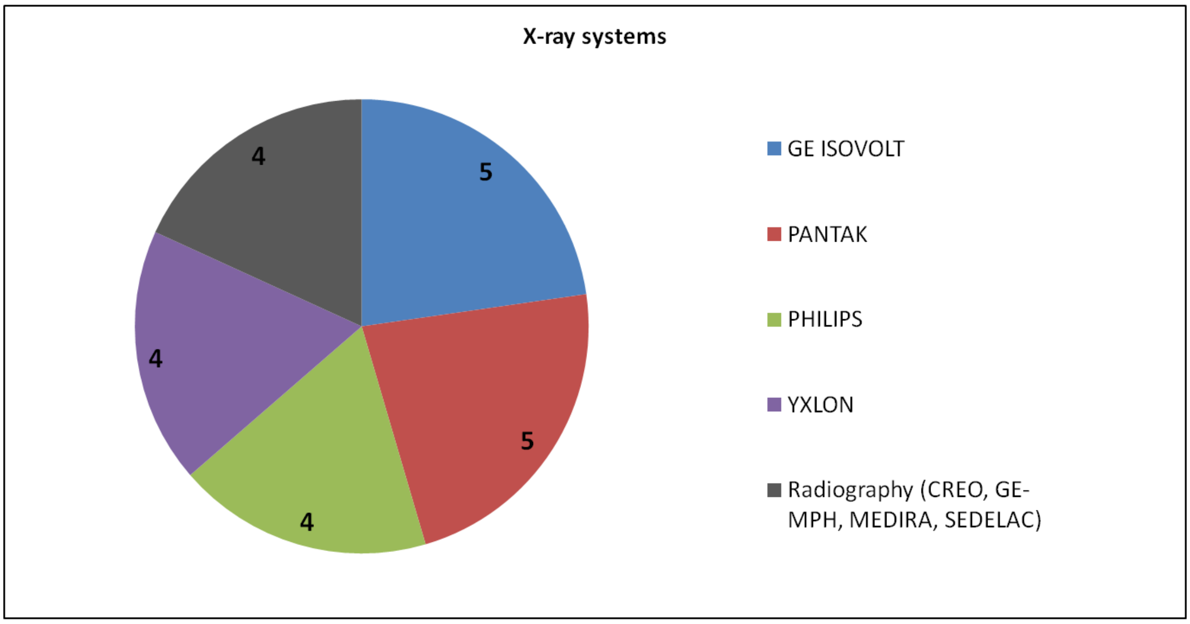


Fig. 1. *The X-ray systems used by the participating laboratories. Types and models are detailed in Table 2.*

Table 2. *X-ray systems used by the participating laboratories.*

Lab	X-ray system	Stated Inherent tube filtration
SCK•CEN	Pantak 350 kV	1.3 mmAl
CMI	Isovolt HS 160	1 mm Be
SURO	Isovolt Titan, X-ray tube GE, type MXR 160	1 mm Be
SIS	Philips MGC 30 Industrial X-ray	4 mmBe
STUK	Seifert Isovolt 160 HS generators and MB 161/4 x-ray tube	1 mmBe
LNE-LNHB	GEMS MPH65, Maxiray 100 X-ray tube	2 mm Al
PTB	XGG generator of Yxlon and MXR165 tube of Comet	4 mm Be
IRCL/GAEC-EIM	PANTAK 225 HF	1 mm Be + 5.2 mm PMMA
MKEH	Philips MCN 321 Tube	2.2 mm Be +2.5 mm AL
IAEA	GE Isovolt Titan 160, tube MRX 160/0.4-3.0 #590030	1 mmBe + PTW monitor chamber
GR	Medira Medium High Frequency, Diagnostic X-ray generator	--
IRP-DOS	PHILIPS MGC 323	3 mm Be window
VSL	MG324 CP + MCN321 from Yxlon - Hamburg	4 mm Be
NRPA	Pantax, HF320/160. X-ray tube: CometMXR-160	1 mm Be
NIOM	Gulmay X-ray Calibration System 300kV	3 mm Be
ITN-LMRI	Yxlon MGG42 + Philips MCN165	1 mm Be
IFIN-HH	SEDECAL (40 - 150 kV, max 10 s, max 650 mA)	2.1 mm Al
VINCA	Philips MG320 #32234	4 mm Al
SIM	X-ray Generator CREOS type XHF-30 with X-ray Tube RAD 8	1,8 mm Al at 70 kVp
JSI	PANTAK HF 160	1 mm Be + 0.3 mm Al
UPC	SEIFERT Isovolt HS of 320 kV. X-ray Seifert, type MB 350	7 mm Be
SSM	Tube Yxlon MG 325/4.5-320 kV, generator Yxlon MGP41	3 mm Be

2.2.2 Radiation qualities and HVL values

Table 3 presents the % deviation of the HVL values reported by the participating laboratories from the IEC 61267 [10] HVL values.

According to IEC 61267, the acceptability criterion of the HVL value for each radiation quality is that the K_{HVL}/K_0 ratio should be between 0.485 and 0.515, where K_{HVL} is the air kerma for the specified radiation quality with an added attenuator equal to the HVL specified at the IEC 61267 and K_0 the air kerma without the attenuator. A subsequent alternative HVL acceptability criterion could be taken as the ratio of the stated (measured) to the specified (IEC) HVL values, which should be between 0.957–1.044 (i.e. ± 4.4 %) [12 (pp 10-12)]. In this respect the values of table 3 indicate the conformity of the participating laboratories' beam qualities to the IEC requirements.

Table 3. *The deviation of the reported HVL from the IEC 61267 HVL values.*

Lab code	HVL deviation in % from the IEC values				
	RQR 3	**RQR 5**	**RQR 6**	**RQR 8**	**RQR 9**
SCK•CEN	0.0 %	0.0 %	0.0 %	0.0 %	0.0 %
CMI	-0.1 %	0.2 %	-0.9 %	2.5 %	1.0 %
SURO	0.6 %	-0.4 %	-1.3 %	3.4 %	1.8 %
SIS	0.0 %	0.0 %	0.0 %	0.0 %	0.0 %
STUK	0.6 %	4.1 %	-0.7 %	-0.3 %	0.6 %
LNE-LNHB	-0.6 %	0.4 %	0.3 %	0.3 %	0.0 %
PTB	-2.8 %	0.7 %	-2.2 %	-2.3 %	-1.8 %
IRCL/GAEC-EIM	1.4 %	0.0 %	-1.9 %	0.3 %	-0.4 %
MKEH	-0.3 %	-0.7 %	-1.3 %	-0.4 %	-1.8 %
IAEA	1.7 %	1.1 %	2.9 %	2.0 %	2.3 %
GR	-1.5%	0.7 %	-0.2 %	-0.2 %	-1.4 %
IRP-DOS	-1.7 %	-0.4 %	1.3 %	2.7 %	2.5 %
VSL	**-20.3 %**	-4.0 %	-3.1 %	**-6.4 %**	**-10.9 %**
NRPA	*	3.0 %	*	2.7 %	-0.4 %
NIOM	1.1 %	0.4 %	-0.7 %	-1.8 %	-3.1 %
ITN-LMRI	-0.6 %	0.0 %	0.0 %	0.0 %	0.0 %
IFIN-HH	1.1%	0.0 %	0.7 %	-1.8 %	0.2 %
VINCA	**10.6 %**	1.9 %	1.3 %	0.7 %	-0.2 %
SIM	-0.3 %	-3.2 %	-0.3 %	0.0 %	0.0 %
JSI	-1.7 %	-1.6 %	1.3 %	0.3 %	2.2 %
UPC	2.2 %	**-6.2 %**	2.0 %	-3.7 %	-1.4 %
SSM	1.1 %	-1.6 %	1.0 %	2.5 %	1.2 %

* not applied in this comparison project

2.2.3 Irradiation conditions: Irradiation field size, irradiation area

Table 4 summarizes the irradiation beam shapes, rectangular (□**)** or circular (ø), and the field size in cm^2, for the calibration of instruments, as reported by the participating laboratories. Every laboratory applied the same radiation field for all radiation qualities. Fig. 2 and Fig. 3 present the frequency distribution of the irradiation areas, A, for KERMA-X and PDC (as KAP meter), respectively.

Table 4. *The X-ray beam shape rectangular (□**)** or circular (ø) and the irradiation areas (field sizes), A, applied for the calibration of the instruments.*

Lab code	**Beam shape and A (cm^2)**		
	KERMA-X	**PDC KAP meter**	**MAGNA**
SCK•CEN	□ 143.7	□ 900 [(1)]	□ 1970.9
CMI	ø 20.9	ø 20.9	ø 176.6
SURO	□ 29.3	□ 29.3	N/A [(2)]
SIS	□ 25.0	ø 260.0	ø 260.0
STUK	ø 27.7	ø 27.7	ø 154.0
LNE-LNHB	□ 27.7	□ 27.7	□ 27.7
PTB	□ 25.0	□ 25.0	ø 78.5
IRCL/GAEC-EIM	□ 27.8	□ 27.4	ø 572.3
MKEH	□ 26.0	□ 27.0	ø 314.0
IAEA	□ 26.0	ø 21.7	ø 283.4
GR	ø 21.2	ø 10.7	ø 86.5
IRP-DOS	ø 17.6	ø 17.6	ø 700.0
VSL	ø 106.5	ø 106.5	ø 100.2
NRPA	□ 27.7	□ 27.7	□110.9
NIOM	□ 27.6	□ 27.6	□ 81.0
ITN-LMRI	ø 21.6	ø 21.6	ø 78.5
IFIN-HH	□ 96.3	□ 218.9	ø 3600.0
VINCA	ø 31.3	ø 113.0	ø 100.6
SIM	ø 87.9	ø 87.9	ø 87.8
JSI	□ 27.7	□ 27.7	ø 201.0
UPC	ø 20.3	ø 20.3	ø 201.1
SSM	□ 25.0	□ 25.0	ø 86.5

(1) According to the calibration procedure applied at SCK•CEN, the beam size was 1970.9 cm^2 (44.4 cm x 44.4 cm), i.e., much larger than the active area of PDC. The PDC's manual gives a nominal area of PDC equal to 30 cm x 30 cm [13, p. 18]. This value (900 cm^2) was used as irradiation area.
(2) No measurements performed.

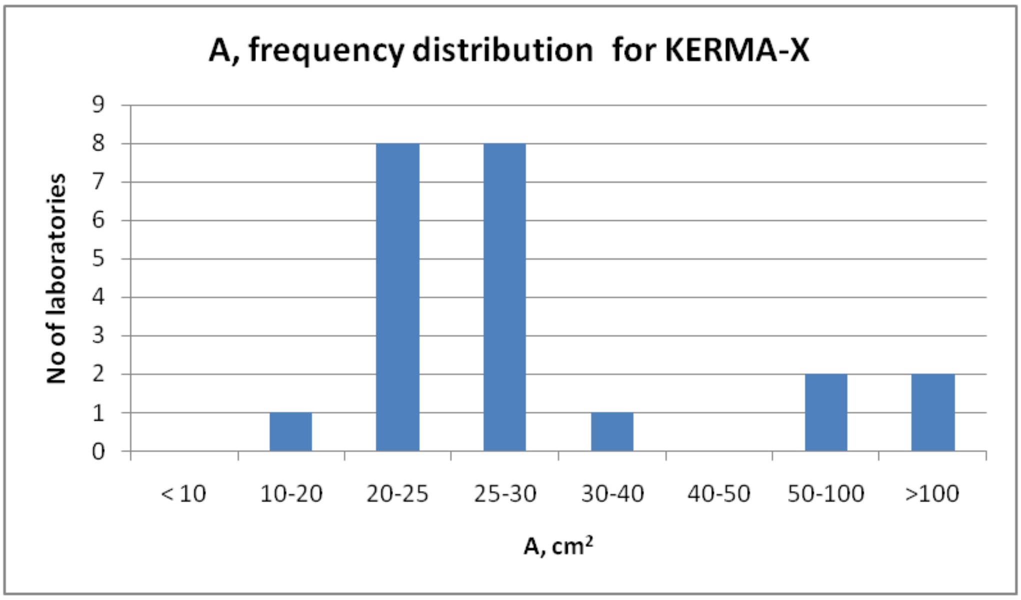


Fig. 2. *The frequency distribution of the reported irradiation areas, A, for KERMA-X calibration.*

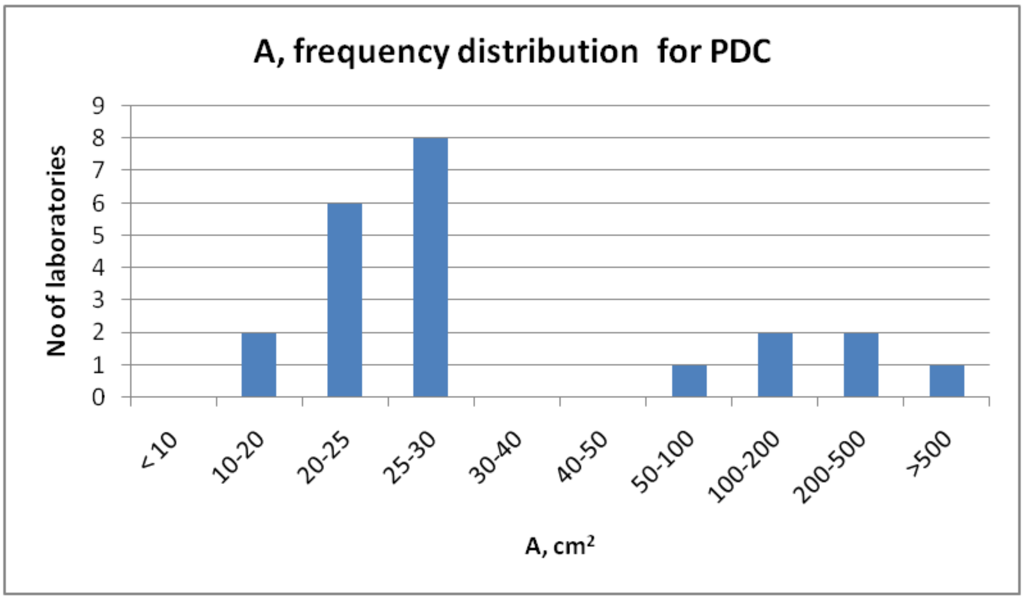


Fig. 3. *The frequency distribution of the reported irradiation areas, A, for PDC calibration as KAP meter.*

2.2.4 Irradiation conditions: Air kerma rate

Table 5 presents the reported $\dot{K}$ values that were applied at calibrations of MAGNA ionization chamber at RQR qualities. Similar $\dot{K}$ values were used for the calibration of KERMA-X and PDC, as well, except in a few cases (SCK•CEN, GR, IFIN-HH and VINCA). The $\dot{K}$ values pertained at each measurement are reported in the respective tables of the calibration results.

Table 5. *The air kerma rates applied for the calibration of MAGNA (similar rates applied for the calibration of the other instruments).*

Lab code	Air kerma rate mGy/min				
	RQR3	RQR5	RQR6	RQR8	RQR9
SCK•CEN	1.6	3.6	4.7	7.3	10.3
CMI	13.8	24.1	30.6	41.9	55.8
SURO	6.2	11.3	14.3	18.4	24.0
SIS	33.3	62.1	81.6	112.3	146.4
STUK	32.6	33.2	33.1	33.4	33.1
LNE-LNHB	57.0	107.1	134.9	192.1	256.7
PTB	55.9	54.4	58.8	64.5	75.9
IRCL/GAEC-EIM	30.8	73.0	74.2	54.3	70.9
MKEH	19.0	19.0	19.0	19.0	19.0
IAEA	20.0	20.2	20.3	20.4	20.6
GR	287.0	275.0	345.0	502.0	675.0
IRP-DOS	15.0	15.0	15.0	15.0	15.0
VSL	26.1	35.1	43.4	61.8	84.3
NRPA		35.0		62.0	82.0
NIOM	19.6	34.1	41.4	58.2	81.6
ITN-LMRI	8.8	15.1	18.5	25.5	15.4
IFIN-HH	8.9	16.0	20.6	29.4	39.1
VINCA	6.1	13.5	17.8	26.7	37.0
SIM	193.8	327.7	397.4	446.1	379.8
JSI	11.4	13.3	13.6	9.1	11.5
UPC	16.1	33.8	38.0	58.7	74.6
SSM	12.9	10.2	10.1	11.0	11.0

Fig. 4 presents the frequency distribution of the $\dot{K}$ values at the RQR qualities for each transfer instrument. Most of the calibrations were performed at air kerma rates between 20 and 100 mGy/min.

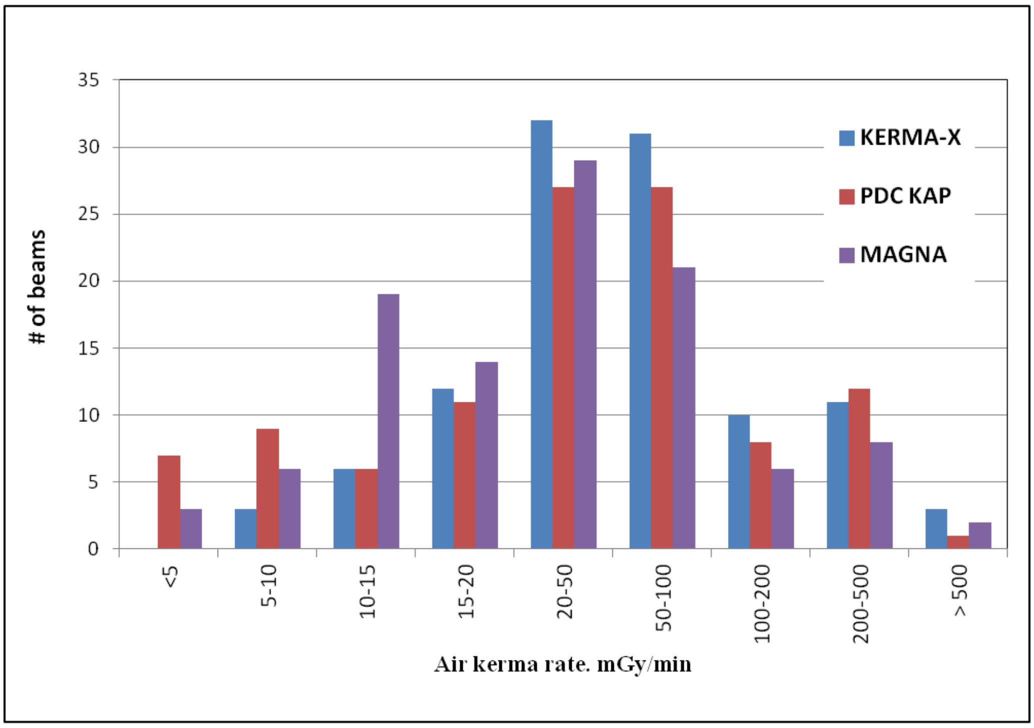


Fig. 4. *The $\dot{K}$ frequency distribution for all RQR radiation qualities, for each transfer instrument.*

2.2.5. Irradiation conditions: Focus to Detector Distance, FDD

The distance between the reference plane of measurement (detector reference point) and focus applied during calibration by the participating laboratories, is shown in Fig. 5.

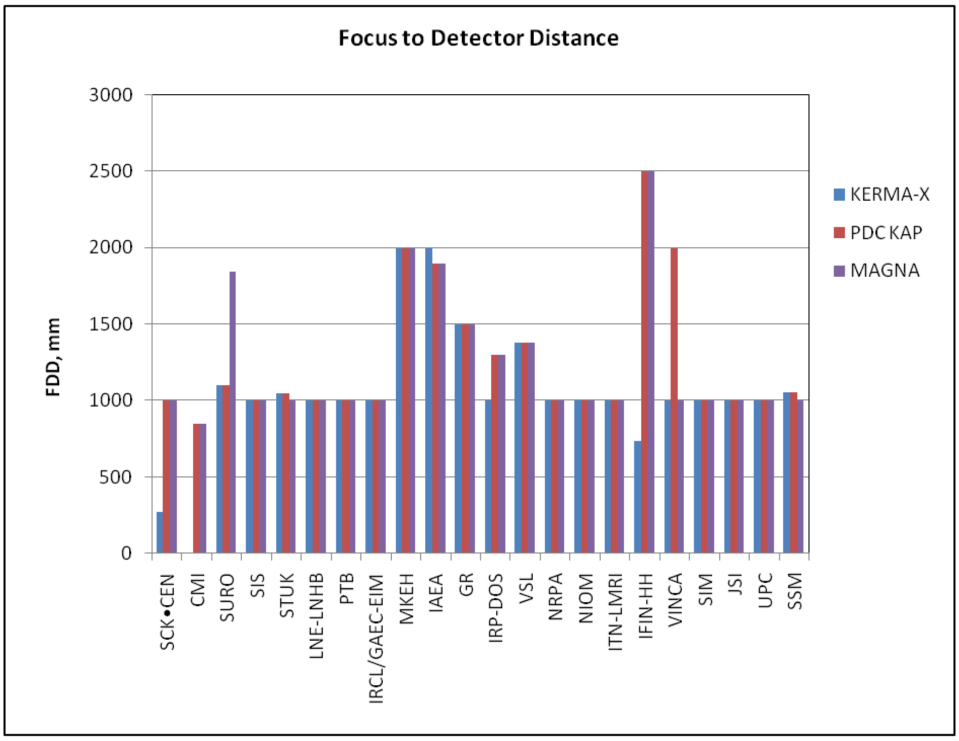


Fig. 5. *The focus to detector distances applied by the participating laboratories during the calibration of KERMA-X, PDC KAP and MAGNA.*

2.3 Source of traceability and the standards of the laboratories.

Four (4) primary standard dosimetry laboratories (PSDLs) participated in this comparison: LNE-LNHB France, MKEH Hungary, PTB Germany and VLS, The Netherlands.

The rest 18 laboratories were secondary standard dosimetry laboratories (SSDLs) that have calibrated their reference chambers against the primary standards in terms of air kerma (Table 6).

The traceability of the participating laboratories (PSDLs and SSDLs) is shown in Fig. 6. The dosimetry reference standards of fifteen (15) laboratories referred directly or indirectly (through SSDLs) to PTB. The rest seven (7) laboratories have traceability to other PSDLs, i.e. BEV, ENEA, LNE-LNHB, MKEH, NPL and VSL.

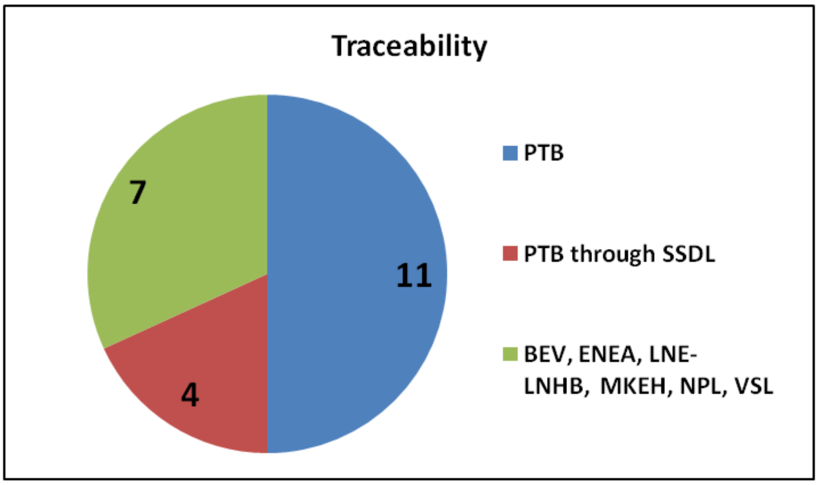


Fig. 6. *The traceability of the dosimetry standards of the participating laboratories.*

Table 6. *The traceability and the reference chambers (type, last calibration date) and the radiation qualities used to obtain the diagnostic radiology reference air kerma values. (The PSDLs in bold)*

	Traceability	Reference Chamber	Latest calibration	Qualities
SCK•CEN	PTB	600 cc Farmer NE 2575C SN 549	7/6/2010	ISO 4037 Narrow series
CMI	BEV	Radcal RC6M s.n. /Exradin A4 s.n. 169	2011	ISO 4037 Narrow series (N10 to N30 and N40 to N300)
SURO	MKEH	Exradin A4	IX.2009	RQR series (IEC 61267), ISO 4037 Narrow series
SIS	NPL	NPL type NE 2611A	1/4/2008	50kV(1.00mmAl), 70kV(2.00mmAl), 100kV(4.00mmAl) and 105kV(5.00mmAl
STUK	PTB	Exradin A3 REF 92717 S/N XR100191	19/2/2010	RQR series (IEC 61267)
LNE-LNHB	**LNE**	**French primary standard (Free-Air Chamber)**		
PTB	**PTB**	**Primary standard free-air chamber "Fasskammer"**		
IRCL/GAEC-EIM	PTB	A3 Exradin	March 2011	RQR, RQT series and RQA5 (IEC 61267)
MKEH	**MKEH**	**ND 1001 #7808**	**06/12/2011**	**RQR and RQT series (IEC 61267**)
IAEA	PTB	EXTRADIN A3 #XR071833	05/12/2011	RQR and RQT series (IEC 61267)
GR	PTB through SSM, Sweden	Radcal 9010	November, 2011	RQR3, RQR5, RQR6, RQR8 and RQR9 (IEC 61267)
IRP-DOS	ENEA-INMRI	PTW TK-30	29/9/2010	ISO 4037 Wide, Narrow and High kerma series, S-Co and S-Cs beams
VSL	**VSL**	**Primary standard free-air-chamber**		
NRPA	PTB	KAP-meter Doseguard 100 #1316, VacuTec 70157 #0401162	19/7/2006	RQR2, RQR5, RQR8, RQR9 and RQR10 (IEC 61267)
OM	PTB	PTW ionization chamber 1cc, type TM77334, s/n: 2269	22/11/2010	RQR series (IEC 61267)
ITN-LMRI	PTB through IAEA	PTW TW-34069-2,5 SN: 00163	15/8/2012	RQR, RQT series and RQA5 (IEC 61267)
IFIN-HH	PTB	Barracuda and Multi-Purpose Detector	17. 03. 2010	RQR5 (IEC 61267)
VINCA	PTB through GAEC, Greece	Magna A 650, sn D 082611	15/11/2008	RQR3, RQR5, RQR7, RQR8 and RQR9 (IEC 61267)
SIM	PTB through PTW Freiburg	PTW Freiburg SFD Chamber Type TM34060-2.5-00219	25/11/2010	RQR and RQA series (IEC 61267)
JSI	PTB	PTW TW 34060-2,5	21/2/2011	RQR3, RQR5, RQR7 and RQR9 (IEC 61267)
UPC	PTB	NE 2530 nº350	2007	RQR2, RQR4, RQR6, RQR8, RQR9 (IEC 61267) and N40, N80, N120 ISO 4037
SSM	PTB	Exradin A3 serial number 169	19/11/2007	RQR series (IEC 61267)

3. Comparison method

3.1. Description of the overall procedures

The comparison protocol had been prepared by the pilot laboratory, revised by the participants and the approved by the CCRI(I) version had been distributed to the participating laboratories. It contained the technical details, the time schedule for the laboratories' participation, the instruments' operational manuals and the procedures for the results evaluation, analysis and assessment.

The schedule of the laboratories' participation in the comparison is presented in Table 7.

The comparison started on 28 March 2011. The first calibration and the relevant checks were carried out by the pilot laboratory. The pilot laboratory's calibration results were submitted immediately to the CCRI Executive Secretary, as a proof of its participation and declaration of the calibration results. Then, the instruments were mailed to the next participants. After every three laboratories, the instruments were returned to the pilot laboratory for an interim re-calibration, hereafter the circulation was continued to the remaining laboratories in accordance with the schedule of calibrations.

The measurement part of the project was completed after seven (7) rounds on 25 July 2012.

Each laboratory sent the calibration report by filling the report template excel sheets including the calibration coefficients and the associate uncertainties as well as a short description of the calibration procedure (including a few photographs and drawings if appropriate) to the pilot laboratory. The submission of the results was completed on middle of October 2012.

Table 7. *The time schedule for the calibration and measurements.*

Laboratory	Period for calibration	Period for transport	Comments
Pilot laboratory, IRCL/GAEC-EIM, Greece	28/3-1/4/2011	4-10/4/2011	Initial calibration - 1st
NIOM, Poland	11-15/4/2011	18-24/4/2011	
UPC, Spain	25-29/4/2011	2-8/5/2011	
STUK, Finland	9-13/5/2011	16-22/5/2011	
IRCL/GAEC-EIM, Greece	23-27/5/2011	30/5-5/6/2011	Re-calibration - 2nd
LNHB, France	6-10/6/2011	13-19/6/2011	
SURO, Czech	20-24/6/2011	27/6-3/7/2011	
CMI, Czech	4-8/7/2011	11-17/7/2011	
IRCL/GAEC-EIM, Greece	18-22/7/2011	25-31/7/2011	Re-calibration - 3rd
SIS, Denmark	1-5/8/2011	8-14/8/2011	
NRPA, Norway	15-19/8/2011	22-28/8/2011	
PTB, Germany	12-16/9/2011	19-25/9/2011	
IRCL/GAEC-EIM, Greece	26-30/9/2011	3-9/10/2011	Re-calibration – 4th
SSM, Sweden	10-14/10/2011	17-23/10/2011	
VINCA, Serbia	24-28/10/2011	31/10-6/11/2011	
IFIN, Romania	7-11/11/2011	14-20/11/2011	
IRCL/GAEC-EIM, Greece	21-25/11/2011	28/11-4/12/2011	Re-calibration – 5th
MKEH, Hungary	5-9/12/2011	12-18/12/2011	
GR, Iceland	9-13/1/2012	16/-22/1/2012	
IAEA			Moved to end
IRCL/GAEC-EIM, Greece	6-10/2/2012	13-19/2/2012	Re-calibration – 6th
ITN, Portugal	20-24/2/2012	27/2-4/3/2012	
SCK-CEN, Belgium	5-9/3/2012	12-18/3/2012	
VSL, Netherlands	19-23/3/2012	26/3-1/4/2012	
IRCL/GAEC-EIM, Greece	2-6/4/2012	9-15/4/2012	Re-calibration – 7th
IRP DOS, Italy	23/4 – 6/5/2012	6-13/5/2012	
JSI, Slovenia	14-18/05/2012	21-27/05/2012	

SIM, Slovakia	28/5-1/6/2012	4-10/6/2012	
IAEA	11-15/6/2012	18-24/6/2012	
IRCL/GAEC-EIM, Greece	28/6/2012		Final calibration

3.2. Transfer instruments

The following instruments were used for the comparison:

i. KERMA-X : IBA KermaX plus (IBA SCANDITRONIX WELLHOFER)

Measuring device : KermaX-plus DDP TinO, Model 120-205, s/n 01E01232
KAP Ionization chamber : IBA Model 120-131 TinO, s/n 01A00120
Accessories: (i) SCANDITRONIX Power Supply Type 8713 MED, (ii) Cable AWM 20251 with adaptor end and (iii) Adaptor cable RS 232 port.

The instrument was provided by the IRCL/GAEC-EIM, Greece (Fig 7)

Fig. 7. *KERMA KAP-meter used in this comparison. The KAP ionization chamber, the measuring device (electrometer) and cables and adaptors are shown.*

The reference point of the KAP ionization chamber was the geometrical centre (middle line) of the effective volume, i.e. the reference plane was located at half the KAP thickness below the front surface. The front surface, facing to the X-ray tube, was marked.
The KAP ionization chamber was vented, so appropriate corrections for air density should be applied.
According to the manufacturer specifications, the nominal active area of the KAP ionization chamber was rectangular with dimensions 146 mm x 146 mm. The chamber had an optical transparency better than 75 %.
This KAP ionization chamber could be used for both incident and transmitted radiation. The calibration procedures for incident and transmitted radiation can be found in literature [11].
KERMA-X could measure simultaneously: the entrance dose (mGy), entrance dose rate (mGy/s), P_{KA} (µGy m^2), P_{KA} rate (µGy m^2/s) and exposure time (with a time resolution of 500 µs).

In this comparison, the device was used in kerma area product mode, P_{KA} in μGy m^2; 60 s accumulation time was suggested.

ii. PCD : Radcal Patient Dose Calibrator PDC (Radcal Corp) s/n 07 0008, part no 165 00 01
Accessories : (i) Charger **(ii)** Socket adapter UK-EE **(iii)** Manual

The instrument was provided by the IAEA (Fig. 8).
The PDC's KAP ionization chamber, display and electronic unit were built in the same device.

Fig. 8. *Radcal Patient Dose Calibrator (PDC) used in this comparison for measurements of air kerma area product,* P_{KA}.

This reference class instrument for "field calibration" of patient dose measurement and control systems could measure simultaneously: entrance dose (mGy), entrance dose rate (mGy/s), P_{KA} (μGy m^2), P_{KA} rate (μGy m^2/s) and field size (mm^2).
The reference point of PDC was at the geometrical centre of the front surface. PDC was vented and applied automatic corrections for air density by its build- in pressure and temperature sensors. According to the manufacturer specifications the nominal active area of the PDC ionization chamber was rectangular with dimensions 300 mm x 300 mm. The device was not optically transparent.
The resolution of the display was 0.01 μGy m^2. There were LOW and HIGH measuring ranges; in this comparison the LOW RANGE was suggested to be used. The instrument was operated in charge mode (60 s exposure - accumulation time was suggested). Zeroing between successive exposures was done automatically or by using the RESET button.

iii. MAGNA : EXRADIN - Standard Imaging MAGNA A650, 3 cc, REF 92650 s/n D082612
Accessories : (i) Protection cap **(ii)** Manual

The instrument was provided by the IRCL/GAEC-EIM, Greece (Fig 9).

Fig 9 : *MAGNA A650 ionization chamber used for air kerma comparison.*

MAGNA was parallel plate ionization chamber with 3 cm^3 active volume and a 3.9 mg/cm^2 Kapton conductive film entrance window. The effective diameter of the chamber was 42 mm. The participating laboratory had to use its own electrometer for the bias voltage supply and the electrical current (charge) measurements. The polarizing voltage was 300 V, with the negative polarity to the middle shielding electrode (guard ring); the outer shielding (wall) was on earth potential. With this polarity configuration the displayed charge values on the electrometer had positive sign (+).
The manufacturer has grooved the reference plane at 3 mm from the entrance window. However, for this comparison, the reference point was at the geometrical centre of the entrance window.

3.3 Calibration quantities and radiation qualities

The instruments were requested to be calibrated as follows:

- KERMA-X in terms of P_{KA} (in Gy cm^2/digit)
- PDC in terms of P_{KA} (in Gy cm^2/digit)
- MAGNA in terms of K_a (in mGy/nC)

The calibrations were performed at the standard X-rays beam qualities according to IEC 61267 as shown in Table 8.

Table 8. *Standard X-ray beam qualities from IEC 61267 [10] used in this comparison*

Beam code	Tube voltage, kV	HVL, mm Al
RQR3	50	1.78
RQR5	70	2.58
RQR6	80	3.01
RQR8	100	3.97
RQR9	120	5.00

3.4. Method of analysis

The comparison result of a participating laboratory at each radiation quality and for each instrument was determined by comparing the calibration coefficient to the respective Comparison Reference Value (CRV). The CRVs were planned to be obtained from the calibration results of the participating PSDLs, i.e. LNE-LNHB (France), MKEH (Hungary), PTB (Germany) and VSL (The Netherlands). However, the HVL values of X-ray beam qualities RQR3, RQR8 and RQR9 established at the VSL were not consistent to the requirements of the IEC 61267, as they differed from the nominal IEC 61267 HVL values by more than 4.4 %, (section 2.2.2 of this report), so the results of VSL have not been used for the CRV determination.

3.4.1. Comparison Reference Value - CRV

The CRV and the associated uncertainty at a radiation quality Q (CRV) were determined as follows:
The weighted mean calibration coefficient at a radiation quality Q, of the three PSDLs, N_{ref}, was deduced, where the weights were equal to the reciprocals of the variances, u^2_i [15], , i.e.

$$\mathbf{N_{ref}} = \left. \sum_{i=1}^{p} \frac{N_i}{u_i^2} \middle/ \sum_{i=1}^{p} \frac{1}{u_i^2} \right. \qquad \textbf{eq. 1a}$$

where:
p : the number of PSDL (p=3)
N_{ref} : the weighted mean of the calibration coefficients at radiation quality Q
N_i : the reported calibration coefficient at the radiation quality, Q of the i^{th} PSDL
u_i : the standard uncertainty of the calibration coefficient at the Q beam quality of the i^{th} PSDL

The internal standard uncertainty of the weighted mean calibration coefficient at the beam quality Q, $u_{int,Nref}$, which took into account the precision of its results, was obtained from [16]

$$u_{int,Nref} = \left(\sum_{i=1}^{p} \frac{1}{u_i^2}\right)^{-1/2} \qquad \textbf{eq. 1b}$$

The external standard uncertainty of the weighted mean calibration coefficient at the beam quality Q, $u_{ext,Nref}$, which took into account the dispersion of the results from the weighted mean, was obtained from [16]

$$u_{ext,Nref} = \sqrt{\frac{\sum_{i=1}^{p} \frac{\left(N_i - N_{ref}\right)^2}{u_i^2}}{\sum_{i=1}^{p} \frac{1}{u_i^2}}} \qquad \textbf{eq. 1c}$$

The uncertainty of weighted mean calibration coefficient was the maximum value of the internal, $u_{int,Nref}$ and external, $u_{ext,Nref}$ uncertainties (eq 1b and 1c).

$$u_{N_{ref}} = \max\left\{u_{int,Nref}\,, u_{ext,Nref}\right\} \qquad \textbf{eq. 1d}$$

The weighted mean and its uncertainty may be inadequate when applied to discrepant data. In order to check the overall consistency of the results the reduced observed chi-squared value, x^2_{obs} was calculated for each the beam quality, Q, [14, 15]

$$x^2_{obs} = \frac{1}{p-1} \sum_{i=1}^{p} \frac{\left(N_i - N_{ref}\right)^2}{u_i^2} \qquad \textbf{eq. 2}$$

If $x^2_{obs} \leq 1$, consistency was pertained; the weighted mean and the associate uncertainty as deduced from eq. 1a and eq. 1b, were accepted as the CRV and the u_{CRV} respectively, i.e.

CRV = N_{ref} and **$u_{CRV} = u_{Nref}$**

If $x^2_{obs} > 1$, consistency failed, so the "Mandel – Paule mean" (M-P mean) approach was followed. According to it, the laboratory variances u_i^2 were incremented by a further variance s^2 to give augmented variances $u^2_{MP,i} = u_i^2 + s^2$. The value of the variance s^2 was chosen such that the modified reduced observed chi-squared value $x^2_{MP,obs}$ (eq. 3) equal one ($x^2_{MP,obs} = 1$) [14].

$$x^2_{MP,obs} = \frac{1}{p-1} \sum_{i=1}^{p} \frac{(N_i - N_{ref})^2}{u_i^2 + s^2} \qquad \textbf{eq. 3}$$

The calculation of the CRV (M-P mean) and its uncertainty proceeded through the same equations as for the weighted mean (eq. 1a – 1d), replacing the stated variances u_i^2 by the augmented variances $u^2_{MP,i}$. Therefore, the M-P weighted mean, $N_{MP,ref}$ and the associate uncertainty $u_{MP,Nref}$ were calculated from

$$\mathbf{N_{MP,ref}} = \left. \sum_{i=1}^{p} \frac{N_i}{u_i^2+s^2} \middle/ \sum_{i=1}^{p} \frac{1}{u_i^2+s^2} \right. \qquad \textbf{eq. 4a}$$

$$u_{int,MP,Nref} = \left(\sum_{i=1}^{p} \frac{1}{u_i^2+s^2}\right)^{-1/2} \qquad \textbf{eq. 4b}$$

$$u_{ext,MP,Nref} = \sqrt{\frac{\sum_{i=1}^{p} \frac{(N_i-N_{ref})^2}{u_i^2+s^2}}{\sum_{i=1}^{p} \frac{1}{u_i^2+s^2}}} \qquad \textbf{eq. 4c}$$

$$u_{MP,N_{ref}} = \max\{u_{int,MP,Nref}\,, u_{ext,MP,Nref}\} \qquad \textbf{eq. 4d}$$

Hence, in case $x^2_{obs} > 1$, the CRV and the u_{CRV} were **CRV = $N_{MP,ref}$** and **u_{CRV} = $u_{MP,Nref}$**.

The arithmetic mean, N_{mean}, of the calibration coefficients and its uncertainty u_{Nmean} were also calculated from

$$N_{mean} = \frac{\sum_{i=1}^{p} N_i}{p} \qquad \textbf{eq. 5a}$$

$$u_{N_{mean}} = \sqrt{\frac{\sum_{i=1}^{p}(N_i - N_{ref})^2}{p\cdot(p-1)}} \qquad \textbf{eq. 5b}$$

However, N_{mean} and u_{Nmean} were not used in the analysis of the results; they were calculated for comparison reasons only.

Finally, it should be mentioned that each calculation methodology of a mean value, i.e. based on the arithmetic mean or weighted mean or other, has advantages, disadvantages and limitations. A limitation of the weighted mean method is that there should be no correlations between laboratories. In this comparison, although such correlations existed, there were restricted to the physical constants being used by the PSDL and has limited influence to the calculation of the CRV and its uncertainties [17]. In order to further reduce such limitations, the methodologies proposed and applied by the CCRI(II) key comparison [14] and other statistical checks described in other parts of this repost, have been considered in this project .

3.4.2. Comparison result

The comparison result R of a participating laboratory (at each radiation quality and per instrument) was expressed as the ratio of the calibration coefficient and the respective CRV.

$$\mathbf{R} = \frac{\mathbf{N}}{\mathbf{CRV}} \qquad \textbf{eq. 6}$$

This EURAMET 1177 supplementary comparison has a few particularities, comparing to the traditional air kerma comparisons; the most important were:

- In principle, there are no direct linking laboratories. The three (3) participating PSDLs (LNE-LNHB, MKEH and PTB) have reported key comparisons neither in terms of air kerma area product, P_{KA}, nor in terms of air kerma (rate) at diagnostic radiology level. The CCRI(I) decided in 2011 that the range of agreed CCRI x-ray qualities ,used for the BIPM.RI-K2, K3, and K7 key comparisons, provide adequate coverage foll all diagnostic x-ray qualities, and the CCRI/12-05 document 'Validity of Ionizing Radiation Comparisons under the CIPM MRA' declares that any CMCs related to other quantites will normally need to be supported by regional supplementary comparisons. Note that only the PTB has published CMC for the air kerma area product quantity. BIPM.RI(I)-K2 and BIPM.RI(I)-K3, between MKEH and BIPM at low and medium CCRI therapy radiation qualities [18, 19, 20, 21]. According to the BIPM and EURAMET database, only the EURAMET RI(I)-S10 has been reported, which is a bilateral supplementary – supporting comparison between IAEA and PTB [17, 22], as well as the EURAMET 536 project which concerned mammography radiation qualities [2].
- The transfer KAP meters used in this comparison were commercial instruments that read directly the P_{KA} and they could not measure electric current; so any correlation of the measurement components between participating laboratories and PSDL or BIPM were not feasible.

In this respect, the methodology used for key comparisons could not be practically applied for the result evaluation of this comparison. Therefore, the following simplified formula was used for the calculation of the variance of the comparison result, R

$$\mathbf{u_R^2 = u_N^2 + u_{Nref}^2 + u_{stab}^2} \qquad \textbf{eq. 7}$$

where u_N and u_{Nref} are the relative standard uncertainties of the calibration coefficient deduced by the laboratory and the uncertainty of the CRV at the radiation quality, respectively and u_{stab} the relative standard uncertainty assigned for the stability of the chamber (eq. 10).
For the laboratories that have not contributed to the calculation of the CRV, the variance of the comparison result, R, was calculated by the following formula,

$$u_{Rj}^2 = u_{Nj}^2 + \frac{\sum_i^p a_i^2 \cdot u_{N,i,PSDL}^2}{\sum_i^p a_i^2} + u_{stab}^2 \qquad \textbf{eq. 8a}$$

where $u_{N,i.PSDL}$ is the relative standard uncertainties of the calibration coefficients reported by the PSDLs, that have contributed to the CRV and a_i is the normalized weighting factor u^2_{CRV} / $u^2_{N,i.PSDi}$ [14].

For the j[th] laboratory (PSDL) that has contributed to the CRV the above formula was changed to

$$u_{R,j}^2 = (1-2a_j)^2 u_{N,j}^2 + \frac{\sum_{i\neq j}^p a_i^2 \cdot u_{N,i,PSDL}^2}{\sum_{i\neq j}^p a_i^2} + u_{stab}^2 \qquad \textbf{eq. 8b}$$

in order to avoid the uncertainty of their results to be taken into account twice.

Finally, the consistency of the comparison result of a laboratory at radiation quality Q and for each transfer instrument was assessed by the En score, as [23]

$$\mathbf{E_n} = \frac{|\mathbf{N}-\mathbf{N_{ref}}|}{\sqrt{\mathbf{U_N^2}+\mathbf{U_{N,ref}^2}+\mathbf{U_{stab}^2}}}, \quad \textbf{eq. 9}$$

where U_N , $U_{N,ref}$ and U_{stab} are the expanded uncertainties (at k=2) of the calibration coefficient determined by the laboratory, the CRV and the stability of the transfer instrument (section 3.5.1), respectively.
En is an objective measure of whether or not an individual result is consistent with the CRV. The use of standard or expanded uncertainties in the En-score formula (eq. 9) is a matter of convention and agreement between the participating laboratories and it is correlated to the critical value that is set for the assessment of a laboratory result.
If standard uncertainties are used in the En-score formula, the critical value is 1.96 (approximately 2). If expanded uncertainties are used, the critical value is 1, and therefore, En ≤ 1 indicates that the laboratory result and the CRV are in agreement within their respective uncertainties.

Unlike z-scores, which consider standard uncertainties and require carefully selected "target" coefficients of variation among the laboratories as critical values, En-score, as in eq. 9, is more objective, robust and easy assessment method [24].
Therefore, in this work, expanded uncertainties in En-score formula were used and the critical value of 1 was set.

3.4.3. Performance tests of the transfer instruments

3.4.3.1. Stability tests of the transfer instruments

At the beginning of each round (7 rounds in total) the pilot laboratory performed stability tests for each transfer instrument, by means of the determination of the calibration coefficients at all (5) beam qualities used in this comparison. Each time, the same irradiation conditions were applied. Therefore, for each beam quality and transfer instrument, seven calibration coefficients were obtained (8 for MAGNA due to an extra calibration), as the ratio of the reference dosimetric quantity, (P_{KA} or K) and instrument reading corrected for all influence quantities.

The stability of each instrument was represented by the standard uncertainty $\mathbf{u_{stab}}$ which was calculated as

$$u_{stab} = \sqrt{u_{Ref}^2 + u_M^2} \quad \textbf{\textit{eq. 10}}$$

$$\mathrm{u_{Ref}} = \sqrt{\frac{\sum_{i=1}^{m} s_{i,Ref}^2}{m}} \quad \textbf{\textit{eq. 11.a}} \qquad \mathrm{u_M} = \sqrt{\frac{\sum_{i=1}^{m} s_{i,M}^2}{m}} \quad \textbf{\textit{eq. 11.b}}$$

where $\mathbf{s_{i,Ref}}$ and $s_{i,M}$ are the relative standard deviation of the reference dosimetric quantity (P_{KA} or K) and instrument readings at the radiation quality i and **m** is the total number of radiation qualities used for the stability check (m=5).
In this respect, the stability took into account both variation of the reference dosimetric quantity and instrument performance.

3 4.3.2. Influence of radiation quality, air kerma rate, $\dot{K}$ and irradiation area, A

The response of the transfer instruments may depend on the radiation quality, air kerma rate, $\dot{K}$, and irradiation area, A. Therefore, to obtain comparable results of calibrations, the calibration conditions should be similar or the calibration coefficient should refer to the same irradiation conditions. As shown in Section 2.2, the calibration conditions varied between the laboratories and, therefore, the influence of the radiation quality, air kerma rate, $\dot{K}$, and irradiation area, A, on the response of the transfer instruments used in this comparison were studied, and respective correction factors, k, were introduced. The corrected calibration coefficient can be calculated from

$$N_{cor} = N \cdot \left(k_Q \cdot k_{rate} \cdot k_{area}\right)^{-1}$$ **eq. 12a**

where k_Q, k_{rate} and k_{area} are the correction factors for the beam quality Q, $\dot{K}$and A, respectively.
The relative standard uncertainty of the corrected calibration coefficient, $u^{rel}_{Ni,cor}$, is

$$u^{rel}_{N_{cor}} = \sqrt{u^2_{N_{rel}} + u^2_{k_{Q,rel}} + u^2_{k_{rate,rel}} + u^2_{k_{area,rel}}}$$ **eq. 12b**

where the components in square-root are the relative standard uncertainties of the N_i, k_Q, k_{rate} and k_{area} respectively.

The radiation beam quality correction factor, k_Q adjusted the laboratory's calibration coefficient to the reference HVL value (average HVL value of the 3 participating PSDLs) for the respective radiation quality.
The k_Q values (for a specific laboratory's results) were obtained from the fitting N_i = f(HVL) curves of that laboratory, where N_i and HVL were the reported calibration coefficients and HVL values.
The uncertainty of the k_Q values should combine the reported uncertainty of the calibration coefficient and the uncertainty due to the fitting of the N_i = f(HVL) curve. For the latest, the root mean square deviation (r.m.s.) was used, as an overall measure of the "goodness of fit". The r.m.s. measures how close the regression line is to all of the points simultaneously. The r.m.s. was computed using the residuals from a regression, as [25]

$$\text{r.m.s} = 100\sqrt{\frac{1}{n-m}\sum_{i=1}^{n}\frac{(N'_i - N_i)^2}{{N'_i}^2}}\ \%$$ **eq. 13**

where N_i is the reported calibration coefficient at certain radiation quality (HVL_i), N'_i, is the value deduced from the regression at the reported HVL_i, n is the number of points of the N_i = f(HVL) curve (n=5, as the number of radiation qualities) and m the number of the parameters used for the regression (e.g. m=4, for cubic fitting).
The k_Q was applied only in the cases where the HVLs of the laboratory's beams differed from the nominal HVL value (IEC 61267) by more than ± 4.4 % (section 2.2.2 of this report). Details on the calculation of the k_Q values and their uncertainties are given in Section 4.2.

The air kerma rate correction factor, k_{rate} , was used to correct the calibration coefficient of the transfer instruments to the reference air kerma rate, $\dot{K}$ value of 50 mGy/min. This reference value corresponded to the $\dot{K}$ values that applied by the participating PSDL. It also was higher than 15 mGy/min, where the influence of the $\dot{K}$ dependence of response of the instruments was negligible (see section 4.2).
The $\dot{K}$ dependence of response and the determination of the k_{rate} correction factors were studied at the IRCL/GAEC-EIM.The measurements performed at the RQR6 (80 kV) radiation quality at distance of 1000 mm from X-ray focus; the air kerma ranged from 2 mGy/min to 90 mGy/min. An Exrading A3 ionization chamber was placed behind the KAP meters at 1050 mm distance from X-ray focus and measured the air kerma simultaneously with the KAP meter. For the determination of the air kerma, appropriate corrections to the A3 readings for the attenuation of the beam and the beam hardening by the KAP meter as well as for the distance from X-ray focus were considered. The k_{rate} vs $\dot{K}$ curves, k_{rate} = f($\dot{K}$), were determined.

The uncertainty of the k_{rate} correction factors was estimated taken into account all influence quantities, as well as the fitting to the $k_{rate} = f(\dot{K})$ curve; for the latter the r.m.s. concept was applied (eq. 13). Details on the calculation of the k_{rate} values and their uncertainties are given in Section 4.2.

The irradiation area correction factor, k_{area} , was used to correct the calibration coefficient of the KAP meters (KERMA-X and PDC) to a reference value of 25 cm^2 of the irradiation area, A. This standard value corresponds to the irradiation areas applied by the participating PSDL for the calibration of the KERMA X (LNE-LNHB 27.7 cm^2, MKEH 26 cm^2 and PTB 25 cm^2) and PDC (LNE-LNHB 27.7cm^2, MKEH 27 cm^2 and PTB 25 cm^2).
The irradiation area dependence of response and the determination of the k_{area} correction factors were studied at the IRCL/GAEC-EIM (for KEPMA-X) and MKEH (for PDC).
The k_{area} vs irradiation area curves were determined for both KAP meters.
The uncertainty of the k_{area} correction factors was estimated taken into account all influence quantities and fitting parameters. Details on the calculation of the k_{area} values and their uncertainties are given in the 4.2 section of this report.

The application of the correction factors had direct impact on the comparison result of a laboratory and the associate uncertainty. The "corrected" comparison result, R_{cor} and its uncertainty $u_{R,cor}$ were obtained from

$$\mathbf{R_{cor}} = \frac{\mathbf{N_{cor}}}{\mathbf{CRV}} \qquad \textbf{eq. 14a}$$

and

$$\mathbf{u^2_{R,cor}} = \mathbf{u^2_R} + \mathbf{u^2_{k_q}} + \mathbf{u^2_{k_{rate}}} + \mathbf{u^2_{k_{area}}} \qquad \textbf{eq. 14b}$$

Finally the corrected En score was given by

$$\mathbf{E_n} = \frac{|\mathbf{N_{cor}} - \mathbf{N_{ref}}|}{\sqrt{\mathbf{U^2_{N,cor}} + \mathbf{U^2_{N,ref}} + \mathbf{U^2_{stab}}}}, \qquad \textbf{eq. 15}$$

where N_{cor} is the corrected calibration coefficient (eq. 12a) and $U_{N,cor}$ the expanded relative uncertainty (k=2) of the N_{cor} (eq. 12b)

3.4.3.3. Automatic corrections for air density of the PDC

The PDC had internal sensors for the measurement of temperature and pressure, so the device performs correction for the air density automatically. Therefore, the PDC reading referred to the reference air density value.
The environmental stabilization and the accuracy of the automatic temperature and pressure correction of the PDC were studied by IRCL/GAEC-EIM (Section 4.2). PDC was turned on and the PDC's temperature and pressure indications were recorded in real time through PDC software. At the same time intervals, the room temperature and pressure were recorded from the reference thermometer and barometer of the IRCL/GAEC-EIM placed close to PDC.

3.4.4. PomPlots

From graphical representations of the comparison results, i.e. plot of the comparison results (R or R_{cor}) and the associated uncertainties against radiation quality (HVL), one can derive a general impression of the quality of the results: i.e. the accuracy of the measurement results and the adequacy of the assigned uncertainty. The data represents the position of the measurement result relative to the reference value, the uncertainty being indicated by an ''error bar''. Alternatively, one can use a type of plot that underlines the importance of the assigned uncertainties, i.e. the PomPlot [27, 28].

The PomPlot displays the relative deviations, D, of the individual results from the reference value, i.e. D = $R_{cor} - 1$, on the horizontal axis and the standard uncertainties u_{Rcor} on the vertical axis.
The ζ-scores, $|\zeta| = |R_{cor}-1| / u_{Rcor}$ = 1, 2, and 3, are represented by diagonal solid lines, creating the aspect of a pyramidal structure. The ζ-score is a measure for the deviation between laboratory result and reference value relative to the total uncertainty. Points on the right-hand side of the graph correspond to results that are higher than the reference value while lower values are situated on the left. When the laboratory result's uncertainty is low, the corresponding point is situated higher in the graph; when the uncertainty is high, the point is situated lower in the graph. Consequently, the most accurate results should be situated close to the top of the pyramid and close to the central line, with D = 0. Points outside of the ζ = ± 3 lines are probably inconsistent with the reference value.

PomPlots were obtained for KERMA-X and PDC comparison results at the RQR5 radiation quality. PomPlots were also deduced for the weighted mean comparison results of KERMA-X and PDC at the RQR5. The results between KERMA-X and PDC were weighted according to the reciprocal of the comparison result variances (eq. 1a and 1b). Therefore, in such a graph, the $u_{Rcor,WM}$ (vertical axis) was plotted against $D_{WM} = R_{cor,WM} - 1$, where

$$\mathbf{R_{cor,WM}} = \left(\frac{\mathbf{R_1}}{\mathbf{u_1^2}} + \frac{\mathbf{R_2}}{\mathbf{u_2^2}}\right) \Bigg/ \left(\frac{\mathbf{1}}{\mathbf{u_1^2}} + \frac{\mathbf{1}}{\mathbf{u_2^2}}\right) \qquad \textbf{eq. 16a}$$

and

$$\mathbf{u_{Rcor,WM}} = \left(\frac{\mathbf{1}}{\mathbf{u_1^2}} + \frac{\mathbf{1}}{\mathbf{u_2^2}}\right)^{-\mathbf{1}/\mathbf{2}} \qquad \textbf{eq. 16b}$$

where R_1 and R_2 are the corrected comparison results, R_{cor}, at RQR5 for KERMA-X and PDC, respectively and u_1 and u_2 their standard uncertainties, u_{Rcor}.

3.4.5. Method for deriving the Degree of Equivalence

The degree of equivalence (DoE) is the degree to which the value of a measurement standard is consistent with the comparison reference value. It is expressed as the difference of the companion result and the respective CRV.
When a number of radiation qualities and instruments are used in a comparison, the results are deduced for each quality and instrument, separately [2, 3, 4, 17, 20], as described in the previous sections.
In this comparison, the DoE was obtained at the RQR5 radiation quality, which is the reference quality of the RQR series [10, 11], i.e.

$$\mathrm{DoE} = |\mathrm{D}| = |R_{\mathrm{cor,RQR5}} - 1| \qquad \textbf{eq. 17}$$

The uncertainty of the DoE was expressed as the expanded uncertainty at k=2, i.e.

$$U_{DoE} = U_D = 2\ u_{DoE} = 2\ u_{Rcor,RQR5}. \qquad \textbf{eq. 18}$$

where $R_{cor,RQR5}$ and $u_{Rcor,RQR5}$ are the corrected comparison result (eq 14a) and its uncertainty (eq 14b) of the laboratory at RQR5 radiation quality.

Regarding the instruments, the DoE for the air kerma area product, PKA, was obtained from the results of PDC. The reasons for this are described in the "Result and Discussion section.
The DoE for the air kerma was obtained from the results of MAGNA.

4. Results and Discussion

4.1. Results of calibrations at the participating laboratories

The results of transfer instrument calibrations at RQR radiation qualities as submitted by the participating laboratories are presented in ANNEX A. The symbols in the column headings are as follows

- HVL : reported HVL in mm Al of the radiation quality
- A : reported irradiation area, in cm^2 at the point of measurement
- $\dot{K}$: reported value of the air kerma rate at the point of measurement
- N_{PKA} : reported calibration coefficient in terms of air kerma area product
- N_K : reported calibration coefficient in terms of air kerma
- U % : reported relative expanded uncertainty of the calibration coefficient, k=2
- u : standard uncertainty (k=1) of the calibration coefficient calculated from U % and N_{PKA} or N_K (three digits are kept for the u values)

A radiation quality established at different laboratories is rarely exactly the same either between the laboratories or with the stated IEC standard quality. For this, in this study, the result analysis considered the radiation qualities in terms of HVL (in mm Al), while in the text the IEC code (e.g. RQR5) was used. This approach is followed in most key, supplementary or other comparisons [2, 3, 4], although in a few others only the radiation code (e.g. kV) is given to the results presentation [20].

4.2. Transfer instruments performance

As described in section 3.6, the performance of the instruments being used in this comparison was studied through the determination of respective correction factors, as presented below.

4.2.1. Performance tests of KERMA-X

4.2.1.1. Stability tests of KERMA-X

Fig. 10 presents the stability tests of the KERMA-X at the RQR qualities. According to eq. 10, 11a and 11b the standard uncertainty for the iKERMA-X stability u_{stab} was 0.79 %.

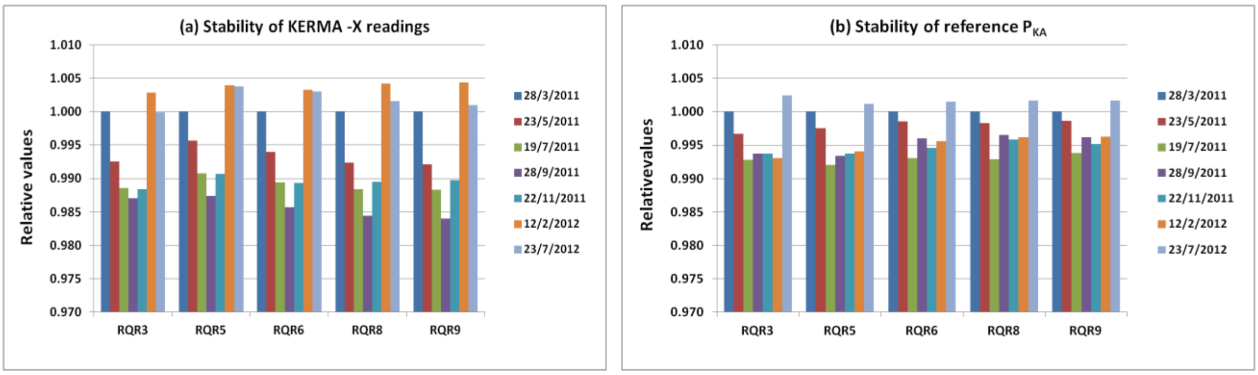


Fig. 10. *Stability checks of KERMA-X at the RQR qualities. The y axes show (a) the normalized KERMA-X readings corrected for air density and (b) the normalized reference* P_{KA} *values pertained during calibration of KERMA-X , as deduced at each round; the normalization was done to the measurements of the* 1^{st} *round.*

4.2.1.2. Energy (radiation quality) dependence of response

The energy dependence of response of KERMA-X is presented in Fig. 11. The MKEH reported calibration results were normalized to the RQR5 quality (y-axis) and plotted against the reported HVL values (x-axis). The measurements were performed at 2 m distance from X-ray focus, irradiation area of 26 cm^2 and air kerma rate close to 18 mGy/min.

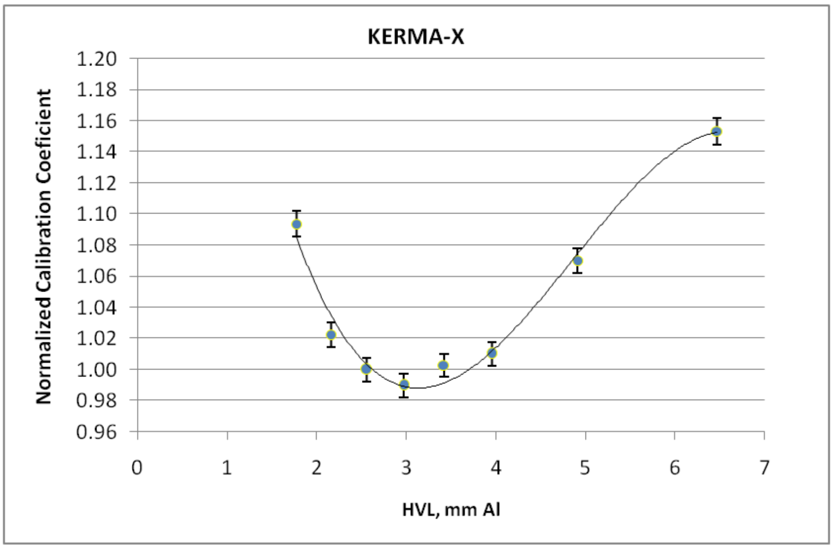


Fig. 11. *The energy dependence of response of KERMA-X KAP meter. The normalization of the calibration coefficients (y-axis) refers to the RQR 5. Irradiation area : 26 cm^2 , air kerma rate ~ 18 mGy/min. The error bars correspond to standard uncertainty (k=1). Initial data provided by MKEH.*

The calibration results of the participating laboratories were corrected for radiation quality (energy) in case the reported HVL value differed from the nominal HVL value (IEC 61267) by ± 4.4 % (Section 2.2.2).

In such cases, the k_Q correction factors were deduced from the calibration results of the participating laboratory. The specific (for each participating laboratory) N_i = f(HVL) curve was obtained, where N_i is the reported calibration coefficient at the respective HVL. Using the fitting curve, the calibration coefficient $N_{i,cor}$ at the standard HVL value (i.e. the average HVL value of the 3 participating PSDLs) was deduced. The k_Q is the ratio of the N_i over $N_{i,cor}$. The standard uncertainties of the k_Q values were obtained from the root mean square deviation (r.m.s.) as computed from eq. 13.

An example, for the VSL results, is given in Fig. 12.

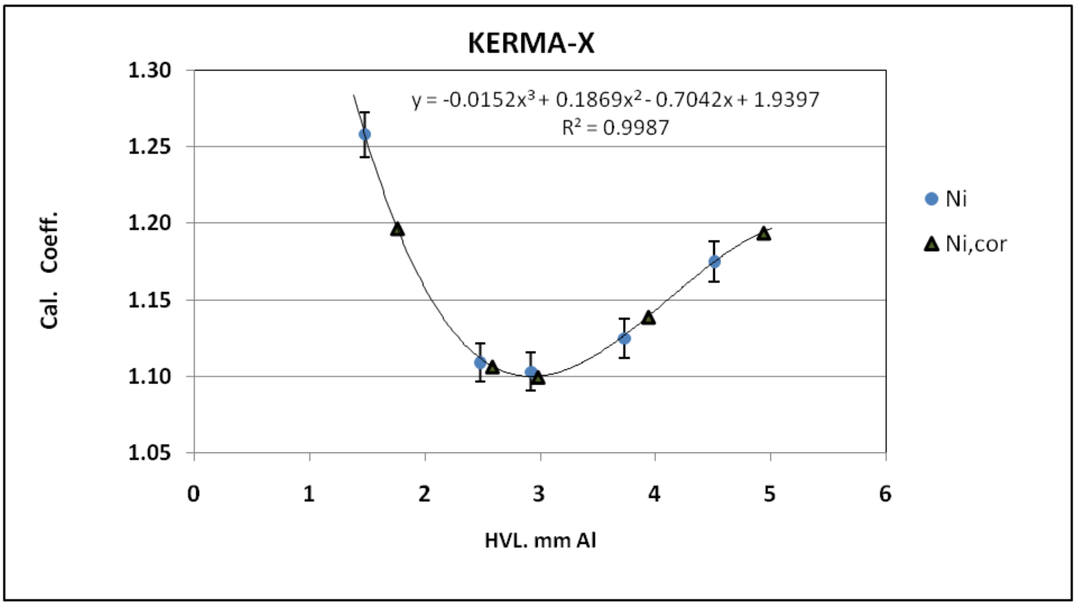


Fig. 12. *Example for the determination of the k_Q correction factor for KERMA-X, using the VSL results. $N_i = f(HVL)$ is the curve for the VSL results (blue circle), where N_i is the reported calibration coefficient at the respective reported HVL. The error bars correspond to the reported standard uncertainty of the calibration coefficients (u_{Ni} = 0.014). The triangles show the corrected calibration coefficients at the standard HVL values (average HVL value of the 3 participating PSDLs) as deduced from the fitted curve. The k_Q values (ratio of N_i / $N_{i,cor}$) were 1.051 at RQR3, 1.002 at RQR5, 1.003 at RQR6, 0.988 at RQR8 and 0.984 at RQR9. The standard uncertainty of the k_Q, expressed as the r.m.s. deviation (Eq. 13) was 0.42 %.*

In similar way, k_Q correction factors and their uncertainties were deduced for the SURO results (for the RQR8), VSL results (for the RQR3, RQR8 and RQR9), VINCA results (for the RQR3) and UPC results (for the RQR5).
Correction for the energy dependence of response were applied at qualities that were inconsistent with the nominal HVL values (IEC 61267), if the calculated k_Q value was significant compared to its uncertainty, i.e. the correction (k_Q) was higher than its uncertainty ($|k_Q - 1| > u_{kQ}$). In the example of VSL results (Fig. 12), corrections were applied at RQR3, RQR8 and RQR9.

4.2.1.3. Air kerma rate, $\dot{K}$, dependence of response

The k_{rate} correction factors for KERMA –X as determined at the IRCL/GAEC-EIM are shown in Fig. 13. As shown in Fig. 13, KERMA X response was quite stable for $\dot{K}$ values higher than 20 mGy/min. Therefore, for $\dot{K}$> 20 mGy/min, corrections for the $\dot{K}$dependence were not necessary.
For those calibrations performed at $\dot{K}$ less than 20 mGy/min (21 cases out of 108 in total), appropriate corrections were considered, if the k_{rate} correction factor was significant compared to its uncertainty.

The k_{rate} correction factors were deduced from the fitted curve as presented in Fig.13.

$$k_{rate} = y_0 + A \cdot e^{Ro \cdot \dot{K}}$$

where y_0 = 1, A=7.23 ± 0.08 and R_0 = - 0.418 ± 0.004

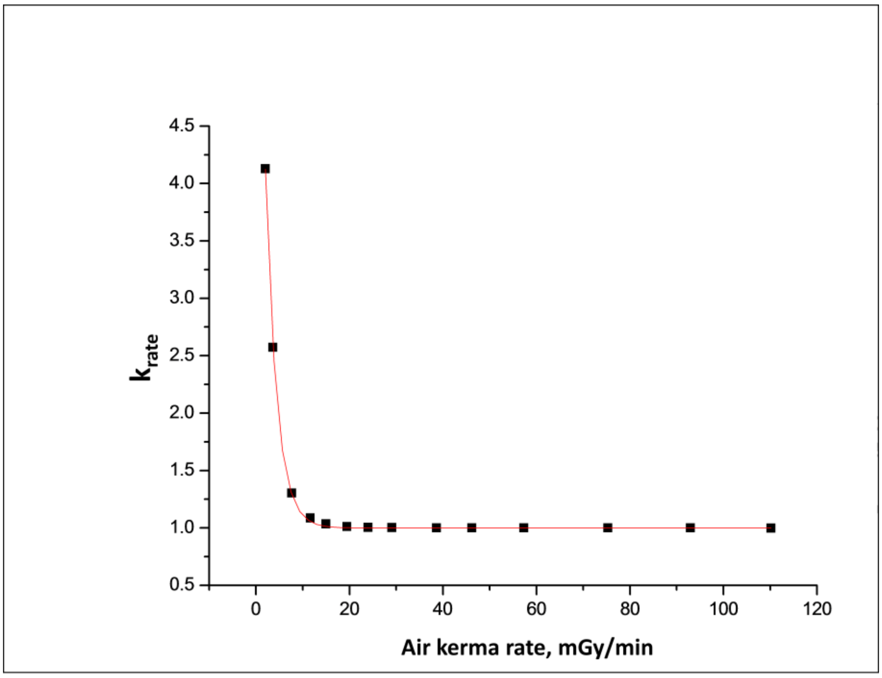


Fig. 13. *The air kerma rate dependence of response and the k_{rate} correction factors for KERMA-X KAP meter. The fitted curve to the $k_{rate} = f(\dot{K})$ relationship for the KERMA-X. The measurement performed at RQR6 (80 kV) and irradiation area of 27.8 cm^2.*

Table 9 presents the calculation of the uncertainty of the k_{rate}.

Table 9. *The uncertainty estimation of k_{rate} for KERMA-X*

	TYPE A %	TYPE B %	Notes
Readings of reference chamber, A3	0.17		Standard uncertainty (SD of the mean) of the A3 readings
Readings of KAP meter	1.29		Standard uncertainty (SD of the mean) of the KERMA- X readings
Scatter contribution		0.58	1 % of the primary beam
Fitting (parameters & curve)		1.17	r.m.s. – eq. 13
Combined	1.30	1.31	
Combined, k=1	1.84		

For the comparison evaluation, k_{rate} corrections factors were applied only to those calibration results obtained at air kerma rates lower than 20 mGy/min, if the calculated k_{rate} value was significant compared to its uncertainty, i.e. the correction (k_{rate}) was higher than its uncertainty, u_{krate} ($| k_{rate} - 1 | > 0.018$).

It is worth mentioning that standards for the air kerma rates do not exist - as in the case of the radiation qualities (IEC 61274). The IEC 60580 concerning the dose area product (DAP) meters does not specify reference air kerma rates values [26]. Therefore, the laboratories may apply air kerma rates according to their procedures.

4.2.1.4. Irradiation area dependence of response

The correction factors, k_{area}, of KERMA–X as determined at the IRCL/GAEC-EIM are shown in Fig. 14. Data has been normalized to a standard irradiation area of 25 cm^2. The measurement performed at RQR3, RQR5 and RQR9 radiation qualities and separate sets of k_{area} correction factors were deduced.

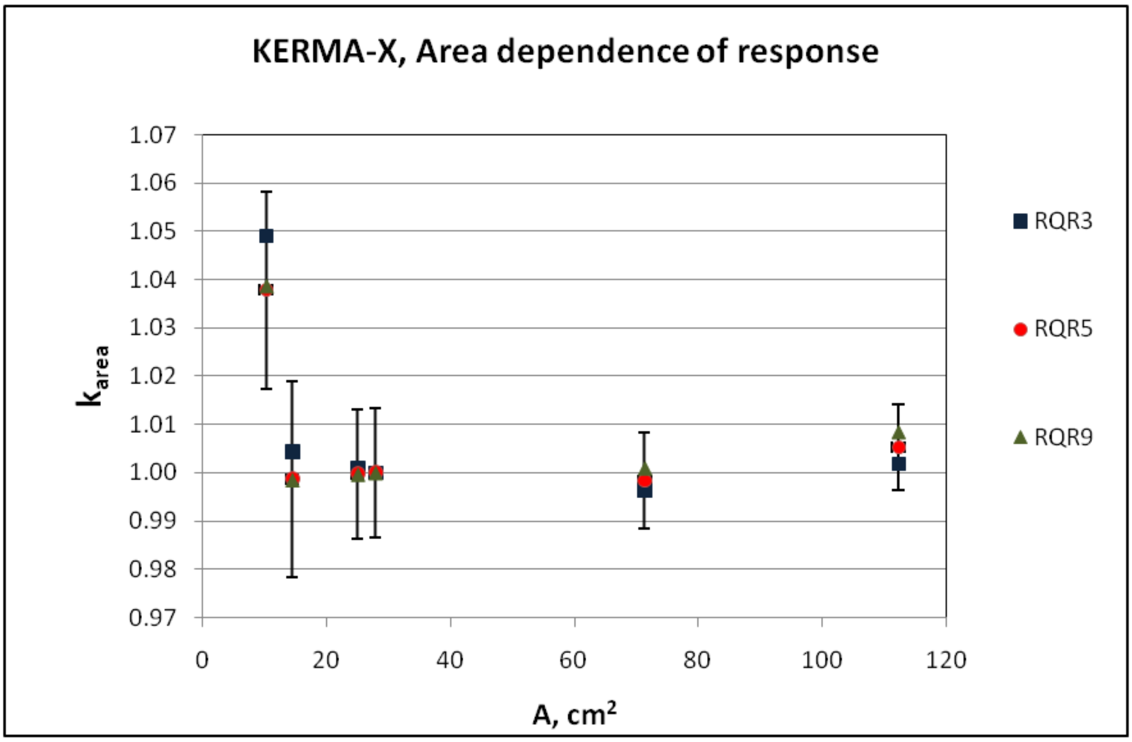


Fig. 14. *The irradiation area dependence of response of the KERMA-X at RQR3, RQR5 and RQR9. The bars corresponds to the standard uncertainties of the k_{area} values at k=1.*

Table 10 presents the calculation of the uncertainty of the k_{area}

Table 10 : The uncertainty estimation of k_{area} for KERMA-X

	TYPE A %	**TYPE B %**	**Notes**
Area determination		1.15	0.5 mm uncertainty for the 50 mm aperture. Respective type B uncertainties deduced for the other apertures (areas)
Distance determination		0.29	5 mm uncertainty @ 1 m from focus
Readings of KAP meter- stability	0.20		C.V. of the KERMA readings
Scattered radiation		0.58	1 % of the primary beam
Combined	0.20	1.32	
Combined, k=1	1.34		

At irradiation areas larger than 15 cm^2, the response of KERMA-X was almost constant; the variation was less than 1 % (Fig. 14). All laboratories performed the calibration using irradiation areas larger than 15 cm^2, most of them between 20 cm^2 and 30 cm^2 (Fig. 2).
Therefore, there was no need to apply correction factors for the irradiation area to any laboratory result.

Concluding on the application of correction factors and their uncertainties to the calibration results of KERMA-X:
k_Q applied only to those results where the radiation quality was not consistent to the IEC 61274 standard, if k_Q was higher than its uncertainty (i.e. $|k_{rate} - 1| > u_{kQ}$).
k_{rate} applied to those results obtained at air kerma rates lower than 20 mGy/min, if k_{rate} was higher than its uncertainty, u_{krate} (i.e. $|k_{rate} - 1| > 0.018$).
k_{area} did not apply to any calibration result.

4.2.2. Performance tests of PDC

4.2.2.1. Stability tests of PDC as a KAP meter

Fig. 15 presents the stability tests of the PDC at the RQR qualities. According to eq. 10, 11a and 11b the standard uncertainty for the PDC (KAP meter) stability u_{stab} was 1.00 %.

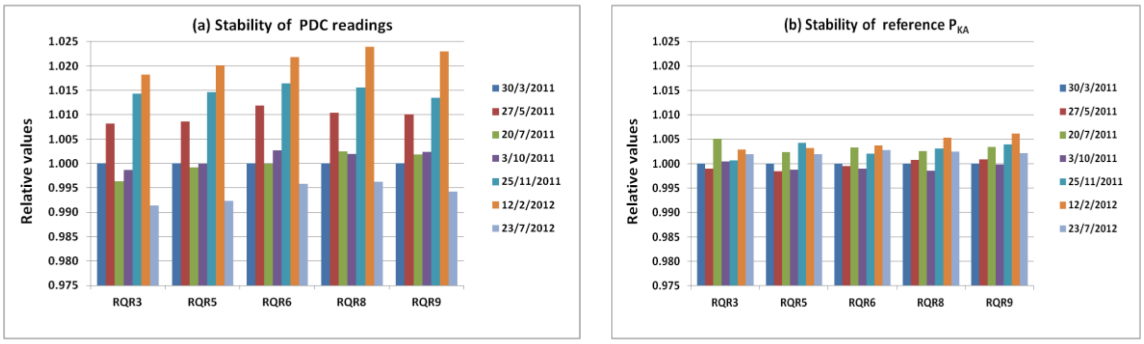


Fig. 15. *Stability checks of PDC at the RQR qualities. The y axes show (a) the normalized PDC readings corrected for air density and (b) the normalized reference P_{KA} values pertained during calibration of PDC, as deduced at each round; the normalization was done to the measurements of the 1^{st} round.*

4.2.2.2. Temperature and pressure internal indications

The temperature stabilization of PDC was checked several times at IRCL/GAEC-EIM.
All checks gave similar results, as those of Fig. 16. From the checks it appeared that the temperature inside PDC, as recorded by the PDC's sensor and displayed in the device's software (in real time), stabilized in about an hour. The difference between temperatures inside the device and the environment was about 6 ^{0}C. It should be noted that PDC was a compact device where the ionization chamber and the electronics were close to each other. The heat given off by the electronics increased the temperature inside the device. This fact may explain the observed difference of the 6 ^{o}C between the device's temperature indication and the room temperature. Furthermore, the increase of temperature that recorded after turning on the device may be due to the electronic heat, until equilibrium is reached. The PDC's ionization chamber operated in the device's internal environment, where certain temperature conditions apply. Due to the compactness of the PDC, it was not possible to check the temperature inside the device.
In a similar manner, the pressure stabilization and accuracy of PDC was checked.
Fig.17 presents the checks of the pressure that recorded by the internal PDC's sensor. The difference between pressure inside the device and the environment was about – 1.5 hPa. This difference may be due to the different performance of PDC's pressure sensor and the reference

barometer. This difference resulted in a 0.2 % difference of the air density correction factor, $k_{P,T}$. The PDC pressure indication stabilized rapidly after turning on the device.

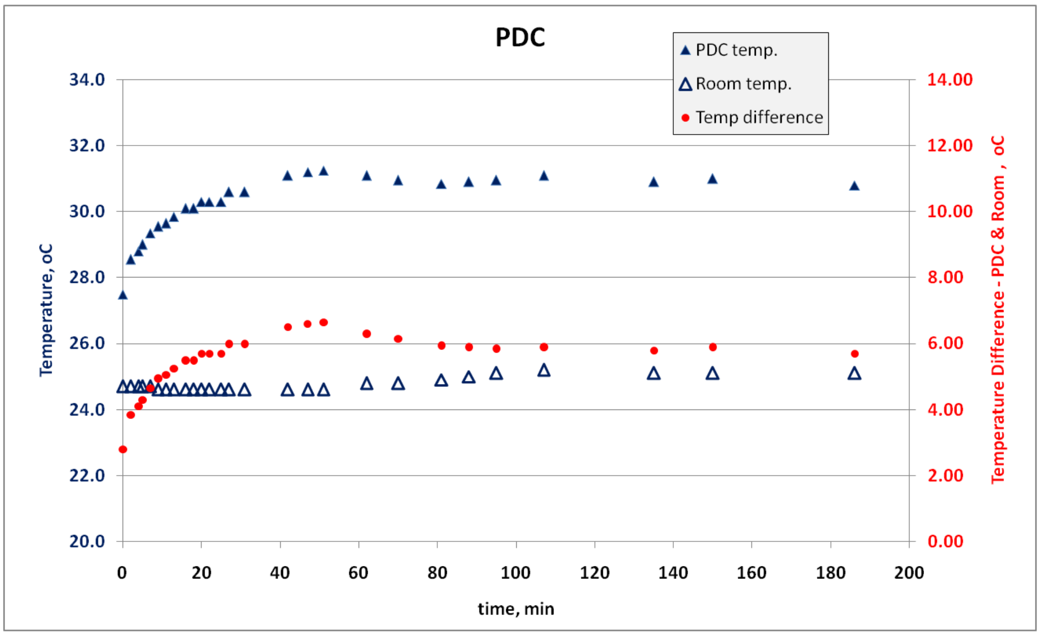


Fig. 16. *The temperature response of PDC. PDC was turned on at 0 min. The blue filled triangles show the temperature recorded by the PDC's internal sensor (left y-axis), the blue hollow triangles show the room temperature (left y-axis) and the red dots presents the difference between PDC's temperature indication and room temperature (right y-axis).*

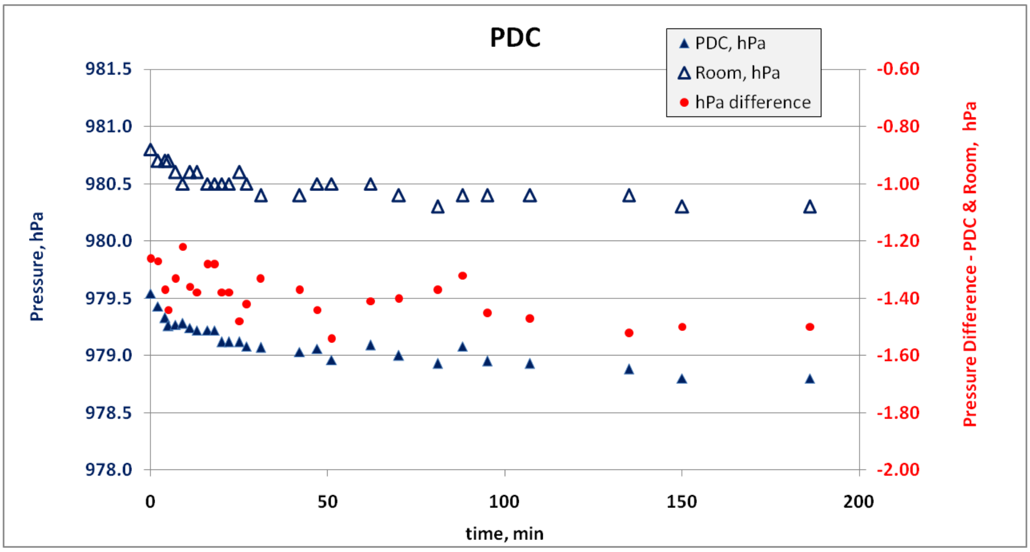


Fig. 17. *The pressure response of PDC. PDC was turned on at 0 min. The blue filled triangles show the pressure recorded by the PDC's internal sensor (left y-axis), the blue hollow triangles show the room pressure (left y-axis) and the red dots presents the difference between PDC's pressure indication and actual room pressure (right y-axis).*

The PDC readings (P_{KA}) were corrected automatically for air density, using the PDC's temperature and pressure indications. According to the comparison protocol, all laboratories considered PDC's P_{KA} readings as being corrected for air density and therefore, did not apply additional correction factor, $k_{P,T}$ in calculations.

In this respect, the calibration results from all laboratories had the same uncertainty due to air density correction made automatically by PDC, and consequently all results could be equally and consistently compared.

4.2.2.3. Energy (radiation quality) dependence of response

The energy dependence of response of PDC is presented in Fig. 18. The MKEH reported calibration results normalized to the RQR5 quality (y-axis) are plotted against the HVL values (x-axis). The measurements were performed at 2 m distance from X-ray focus, irradiation area of 26 cm^2 and air kerma rate close to 18 mGy/min.

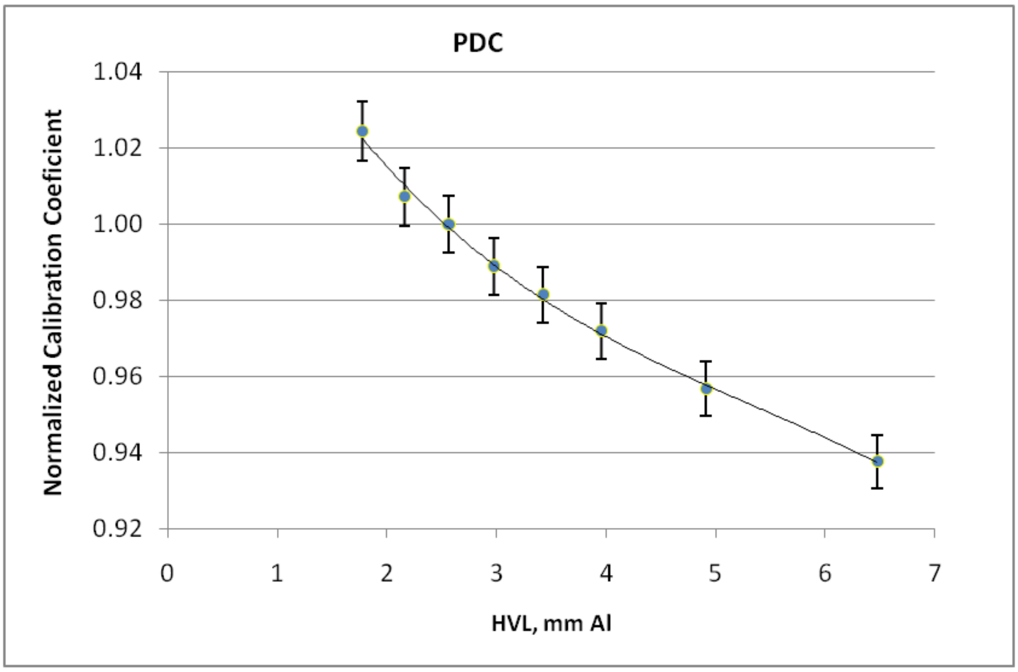


Fig. 18. *The energy dependence of response of PDC. The normalization of the calibration coefficients (y-axis) refers to the RQR 5 quality. Irradiation area was 27 cm^2 and the air kerma rate ~ 18 mGy/min. The error bars correspond to standard uncertainty (k=1). Initial data provided by MKEH.*

As in the case of KERMA-X, the calibration results of the participating laboratories were corrected for radiation quality (energy) in case where the reported HVL values differ from the nominal HVL values (IEC 61267) by ± 4.4 % (Section 2.2.2).

In such cases, the k_Q correction factors were deduced from the calibration results of the participating laboratory. The specific (for each participating laboratory) N_i = f(HVL) curve was obtained, where N_i is the reported calibration coefficient at the respective HVL. Using the fitted curve, the calibration coefficient $N_{i,cor}$ at the standard HVL value (i.e. average HVL value of the 3 participating PSDLs) was deduced. The k_Q is the ratio of the N_i over $N_{i,cor}$. The standard uncertainty of the k_Q values were obtained from the root mean square deviation (r.m.s.) as computed from eq. 13.

An example, for the VSL results, is given in Fig. 19.

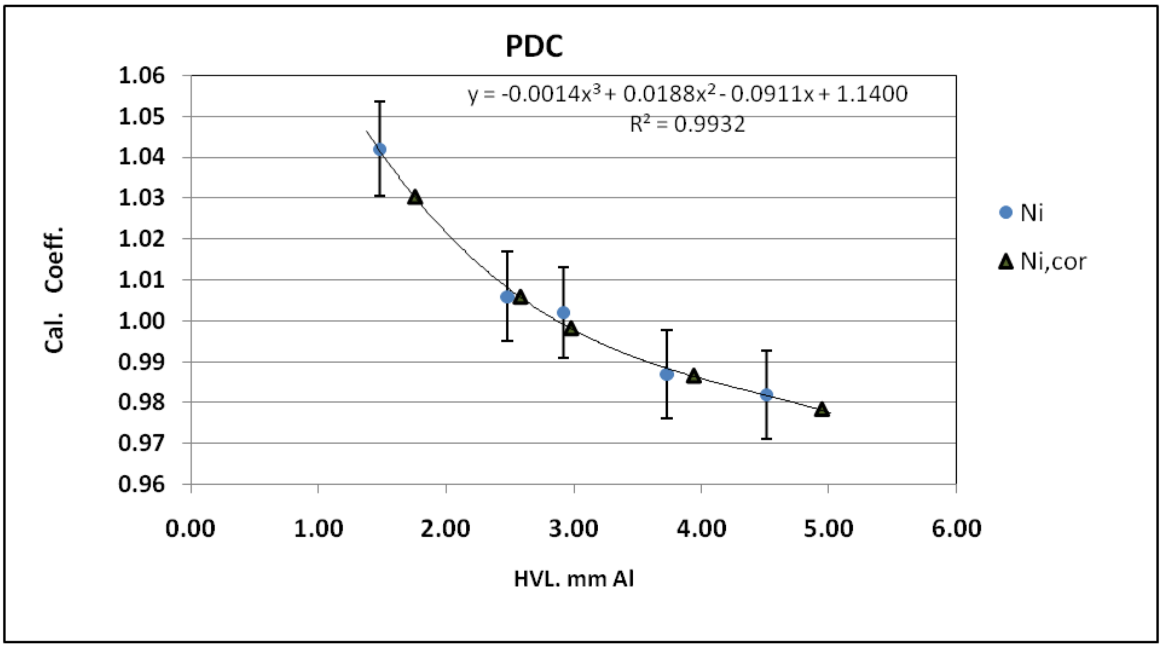


Fig. 19 : *Example for the determination of the k_Q correction factors for PDC, using the VSL results. N_i = f(HVL) is the curve for the VSL results (blue circle), where N_i is the reported calibration coefficient at the respective reported HVL. The error bars correspond to the reported standard uncertainty of the calibration coefficients (u_{Ni} = 0.011). The triangles show the corrected calibration coefficients at the standard HVL values (average HVL value of the 3 participating PSDLs) as deduced from the fitting curve. The k_Q values (ratio of N_i / $N_{i,cor}$) were 1.011 at RQR3, 1.000 at RQR5, 1.004 at RQR6, 1.001 at RQR8 and 1.004 at RQR9. The standard uncertainty of the k_Q, expressed as the r.m.s. deviation (eq 13) was 0.39 %.*

In similar way, k_Q correction factors and their uncertainties were deduced for the SURO results (for the RQR8), VSL results (for the RQR3, RQR8 and RQR9), VINCA results (for the RQR3) and UPC results (for the RQR5).

Correction for the energy dependence of response were applied at qualities that were inconsistent with the nominal HVL values (IEC 61267), if the calculated k_Q value was significant compared to its uncertainty, i.e. the correction (k_Q) was higher than its uncertainty ($|k_Q - 1| > u_{kQ}$). In the example of VSL results (Fig. 19), corrections were applied at RQR3 and RQR9 (RQR6 quality was consistent with IEC 61267).

4.2.2.4. Air kerma rate, $\dot{K}$, dependence of response

The k_{rate} correction factors as determined at the IRCL/GAEC-EIM are shown in Fig. 20. At $\dot{K}$ > 15 mGy/min the PDC air kerma rate dependence of response was stable (within ± 1 %). For $\dot{K}$< 15 mGy/min, PDC underestimated the P_{KA}; at $\dot{K}$< 4.5 mGy/min the air kerma dependence of response was greater than 5 %.

Therefore, for $\dot{K}$> 15 mGy/min, corrections for the $\dot{K}$ dependence were not necessary.
For those calibrations performed at $\dot{K}$ less than 15 mGy/min (22 cases out of 108 in total), appropriate corrections were considered, if the k_{rate} correction factor was significant compared to its uncertainty.

The k_{rate} correction factors were deduced from the fitted curve of Fig. 20

$$k_{rate} = a \cdot e^{b/(K+c)}$$

where a = 0.9973 ± 0.001, b = 0.196 ± 0.003 and c = -0.36 ± 0.04

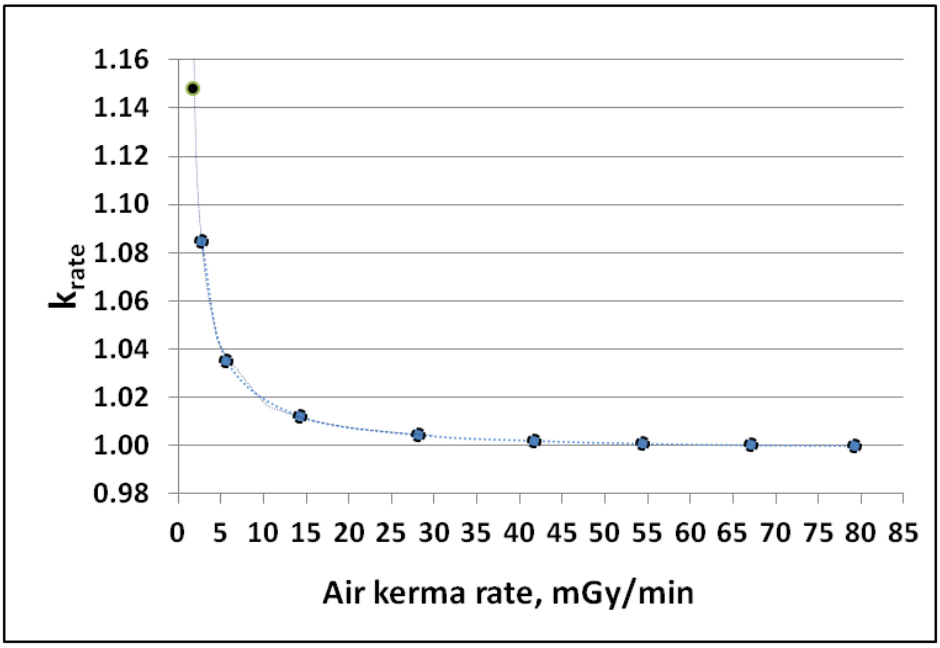


Fig. 20. *The k_{rate} correction factors for the PDC.* The fitting curve to the $k_{rate} = f(\dot{K})$ relationship for the PDC. The measurements performed at RQR 5 (70 kV) and irradiation area of 27 mm^2.

Table 11 presents the calculation of the uncertainty of the k_{rate}

Table 11. *The uncertainty estimation of k_{rate} for PDC.*

	TYPE A	***TYPE B***	***Notes***
	%	***%***	
Readings of reference chamber, A3	0.16		Standard uncertainty (SD of the mean) of the A3 readings
Readings of KAP meter	0.15		Standard uncertainty (SD of the mean) of the PDC readings
Scatter contribution		0.58	1 % of the primary beam
Fitting (parameters & curve)		0.04	r.m.s. eq. 13
Combined	0.22	0.58	
Combined, k=1	0.62		

For the comparison evaluation, k_{rate} corrections factors were applied only to those calibration results obtained at air kerma rates lower than 15 mGy/min, if the calculated k_{rate} value was significant compared to its uncertainty, i.e. the k_{rate} was higher than its uncertainty, u_{krate} (i.e. $|k_{rate} - 1| > 0.006$).

As commented earlier, standard values for the air kerma rates do not exist - as in the case of the radiation qualities (IEC 61274). The IEC 60580 concerning the dose area product (DAP) meters, does not specify reference air kerma rates values [26]. Therefore, the laboratories may apply air kerma rates according to their procedures.

4.2.2.5. Irradiation area, A, dependence of response

The k_{area} correction factors were determined using the reported calibration coefficients of the MKEH at RQR3, RQR5 and RQR9. The k_{area} corresponded to the normalized calibration coefficients at 25 cm^2 irradiation area (Fig. 21).

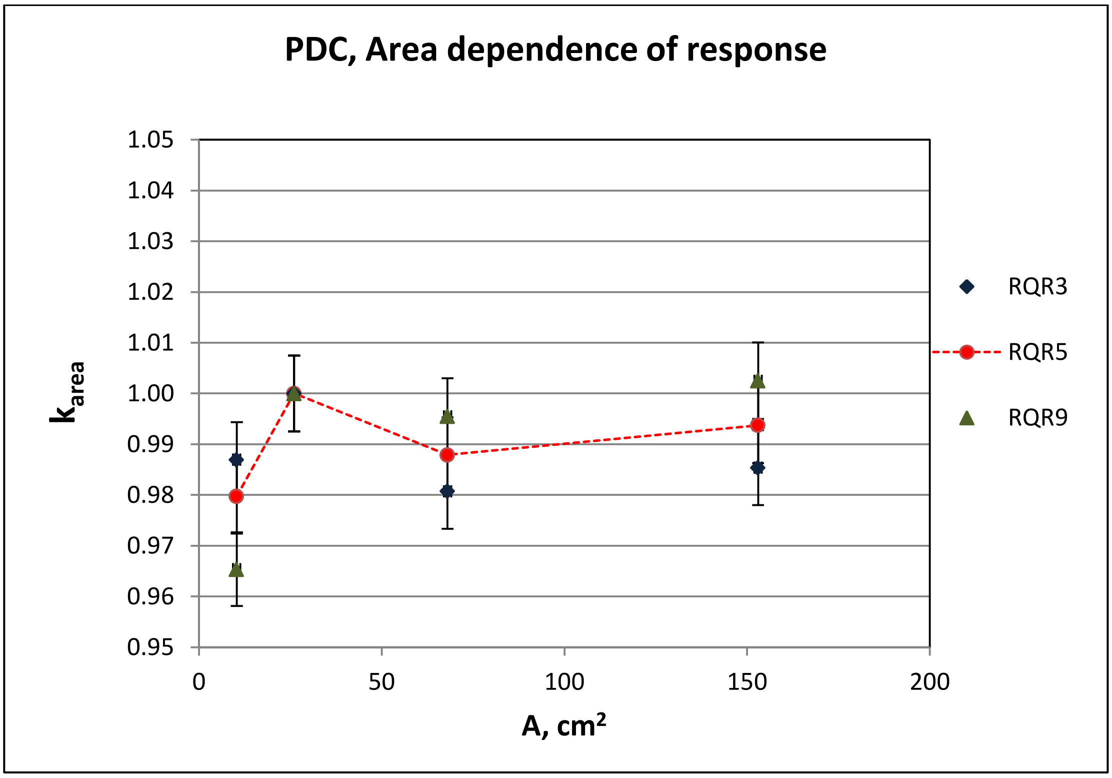


Fig. 21. *The k_{area} = f(A) relationship for PDC. Data are normalized to 25 cm^2 area. The error bars correspond to the uncertainty u=0.75 % (k=1). Initial data provided by MKEH.*

Depending on the irradiation area, A, that was applied, the k_{area} correction factors have been determined at three groups of irradiation areas, A : (a) for A < 26 cm^2 (b) for 26 cm^2 < A < 68 cm^2 and (c) for A > 68 cm^2. Furthermore, as Fig. 21 demonstrates, the irradiation area dependence of response also depended on the radiation quality. Therefore, separate k_{area} values were obtained for a specific radiation quality. The k_{area} values obtained at RQR5 and RQR9 were used for the RQR6 and RQR8, respectively.

At each group of irradiation areas and radiation quality, the k_{area} were determined by linear interpolation of data (Fig 21). The standard uncertainties of the the k_{area} were calculated for each individual case, as demonstrated in Table 12. An uncertainty of 0.5 mm was assigned to the measurement of the irradiation field dimension (either square edge or diameter). The uncertainty due to the linear fitting was calculated from linear regression analysis.

Table 12 gives an example for the calculation of the k_{area} uncertainty at RQR 5 and 28 cm^2 irradiation area. The respective k_{area} value, in this example, was 1.00 (Fig. 21). Similar uncertainty calculations were performed for each irradiation area and radiation quality for all results.

Table 12. *Example for uncertainty estimation of k_{area} for PDC,* at RQR 5 and 28 cm^2 irradiation area.

	TYPE A %	TYPE B %	Notes
Area determination		1.10	Uncertainty of 0.5 mm for a 52.6 mm x 52.6 mm square field, A = 28 cm^2
Linear fitting		0.72	Uncertainty of the linear fitting of 28 cm^2 to to the range 10 cm^2 < A < 68 cm^2
Combined		1.31	
Combined, k=1	1.31		

Most of the laboratories performed the calibrations at irradiation areas, A, between 20 cm^2 and 30 cm^2 (Fig. 3). Two laboratories performed the calibration at smaller than 20 cm^2 areas, i.e. IRP-DOS at 17.6 cm^2 and GR at 10.7 cm^2 and four laboratories performed the calibration at larger than 30 cm^2 areas, i.e. SCK•CEN at 900 cm^2, SIS at 260 cm^2, VSL at 106.5 cm^2, IFIN-HH at 218.9 cm^2, VINCA 113.04 cm^2, SIM at 87.9 cm^2.

The k_{area} corrections factors were applied to those cases where the k_{area} correction factor was significant compared to its standard combined uncertainty, i.e. if k_{area} was higher larger than its uncertainty ($|k_{area} - 1| > u_{karea}$).

As previously mentioned, reference values for the irradiation area do not exist - as in the case of the radiation qualities (IEC 61274) –. The IEC 60580 concerning the dose area product (DAP) meters, does not specify reference irradiation areas values [26]. Therefore, the laboratories may apply irradiation areas according to their procedures.

Concluding on the application of correction factors and their uncertainties to the calibration results of the PDC:
k_Q was applied to those results where the radiation quality was not consistent to the IEC 61274 standard, if k_Q was higher than its uncertainty (i.e. $|k_Q - 1| > u_{kQ}$).
k_{rate} was applied to those results obtained at air kerma rates lower than 15 mGy/min, if k_{rate} was higher than its uncertainty, u_{krate} (i.e. $|k_{rate} - 1| > 0.006$).
k_{area} was applied, if k_{area} value was significant, i.e. if k_{area} was higher larger than its uncertainty ($|k_{area} - 1| > u_{karea}$).

4.2.3. Performance of MAGNA

4.2.3.1. Stability of MAGNA chamber

Fig. 22 presents the stability tests of the MAGNA at the RQR qualities. According to eq. 10,11a and 11b the standard uncertainty for the MAGNA stability u_{stab} was 0.30 %.

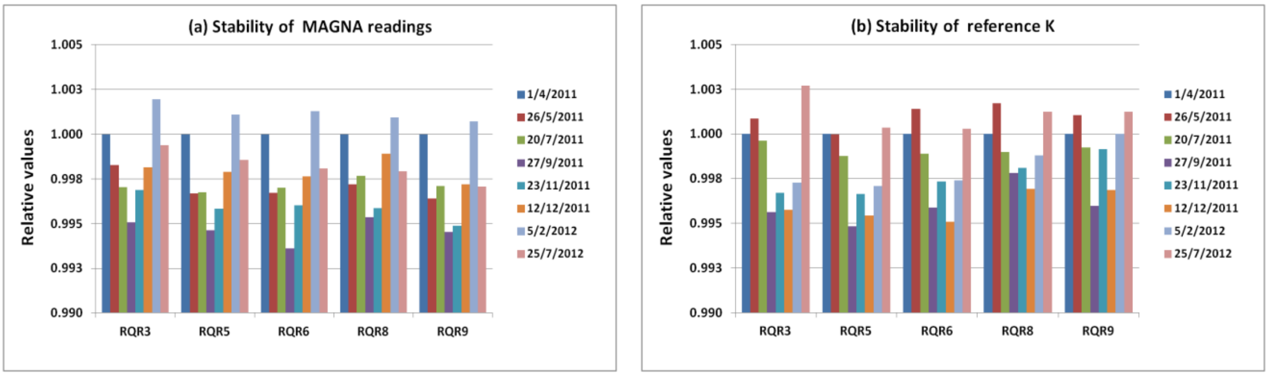


Fig.22. *Stability checks of MAGNA at the RQR qualities. The y axes show (a) the normalized MAGNA readings corrected for air density and (b) the normalized reference K values pertained during calibration of MAGNA, as deduced at each round; the normalization was done to the measurements of the 1st round. MAGNA chamber has been calibrated an extra time – compared to the other instruments - after a minor repair (glued) of its stem*

4.2.3.2. Energy (radiation quality) dependence of response

The energy dependence of response of MAGNA is presented in Fig. 23. The measurements were performed at air kerma rate close to 18 mGy/min.

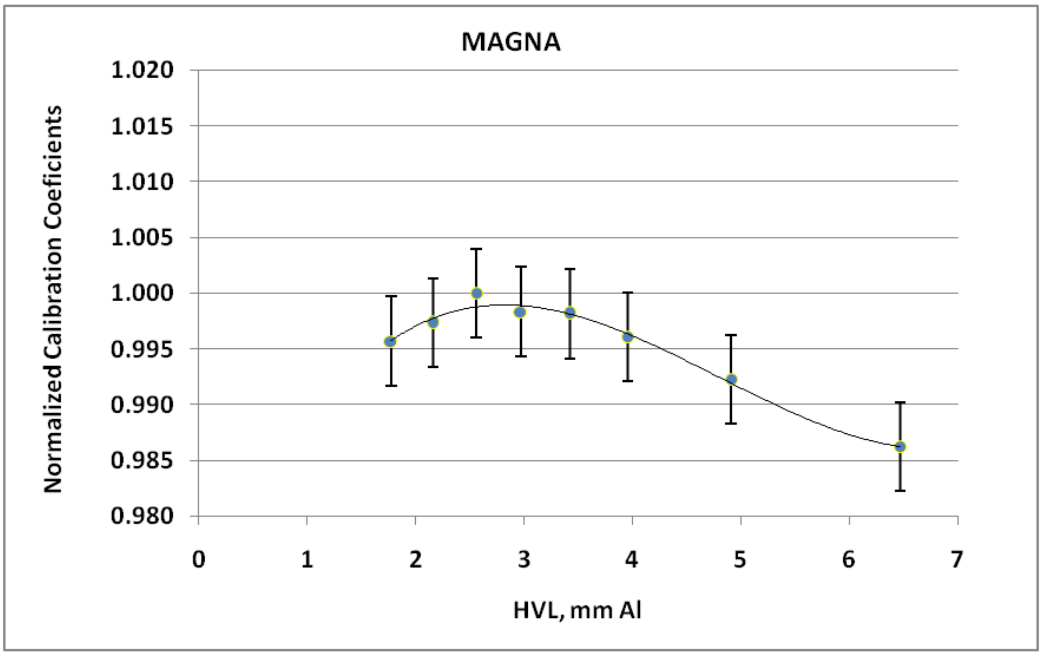


Fig. 23. *The energy dependence of response of MAGNA. The normalization of the calibration coefficients (y-axis) refers to the RQR 5 radiation quality. The error bars correspond to standard uncertainty (k=1). Initial data provided by MKEH.*

As fig. 23 shows, MAGNA chamber had low energy dependence of response. The differences of the radiation qualities of the participating laboratories from the nominal HVL values (IEC 61267) had insignificant effect to the energy response of the chamber, taking into account the uncertainties of the measurements. Fig. 24 demonstrates this evidence by giving an example for the VSL radiation qualities.

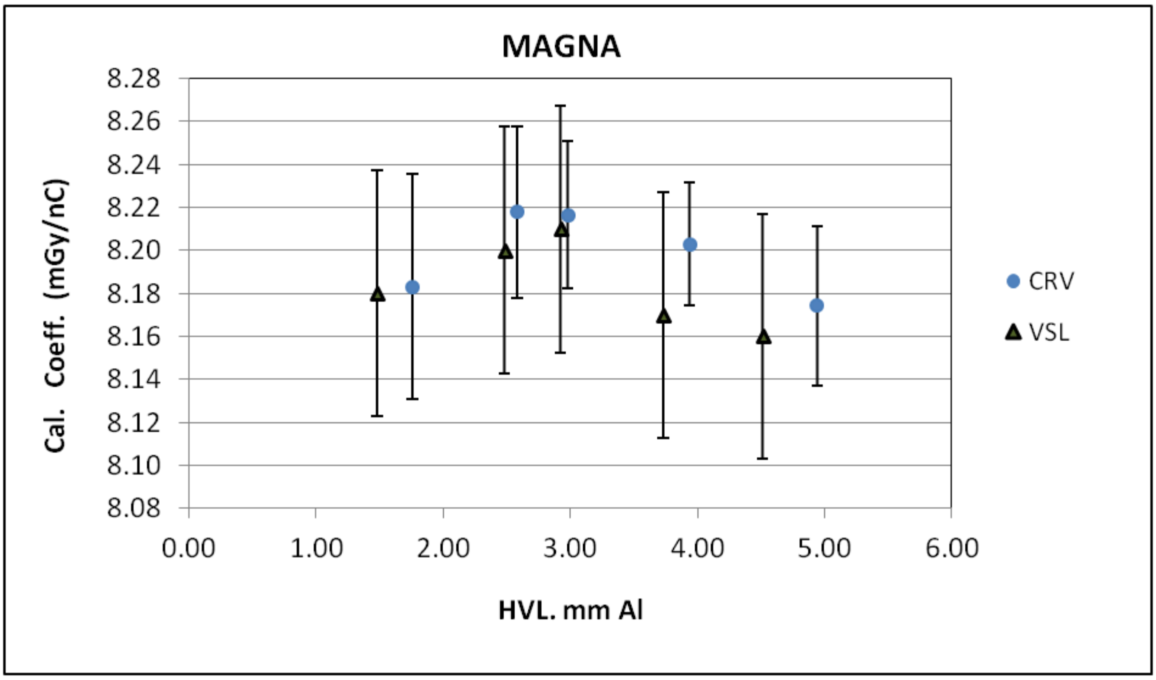


Fig. 24. *CRV and VSL calibration results of MAGNA. The error bars indicate the standard uncertainty of the calibration coefficients.*

Therefore, $k_Q = 1$ was applied for all radiation beams of the participating laboratories.

4.2.3.3. Air kerma rate, $\dot{K}$, dependence of response

The air kerma rate, $\dot{K}$, dependence of response of MAGNA was studied at the IRCL/GAEC-EIM at RQR5 (70 kV) at a range of 2 mGy/min to 80 mGy/min. At this air kerma rate range, MAGNA exhibited flat response, i.e. the relationship of the normalized to 50 mGy/min readings of MAGNA and air kerma rates, $\dot{K}$was constant (horizontal line).
Therefore, no corrections for the air kerma rate, $\dot{K}$, dependence of response have applied to the calibration results

4.2.3.4. Irradiation area dependence of response

The irradiation area, A, dependence of response of MAGNA is meaningless, if the irradiation area covers the chamber's cross-section totally and the scattered radiation in minimized. These two components are related to the calibration procedures of the laboratory and are irrelevant to the MAGNA performance characteristics. Therefore, no corrections for the irradiation area dependence of response have been applied to the calibration results.

Concluding on the application of correction factors and their uncertainties to the calibration results of the MAGNA:

k_Q has been applied only to those results where the radiation quality was not consistent to the IEC 61274 standard, if k_Q was higher than its uncertainty (i.e. $|k_Q - 1| > u_{kQ}$).

k_{rate} and k_{area} correction factors have not been applied to any results.

4.2.4. General comments on the instruments performance

Both KAP meters used transfer instruments in this comparison showed significant air kerma rate dependence of response at very low rates. This could be attributed to the design and the electronics of the instruments.

According to the KERMA-X manufacturer specifications [30], the instrument's minimum $\dot{K}$ effective range of measurement is 6 mGy/min (the maximum being 30,000 mGy/min); within this range the stated $\dot{K}$ linearity is 5 %. However, the measurements and the results of this project showed that 5 % $\dot{K}$ linearity was achieved for 14 mGy/min or higher, while at $\dot{K}$ = 6 mGy/min the $\dot{K}$ linearity was about 80 % (fig. 13).

PDC was exhibited lower air kerma rate dependence of response than KERA-X. According to PDC manufacturer, the minimum rated $\dot{K}$ is 1 μGy m^2/min, corresponding to 0.4 mGy/min approximately for 27 cm^2 irradiation area. Manufacturer does not provide rated linearity values. PDC results showed that linearity of 5 % was achieved at $\dot{K}$ higher than 4.2 mGy/min.

It should be mentioned that in clinical practice the KAP meter is mounded on the X-ray tube housing and therefore it is exposed to $\dot{K}$ values much higher (tens order of magnitude) than the aforementioned minimum rates. The calibration laboratories should investigate the actual minimum $\dot{K}$ effective range of the instrument and apply appropriate $\dot{K}$ values. Furthermore, the calibration laboratories should be capable to establish X-ray beams with high $\dot{K}$ values that resemble the clinical practices, instrument specifications and the user's needs. If these conditions are met, the influence of the $\dot{K}$ dependence of response of the KAP meter is minimized.

4.3. Determination of the Comparison Reference Value (CRV)

The Comparison Reference Values (CRVs) were determined from the results of all participating PSDLs that were not outliers. This methodology was agreed by the participants (EURAMET and EURADOS respective projects) and it was stated to the comparison protocol. As reported in section 3.4.2, there are available results of neither key comparison for diagnostic radiology radiation qualities, nor supplementary comparisons for the air kerma area product quantity.

On the other hand,

For this, according to the method described in section 3.4 and the calibration results submitted by the three PSDLs, **LNE-NLHB, France, MKEH, Hungary and PTB, Germany,** (section 4.1), the Comparison Reference Values (CRV) were determined as follows, for each radiation quality and instrument.

As noted in section 3.4, VSL, Netherlands reported HVL values that differed more than 4.4 % from the IEC 61627, for the radiation qualities RQR3, RQR8 and RQR9. Therefore, the VSL radiation qualities were not consistent to the requirements of the IEC. Although the HVL values of VSL at RQR5 and RQR6 radiation qualities differed less than 4.4 % from the IEC 61627 (4 % and 3 %

respectively), the results at these beams were not either included to the CRV; this was because it was considered that the same PSDLs should contribute to the CRV for all radiation qualities.

The radiation qualities used by the three participating PSDLs were in agreement with the IEC 61267 standard. Furthermore, the air kerma rate $\dot{K}$, and the irradiation field area, A, that applied by the laboratories during the calibrations of the instruments were similar, and therefore their influence to the response of the instruments was negligible (less than 1 %). Therefore, there was no need to correct the reported calibration coefficient, N_i to the reference irradiation conditions (section 3.6). At each radiation quality, $N_{i,cor}$ equals N_i as well as their uncertainties were the same.

The procedure for CRV determination is described in section 3.4.
Furthermore, a check for outliers was performed. Taking into account the small number of data (3 per radiation quality), the Dixon Q test [31] was applied, since it was the most appropriate for limited number of values.
According the Dixon Q test, the Q value was calculated from $Q = (N_{value} - N_{closest}) / N_{range}$, where
N_{value} : the value being tested as a possible outlier
$N_{closest}$: the value of the data set being closest to the N_{value}, and
N_{range} : the range of the data set, i.e. the difference between maximum and minimum values.
If $Q > 0.988$ (at 99 % confidence level, for data set of 3 values), then N_{value} is an outlier.

The result evaluation has shown that there are not outliers.

The following sections present the CRV and the associate uncertainty for KERMA-X, PDC and MAGNA.

4.3.1. CRV for KERMA-X

Table 13 presents data regarding the determination of the CRV and the associate uncertainty for the KERMA-X, as:

- mean HVL, the average HVL value of the participating PSDLs
- arithmetic mean of the calibration coefficients and its uncertainty (eq. 5a & 5b)
- weighted mean of the calibration coefficients and its standard uncertainty (eq. 1a & 1d)
- value of the x^2_{obs} test (eq. 2)
- s^2 for $x^2_{MP,obs} = 1$ (eq. 3)
- M-P mean and its standard uncertainty (eq. 4a & 4d)
- CRV and the associate standard uncertainty (final result)

The uncertainties listed in table 13 are the combined standard uncertainties.The calibration data of each individual laboratory are presented in Appendix A.

Table 13. *CRV and the associated standard uncertainty for KERMA-X.*

	Mean HVL **mm Al**	**Arithmetic mean** $N_{mean} \pm u_{Nmean}$ **Gy cm²/ Gy cm²**	**Weighted mean** $N_{ref} \pm u_{Nref}$ **Gy cm²/ Gy cm²**	x^2_{obs}	s^2	**M-P mean** $N_{MP,ref} \pm u_{MP,Nref}$ **Gy cm²/ Gy cm²**	**Final result** $CRV \pm u_{CRV}$ **Gy cm²/ Gy cm²**
RQR3	1.759	1.192 ± 0.017	1.189 ± 0.019	5.644	0.02011	1.191 ± 0.018	**1.191 ± 0.018**
RQR5	2.583	1.091 ± 0.016	1.091 ± 0.007	0.943	--	--	**1.091 ± 0.007**
RQR6	2.979	1.084 ± 0.015	1.084 ± 0.004	0.349	--	--	**1.084 ± 0.004**
RQR8	3.939	1.105 ± 0.015	1.105 ± 0.006	0.841	--	--	**1.105 ± 0.006**
RQR9	4.940	1.155 ± 0.015	1.154 ± 0.017	5.827	0.01899	1.155 ± 0.012	**1.155 ± 0.017**

Fig. 25 shows the reported calibration coefficients N_{PKA} and the CRV (Gy cm^2 / Gy cm^2) and the associate standard uncertainties for the KERMA KAP meter.

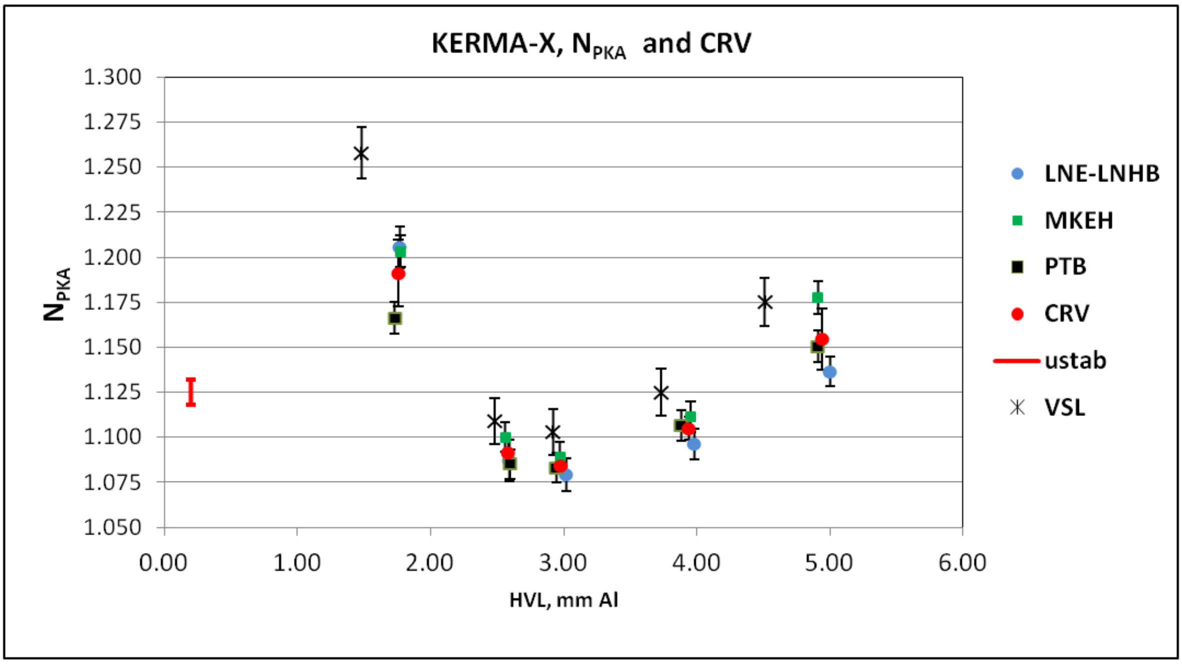


Fig. 25. *The calibration coefficients N_{PKA} (Gy cm^2 / Gy cm^2) and their standard uncertainties for KERMA-X, as reported by the participating PSDLs. The CRVs and their standard uncertainties at each quality are shown (red dots). The CRV's HVL values correspond to the average HVL value of the PSDLs. The red bar at the left side of the graph show the standard uncertainty of the stability, u_{stab} ,of KERMA-X (u_{stab} is not included to the N_{PKA} and CRV uncertainties). VSL's results have not contributed to the CRV.*

4.3.2. CRV for PDC

Table 14 presents data regarding the determination of the CRV and the associate uncertainty for PDC, as:

- mean HVL, the average HVL value of the participating PSDLs
- arithmetic mean of the calibration coefficients and its uncertainty (eq. 5a & 5b)
- weighted mean of the calibration coefficients and its standard uncertainty (eq. 1a & 1d)
- value of the x^2_{obs} test (eq. 2)
- s^2 for $x^2_{MP,obs}$ = 1 (eq. 3)
- M-P mean and its standard uncertainty (eq. 4a & 4d)
- CRV and the associate standard uncertainty (final result)

The uncertainties listed in table 14 are the combined standard uncertainties. The calibration data of each individual laboratory are presented in Appendix A.

Table 14. *CRV and the associated standard uncertainty for PDC.*

	Mean HVL mm Al	**Arithmetic mean $N_{mean} \pm u_{Nmean}$ Gy cm^2/ Gy cm^2**	**Weighted mean $N_{ref} \pm u_{Nref}$ Gy cm^2/ Gy cm^2**	**x^2_{obs}**	**s^2**	**M-P mean $N_{MP,ref} \pm u_{MP,Nref}$ Gy cm^2/ Gy cm^2**	**Final result CRV ± u_{CRV} Gy cm^2/ Gy cm^2**
RQR3	1.759	0.998 ± 0.013	0.998 ± 0.016	7.131	0.01857	0.998 ± 0.016	**0.998 ± 0.016**
RQR5	2.583	0.978 ± 0.013	0.977 ± 0.015	6.299	0.01651	0.978 ± 0.015	**0.978 ± 0.015**
RQR6	2.979	0.970 ± 0.012	0.969 ± 0.014	5.929	0.01563	0.969 ± 0.014	**0.969 ± 0.014**
RQR8	3.939	0.955 ± 0.013	0.954 ±0.014	5.625	0.01495	0.954 ± 0.014	**0.954 ± 0.014**
RQR9	4.940	0.943 ± 0.012	0.943 ± 0.012	4.059	0.01212	0.943 ± 0.011	**0.943± 0.011**

Fig 26 shows the reported calibration coefficients N_{PKA} and the CRV (Gy cm^2 / Gy cm^2) and the associate standard uncertainties for PDC.

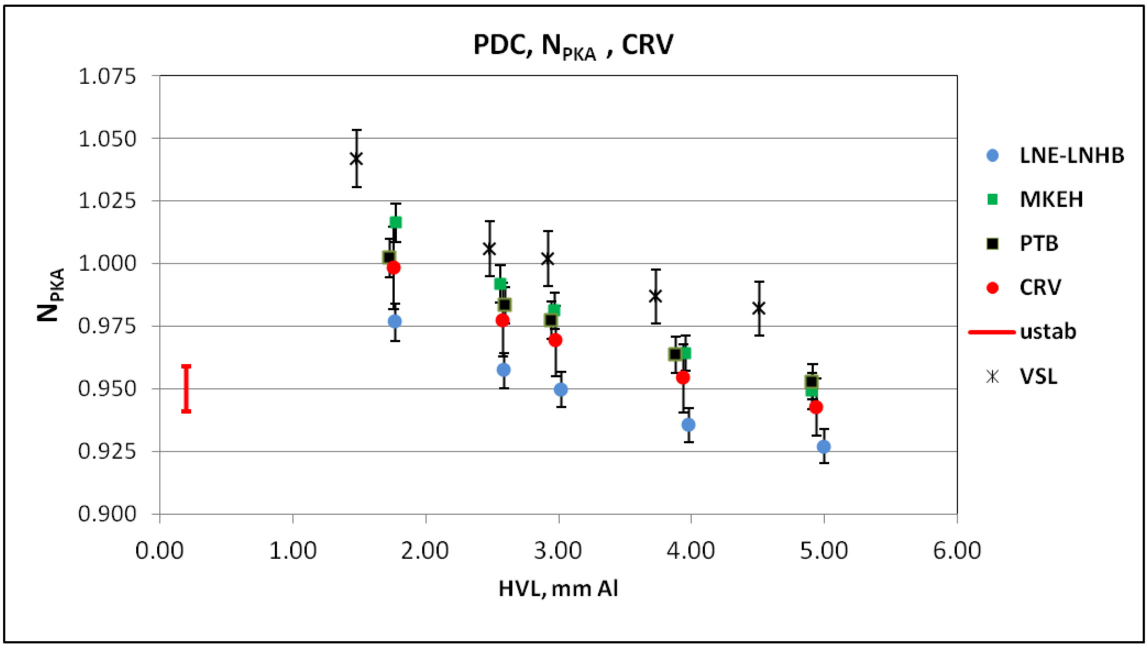


Fig. 26. *The calibration coefficients N_{PKA} (Gy cm^2 / Gy cm^2) and their standard uncertainties for the PDC, as reported by the participating PSDLs,. The CRVs and their standard uncertainties at each quality are shown (red dots). The CRV's HVL values correspond to the average HVL value of the PSDLs. The red bar at the left side of the graph show the standard uncertainty of the stability, u_{stab} ,of PDC (u_{stab} is not included to the N_{PKA} and CRV uncertainties). VSL's results have not contributed to the CRV.*

4.3.3. CRV for MAGNA

Table 15 presents data regarding the determination of the CRV and the associate uncertainty for MAGNA, as:

- mean HVL, the average HVL value of the participating PSDLs
- arithmetic mean of the calibration coefficients and its uncertainty (eq. 5a & 5b)
- weighted mean of the calibration coefficients and its standard uncertainty (eq. 1a & 1d)
- value of the x^2_{obs} test (eq. 2)
- s^2 for $x^2_{MP,obs}$ = 1 (eq. 3)
- M-P mean and its standard uncertainty (eq. 4a & 4d)
- CRV and the associate standard uncertainty (final result)

The uncertainties listed in table 4.3.2 are the combined standard uncertainties. The calibration data of each individual laboratory are presented in Appendix A.

Table 15. *CRV and the associate standard uncertainty for MAGNA.*

	Mean HVL mm Al	**Arithmetic mean $N_{mean} \pm u_{Nmean}$ mGy / nC**	**Weighted mean $N_{ref} \pm u_{Nref}$ mGy / nC**	**x^2_{obs}**	**s^2**	**M-P mean $N_{MP,ref} \pm u_{MP,Nref}$ mGy / nC**	**Final result CRV ± u_{CRV} mGy / nC**
RQR3	1.759	8.184 ± 0.055	8.180 ± 0.053	4.181	0.05559	8.183 ± 0.052	**8.183 ± 0.052**
RQR5	2.583	8.219 ± 0.056	8.216 ± 0.041	2.240	0.03723	8.218 ± 0.040	**8.218 ± 0.040**
RQR6	2.979	8.218 ± 0.055	8.215 ± 0.034	1.770	0.02731	8.217 ± 0.034	**8.217 ± 0.034**
RQR8	3.939	8.205 ± 0.055	8.203 ± 0.029	1.200	0.01397	8.203 ± 0.028	**8.203 ± 0.028**
RQR9	4.940	8.176 ± 0.055	8.173 ± 0.037	2.040	0.03199	8.174 ± 0.037	**8.174 ± 0.037**

Fig. 27 shows the reported calibration coefficients N_K and the CRV (mGy / mGy) and the associate standard uncertainties for the MAGNA.

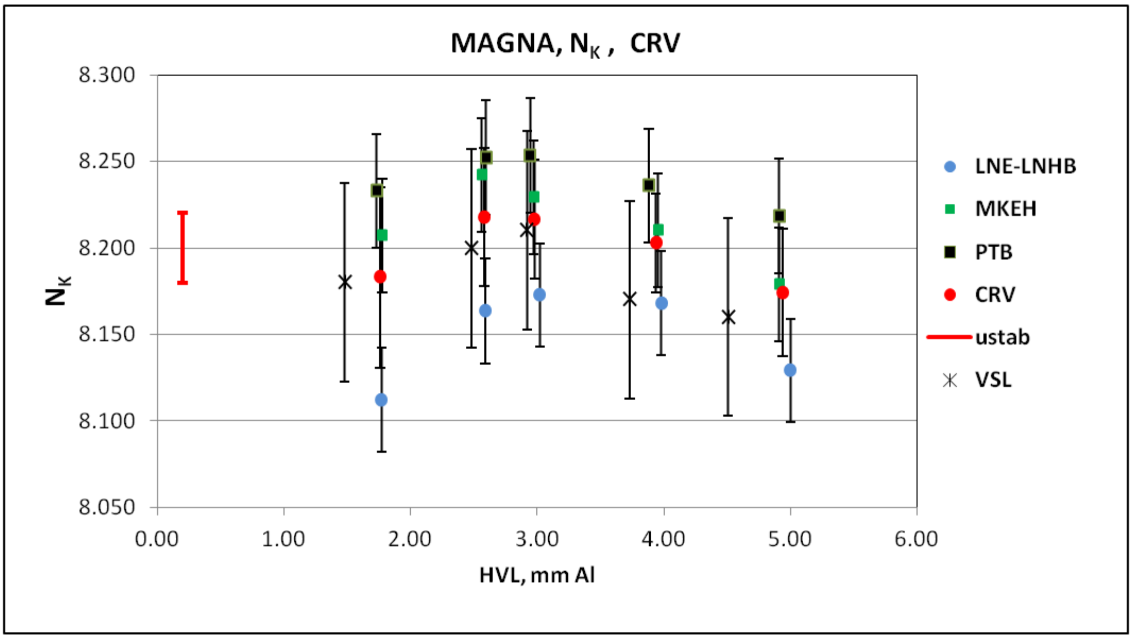


Fig. 27. *The calibration coefficients N_K (mGy /nC) and their standard uncertainties for the MAGNA, as by the participating PSDLs,. The CRVs and their standard uncertainties at each quality are shown (red dots). The CRV's HVL values correspond to the average HVL value of the PSDLs. The red bar at the left side of the graph show the standard uncertainty of the stability, u_{stab}, of MAGNA (u_{stab} is not included to the N_K and CRV uncertainties). VSL's results have not contributed to the CRV.*

4.4. Comparison result evaluation

The following sections present the evaluation of the results, as described in section 3.4.2 and 3.6.2.
The non-corrected comparison results, R (eq. 6), their standard uncertainties u_R (eq. 7) and the En scores (eq. 9) of each participating laboratory (at each radiation quality and per instrument) have been calculated and presented in Tables 16, 17 and 18.

As described in section 4.2., when necessary, appropriate correction factors k_Q, k_{area} and k_{rate} have been applied to the reported calibration coefficients, in order all results to refer to the reference conditions of radiation quality, irradiation area and air kerma rate. The respective corrected comparison results, R_{cor}, their standard uncertainties $u_{R,cor}$ and the corrected En_{cor} scores have been deduced according to eq. 14a, 14b and 15, respectively and presented also in Tables 16, 17 and 18.

Finally, it must be mentioned that the results could not been corrected for different traceability of the laboratories, i.e. the differences of the measured quantity due to the differences of the primary standards of air kerma.

4.4.1. Comparison results of KERMA-X

Table 16 presents the comparison results of KERMA-X.
The first three (left side) columns of Table 16 give the non-corrected comparison result, R (ratio of reported calibration coefficient and CRV) and its standard uncertainty, u_R, for KERMA-X, as well as the E_n scores for the non-corrected results.
The rest of the columns indicate:
k_Q, k_{area} & k_{rate} : correction factors for energy, irradiation area and air kerma rate that were applied to the reported calibration coefficients, N_{PKA}
$N_{PKA,cor}$: calibration coefficient corrected for energy, irradiation area and air kerma rate, i.e

$$N_{PKA,cor} = N_{PKA} \cdot k_Q \cdot k_{area} \cdot k_{rate}$$

R_{cor} : comparison result (ratio of corrected calibration coefficient and CRV), corrected for energy, irradiation area and air kerma rate
u_{Rcor} : standard uncertainty of the R_{cor}
$E_{n,cor}$: score using results corrected for energy, irradiation area and air kerma rate

The results are presented in alphabetic order of the laboratories' codes used in this report.

Table 16. *The comparison results for* ***KERMA-X.***

		Non-corrected			Correction factors			Corrected for Q, A and $\dot{K}$ (if applied)			
		R	u_R (k=1)	E_n	k_Q	k_{area}	k_{rate}	$N_{PKA,cor}$ Gy cm^2/Gy cm^2	R_{cor}	u_{Rcor} (k=1)	$E_{n,cor}$
SCK•CEN	RQR3	1.058	0.028	1.07	--	--	--	Same as non-corrected			
	RQR5	1.173	0.026	3.39	--	--	--				
	RQR6	1.199	0.026	3.90	--	--	--				
	RQR8	1.258	0.028	4.79	--	--	--				
	RQR9	1.255	0.033	4.23	--	--	--				
CMI	RQR3	1.008	0.033	0.11	--	--	--	Same as non-corrected			
	RQR5	0.990	0.029	0.17	--	--	--				
	RQR6	0.996	0.029	0.06	--	--	--				
	RQR8	0.995	0.029	0.08	--	--	--				
	RQR9	0.970	0.032	0.48	--	--	--				
SURO	RQR3	0.997	0.023	0.05	--	--	--	Same as non-corrected			
	RQR5	0.981	0.019	0.51	--	--	--	Same as non-corrected			
	RQR6	0.990	0.018	0.28	--	--	--	Same as non-corrected			
	RQR8	0.982	0.023	0.39	1.009	--	--	1.085	0.982	0.023	0.39
	RQR9	0.989	0.023	0.24	--	--	--	Same as non-corrected			
SIS	RQR3	0.907	0.023	1.90	--	--	--	Same as non-corrected			
	RQR5	0.907	0.020	2.27	--	--	--				
	RQR6	0.923	0.020	1.94	--	--	--				
	RQR8	0.914	0.020	2.12	--	--	--				
	RQR9	0.918	0.024	1.68	--	--	--				
STUK	RQR3	0.992	0.020	0.19	--	--	--	Same as non-corrected			
	RQR5	0.995	0.015	0.18	--	--	--				
	RQR6	1.006	0.014	0.23	--	--	--				
	RQR8	1.008	0.015	0.28	--	--	--				
	RQR9	1.003	0.020	0.09	--	--	--				
LNE-LNHB	RQR3	1.012	0.020	0.31	--	--	--	Same as non-corrected			
	RQR5	0.996	0.015	0.12	--	--	--				
	RQR6	0.995	0.012	0.19	--	--	--				
	RQR8	0.992	0.012	0.32	--	--	--				
	RQR9	0.984	0.018	0.44	--	--	--				
PTB	RQR3	0.979	0.018	0.56	--	--	--	Same as non-corrected			
	RQR5	0.995	0.013	0.22	--	--	--				
	RQR6	0.999	0.011	0.04	--	--	--				
	RQR8	1.001	0.012	0.06	--	--	--				
	RQR9	0.996	0.018	0.10	--	--	--				
IRCL/GAEC-EIM	RQR3	0.954	0.021	1.09	--	--	--	Same as non-corrected			
	RQR5	0.960	0.016	1.21	--	--	--				
	RQR6	0.962	0.015	1.22	--	--	--				
	RQR8	0.970	0.016	0.93	--	--	--				
	RQR9	0.969	0.021	0.73	--	--	--				

Table 16 con'd : The comparison results for **KERMA-X.**

		Non-corrected			Correction factors			Corrected for Q, A, and $\dot{K}$ (if applied)			
		R	**u_R (k=1)**	**E_n**	**k_Q**	**k_{area}**	**k_{rate}**	**$N_{PKA,cor}$ Gy cm^2/Gy cm^2**	**R_{cor}**	**u_{Rcor} (k=1)**	**$E_{n,cor}$**
MKEH	RQR3	1.010	0.019	0.28	--	--	--	Same as non-corrected			
	RQR5	1.008	0.013	0.33	--	--	--				
	RQR6	1.005	0.012	0.20	--	--	--				
	RQR8	1.006	0.012	0.24	--	--	--				
	RQR9	1.019	0.019	0.53	--	--	--				
IAEA	RQR3	0.990	0.018	0.26	--	--	--	Same as non-corrected			
	RQR5	0.989	0.012	0.46	--	--	--				
	RQR6	0.988	0.011	0.52	--	--	--				
	RQR8	1.000	0.012	0.00	--	--	--				
	RQR9	1.006	0.018	0.17	--	--	--				
GR	RQR3	1.025	0.026	0.49	--	--	--	Same as non-corrected			
	RQR5	1.029	0.022	0.68	--	--	--				
	RQR6	1.008	0.021	0.19	--	--	--				
	RQR8	1.004	0.021	0.11	--	--	--				
	RQR9	1.003	0.025	0.07	--	--	--				
IRP-DOS	RQR3	0.949	0.046	0.56	--	--	--	Same as non-corrected			
	RQR5	0.981	0.045	0.21	--	--	--				
	RQR6	0.996	0.046	0.04	--	--	--				
	RQR8	1.005	0.046	0.05	--	--	--				
	RQR9	0.996	0.048	0.05	--	--	--				
VSL	RQR3	1.056	0.022	1.34	1.051	--	--	1.197	1.005	0.021	0.12
	RQR5	1.016	0.016	0.53	--	--	--	Same as non-corrected			
	RQR6	1.018	0.015	0.60	--	--	--	Same as non-corrected			
	RQR8	1.018	0.015	0.60	0.988	--	--	1.139	1.030	0.016	0.97
	RQR9	1.017	0.021	0.42	0.984	--	--	1.194	1.034	0.021	0.81
NRPA	RQR3							Same as non-corrected			
	RQR5	0.986	0.023	0.29	--	--	--				
	RQR6										
	RQR8	1.002	0.024	0.04	--	--	--				
	RQR9	0.997	0.028	0.05	--	--	--				
NIOM	RQR3	1.041	0.037	0.56	--	--	--	Same as non-corrected			
	RQR5	1.022	0.033	0.33	--	--	--				
	RQR6	1.020	0.033	0.31	--	--	--				
	RQR8	1.016	0.032	0.25	--	--	--				
	RQR9	1.003	0.035	0.04	--	--	--				

Table 16 con'd : The comparison results for **KERMA-X.**

		Non-corrected			Correction factors			Corrected for Q, area and $\dot{K}$ (if applied)			
		R	**u_R (k=1)**	**E_n**	**k_Q**	**k_{area}**	**k_{rate}**	**$N_{PKA,cor}$ Gy cm^2/Gy cm^2**	**R_{cor}**	**u_{Rcor} (k=1)**	**$E_{n,cor}$**
ITN-LMRI	RQR3	0.621	0.030	5.83	--	--	1.182	0.626	0.525	0.027	6.93
	RQR5	0.780	0.036	3.04	--	--	--	Same as non-corrected			
	RQR6	0.827	0.037	2.29	--	--	--				
	RQR8	0.798	0.036	2.74	--	--	--				
	RQR9	0.738	0.035	3.56	--	--	--				
IFIN-HH	RQR3	0.920	0.023	1.65	--	--	--	Same as non-corrected			
	RQR5	0.978	0.016	0.67	--	--	--				
	RQR6	0.988	0.015	0.38	--	--	--				
	RQR8	0.996	0.016	0.11	--	--	--				
	RQR9	0.992	0.021	0.20	--	--	--				
VINCA	RQR3	1.612	0.101	3.12	0.970	--	1.566	1.264	1.061	0.101	0.34
	RQR5	1.072	0.065	0.56	--	--	1.026	1.140	1.045	0.066	0.34
	RQR6	1.033	0.063	0.27	--	--	--	Same as non-corrected			
	RQR8	1.023	0.062	0.18	--	--	--	Same as non-corrected			
	RQR9	1.013	0.063	0.10	--	--	--	Same as non-corrected			
SIM	RQR3	0.926	0.029	1.26	--	--	--	Same as non-corrected			
	RQR5	0.950	0.026	0.95	--	--	--				
	RQR6	0.958	0.026	0.81	--	--	--				
	RQR8	0.966	0.026	0.65	--	--	--				
	RQR9	0.983	0.030	0.28	--	--	--				
JSI	RQR3	1.205	0.025	4.58	--	--	1.059	1.355	1.138	0.032	2.52
	RQR5	1.172	0.017	5.54	--	--	1.028	1.244	1.140	0.027	3.04
	RQR6	1.153	0.017	4.82	--	--	1.024	1.221	1.127	0.026	2.71
	RQR8	1.298	0.019	8.67	--	--	1.161	1.236	1.118	0.026	2.38
	RQR9	1.230	0.030	4.14	--	--	1.059	1.341	1.161	0.036	2.55
UPC	RQR3	1.066	0.027	1.26	--	--	--	Same as non-corrected			
	RQR5	1.006	0.021	0.14	1.009	--	--	1.088	0.997	0.025	0.06
	RQR6	0.996	0.020	0.11	--	--	--	Same as non-corrected			
	RQR8	1.001	0.021	0.03	--	--	--	Same as non-corrected			
	RQR9	0.997	0.025	0.06	--	--	--	Same as non-corrected			
SSM	RQR3	0.966	0.020	0.83	--	--	--	Same as non-corrected			
	RQR5	0.984	0.015	0.53	--	--	--				
	RQR6	0.983	0.015	0.57	--	--	--				
	RQR8	0.986	0.015	0.45	--	--	--				
	RQR9	0.984	0.020	0.40	--	--	--				

Fig. 28 presents the corrected comparison results, R_{cor} for KERMA-X, i.e. the ratio of the corrected calibration coefficient and the respective CRV.

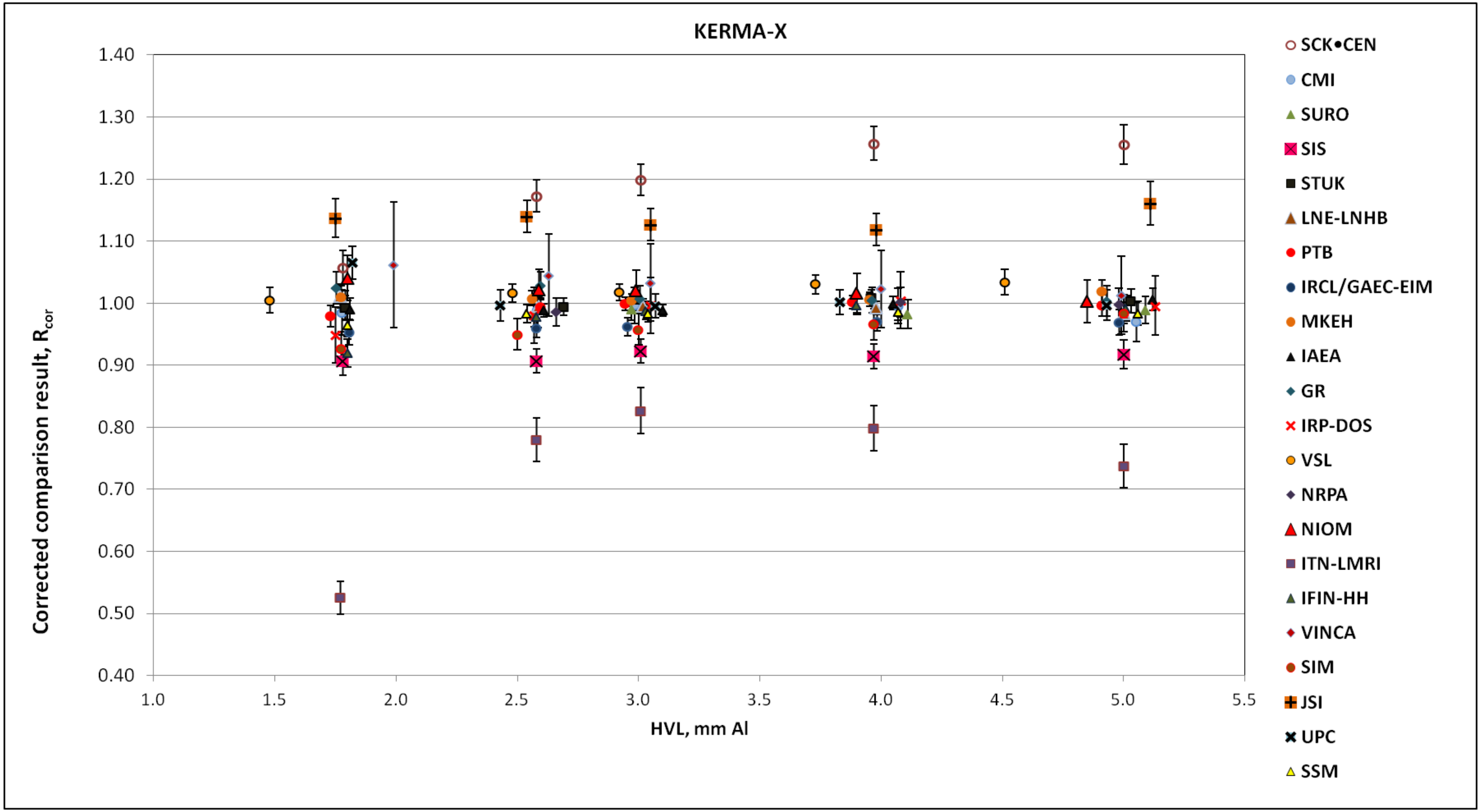


Fig. 28. *The corrected comparison results, R_{cor} for the KERMA-X KAP meter, i.e. the ratio of the corrected calibration coefficient and the respective CRV.The error bars represent the standard uncertainties.*

Fig. 29 presents the frequence distribution of the comparison results, R for the KERMA-X KAP meter.

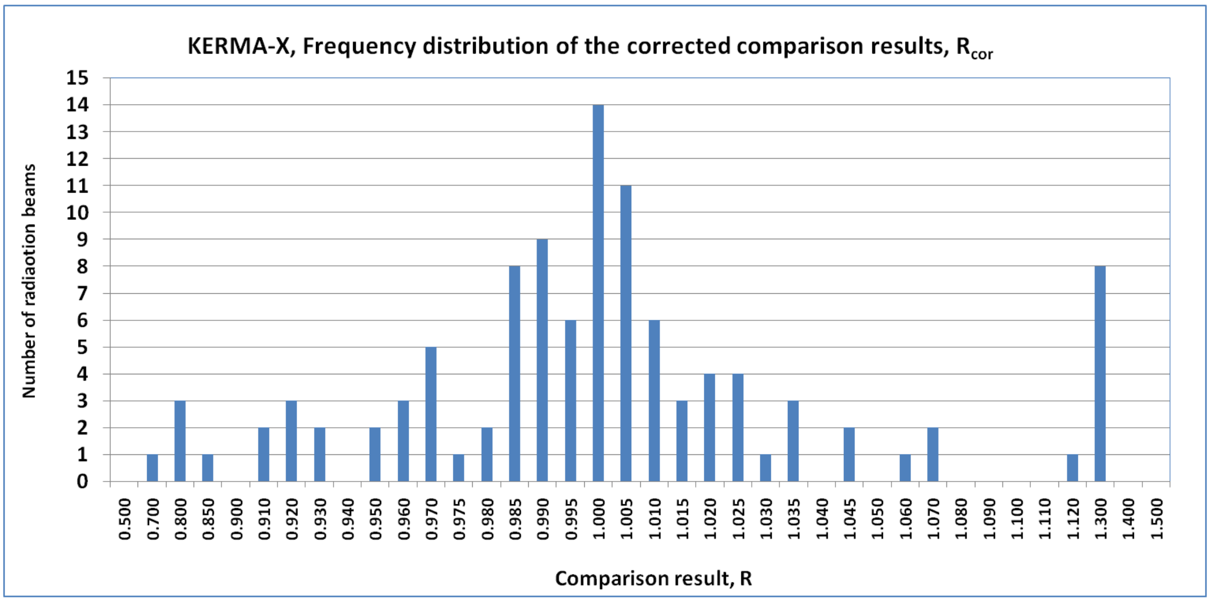


Fig. 29. *The frequency distribution of the corrected comparison results, R_{cor} for the KERMA-X KAP meter.*

It can be seen from table 16 that in most cases, the application of the correction factors improved the consistency of the results. For example, for VSL at RQR3 radiation quality, which deviated from the IEC standard by -15.8 % (in terms of HVL), the k_Q factors have resulted R values closer to 1.0, while the E_n scores was decreased. For VINCA and JSI, where low air kerma rates were applied (differences up to ~60 % from the reference $\dot{K}$), the application of the k_{rate} resulted R values closer to 1.0, while the E_n scores improved.
However, there were cases (e.g. ITN-LMRI, SURO, VSL at RQR8 and RQR9) where the corrections derived worse comparison results, R_{cor} compared to the respective non-corrected R. It was not possible to conclude whether this finding was due to the laboratory measurements or to the instrument performance.

It was evident from the analysis of the results that the application of the correction factors removes the undesirable high air kerma rate $\dot{K}$ dependence of responce of the instrument.
The high energy and air kerma rate dependence of the response of KERMA-X at low air kerma rates makes its characteristics non-ideal as a transfer instrument for KAP-meter calibration comparison. However, the KAP meter used as transfer instruments in this comparison are widely used in clinical practices and higher quality, reference class KAP meters were not commercially available. Due to these limitations, the approach chosen here has been justified: for a meaningful comparison of the calibration capabilities of different laboratories, the effect of this undesirable instrument's characteristics have been removed by using appropriate correction factors k_Q and k_{rate}, while the uncertainty of these correction factors has been taken into account in the evaluation of the uncertainty of the comparison values (Section 4.6).

4.4.2. Comparison results of the PDC KAP meter

Table 17 presents the comparison results of PDC.

The first three (left side) columns of Table 17 give the non-corrected comparison result, R (ratio of reported calibration coefficient and CRV) and its standard uncertainty, u_R, for PDC, as well as the E_n scores for the non-corrected results.

The rest of the columns indicate:

k_Q, k_{area} & k_{rate} : correction factors for energy, irradiation area and air kerma rate that were applied to the reported calibration coefficients, N_{PKA}

$N_{PKA,cor}$: calibration coefficient corrected for energy, irradiation area and air kerma rate, i.e

$$N_{PKA,cor} = N_{PKA} \cdot k_Q \cdot k_{area} \cdot k_{rate}$$

R_{cor} : comparison result (ratio of corrected calibration coefficient and CRV), corrected for energy, irradiation area and air kerma rate

u_{Rcor} : standard uncertainty of the R_{cor}

$E_{n,cor}$: score using the results corrected for energy, irradiation area and air kerma rate

The results are presented in alphabetic order of the laboratories' codes used in this report.

Table 17 : *The comparison results for* ***PDC***

		Non-corrected			Correction factors			Corrected for Q, A and $\dot{K}$ (if applied)			
		R	u_R (k=1)	E_n	k_Q	k_{area}	k_{rate}	$N_{PKA,cor}$ Gy cm^2/Gy cm^2	R_{cor}	u_{Rcor} (k=1)	$E_{n,cor}$
SCK•CEN	RQR3	0.892	0.019	2.60	--	--	1.148	0.775	0.777	0.017	5.17
	RQR5	0.890	0.018	2.73	--	--	1.147	0.758	0.776	0.017	5.33
	RQR6	0.877	0.018	3.16	--	--	1.055	0.806	0.831	0.017	4.13
	RQR8	0.891	0.018	2.78	--	--	1.041	0.816	0.856	0.018	3.50
	RQR9	0.901	0.016	2.81	--	--	1.024	0.830	0.880	0.017	3.19
CMI	RQR3	0.982	0.033	0.27	--	--	1.012	0.968	0.970	0.033	0.44
	RQR5	0.971	0.032	0.44	--	--	--	Same as non-corrected			
	RQR6	0.980	0.032	0.30	--	--	--	Same as non-corrected			
	RQR8	0.985	0.033	0.22	--	--	--	Same as non-corrected			
	RQR9	0.986	0.031	0.22	--	--	--	Same as non-corrected			
SURO	RQR3	0.999	0.024	0.02	--	--	--	Same as non-corrected			
	RQR5	0.995	0.023	0.11	--	--	--				
	RQR6	0.997	0.023	0.07	--	--	--				
	RQR8	1.000	0.023	0.00	--	--	--				
	RQR9	1.001	0.021	0.03	--	--	--				
SIS	RQR3	0.992	0.028	0.14	--	--	--	Same as non-corrected			
	RQR5	1.002	0.028	0.04	--	--	--				
	RQR6	1.011	0.027	0.21	--	--	--				
	RQR8	1.017	0.028	0.31	--	--	--				
	RQR9	1.018	0.026	0.35	--	--	--				
STUK	RQR3	0.992	0.022	0.18	--	--	--	Same as non-corrected			
	RQR5	0.994	0.021	0.14	--	--	--				
	RQR6	0.997	0.021	0.07	--	--	--				
	RQR8	0.999	0.021	0.03	--	--	--				
	RQR9	0.999	0.019	0.03	--	--	--				
LNE-LNHB	RQR3	0.979	0.020	0.52	--	--	--	Same as non-corrected			
	RQR5	0.979	0.019	0.53	--	--	--				
	RQR6	0.980	0.019	0.52	--	--	--				
	RQR8	0.981	0.019	0.51	--	--	--				
	RQR9	0.983	0.017	0.50	--	--	--				
PTB	RQR3	1.004	0.020	0.11	--	--	--	Same as non-corrected			
	RQR5	1.006	0.020	0.14	--	--	--				
	RQR6	1.009	0.019	0.23	--	--	--				
	RQR8	1.010	0.019	0.26	--	--	--				
	RQR9	1.011	0.017	0.31	--	--	--				
IRCL/GAEC-EIM	RQR3	0.995	0.024	0.11	--	--	--	Same as non-corrected			
	RQR5	0.998	0.024	0.04	--	--	--				
	RQR6	1.000	0.023	0.00	--	--	--				
	RQR8	1.001	0.023	0.02	--	--	--				
	RQR9	1.000	0.022	0.00	--	--	--				

Table 17 con'd : *The comparison results for* ***PDC***

		Non-corrected			Correction factors			Corrected for Q, A and $\dot{K}$ (if applied)			
		R	u_R (k=1)	E_n	k_Q	k_{area}	k_{rate}	$N_{PKA,cor}$ Gy cm^2/Gy cm^2	R_{cor}	u_{Rcor} (k=1)	$E_{n,cor}$
MKEH	RQR3	1.018	0.021	0.45	--	--	--	Same as non-corrected			
	RQR5	1.014	0.020	0.36	--	--	--				
	RQR6	1.013	0.019	0.33	--	--	--				
	RQR8	1.011	0.019	0.28	--	--	--				
	RQR9	1.007	0.017	0.19	--	--	--				
IAEA	RQR3	1.008	0.020	0.21	--	--	--	Same as non-corrected			
	RQR5	1.009	0.020	0.22	--	--	--				
	RQR6	1.012	0.019	0.31	--	--	--				
	RQR8	1.012	0.020	0.32	--	--	--				
	RQR9	1.009	0.017	0.25	--	--	--				
GR	RQR3	1.024	0.027	0.45	--	0.987	--	1.035	1.038	0.033	0.59
	RQR5	1.050	0.027	0.94	--	0.980	--	1.048	1.072	0.033	1.12
	RQR6	1.066	0.027	1.25	--	0.980	--	1.054	1.088	0.033	1.38
	RQR8	1.063	0.027	1.19	--	0.966	--	1.050	1.100	0.034	1.56
	RQR9	1.070	0.026	1.40	--	0.966	--	1.045	1.108	0.033	1.73
IRP-DOS	RQR3	0.969	0.047	0.33	--	--	--	Same as non-corrected			
	RQR5	0.997	0.048	0.03	--	--	--	Same as non-corrected			
	RQR6	1.008	0.049	0.08	--	--	--	Same as non-corrected			
	RQR8	1.004	0.049	0.04	--	0.982	--	0.976	1.023	0.051	0.22
	RQR9	0.999	0.048	0.01	--	0.982	--	0.959	1.017	0.050	0.17
VSL	RQR3	1.044	0.023	1.00	1.011	--	--	1.031	1.033	0.023	0.73
	RQR5	1.029	0.022	0.67	--	--	--	Same as non-corrected			
	RQR6	1.034	0.021	0.81	--	--	--	Same as non-corrected			
	RQR8	1.035	0.022	0.82	--	--	--	Same as non-corrected			
	RQR9	1.041	0.020	1.08	1.004	--	--	0.978	1.037	0.020	0.95
NRPA	RQR3				--	--	--	Same as non-corrected			
	RQR5	0.998	0.027	0.04	--	--	--				
	RQR6				--	--	--				
	RQR8	1.004	0.027	0.08	--	--	--				
	RQR9	0.998	0.025	0.04	--	--	--				
NIOM	RQR3	1.183	0.042	2.28	--	--	--	Same as non-corrected			
	RQR5	1.111	0.039	1.48	--	--	--				
	RQR6	1.099	0.038	1.34	--	--	--				
	RQR8	1.075	0.037	1.02	--	--	--				
	RQR9	1.060	0.036	0.86	--	--	--				

Table 17 con'd : *The comparison results for* ***PDC***

		Non-corrected			Correction factors			Corrected for Q, A and $\dot{K}$ (if applied)			
		R	u_R (k=1)	E_n	k_Q	k_{area}	k_{rate}	$N_{PKA,cor}$ Gy cm^2/Gy cm^2	R_{cor}	u_{Rcor} (k=1)	$E_{n,cor}$
ITN-LMRI	RQR3	1.038	0.050	0.38	--	--	1.021	1.015	1.017	0.051	0.17
	RQR5	1.107	0.053	1.02	--	--	1.011	1.072	1.096	0.054	0.92
	RQR6	1.110	0.053	1.05	--	--	--	Same as non-corrected			
	RQR8	1.159	0.056	1.46	--	--	--	Same as non-corrected			
	RQR9	1.198	0.056	1.79	--	--	--	Same as non-corrected			
IFIN-HH	RQR3	0.961	0.025	0.75	--	--	--	Same as non-corrected			
	RQR5	0.972	0.022	0.62	--	--	--				
	RQR6	0.964	0.021	0.84	--	--	--				
	RQR8	0.965	0.021	0.80	--	--	--				
	RQR9	0.964	0.019	0.91	--	--	--				
VINCA	RQR3	1.122	0.071	0.87	0.992	--	1.169	0.965	0.967	0.061	0.26
	RQR5	1.125	0.071	0.89	--	--	1.061	1.037	1.060	0.067	0.45
	RQR6	1.115	0.070	0.83	--	--	1.044	1.035	1.068	0.067	0.51
	RQR8	1.111	0.070	0.81	--	--	1.027	1.032	1.082	0.068	0.61
	RQR9	1.113	0.069	0.83	--	--	1.018	1.031	1.094	0.068	0.69
SIM	RQR3	0.945	0.030	0.90	--	0.982	--	0.960	0.962	0.032	0.59
	RQR5	0.944	0.030	0.92	--	--	--	Same as non-corrected			
	RQR6	0.944	0.029	0.94	--	--	--	Same as non-corrected			
	RQR8	0.945	0.029	0.92	--	--	--	Same as non-corrected			
	RQR9	0.963	0.029	0.64	--	--	--	Same as non-corrected			
JSI	RQR3	1.022	0.022	0.51	--	--	1.015	1.005	1.007	0.022	0.15
	RQR5	1.023	0.021	0.56	--	--	1.013	0.988	1.010	0.022	0.24
	RQR6	1.023	0.020	0.58	--	--	1.012	0.980	1.011	0.021	0.26
	RQR8	1.027	0.021	0.68	--	--	1.020	0.961	1.007	0.021	0.17
	RQR9	1.020	0.018	0.55	--	--	1.015	0.947	1.005	0.019	0.12
UPC	RQR3	1.001	0.028	0.02	--	--	--	Same as non-corrected			
	RQR5	1.001	0.027	0.01	--	--	--	Same as non-corrected			
	RQR6	0.999	0.027	0.01	--	--	--	Same as non-corrected			
	RQR8	0.999	0.027	0.02	--	0.987	--	0.965	1.012	0.030	0.20
	RQR9	0.998	0.025	0.05	--	0.987	--	0.953	1.011	0.029	0.19
SSM	RQR3	1.020	0.023	0.45	--	--	1.015	1.003	1.005	0.023	0.11
	RQR5	1.028	0.022	0.63	--	--	1.020	0.986	1.008	0.023	0.17
	RQR6	1.027	0.022	0.63	--	--	1.020	0.976	1.007	0.022	0.15
	RQR8	1.027	0.022	0.63	--	--	1.018	0.963	1.009	0.023	0.21
	RQR9	1.031	0.020	0.78	--	--	1.018	0.955	1.013	0.021	0.31

Fig. 30 presents the corrected comparison results, R_{cor} for the PDC KAP meter, i.e. the ratio of the corrected calibration coefficient and the respective CRV.

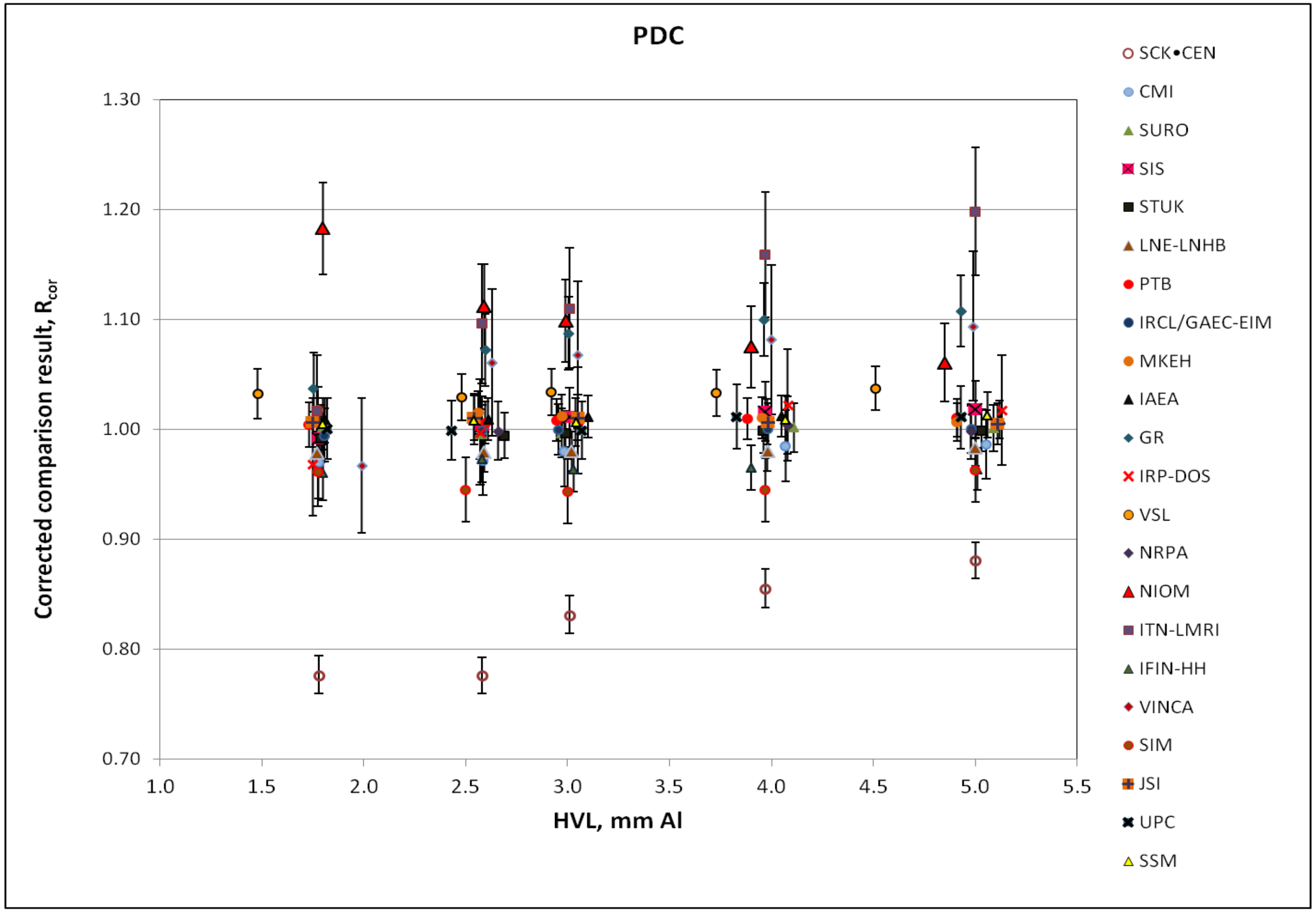


Fig. 30. *The corrected comparison results, R for the PDC KAP meter, i.e. the ratio of the corrected calibration coefficient and the respective CRV.The error bars represent the standard uncertainties..*

Fig. 31 presents the frequence distribution of the corrected comparison results, R_{cor} for the PDC KAP meter.

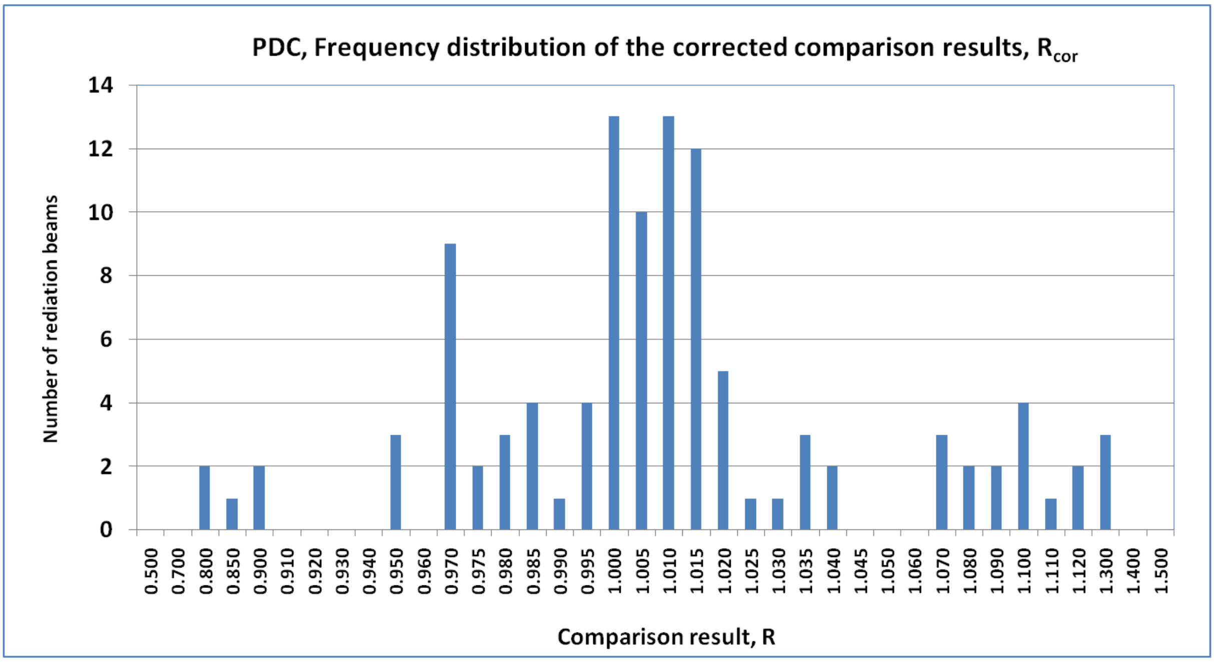


Fig. 31. *The frequency distribution of the corrected comparison results, R_{cor} for the PDC KAP meter.*

It can be seen from Table 17 that in practice the correction for k_Q is almost negligible, due to the good energy dependence of response of PDC.

The correction for irradiation area, k_{area}, was less than 2 %. As mentioned earlier, SCK•CEN performed the calibration of PDC using a beam size of 1970.9 cm^2 (44.4 cm x 44.4 cm), much larger than the active area of the PDC. For this k_{area} correction factors were not applied to the SCK•CEN results.

The correction k_{rate} could be significant (up to 17 %), when small air kerma rates were used (e.g. for VINCA and JSI). Therefore, the relatively high air kerma rate dependence of the response of PDC, used as a KAP meter, makes its characteristics non-ideal as a transfer instrument for KAP-meter calibration comparison. However, PDC used as transfer instruments in this comparison is widely used in clinical practices and KAP meter having better performances was not commercially available. Due to these limitations, the approach chosen here has been justified: for a meaningful comparison of the calibration capabilities of different laboratories, the effect of this undesirable instrument's characteristics have been removed by using appropriate correction factors k_{rate}, while the uncertainty of these correction factors has been taken into account in the evaluation of the uncertainty of the comparison values ($u_{R,}$ and u_D in Section 4.6).

4.4.3. Comparison results of MAGNA.

Table 18 presents the comparison results of MAGNA.

The first three (left side) columns of Table 18 give the non-corrected comparison result, R (ratio of reported calibration coefficient and CRV) and its standard uncertainty, u_R, for MAGNA, as well as the En scores for the non-corrected results.

As discussed in section 4.2.3, correction factors for the energy dependence of response (k_Q) of the MAGNA were applied to limited cases, i.e. for VSL (at RQR3) and UPC (at RQR5), while no corrections were applied for the beam size and air kerma rate dependence of response. Table 18 presents the corrected comparison results, R_{cor} and their standard uncertainty u_{Rcor} and the corrected $E_{n,cor}$ scores for these laboratories at the respective RQR radiation quality.

The results are presented in alphabetic order of the laboratories' codes used in this report.

Table 18. *The comparison results for* ***MAGNA***

		Non-corrected			**Correction factors**			**Corrected for Q, area and $\dot{K}$ rate (if applied)**			
		R	**u_R (k=1)**	**E_n**	**k_Q**	**k_{area}**	**k_{rate}**	**$N_{K,cor}$ mGy / nC**	**R_{cor}**	**u_{Rcor} (k=1)**	**$E_{n,cor}$**
SCK•CEN	RQR3	0.872	0.010	5.88	--	--	--	Same as non-corrected			
	RQR5	0.860	0.010	7.00	--	--	--				
	RQR6	0.881	0.010	6.07	--	--	--				
	RQR8	0.874	0.009	6.64	--	--	--				
	RQR9	0.886	0.010	5.68	--	--	--				
CMI	RQR3	1.011	0.020	0.27	--	--	--	Same as non-corrected			
	RQR5	1.006	0.019	0.16	--	--	--				
	RQR6	1.007	0.019	0.18	--	--	--				
	RQR8	1.007	0.019	0.19	--	--	--				
	RQR9	1.009	0.019	0.24	--	--	--				
SURO	RQR3	Measurements not available									
	RQR5										
	RQR6										
	RQR8										
	RQR9										
SIS	RQR3	1.003	0.014	0.12	--	--	--	Same as non-corrected			
	RQR5	0.995	0.013	0.18	--	--	--				
	RQR6	1.003	0.013	0.11	--	--	--				
	RQR8	1.002	0.012	0.08	--	--	--				
	RQR9	1.001	0.013	0.03	--	--	--				
STUK	RQR3	1.003	0.010	0.17	--	--	--	Same as non-corrected			
	RQR5	1.002	0.009	0.13	--	--	--				
	RQR6	1.002	0.009	0.10	--	--	--				
	RQR8	1.001	0.009	0.04	--	--	--				
	RQR9	1.000	0.009	0.03	--	--	--				
LNE-LNHB	RQR3	0.991	0.008	0.55	--	--	--	Same as non-corrected			
	RQR5	0.993	0.007	0.49	--	--	--				
	RQR6	0.995	0.006	0.43	--	--	--				
	RQR8	0.996	0.006	0.36	--	--	--				
	RQR9	0.995	0.007	0.42	--	--	--				
PTB	RQR3	1.006	0.008	0.38	--	--	--	Same as non-corrected			
	RQR5	1.004	0.007	0.30	--	--	--				
	RQR6	1.004	0.007	0.34	--	--	--				
	RQR8	1.004	0.006	0.33	--	--	--				
	RQR9	1.005	0.007	0.40	--	--	--				
IRCL/GAEC-EIM	RQR3	1.008	0.010	0.39	--	--	--	Same as non-corrected			
	RQR5	1.006	0.009	0.34	--	--	--				
	RQR6	1.005	0.009	0.28	--	--	--				
	RQR8	1.003	0.009	0.17	--	--	--				
	RQR9	1.004	0.009	0.19	--	--	--				

Table 18 con'd : The comparison results for **MAGNA**

		Non-corrected			Correction factors			Corrected for Q, area and $\dot{K}$ (if applied)			
		R	u_R (k=1)	E_n	k_Q	k_{area}	k_{rate}	$N_{K,cor}$ mGy / nC	R_{cor}	u_{Rcor} (k=1)	$E_{n,cor}$
MKEH	RQR3	1.003	0.008	0.18	--	--	--	Same as non-corrected			
	RQR5	1.003	0.007	0.21	--	--	--				
	RQR6	1.001	0.006	0.11	--	--	--				
	RQR8	1.001	0.006	0.07	--	--	--				
	RQR9	1.001	0.007	0.05	--	--	--				
IAEA	RQR3	1.003	0.009	0.15	--	--	--	Same as non-corrected			
	RQR5	1.003	0.008	0.20	--	--	--				
	RQR6	1.003	0.008	0.22	--	--	--				
	RQR8	1.002	0.007	0.14	--	--	--				
	RQR9	1.003	0.008	0.17	--	--	--				
GR	RQR3	0.989	0.020	0.29	--	--	--	Same as non-corrected			
	RQR5	0.986	0.019	0.38	--	--	--				
	RQR6	0.988	0.019	0.31	--	--	--				
	RQR8	0.984	0.019	0.43	--	--	--				
	RQR9	0.976	0.019	0.63	--	--	--				
IRP-DOS	RQR3	0.962	0.039	0.49	--	--	--	Same as non-corrected			
	RQR5	0.992	0.040	0.10	--	--	--				
	RQR6	0.998	0.040	0.03	--	--	--				
	RQR8	1.007	0.041	0.09	--	--	--				
	RQR9	1.012	0.041	0.14	--	--	--				
VSL	RQR3	1.000	0.010	0.02	0.998	--	--	8.20	1.002	0.010	0.08
	RQR5	0.998	0.009	0.13	--	--	--	Same as non-corrected			
	RQR6	0.999	0.009	0.05	--	--	--	Same as non-corrected			
	RQR8	0.996	0.008	0.26	--	--	--	Same as non-corrected			
	RQR9	0.998	0.009	0.10	--	--	--	Same as non-corrected			
NRPA	RQR3				--	--	--	Same as non-corrected			
	RQR5	0.986	0.016	0.45	--	--	--				
	RQR6				--	--	--				
	RQR8	0.991	0.016	0.29	--	--	--				
	RQR9	0.986	0.016	0.44	--	--	--				
NIOM	RQR3	1.013	0.027	0.24	--	--	--	Same as non-corrected			
	RQR5	1.011	0.027	0.20	--	--	--				
	RQR6	1.011	0.026	0.22	--	--	--				
	RQR8	1.003	0.026	0.06	--	--	--				
	RQR9	0.999	0.027	0.01	--	--	--				

Table 18 con'd : The comparison results for **MAGNA**

		Non-corrected			**Correction factors**			**Corrected for Q, area and $\dot{K}$ (if applied)**			
		R	**u_R (k=1)**	**E_n**	**k_Q**	**k_{area}**	**k_{rate}**	**$N_{K,cor}$ mGy / nC**	**R_{cor}**	**u_{Rcor} (k=1)**	**$E_{n,cor}$**
ITN-LMRI	RQR3	1.005	0.009	0.29	--	--	--	Same as non-corrected			
	RQR5	1.005	0.008	0.32	--	--	--				
	RQR6	1.008	0.008	0.50	--	--	--				
	RQR8	1.003	0.007	0.22	--	--	--				
	RQR9	1.000	0.008	0.01	--	--	--				
IFIN-HH	RQR3	0.994	0.020	0.15	--	--	--	Same as non-corrected			
	RQR5	0.994	0.014	0.22	--	--	--				
	RQR6	0.994	0.014	0.23	--	--	--				
	RQR8	1.000	0.014	0.01	--	--	--				
	RQR9	1.003	0.014	0.12	--	--	--				
VINCA	RQR3	1.020	0.016	0.62	--	--	--	Same as non-corrected			
	RQR5	1.021	0.016	0.66	--	--	--				
	RQR6	1.019	0.016	0.60	--	--	--				
	RQR8	1.014	0.015	0.46	--	--	--				
	RQR9	1.013	0.016	0.41	--	--	--				
SIM	RQR3	1.008	0.026	0.14	--	--	--	Same as non-corrected			
	RQR5	1.013	0.026	0.26	--	--	--				
	RQR6	1.014	0.026	0.26	--	--	--				
	RQR8	1.009	0.026	0.17	--	--	--				
	RQR9	1.016	0.026	0.31	--	--	--				
JSI	RQR3	0.999	0.011	0.06	--	--	--	Same as non-corrected			
	RQR5	1.002	0.010	0.13	--	--	--				
	RQR6	0.998	0.010	0.08	--	--	--				
	RQR8	0.997	0.009	0.15	--	--	--				
	RQR9	1.003	0.010	0.13	--	--	--				
UPC	RQR3	1.008	0.012	0.35	--	--	--	Same as non-corrected			
	RQR5	0.999	0.011	0.06	0.998	--	--	8.22	1.001	0.012	0.01
	RQR6	1.005	0.011	0.25	--	--	--	Same as non-corrected			
	RQR8	0.998	0.011	0.09	--	--	--	Same as non-corrected			
	RQR9	1.001	0.011	0.03	--	--	--	Same as non-corrected			
SSM	RQR3	1.006	0.014	0.21	--	--	--	Same as non-corrected			
	RQR5	1.004	0.013	0.15	--	--	--				
	RQR6	1.003	0.013	0.11	--	--	--				
	RQR8	1.003	0.013	0.13	--	--	--				
	RQR9	1.002	0.013	0.07	--	--	--				

Fig. 32 presents the corrected comparison results, R_{cor} for the MAGNA ionization chamber, i.e. the ratio of the corrected calibration coefficient and the respective CRV.

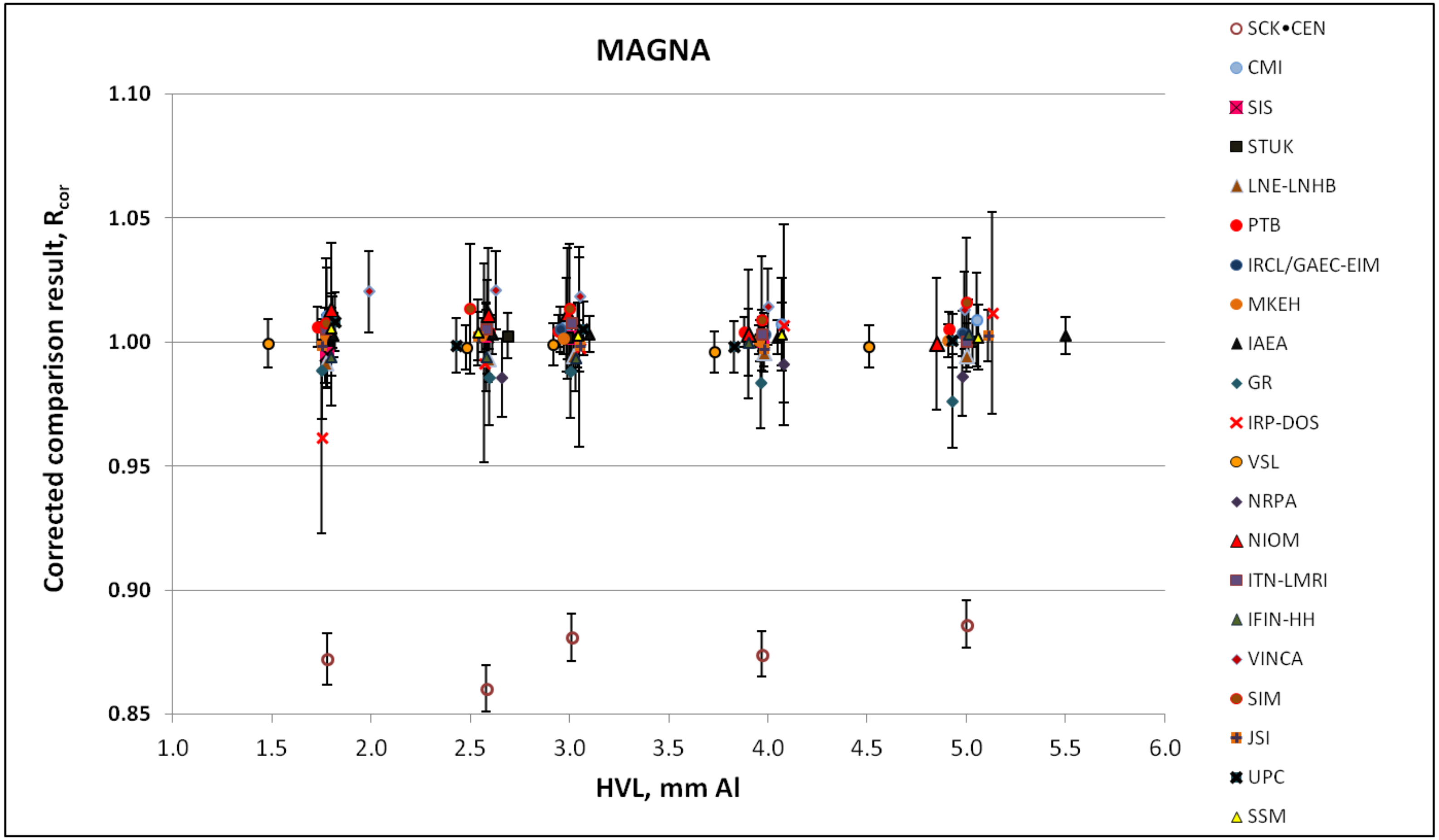


Fig. 32. *The corrected comparison results, R_{cor} for the MAGNA ionization chamber, i.e. the ratio of the corrected calibration coefficient and the respective CRV. The error bars represent the standard uncertainties.*

Fig. 33 presents the frequence distribution of the corrected comparison results, R_{cor} for the MAGNA.

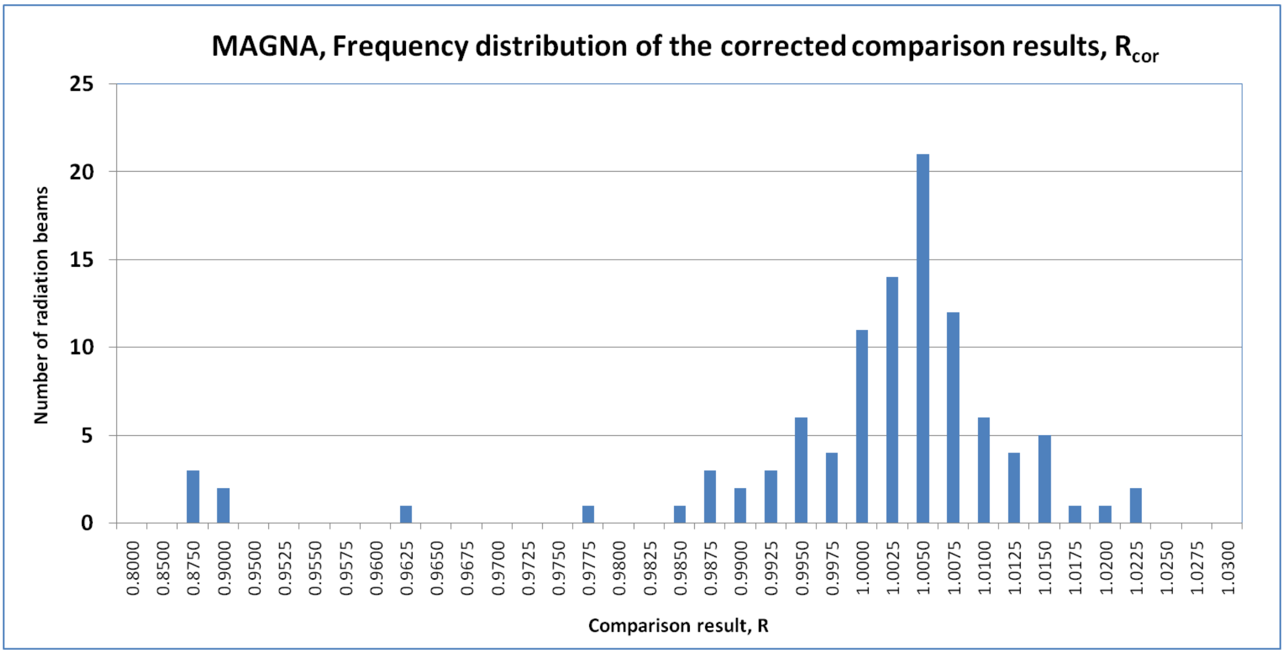


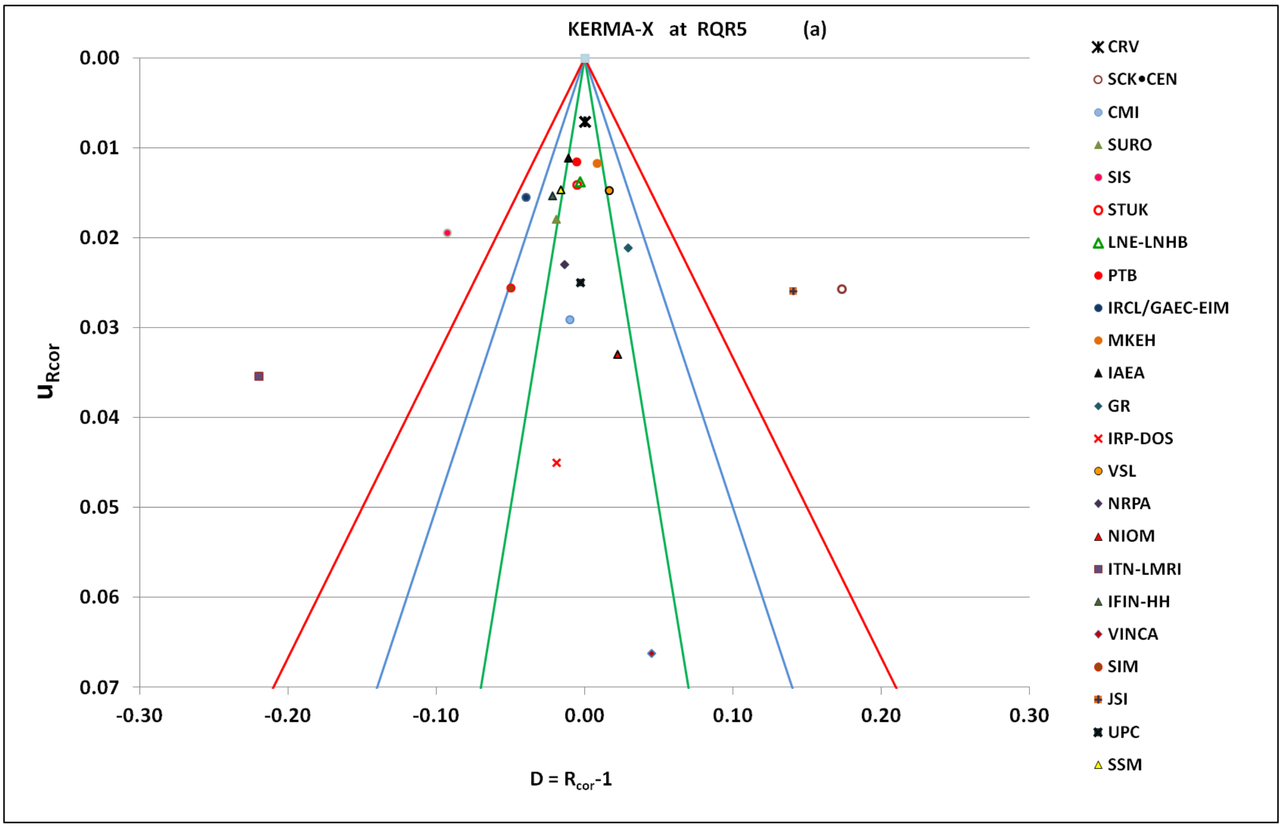
Fig. 33. *The frequency distribution of the-corrected comparison results, R_{cor} for the MAGNA ionization chamber.*

From Table 18 it can be seen that in practice the correction for k_Q is negligible, due to the low energy dependence of response of MAGNA.

4.5. PomPlots

Following the method described in 3.4.4., Fig. 34 (a and b) shows the PomPlots of KERMA-X and PDC comparison results at the RQR5 radiation quality.
Fig. 35 demonstrates the PomPlot of the weighted mean comparison result of KERMA-X and PDC at the RQR5. The results between KERMA-X and PDC were weighted according to the reciprocal of the comparison result variances (eq. 16a and 16b).

Fig. 36 presents the PomPlot of MAGNA comparison results at the RQR5.
Similar PomPlots could be derived for the rest of the radiation qualities.



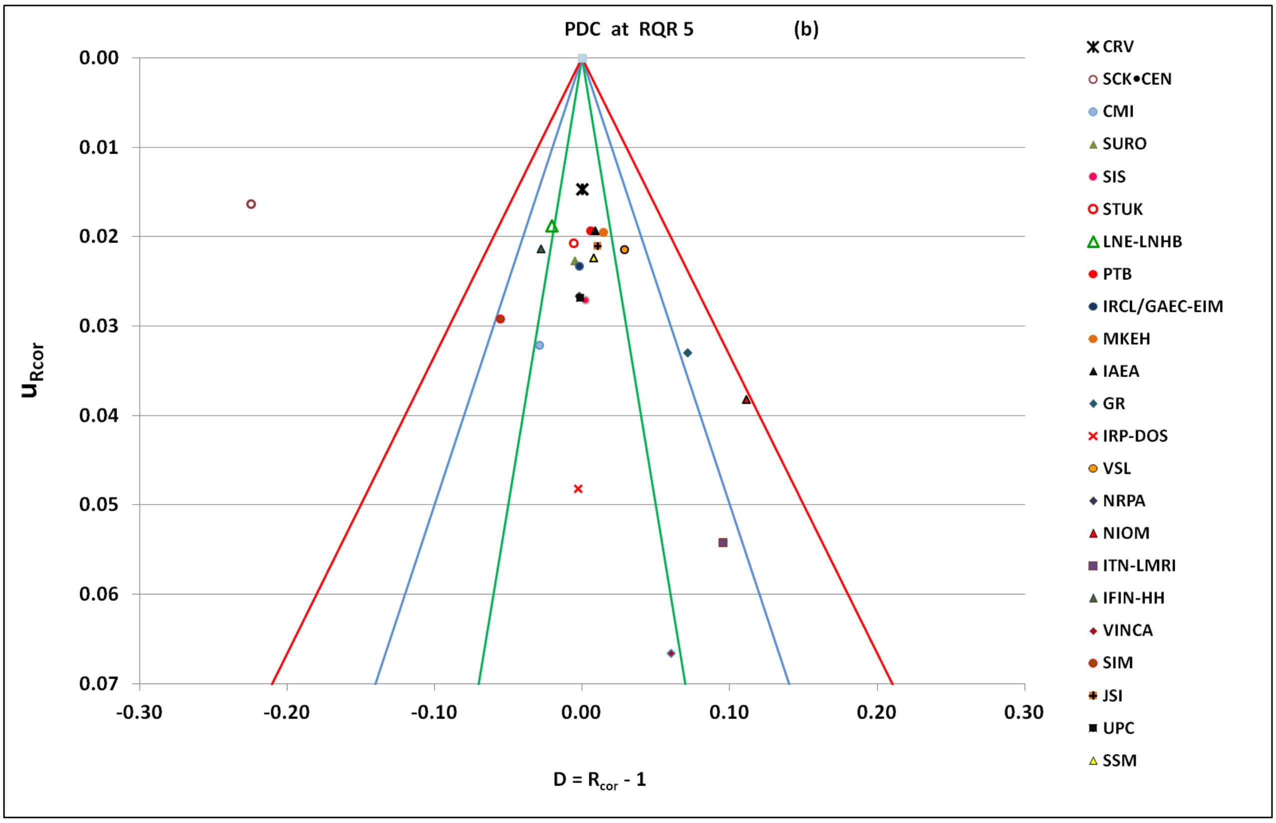


Fig. 34. *The PomPlots for KERMA-X (a) and PDC (b) comparison results at RQR 5 radiation quality. The u_{Rcor} (y-axis) is the standard uncertainties of the R_{cor} values. The * point at the top corresponds to the comparison reference value (its deviation from the CRV is zero) and its standard uncertainty. The green, blue and red lines indicate the ζ scores ±1, ±2 and ± 3 respectively.*

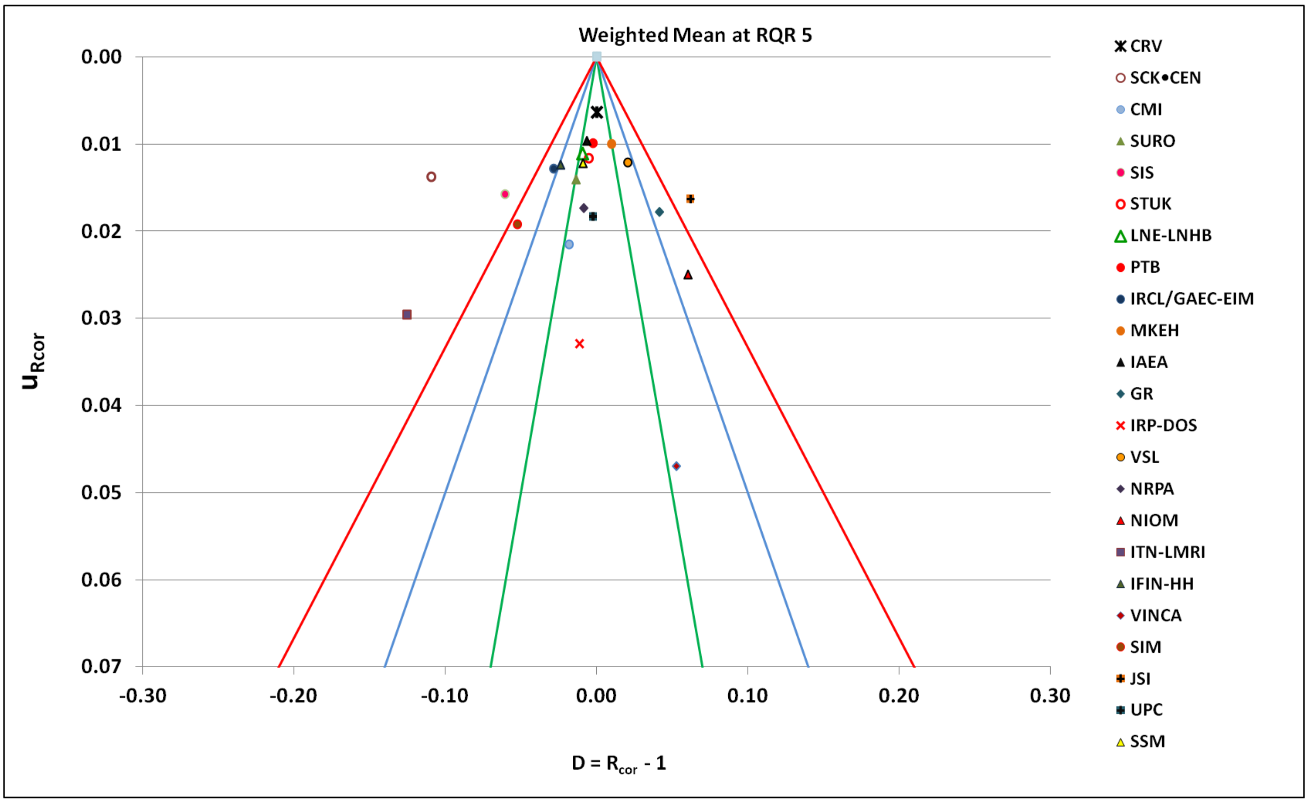


Fig. 35. *The PomPlots for KERMA-X and PDC weighted mean comparison results at RQR 5 radiation quality. The u_{Rcor} (y-axis) is the standard uncertainties of the R_{cor} values. The * point at the top corresponds to the comparison reference value (its deviation from the CRV is zero) and its standard uncertainty. The green, blue and red lines indicate the ζ scores ±1, ±2 and ± 3 respectively.*

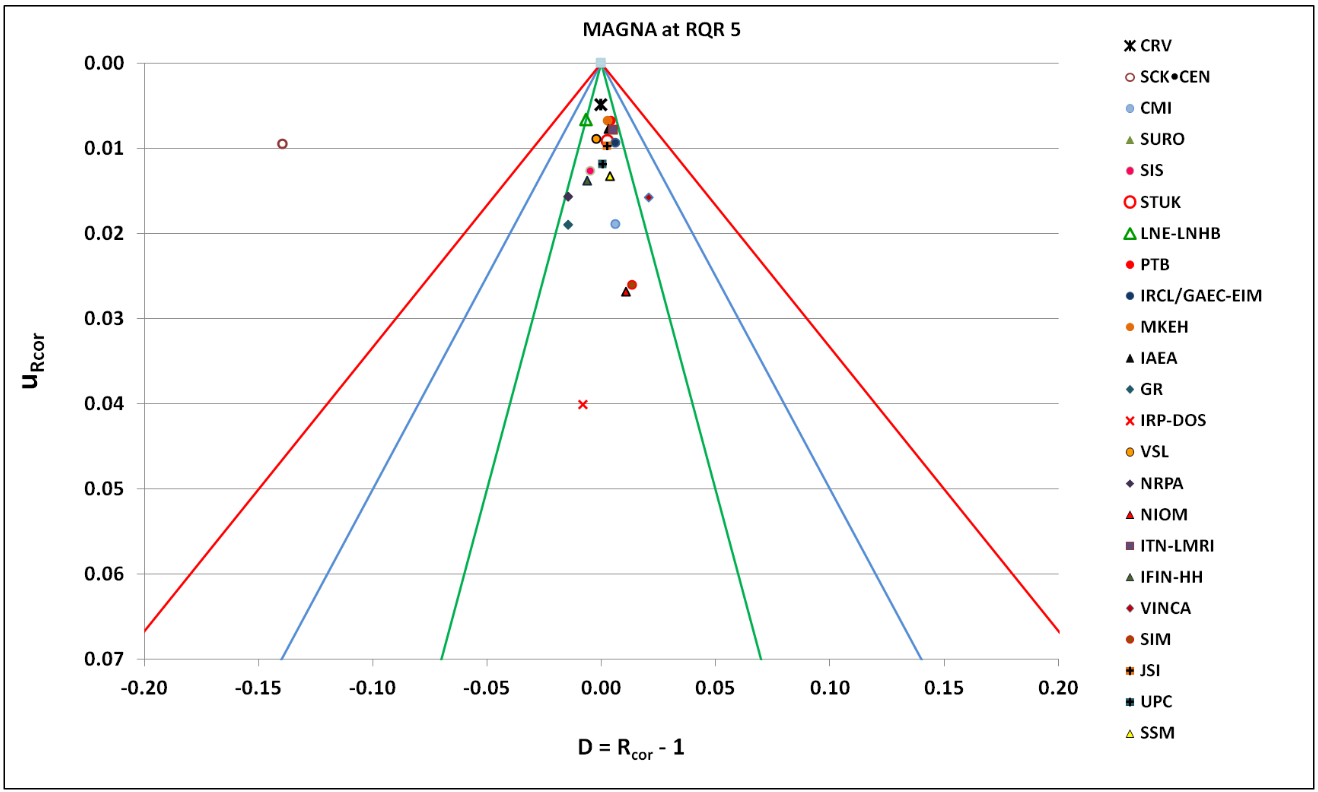


***Fig. 36**. The PomPlot for MAGNA comparison results at RQR 5 radiation quality. The u_{Rcor} (y-axis) is the standard uncertainties of the R_{cor} values. The * point at the top corresponds to the comparison reference value (its deviation from the CRV is zero) and its standard uncertainty. The green, blue and red lines indicate the ζ scores ± 1, ± 2 and ± 3 respectively.*

The PomPlots in terms of P_{KA} for KERMA-X and PDC, separately, showed that most of the results were included between ζ scores lines of ± 3. Only in 4 cases for KERMA-X and in 1 case for PDC the results might be inconsistent with the reference value (CRV), as the respective points located outside ζ scores lines of ± 3.

Fig. 34a (for KERMA-X) shows that most of the points were at the left side of the PomPlots, denoting that most of the calibration coefficients were lower than the CRV. The opposite is observed for PDC (Fig 34b). These observations nearly cancelled out, when the weighed mean of the KERMA-X and PDC results was considered (Fig. 35). According to Fig. 35, the weighted mean results of three cases were inconsistent with CRV. Most of the points situated close to the CRV (upper parts of graphs) indicating that the uncertainties were low and comparable to that of the CRV.

The PomPlot for air kerma (Fig 36) shows that all (except one) calibration results were consistent to the CRV. More specifically, all points (except two) were situated close along the central line D = 0, while only one point lay outside the ζ-score = ± 3 line. The uncertainties of the results were low, as almost all points were located at the upper part of the graph.

The PomPlots at RQR5 (Fig. 34 – 36) were also related to the degree of equivalence, as presented below (section 4.7).

4.6. Proposal for the Degree of Equivalence

Following the method described in section 3.4.5, the degrees of equivalence for the air kerma area product, $(DoE)_{PKA}$ and the associated uncertainties were obtained from the comparison results at RQR5 radiation quality (eq. 17 and eq. 18) of PDC.
The PDC was selected due to its better performance characteristic than KERMA-X, as summarized in table 19.

Table 19. *Summary of the performance characteristics of PDC and KERMA-X*

Performance characteristic	PDC	KERMA-X
Energy dependence of response in RQR3 - RQR9 range	(Fig. 18) 8 %; Smoothly decreasing response shape	(Fig. 11) 10 %; Hyperbolic response shape
Air kerma rat, $\dot{K}$, dependence of response	(Fig. 20) 15 % at low $\dot{K}$; Stable response at $\dot{K}$ > 15 mGy/min	(Fig. 20) 400 % at low $\dot{K}$; Stable response at $\dot{K}$ > 20 mGy/min
Area, A, dependence of response	(Fig. 21) 4 %	(Fig. 14) 5 %
Stability during calibration	1.00 %	0.79 %

The DoE for the air kerma, $(DoE)_K$ and the associated uncertainties were obtained from the comparison results at RQR5 radiation quality (eq. 17 and eq. 18) of MAGNA and are presented in table 20. The respective expanded uncertainties (k=2) U_D, $U_{DoE,PKA}$ and $U_{DoE,K}$ are also presented.

Grey rows in the table show the laboratories having submitted diagnostic radiology level CMCs to BIPM KCDB.

Table 20. *Degrees of equivalence at RQR 5 radiation quality, in terms of the difference D, (DoE = │D│), with respect to the comparison reference value and its associated expanded (k = 2) uncertainty for air kerma area product, P_{KA} and air kerma, K.*

Laboratory	Air Kerma Area Product, P_{KA} PDC (DoE)$_{PKA}$ %	$U_{DoE,PKA}$ % k=2	Air kerma, K MAGNA (DoE)$_K$ %	$U_{DoE,K}$ %, k=2
SCK•CEN	-22.4 %	3.3 %	-14.0 %	1.9 %
CMI	-2.9 %	6.5 %	0.6 %	3.8 %
SURO	-0.5 %	4.6 %		
SIS	0.2 %	5.5 %	-0.5 %	2.6 %
STUK	-0.6 %	4.2 %	0.2 %	1.8 %
LNE-LNHB	-2.1 %	3.8 %	-0.7 %	1.4 %
PTB	0.6 %	3.9 %	0.4 %	1.4 %
IRCL/GAEC-EIM	-0.2 %	4.7 %	0.6 %	1.9 %
MKEH	1.4 %	4.0 %	0.3 %	1.4 %
IAEA	0.9 %	4.0 %	0.3 %	1.6 %
GR	7.2 %	6.7 %	-1.4 %	3.8 %
IRP-DOS	-0.3 %	9.7 %	-0.8 %	8.0 %
VSL	2.9 %	4.4 %	-0.2 %	1.8 %
NRPA	-0.2 %	5.4 %	-1.4 %	3.2 %
NIOM	11.1 %	7.7 %	1.1 %	5.4 %
ITN-LMRI	9.6 %	10.9 %	0.5 %	1.6 %
IFIN-HH	-2.8 %	4.3 %	-0.6 %	2.8 %
VINCA	6.0 %	13.4 %	2.1 %	3.2 %
SIM	-5.6 %	5.9 %	1.3 %	5.2 %
JSI	1.0 %	4.3 %	0.2 %	2.0 %
UPC	-0.1 %	5.4 %	0.1 %	2.4 %
SSM	0.8 %	4.5 %	0.4 %	2.7 %

Fig. 37 presents the DoE, in terms of the difference, D, for air kerma area product, (DoE)$_{PKA}$, as deduced from the comparison results of PDC at RQR 5 radiation quality. The associated expanded uncertainties are shown as “error bars”.

Fig. 38 presents the DoE, in terms of the difference, D, for air kerma, (DoE)$_K$, as deduced from the of the weighted mean of the comparison results of MAGNA. The associated expanded uncertainties are shown as “error bars”.

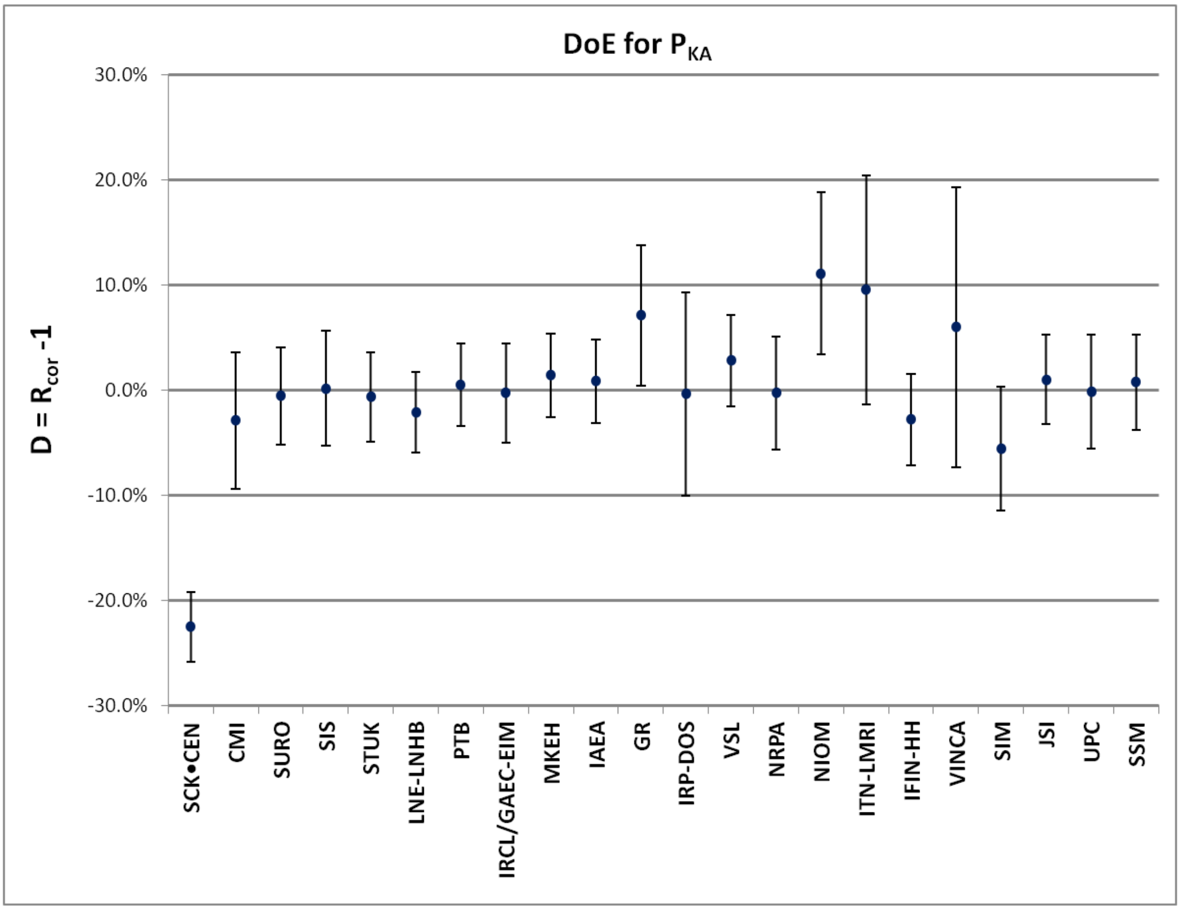


Fig. 37. *The Degrees of Equivalence, DoE, in terms of the difference, D, and the associated uncertainties for air kerma area product,* P_{KA} *. D values were calculated from the comparison results, Rcor, at RQR 5 for PDC. The error bars correspond to the expanded uncertainty of D (k = 2).*

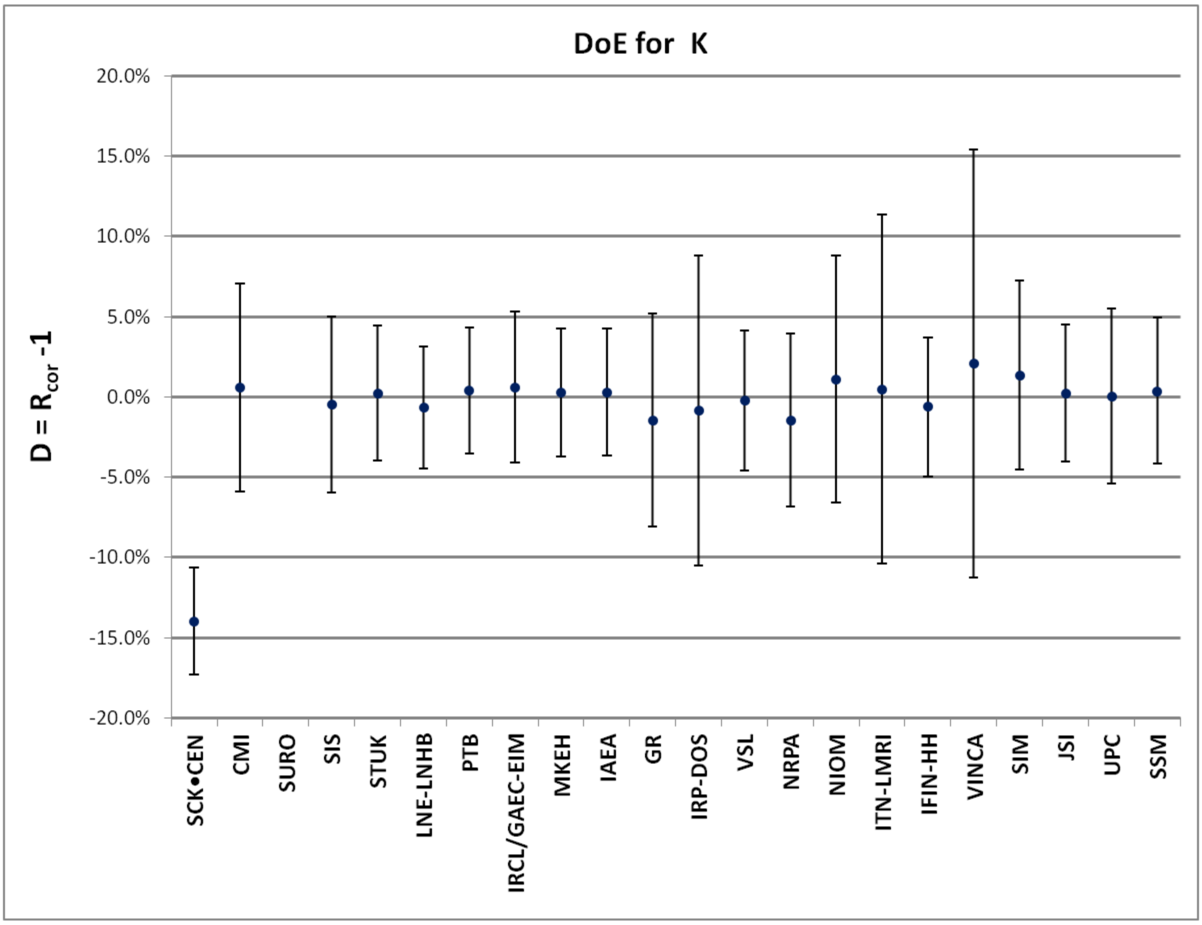


Fig. 38. *The Degrees of Equivalence, DoE, in terms of the difference, D, and the associated uncertainties for air kerma, K. D values were calculated from the corrected companion results, Rcor, at RQR 5 for MAGNA. The error bars correspond to the expanded uncertainty of D (k = 2).*

4.7 Comments on laboratories results

The SCK•CEN inconsistencies of the results have been assessed and possible reasons have been identified : KERMA-X was calibrated very close to the X-ray tube focus (at 27 cm distance); PDC was exposed to a beam size much larger than the active area of the PDC and then the readings were adjusted to the nominal area of PDC; PDC calibration was performed at very low air kerma rates (~ 2 mGy/min). Moreover, SCK•CEN has not being performed routine calibrations of KAP meters at RQR beam qualities, yet. In addition, the X-ray unit, used for the measurement in this comparison, was already in process of being replaced with a new dual tube system. The X-ray generator will be removed, soon.

SIS, IRCL/GAEC-EIM, VSL, JSI and SSM results for PDC were consistent with the CRV; however that was not the case for the KERMA-X results.

IRCL/GAEC-EIM had been identified this discrepancy in advance, after submitting the calibration results to the CCRI Executive Secretary (April 2011). According to IRCL/GAEC-EIM calibration procedures of KAP meters and pencil types ionization chambers, where apertures should be used to define the irradiation area, the measured air kerma had to be corrected for the influence of scattered and extra focal radiation from apertures. The reference correction factor for the 50 mm aperture that is being used is 1.016 [29]. By mistake, this correction factor was not applied to the KERMA-X result evaluation. If such corrections had been applied, the results would be consistent with the reference values; i.e. the $D \pm U_D$ for KERMA-X would be -2.2 % ± 2.2 % and the $(DoE)_{PKA}$ for the P_{KA} -1.3 % ± 1.6 %.

GR and NIOM showed consistent results for KERMA-X, but not for PDC. GR performed the PDC measurements at small irradiation area (~ 10 cm^2), which might explain the results. The weighted mean P_{KA} results for GR and NIOM were outside the associated expanded uncertainties. Both laboratories exhibited air kerma results consistent to the CRV.

ITN-LMRI, IFIN-HH and SIM results in respect to the P_{KA} for both KERMA-X and PDC may not be consistent with the CRV. Since, the results for air kerma, K, were consistent with the CRV, the P_{KA} inconsistencies might be due to the calibration procedures as well as to the performance characteristics of the transfer instruments.

Finally, it should be mentioned that all (except two) participating laboratories exhibited consistent air kerma results with the CRV.

5. Conclusion

The first EURAMET wide scale supplementary comparison in the field of diagnostic radiology for air kerma area product, P_{KA}, and air kerma, K, (EURAMET project #1177 was performed successfully.

The comparison measurements were performed in conjunction with a EURADOS project and an IAEA Coordinated Research Program. For the EURAMET comparison, standard beam qualities (RQR qualities) for incident radiation were applied for measurements and calibrations of the transfer instruments: two KAP meters and two air kerma meters. However, for the analysis of the comparison results within the EURAMET 1177 project both KAP meters (PDC and KERMA-X) but only one air kerma meter (MAGNA) were used. In the frame of the EURADOS and IAEA projects as a feasibility study non-standard and transmitted radiation beam qualities have also been applied.

The reproducibility of the measurements carried out with the transfer instruments was established through repeated measurements made at the IRCL/GAEC-EIM (pilot laboratory) over the course of the comparison and it was very satisfactory ($u_{stab} \leq 1$ %).

The performance of the transfer instruments was tested by the pilot laboratory and a few other laboratories. These test results revealed that the characteristics of the transfer instruments were not optimal for transfer standard propose: the need for a correction for the dependence of the instrument's response on radiation energy (beam quality correction) was practically negligible, but corrections for the dependence of the instrument's response on the area and air kerma rate were significant in some cases (up to about 60 % in the worst case). However, the KAP meters used as transfer instruments were selected due to their common use in clinical practices and because better quality KAP meters were not commercially available. Due to these limitations, a pragmatic approach was justified: for a meaningful comparison of the calibration capabilities of different laboratories, the effect of the undesirable instrument's characteristics were removed by using appropriate correction factors, and the uncertainty of these correction factors were taken into account in the evaluation of the uncertainty of the comparison values.
The 216 KAP meter calibrations of the two different transfer KAP meters in terms of air kerma area product were consistent within 5 % except 40 results of 8 participants .
The 103 air kerma calibrations were consistent within 1.7 %, except 10 results of 4 participants.
The comparison results, based on the DoE values in Table 20, could support the published CMCs of the participants except the 2.0 % uncertainty on KAP meter calibration at the VSL.
Note that this evaluation based on the deviation from the reference value calculated for the RQR 5 quality only , without taking into account the increased uncertaities of the DoE values coming from the less robust CRV values and uncertainties of the k_{rate}, k_Q, k_{area} corrections required.

6. Acknowledgments

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7. References

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APPENDIX A : The submitted results of the participating laboratories

Notation

HVL : reported HVL in mm Al of the radiation quality
A : reported irradiation area, in cm^2 at the point of measurement
$\dot{K}$: reported value of the air kerma rate at the point of measurement
N_{PKA} : reported calibration coefficient in terms of air kerma area product
N_K : reported calibration coefficient in terms of air kerma
U % : reported expanded relative uncertainty of the calibration coefficient, *k* = 2
u : standard uncertainty (*k* = 1) of the calibration coefficient calculated from U % and N_{PKA} or N_K (three digits are kept for all *u* values)

The results are presented in alphabetic order of the laboratories' country name.

SCK•CEN : Belgian Nuclear Research Centre, Belgium

SCK•CEN.1 : KERMA KAP meter in terms of air kerma area product

	HVL mm Al	A cm^2	$\dot{K}$ mGy/min	N_{PKA} Gy cm^2/Gy cm^2	U % (*k*=2)	u (*k*=1) Gy cm^2/Gy cm^2
RQR3	1.78	143.70	24.13	1.26	4.00	0.025
RQR5	2.58	143.70	52.80	1.28	4.00	0.026
RQR6	3.01	143.70	67.48	1.3	4.00	0.026
RQR8	3.97	143.70	107.84	1.39	4.00	0.028
RQR9	5.00	143.70	151.87	1.45	4.00	0.029

SCK•CEN.2 : PDC KAP meter in terms of air kerma area product

	HVL mm Al	A cm^2	$\dot{K}$ mGy/min	N_{PKA} Gy cm^2/Gy cm^2	U % (*k*=2)	u (*k*=1) Gy cm^2/Gy cm^2
RQR3	1.78	900.00	1.75	0.89	1.97	0.009
RQR5	2.58	900.00	1.76	0.87	1.92	0.008
RQR6	3.01	900.00	3.85	0.85	1.90	0.008
RQR8	3.97	900.00	4.89	0.85	1.88	0.008
RQR9	5.00	900.00	7.86	0.85	1.89	0.008

SCK•CEN.3 : MAGNA ionization chamber in terms of air kerma

	HVL mm Al	A cm^2	$\dot{K}$ mGy/min	N_K mGy / nC	U % (*k*=2)	u (*k*=1) mGy / nC
RQR3	1.78	1970.90	1.62	7.138	1.90	**0.068**
RQR5	2.58	1970.90	3.55	7.070	1.90	**0.067**
RQR6	3.01	1970.90	4.72	7.239	1.90	**0.069**
RQR8	3.97	1970.90	7.27	7.171	1.90	**0.068**
RQR9	5.00	1970.90	10.25	7.244	1.90	**0.069**

CMI : Czech Metrology Institute, Czech Rep.

CMI.1 : KERMA KAP meter in terms of air kerma area product

	HVL	**A**	$\dot{K}$	**N$_{PKA}$**	**U %**	**u (*k*=1)**
	mm Al	**cm^2**	**mGy/min**	**Gy cm^2/Gy cm^2**	**(*k*=2)**	**Gy cm^2/Gy cm^2**
RQR3	1.778	20.85	13.8	1.20	5.6	0.034
RQR5	2.584	20.85	24.1	1.08	5.6	0.030
RQR6	2.984	20.85	30.6	1.08	5.6	0.030
RQR8	4.07	20.85	41.9	1.10	5.6	0.031
RQR9	5.053	20.85	55.8	1.12	5.6	0.031

CMI.2 : PDC KAP meter in terms of air kerma area product

	HVL	**A**	$\dot{K}$	**N$_{PKA}$**	**U %**	**u (*k*=1)**
	mm Al	**cm^2**	**mGy/min**	**Gy cm^2/Gy cm^2**	**(*k*=2)**	**Gy cm^2/Gy cm^2**
RQR3	1.778	20.85	13.8	0.98	5.6	0.027
RQR5	2.584	20.85	24.1	0.95	5.6	0.027
RQR6	2.984	20.85	30.6	0.95	5.6	0.027
RQR8	4.07	20.85	41.9	0.94	5.6	0.026
RQR9	5.053	20.85	55.8	0.93	5.6	0.026

CMI.3 : MAGNA ionization chamber in terms of air kerma

	HVL	**A**	$\dot{K}$	**N$_K$**	**U %**	**u (*k*=1)**
	mm Al	**cm^2**	**mGy/min**	**mGy / nC**	**(*k*=2)**	**mGy / nC**
RQR3	1.778	113	13.8	8.27	3.6	**0.149**
RQR5	2.584	113	24.1	8.27	3.6	**0.149**
RQR6	2.984	113	30.6	8.27	3.6	**0.149**
RQR8	4.070	113	41.9	8.26	3.6	**0.149**
RQR9	5.053	113	55.8	8.25	3.6	**0.148**

SURO : "SURO" National Radiation Protection Institute, Czech Rep.

SURO.1 : KERMA KAP meter in terms of air kerma area product

	HVL	**A**	$\dot{K}$	**N_{PKA}**	**U %**	**u (*k*=1)**
	mm Al	**cm^2**	**mGy/min**	**Gy cm^2/Gy cm^2**	**(*k*=2)**	**Gy cm^2/Gy cm^2**
RQR3	1.79	29.29	17.65	1.188	3.2	0.019
RQR5	2.57	29.29	31.51	1.07	3.2	0.017
RQR6	2.97	29.29	39.8	1.073	3.2	0.017
RQR8	4.11	29.29	51.32	1.095	3.2	0.018
RQR9	5.09	29.29	66.74	1.142	3.2	0.018

SURO.2 : PDC KAP meter in terms of air kerma area product

	HVL	**A**	$\dot{K}$	**N_{PKA}**	**U %**	**u (*k*=1)**
	mm Al	**cm^2**	**mGy/min**	**Gy cm^2/Gy cm^2**	**(*k*=2)**	**Gy cm^2/Gy cm^2**
RQR3	1.79	29.29	17.7	1.00	2.9	0.014
RQR5	2.57	29.29	31.5	0.97	2.9	0.014
RQR6	2.97	29.29	39.8	0.97	2.9	0.014
RQR8	4.11	29.29	51.3	0.95	2.9	0.014
RQR9	5.09	29.29	66.7	0.94	2.9	0.014

SURO.3 : MAGNA ionization chamber in terms of air kerma

	HVL	**A**	$\dot{K}$	**N_K**	**U %**	**u (*k*=1)**
	mm Al	**cm^2**	**mGy/min**	**mGy / nC**	**(*k*=2)**	**mGy / nC**
RQR3						
RQR5						
RQR6						
RQR8						
RQR9						

No calibration was performed

SIS : National Institute of Radiation Protection, Denmark

SIS.1 : KERMA KAP meter in terms of air kerma area product

	HVL mm Al	A cm^2	$\dot{K}$ mGy/min	N_{PKA} Gy cm^2/Gy cm^2	U % (*k*=2)	u (*k*=1) Gy cm^2/Gy cm^2
RQR3	1.78	25.00	33.30	1.08	3.90	0.021
RQR5	2.58	25.00	62.10	0.99	3.90	0.019
RQR6	3.01	25.00	81.60	1.00	3.90	0.020
RQR8	3.97	25.00	112.30	1.01	3.90	0.020
RQR9	5.00	25.00	146.40	1.06	3.90	0.021

SIS.2 : PDC KAP meter in terms of air kerma area product

	HVL mm Al	A cm^2	$\dot{K}$ mGy/min	N_{PKA} Gy cm^2/Gy cm^2	U % (*k*=2)	u (*k*=1) Gy cm^2/Gy cm^2
RQR3	1.78	260.00	33.30	0.99	4.10	0.020
RQR5	2.58	260.00	62.10	0.98	4.10	0.020
RQR6	3.01	260.00	81.60	0.98	4.10	0.020
RQR8	3.97	260.00	112.30	0.97	4.10	0.020
RQR9	5.00	260.00	146.40	0.96	4.10	0.020

SIS.3 : MAGNA ionization chamber in terms of air kerma

	HVL mm Al	A cm^2	$\dot{K}$ mGy/min	N_K mGy / nC	U % (*k*=2)	u (*k*=1) mGy / nC
RQR3	1.780	260.00	33.3	8.21	2.30	0.094
RQR5	2.580	260.00	62.1	8.18	2.30	0.094
RQR6	3.010	260.00	81.6	8.24	2.30	0.095
RQR8	3.970	260.00	112.3	8.22	2.30	0.095
RQR9	5.000	260.00	146.4	8.18	2.30	0.094

STUK : Radiation and Nuclear Safety Authority, Finland

STUK.1: KERMA KAP meter in terms of air kerma area product

	HVL	**A**	$\dot{K}$	**N_{PKA}**	**U %**	**u (*k*=1)**
	mm Al	**cm^2**	**mGy/min**	**Gy cm^2/Gy cm^2**	**(*k*=2)**	**Gy cm^2/Gy cm^2**
RQR3	1.79	27.74	32.59	1.182	2.2	0.013
RQR5	2.69	27.74	33.23	1.085	2.2	0.012
RQR6	2.99	27.74	33.14	1.091	2.2	0.012
RQR8	3.96	27.74	33.35	1.114	2.2	0.012
RQR9	5.03	27.74	33.12	1.159	2.2	0.013

STUK.2 : PDC KAP meter in terms of air kerma area product

	HVL	**A**	$\dot{K}$	**N_{PKA}**	**U %**	**u (*k*=1)**
	mm Al	**cm^2**	**mGy/min**	**Gy cm^2/Gy cm^2**	**(*k*=2)**	**Gy cm^2/Gy cm^2**
RQR3	1.79	27.74	32.59	0.990	2.2	0.011
RQR5	2.69	27.74	33.23	0.972	2.2	0.011
RQR6	2.99	27.74	33.14	0.966	2.2	0.011
RQR8	3.96	27.74	33.35	0.953	2.2	0.010
RQR9	5.03	27.74	33.12	0.942	2.2	0.010

STUK 3 : MAGNA ionization chamber in terms of air kerma

	HVL	**A**	$\dot{K}$	**N_K**	**U %**	**u (*k*=1)**
	mm Al	**cm^2**	**mGy/min**	**mGy / nC**	**(*k*=2)**	**mGy / nC**
RQR3	1.79	154	32.59	8.211	1.5	**0.062**
RQR5	2.69	154	33.23	8.238	1.5	**0.062**
RQR6	2.99	154	33.14	8.231	1.5	**0.062**
RQR8	3.96	154	33.35	8.208	1.5	**0.062**
RQR9	5.03	154	33.12	8.178	1.5	**0.061**

LNE-LNHB : Laboratoire National Henri Becquerel/Commissariat à l'Energie Atomique, France

LNE-LNHB.1 : KERMA KAP meter in terms of air kerma area product

	HVL mm Al	A cm^2	$\dot{K}$ mGy/min	N_{PKA} Gy cm^2/Gy cm^2	U % (k=2)	u (k=1) Gy cm^2/Gy cm^2
RQR3	1.77	27.70	57.04	1.206	1.93	0.012
RQR5	2.59	27.70	107.13	1.087	2.11	0.011
RQR6	3.02	27.70	134.91	1.0790	1.70	0.009
RQR8	3.98	27.70	192.13	1.0963	1.54	0.008
RQR9	5.00	27.70	256.69	1.1365	1.47	0.008

LNE-LNHB.2 : PDC KAP meter in terms of air kerma area product

	HVL mm Al	A cm^2	$\dot{K}$ mGy/min	N_{PKA} Gy cm^2/Gy cm^2	U % (k=2)	u (k=1) Gy cm^2/Gy cm^2
RQR3	1.77	27.70	57.04	0.9768	1.52	0.007
RQR5	2.59	27.70	107.13	0.9575	1.46	0.007
RQR6	3.02	27.70	134.91	0.9499	1.44	0.007
RQR8	3.98	27.70	192.13	0.9355	1.45	0.007
RQR9	5.00	27.70	256.69	0.9271	1.47	0.007

LNE-LNHB.3 : MAGNA ionization chamber in terms of air kerma

	HVL mm Al	A cm^2	$\dot{K}$ mGy/min	N_K mGy / nC	U % (k=2)	u (k=1) mGy / nC
RQR3	1.77	27.67	57.04	8.112	0.74	0.030
RQR5	2.59	27.67	107.13	8.163	0.74	0.030
RQR6	3.02	27.67	134.91	8.173	0.73	0.030
RQR8	3.98	27.67	192.13	8.168	0.74	0.030
RQR9	5.00	27.67	256.69	8.129	0.74	0.030

PTB: Physikalisch-Technische Bundesanstalt, Germany

PTB.1 : KERMA KAP meter in terms of air kerma area product

	HVL mm Al	**A** cm^2	$\dot{K}$ mGy/min	N_{PKA} Gy cm^2/Gy cm^2	**U %** (*k*=2)	**u (*k*=1)** Gy cm^2/Gy cm^2
RQR3	1.731	25.00	56.0	1.166	1.50	0.009
RQR5	2.597	25.00	54.4	1.085	1.50	0.008
RQR6	2.946	25.00	58.8	1.083	1.50	0.008
RQR8	3.882	25.00	64.5	1.107	1.50	0.008
RQR9	4.911	25.00	76.0	1.151	1.50	0.009

PTB.2 : PDC KAP meter in terms of air kerma area product

	HVL mm Al	**A** cm^2	$\dot{K}$ mGy/min	N_{PKA} Gy cm^2/Gy cm^2	**U %** (*k*=2)	**u (*k*=1)** Gy cm^2/Gy cm^2
RQR3	1.731	25.00	55.8	1.002	1.50	0.008
RQR5	2.597	25.00	54.4	0.984	1.50	0.007
RQR6	2.946	25.00	58.8	0.977	1.50	0.007
RQR8	3.882	25.00	64.4	0.964	1.50	0.007
RQR9	4.911	25.00	76.0	0.953	1.50	0.007

PTB.3 : MAGNA ionization chamber in terms of air kerma

	HVL mm Al	**A** cm^2	$\dot{K}$ mGy/min	N_K mGy / nC	**U %** (*k*=2)	**u (*k*=1)** mGy / nC
RQR3	1.731	78.50	55.94	8.23	0.80	0.033
RQR5	2.597	78.50	54.41	8.25	0.80	0.033
RQR6	2.946	78.50	58.80	8.25	0.80	0.033
RQR8	3.882	78.50	64.45	8.24	0.80	0.033
RQR9	4.911	78.50	75.95	8.22	0.80	0.033

IRCL/GAEC-EIM : Ionizing Radiation Calibration Laboratory, Greek Atomic Energy Commission, Greece

IRCL/GAEC-EIM.1 : KERMA KAP meter in terms of air kerma area product

	HVL	**A**	$\dot{K}$	N_{PKA}	**U %**	**u (*k*=1)**
	mm Al	**cm²**	**mGy/min**	**Gy cm²/Gy cm²**	**(*k*=2)**	**Gy cm²/Gy cm²**
RQR3	1.81	27.83	30.98	1.14	2.69	0.015
RQR5	2.58	27.83	73.35	1.05	2.69	0.014
RQR6	2.96	27.83	74.51	1.04	2.69	0.014
RQR8	3.98	27.83	54.58	1.07	2.69	0.014
RQR9	4.98	27.83	71.24	1.12	2.69	0.015

IRCL/GAEC-EIM.2 : PDC KAP meter in terms of air kerma area product

	HVL	**A**	$\dot{K}$	N_{PKA}	**U %**	**u (*k*=1)**
	mm Al	**cm²**	**mGy/min**	**Gy cm²/Gy cm²**	**(*k*=2)**	**Gy cm²/Gy cm²**
RQR3	1.81	27.36	31.0	0.99	3.0	0.015
RQR5	2.58	27.36	73.3	0.98	3.0	0.015
RQR6	2.95	27.36	74.5	0.97	3.0	0.015
RQR8	3.98	27.36	54.6	0.96	3.0	0.015
RQR9	4.98	27.36	71.2	0.94	3.0	0.014

IRCL/GAEC-EIM.3 : MAGNA ionization chamber in terms of air kerma

	HVL	**A**	$\dot{K}$	N_K	**U %**	**u (*k*=1)**
	mm Al	**cm²**	**mGy/min**	**mGy / nC**	**(*k*=2)**	**mGy / nC**
RQR3	1.81	572.27	30.81	8.25	1.5	0.062
RQR5	2.58	572.27	73.04	8.27	1.5	0.062
RQR6	2.95	572.27	74.25	8.26	1.5	0.062
RQR8	3.98	572.27	54.32	8.23	1.5	0.062
RQR9	4.98	572.27	70.93	8.20	1.5	0.062

MKEH: Hungarian Trade Licensing Office, Hungary

MKEH.1 : KERMA KAP meter in terms of air kerma area product

	HVL mm Al	A cm^2	$\dot{K}$ mGy/min	N_{PKA} Gy cm^2/Gy cm^2	U % (k=2)	u (k=1) Gy cm^2/Gy cm^2
RQR3	1.775	26	19	1.203	1.5	0.009
RQR5	2.561	26	19	1.100	1.5	0.008
RQR6	2.972	26	19	1.089	1.5	0.008
RQR8	3.954	26	19	1.111	1.5	0.008
RQR9	4.910	26	19	1.178	1.5	0.009

MKEH.2 : PDC KAP meter in terms of air kerma area product

	HVL mm Al	A cm^2	$\dot{K}$ mGy/min	N_{PKA} Gy cm^2/Gy cm^2	U % (k=2)	u (k=1) Gy cm^2/Gy cm^2
RQR3	1.775	27	19	1.0163	1.5	0.008
RQR5	2.561	27	19	0.9921	1.5	0.007
RQR6	2.972	27	19	0.9812	1.5	0.007
RQR8	3.954	27	19	0.9644	1.5	0.007
RQR9	4.910	27	19	0.9492	1.5	0.007

MKEH.3 : MAGNA ionization chamber in terms of air kerma

	HVL mm Al	A cm^2	$\dot{K}$ mGy/min	N_K mGy / nC	U % (k=2)	u (k=1) mGy / nC
RQR3	1.775	314	19	8.207	0.8	0.033
RQR5	2.561	314	19	8.242	0.8	0.033
RQR6	2.972	314	19	8.229	0.8	0.033
RQR8	3.954	314	19	8.210	0.8	0.033
RQR9	4.910	314	19	8.179	0.8	0.033

IAEA : International Atomic Energy Agency

IAEA.1 : KERMA KAP meter in terms of air kerma area product

	HVL	**A**	$\dot{K}$	**N$_{PKA}$**	**U %**	**u (*k*=1)**
	mm Al	**cm^2**	**mGy/min**	**Gy cm^2/Gy cm^2**	**(*k*=2)**	**Gy cm^2/Gy cm^2**
RQR3	1.81	21.92	20.00	1.180	1.4	0.008
RQR5	2.61	21.92	20.20	1.079	1.4	0.008
RQR6	3.10	21.92	20.30	1.071	1.4	0.007
RQR8	4.05	21.92	20.40	1.105	1.4	0.008
RQR9	5.12	21.92	20.60	1.162	1.4	0.008

IAEA.2 : PDC KAP meter in terms of air kerma area product

	HVL	**A**	$\dot{K}$	**N$_{PKA}$**	**U %**	**u (*k*=1)**
	mm Al	**cm^2**	**mGy/min**	**Gy cm^2/Gy cm^2**	**(*k*=2)**	**Gy cm^2/Gy cm^2**
RQR3	1.81	21.74	20.0	1.006	1.5	0.008
RQR5	2.61	21.74	20.2	0.987	1.5	0.007
RQR6	3.1	21.74	20.3	0.981	1.5	0.007
RQR8	4.05	21.74	20.4	0.966	1.5	0.007
RQR9	5.12	21.74	20.6	0.951	1.5	0.007

IAEA.3 : MAGNA ionization chamber in terms of air kerma

	HVL	**A**	$\dot{K}$	**N$_K$**	**U %**	**u (*k*=1)**
	mm Al	**cm^2**	**mGy/min**	**mGy / nC**	**(*k*=2)**	**mGy / nC**
RQR3	1.81	283.39	20.0	8.205	1.1	0.045
RQR5	2.61	283.39	20.2	8.243	1.1	0.045
RQR6	3.10	283.39	20.3	8.244	1.1	0.045
RQR8	4.05	283.39	20.4	8.219	1.1	0.045
RQR9	5.12	283.39	20.6	8.195	1.1	0.045

GR : Icelandic Radiation Safety Authority / Geislavarnir ríkisins, Iceland

IS.1 : KERMA KAP meter in terms of air kerma area product

	HVL mm Al	A cm^2	$\dot{K}$ mGy/min	N_{PKA} Gy cm^2/Gy cm^2	U % (*k*=2)	u (*k*=1) Gy cm^2/Gy cm^2
RQR3	1.754	21.24	295	1.221	3.7	0.023
RQR5	2.597	21.24	281	1.123	3.7	0.021
RQR6	3.005	21.24	352	1.092	3.7	0.020
RQR8	3.963	21.24	513	1.110	3.7	0.021
RQR9	4.930	21.24	688	1.159	3.7	0.021

GR.2 : PDC KAP meter in terms of air kerma area product

	HVL mm Al	A cm^2	$\dot{K}$ mGy/min	N_{PKA} Gy cm^2/Gy cm^2	U % (*k*=2)	u (*k*=1) Gy cm^2/Gy cm^2
RQR3	1.754	10.7	261	1.022	3.7	0.019
RQR5	2.597	10.7	254	1.027	3.7	0.019
RQR6	3.005	10.7	315	1.033	3.7	0.019
RQR8	3.963	10.7	470	1.014	3.7	0.019
RQR9	4.930	10.7	641	1.009	3.7	0.019

GR.3 : MAGNA ionization chamber in terms of air kerma

	HVL mm Al	A cm^2	$\dot{K}$ mGy/min	N_K mGy / nC	U % (*k*=2)	u (*k*=1) mGy / nC
RQR3	1.754	78.5	287	8.09	3.7	0.150
RQR5	2.597	78.5	275	8.10	3.7	0.150
RQR6	3.005	78.5	345	8.12	3.7	0.150
RQR8	3.963	78.5	502	8.07	3.7	0.149
RQR9	4.930	78.5	675	7.98	3.7	0.148

IRP-DOS : Istituto di Radioprotezione, ENEA, Italy

IRP-DOS.1 : KERMA KAP meter in terms of air kerma area product

	HVL mm Al	A cm^2	$\dot{K}$ mGy/min	N_{PKA} Gy cm^2/Gy cm^2	U % (*k*=2)	u (*k*=1) Gy cm^2/Gy cm^2
RQR3	1.75	17.62	50	1.13	9	0.051
RQR5	2.57	17.62	70	1.07	9	0.048
RQR6	3.05	17.62	70	1.08	9	0.049
RQR8	4.08	17.62	70	1.11	9	0.050
RQR9	5.13	17.62	90	1.15	9	0.052

IRP-DOS.2 : PDC KAP meter in terms of air kerma area product

	HVL mm Al	A cm^2	$\dot{K}$ mGy/min	N_{PKA} Gy cm^2/Gy cm^2	U % (*k*=2)	u (*k*=1) Gy cm^2/Gy cm^2
RQR3	1.75	17.62	50.00	0.97	9	0.044
RQR5	2.57	17.62	70.00	0.98	9	0.044
RQR6	3.05	17.62	70.00	0.98	9	0.044
RQR8	4.08	17.62	70.00	0.96	9	0.043
RQR9	5.13	17.62	90.00	0.94	9	0.042

IRP-DOS.3 : MAGNA ionization chamber in terms of air kerma

	HVL mm Al	A cm^2	$\dot{K}$ mGy/min	N_K mGy / nC	U % (*k*=2)	u (*k*=1) mGy / nC
RQR3	1.750	700	15.00	7.87	8	0.315
RQR5	2.570	700	15.00	8.15	8	0.326
RQR6	3.050	700	15.00	8.20	8	0.328
RQR8	4.080	700	15.00	8.26	8	0.330
RQR9	5.130	700	15.00	8.27	8	0.331

VSL : Dutch Metrology Institute, The Netherlands

VSL.1 : KERMA KAP meter in terms of air kerma area product

	HVL mm Al	A cm^2	$\dot{K}$ mGy/min	N_{PKA} Gy cm^2/Gy cm^2	U % (*k*=2)	u (*k*=1) Gy cm^2/Gy cm^2
RQR3	1.48	106.50	26.1	1.258	2.3	0.014
RQR5	2.48	106.50	35.1	1.109	2.3	0.013
RQR6	2.92	106.50	43.4	1.103	2.3	0.013
RQR8	3.73	106.50	61.8	1.125	2.3	0.013
RQR9	4.51	106.50	84.3	1.175	2.3	0.014

VSL.2 : PDC KAP meter in terms of air kerma area product

	HVL mm Al	A cm^2	$\dot{K}$ mGy/min	N_{PKA} Gy cm^2/Gy cm^2	U % (*k*=2)	u (*k*=1) Gy cm^2/Gy cm^2
RQR3	1.48	106.50	26.1	1.042	2.2	0.011
RQR5	2.48	106.50	35.1	1.006	2.2	0.011
RQR6	2.92	106.50	43.4	1.002	2.2	0.011
RQR8	3.73	106.50	61.8	0.987	2.2	0.011
RQR9	4.51	106.50	84.3	0.982	2.2	0.011

VSL.3 : MAGNA ionization chamber in terms of air kerma

	HVL mm Al	A cm^2	$\dot{K}$ mGy/min	N_K mGy / nC	U % (*k*=2)	u (*k*=1) mGy / nC
RQR3	1.48	100.24	26.1	8.18	1.40	0.057
RQR5	2.48	100.24	35.1	8.20	1.40	0.057
RQR6	2.92	100.24	43.4	8.21	1.40	0.057
RQR8	3.73	100.24	61.8	8.17	1.40	0.057
RQR9	4.51	100.24	84.3	8.16	1.40	0.057

NRPA : Norwegian Radiation Protection Authority, Norway

NRPA.1 : KERMA KAP meter in terms of air kerma area product

	HVL mm Al	A cm^2	$\dot{K}$ mGy/min	N_{PKA} Gy cm^2/Gy cm^2	U % (*k*=2)	u (*k*=1) Gy cm^2/Gy cm^2
RQR3						
RQR5	2.66	27.7	35	1.076	4.3	0.023
RQR6						
RQR8	4.08	27.7	62	1.107	4.4	0.024
RQR9	4.98	27.7	82	1.152	4.4	0.025

NRPA.2 : PDC KAP meter in terms of air kerma area product

	HVL mm Al	A cm^2	$\dot{K}$ mGy/min	N_{PKA} Gy cm^2/Gy cm^2	U % (*k*=2)	u (*k*=1) Gy cm^2/Gy cm^2
RQR3						
RQR5	2.66	27.7	35	0.976	4.0	0.020
RQR6						
RQR8	4.08	27.7	62	0.958	4.0	0.019
RQR9	4.98	27.7	82	0.941	4.0	0.019

NRPA.3 : MAGNA ionization chamber in terms of air kerma

	HVL mm Al	A cm^2	$\dot{K}$ mGy/min	N_K mGy / nC	U % (*k*=2)	u (*k*=1) mGy / nC
RQR3						
RQR5	2.660	110.88	35	8.1	3.0	0.122
RQR6						
RQR8	4.080	110.88	62	8.1	3.0	0.122
RQR9	4.980	110.88	82	8.1	3.0	0.121

NIOM : Nofer Institute of Occupational Medicine, Poland

NIOM.1 : KERMA KAP meter in terms of air kerma area product

	HVL mm Al	A cm^2	$\dot{K}$ mGy/min	N_{PKA} Gy cm^2/Gy cm^2	U % (*k*=2)	u (*k*=1) Gy cm^2/Gy cm^2
RQR3	1.80	27.56	19.55	1.240	6.2	0.038
RQR5	2.59	27.56	34.05	1.115	6.2	0.035
RQR6	2.99	27.56	41.43	1.106	6.2	0.034
RQR8	3.90	27.56	58.16	1.123	6.1	0.034
RQR9	4.85	27.56	81.58	1.158	6.1	0.035

NIOM.2 : PDC KAP meter in terms of air kerma area product

	HVL mm Al	A cm^2	$\dot{K}$ mGy/min	N_{PKA} Gy cm^2/Gy cm^2	U % (*k*=2)	u (*k*=1) Gy cm^2/Gy cm^2
RQR3	1.80	27.56	19.6	1.18	6.00	0.035
RQR5	2.59	27.56	34.1	1.09	5.90	0.032
RQR6	2.99	27.56	41.4	1.07	5.90	0.031
RQR8	3.90	27.56	58.2	1.03	6.00	0.031
RQR9	4.85	27.56	81.6	1.00	6.00	0.030

NIOM 3 : MAGNA ionization chamber in terms of air kerma

	HVL mm Al	A cm^2	$\dot{K}$ mGy/min	N_K mGy / nC	U % (*k*=2)	u (*k*=1) mGy / nC
RQR3	1.80	81.0	19.60	8.29	5.1	0.211
RQR5	2.59	81.0	34.10	8.31	5.2	0.216
RQR6	2.99	81.0	41.40	8.31	5.1	0.212
RQR8	3.90	81.0	58.20	8.23	5.1	0.210
RQR9	4.85	81.0	81.60	8.17	5.2	0.212

ITN-LMRI : Nuclear and Technology Institute, Metrology Laboratory for Ionising Radiation and Radiocativity, Portugal

ITN-LMRI.1 : KERMA KAP meter in terms of air kerma area product

	HVL mm Al	A cm^2	$\dot{K}$ mGy/min	N_{PKA} Gy cm^2/Gy cm^2	U % (*k*=2)	u (*k*=1) Gy cm^2/Gy cm^2
RQR3	1.77	21,565	8.8	0.740	8.9	0.033
RQR5	2.58	21,565	15.1	0.851	8.9	0.038
RQR6	3.01	21,565	18.5	0.896	8.9	0.040
RQR8	3.97	21,565	25.5	0.882	8.9	0.039
RQR9	5.00	21,565	24.5	0.852	8.9	0.038

ITN-LMRI.2 : PDC KAP meter in terms of air kerma area product

	HVL mm Al	A cm^2	$\dot{K}$ mGy/min	N_{PKA} Gy cm^2/Gy cm^2	U % (*k*=2)	u (*k*=1) Gy cm^2/Gy cm^2
RQR3	1.77	21,565	8.8	1.036	8.9	0.046
RQR5	2.58	21,565	15.1	1.083	8.9	0.048
RQR6	3.01	21,565	18.5	1.076	8.9	0.048
RQR8	3.97	21,565	25.5	1.106	8.9	0.049
RQR9	5.00	21,565	24.5	1.130	8.9	0.050

ITN-LMRI.3 : MAGNA ionization chamber in terms of air kerma

	HVL mm Al	A cm^2	$\dot{K}$ mGy/min	N_K mGy / nC	U % (*k*=2)	u (*k*=1) mGy / nC
RQR3	1.77	79	8.8	8.225	1.1	0.045
RQR5	2.58	79	15.1	8.260	1.1	0.045
RQR6	3.01	79	18.5	8.279	1.1	0.046
RQR8	3.97	79	25.5	8.229	1.1	0.045
RQR9	5.00	79	24.5	8.175	1.1	0.045

IFIN-HH : Horia Hulubei National Institute of R&D for Physics and Nuclear Engineering (IFIN-HH), Romania

IFIN-HH.1 : KERMA KAP meter in terms of air kerma area product

	HVL **mm Al**	**A** **cm^2**	$\dot{K}$ **mGy/min**	**N$_{PKA}$** **Gy cm^2/Gy cm^2**	**U %** **(*k*=2)**	**u (*k*=1)** **Gy cm^2/Gy cm^2**
RQR3	1.80	96.3	136.94	1.0953	3.8	0.021
RQR5	2.58	96.3	242.34	1.0672	2.6	0.014
RQR6	3.03	96.3	310.98	1.0713	2.6	0.014
RQR8	3.90	96.3	440.92	1.1009	2.6	0.014
RQR9	5.01	96.3	577.53	1.1455	2.6	0.015

IFIN-HH.2 : PDC KAP meter in terms of air kerma area product

	HVL **mm Al**	**A** **cm^2**	$\dot{K}$ **mGy/min**	**N$_{PKA}$** **Gy cm^2/Gy cm^2**	**U %** **(*k*=2)**	**u (*k*=1)** **Gy cm^2/Gy cm^2**
RQR3	1.80	218.88	105	0.959	3.7	0.018
RQR5	2.58	218.88	196	0.951	2.6	0.012
RQR6	3.03	218.88	251	0.934	2.6	0.012
RQR8	3.90	218.88	354	0.921	2.6	0.012
RQR9	5.01	218.88	465	0.909	2.6	0.012

IFIN-HH.3 : MAGNA ionization chamber in terms of air kerma

	HVL **mm Al**	**A** **cm^2**	$\dot{K}$ **mGy/min**	**N$_K$** **mGy / nC**	**U %** **(*k*=2)**	**u (*k*=1)** **mGy / nC**
RQR3	1.80	3600	8.9	8.135	3.7	0.152
RQR5	2.58	3600	16.0	8.168	2.6	0.104
RQR6	3.03	3600	20.6	8.164	2.6	0.104
RQR8	3.90	3600	29.4	8.201	2.6	0.105
RQR9	5.01	3600	39.1	8.202	2.6	0.105

VINCA : "VINCA" Institute of Nuclear Science, Radiation and Environmental Protection Laboratory, Serbia

VINCA.1 : KERMA KAP meter in terms of air kerma area product

	HVL mm Al	**A** cm^2	$\dot{K}$ mGy/min	N_{PKA} Gy cm^2/Gy cm^2	**U %** (*k*=2)	**u (*k*=1)** Gy cm^2/Gy cm^2
RQR3	1.99	31.313	6.09	1.92	12	0.115
RQR5	2.63	31.313	13.45	1.17	12	0.070
RQR6	3.05	31.313	17.78	1.12	12	0.067
RQR8	4.00	31.313	26.70	1.13	12	0.068
RQR9	4.99	31.313	37.03	1.17	12	0.070

VINCA.2 : PDC KAP meter in terms of air kerma area product

	HVL mm Al	**A** cm^2	$\dot{K}$ mGy/min	N_{PKA} Gy cm^2/Gy cm^2	**U %** (*k*=2)	**u (*k*=1)** Gy cm^2/Gy cm^2
RQR3	1.99	113.04	1.6	1.12	12.0	0.067
RQR5	2.63	113.04	3.5	1.10	12.0	0.066
RQR6	3.05	113.04	4.7	1.08	12.0	0.065
RQR8	4.00	113.04	7.1	1.06	12.0	0.064
RQR9	4.99	113.04	9.9	1.05	12.0	0.063

VINCA.3 : MAGNA ionization chamber in terms of air kerma

	HVL mm Al	**A** cm^2	$\dot{K}$ mGy/min	N_K mGy / nC	**U %** (*k*=2)	**u (*k*=1)** mGy / nC
RQR3	1.990	101	6.09	8.35	2.9	0.121
RQR5	2.630	101	13.45	8.39	2.9	0.122
RQR6	3.050	101	17.78	8.37	2.9	0.121
RQR8	4.000	101	26.70	8.32	2.9	0.121
RQR9	4.990	101	37.03	8.28	2.9	0.120

SIM : Slovak Institute of Metrology, Slovakia

SIM.1 : KERMA KAP meter in terms of air kerma area product

	HVL mm Al	A cm^2	$\dot{K}$ mGy/min	N_{PKA} Gy cm^2/Gy cm^2	U % (*k*=2)	u (*k*=1) Gy cm^2/Gy cm^2
RQR3	1.78	87.90	194.25	1.1033	5.14	0.028
RQR5	2.50	87.49	328.52	1.0367	5.08	0.026
RQR6	3.00	87.65	398.38	1.0381	5.12	0.027
RQR8	3.97	87.90	447.21	1.0671	5.06	0.027
RQR9	5.00	87.90	379.83	1.1356	5.15	0.029

SIM.2 : PDC KAP meter in terms of air kerma area product

	HVL mm Al	A cm^2	$\dot{K}$ mGy/min	N_{PKA} Gy cm^2/Gy cm^2	U % (*k*=2)	u (*k*=1) Gy cm^2/Gy cm^2
RQR3	1.775	87.90	194.25	0.943	5.14	0.024
RQR5	2.500	87.49	328.52	0.924	5.07	0.023
RQR6	3.000	87.65	398.38	0.915	5.12	0.023
RQR8	3.970	87.90	447.21	0.902	5.06	0.023
RQR9	5.000	87.90	379.83	0.908	5.15	0.023

SIM.3 : MAGNA ionization chamber in terms of air kerma

	HVL mm Al	A cm^2	$\dot{K}$ mGy/min	N_K mGy / nC	U % (*k*=2)	u (*k*=1) mGy / nC
RQR3	1.775	88	193.77	8.245	5.03	0.208
RQR5	2.500	88	327.71	8.328	5.03	0.209
RQR6	3.000	88	397.40	8.329	5.03	0.210
RQR8	3.970	88	446.11	8.276	5.03	0.208
RQR9	5.000	88	379.83	8.305	5.04	0.209

JSI : Jozef Stefan Institute, Slovenia

JSI.1 : KERMA KAP meter in terms of air kerma area product

	HVL mm Al	A cm^2	$\dot{K}$ mGy/min	N_{PKA} Gy cm^2/Gy cm^2	U % (k=2)	u (k=1) Gy cm^2/Gy cm^2
RQR3	1.75	27.7	11.5	1.435	2.4	0.008
RQR5	2.54	27.7	13.3	1.279	2.0	0.008
RQR6	3.05	27.7	13.7	1.250	2.3	0.009
RQR8	3.98	27.7	9.1	1.435	2.2	0.008
RQR9	5.11	27.7	11.5	1.420	3.6	0.013

JSI.2 : PDC KAP meter in terms of air kerma area product

	HVL mm Al	A cm^2	$\dot{K}$ mGy/min	N_{PKA} Gy cm^2/Gy cm^2	U % (k=2)	u (k=1) Gy cm^2/Gy cm^2
RQR3	1.75	27.7	11.4	1.020	2.0	0.010
RQR5	2.54	27.7	13.3	1.001	1.8	0.009
RQR6	3.05	27.7	13.6	0.992	1.9	0.010
RQR8	3.98	27.7	9.1	0.980	1.9	0.010
RQR9	5.11	27.7	11.5	0.962	1.8	0.009

JSI.3 : MAGNA ionization chamber in terms of air kerma

	HVL mm Al	A cm^2	$\dot{K}$ mGy/min	N_K mGy / nC	U % (k=2)	u (k=1) mGy / nC
RQR3	1.75	201	11.4	8.17	1.6	0.065
RQR5	2.54	201	13.3	8.24	1.6	0.066
RQR6	3.05	201	13.6	8.20	1.8	0.074
RQR8	3.98	201	9.1	8.18	1.6	0.066
RQR9	5.11	201	11.5	8.20	1.8	0.073

UPC : Universitat Politècnica de Catalunya, (UPC), Spain

UPC.1 : KERMA KAP meter in terms of air kerma area product

	HVL mm Al	A cm^2	$\dot{K}$ mGy/min	N_{PKA} Gy cm^2/Gy cm^2	U % (*k*=2)	u (*k*=1) Gy cm^2/Gy cm^2
RQR3	1.82	20.3	16.1	1.269	3.7	0.023
RQR5	2.43	20.3	33.8	1.097	3.7	0.020
RQR6	3.07	20.3	38.0	1.079	3.7	0.020
RQR8	3.83	20.3	58.7	1.106	3.7	0.020
RQR9	4.93	20.3	74.6	1.152	3.7	0.021

UPC.2 : PDC KAP meter in terms of air kerma area product

	HVL mm Al	A cm^2	$\dot{K}$ mGy/min	N_{PKA} Gy cm^2/Gy cm^2	U % (*k*=2)	u (*k*=1) Gy cm^2/Gy cm^2
RQR3	1.82	20.3	16.1	0.999	4.0	0.020
RQR5	2.43	20.3	33.8	0.979	4.0	0.020
RQR6	3.07	20.3	38.0	0.968	4.0	0.019
RQR8	3.83	20.3	58.7	0.953	4.0	0.019
RQR9	4.93	20.3	74.6	0.941	4.0	0.019

UPC.3 : MAGNA ionization chamber in terms of air kerma

	HVL mm Al	A cm^2	$\dot{K}$ mGy/min	N_K mGy / nC	U % (*k*=2)	u (*k*=1) mGy / nC
RQR3	1.820	201.1	16.1	8.250	1.9	0.078
RQR5	2.430	201.1	33.8	8.207	1.9	0.078
RQR6	3.070	201.1	38.0	8.261	1.9	0.078
RQR8	3.830	201.1	58.7	8.187	1.9	0.078
RQR9	4.930	201.1	74.6	8.180	1.9	0.078

SSM : Swedish Radiation Safety Authority, Sweden

SSM.1 : KERMA KAP meter in terms of air kerma area product

	HVL mm Al	A cm^2	$\dot{K}$ mGy/min	N_{PKA} Gy cm^2/Gy cm^2	U % (*k*=2)	u (*k*=1) Gy cm^2/Gy cm^2
RQR3	1.80	25	33	1.150	2.4	0.014
RQR5	2.54	25	61	1.073	2.4	0.013
RQR6	3.04	25	36	1.066	2.4	0.013
RQR8	4.07	25	99	1.090	2.4	0.013
RQR9	5.06	25	132	1.136	2.4	0.014

SSM.2 : PDC KAP meter in terms of air kerma area product

	HVL mm Al	A cm^2	$\dot{K}$ mGy/min	N_{PKA} Gy cm^2/Gy cm^2	U % (*k*=2)	u (*k*=1) Gy cm^2/Gy cm^2
RQR3	1.80	25	11.6	1.018	2.4	0.012
RQR5	2.54	25	9.2	1.005	2.4	0.012
RQR6	3.04	25	9.1	0.995	2.4	0.012
RQR8	4.07	25	10.0	0.980	2.4	0.012
RQR9	5.06	25	10.0	0.972	2.4	0.012

SSM.3 : MAGNA ionization chamber in terms of air kerma

	HVL mm Al	A cm^2	$\dot{K}$ mGy/min	N_K mGy / nC	U % (*k*=2)	u (*k*=1) mGy / nC
RQR3	1.80	86.5	12.9	8.23	2.4	0.099
RQR5	2.54	86.5	10.2	8.25	2.4	0.099
RQR6	3.04	86.5	10.1	8.24	2.4	0.099
RQR8	4.07	86.5	11.0	8.23	2.4	0.099
RQR9	5.06	86.5	11.0	8.19	2.4	0.098