INTERCOMPARISONS AS AN IMPORTANT ELEMENT OF QUALITY ASSURANCE IN METROLOGY OF IONISING RADIATION

by

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Intercomparisons are important activities performed to ensure that the services provided by calibration laboratories to end-users follow internationally accepted standards. Ionizing radiation dosimetry intercomparisons are usually of two types – postal thermoluminescent dosimeter intercomparisons and ionization chamber calibration intercomparisons. In this paper, both types of intercomparisons are analysed together with the results of seven years of participation in such intercomparisons. Several discrepancies were discovered as a result of intercomparisons analysis and the resolution of the discrepancies was discussed.

Key words: dosimetry, metrology, intercomparison, quality assurance

INTRODUCTION

The international measurement system (IMS) for radiation metrology provides the framework for dosimetry in different areas of application. It ensures consistency in radiation dosimetry by disseminating to users calibrated radiation instruments which are traceable to primary standards. The IMS consists of Bureau International des Poids et Mesures (BIPM), national primary standard dosimetry laboratories (PSDL), secondary standards dosimetry laboratories (SSDL) and various users performing measurements [1]. A PSDL is a national laboratory designated by the government for the purpose of developing, maintaining and improving primary standards in radiation dosimetry. A PSDL participates in the international measurement system by making comparisons through the medium of BIPM and provides calibration services for secondary standard instruments. An SSDL may be either national or regional. A national SSDL is a laboratory which has been designated by the competent national authorities to undertake the duties of a calibrating laboratory within that country. An SSDL is equipped with secondary standards which are calibrated against the primary standards of laboratories participating in the IMS [2-4]. A decade ago, SSDL were focused only on the calibrations in the field of radiotherapy and radiation protection [3, 4], while diagnostic radiology calibrations have drawn attention in the last decade due to increased demands for establishment of quality assurance programme in diagnostic radiology [1].

SSDL in Vinča Institute of Nuclear Sciences (VINS-SSDL) is operating within Radiation and Environment Protection Department of the Vinča Institute. VINS-SSDL became a member of the SSDL network established by the International Atomic Energy Agency (IAEA) and World Health Organization (WHO) in 1978. The network was established in 1976 [2]. The Laboratory is unique in the country and responsible for the realization of the SI units and the maintenance of the national standards. It provides calibrations of dosimeters in radiotherapy, radiation protection and in the field of diagnostic radiology.

The status of the Laboratory in the national metrology system has changed in 2013 when a Memorandum of Understanding between the Directorate of Measures and Precious Metals (DMDM) and Vinča Institute was signed on 4 July 2013. Since September 2014, it has been a Designated Institute (DI) [5] for ionizing radiation as listed at BIPM database available in Appendix A of BIPM Key Comparison Database (KCDB). VINS-SSDL is externally accredited by Accreditation Body of Serbia according to ISO/IEC 17025:2006 [6]. Therefore, VINS-SSDL calibration laboratory ensures that its calibration services achieve a level of quality in execution and delivery that is commensurate with the requirements of its quality management system. With this management system, the VINS-SSDL is committing itself to a continuous process of improvement. With accurate dosimetry as a

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key concern in the quality policy of the VINS -SSDL, the major objective of the management system is to operate the Laboratory at the highest possible quality standard. All measurements and calibrations within the Laboratory are carried out in accordance with the methods documented in the management system.

Intercomparisons are gaining importance both in national and international scopes, due to the requirements put forward by accreditation bodies and international metrology organizations. Participation in intercomparisons has many benefits for laboratories: evaluation of laboratories' performance, identification of problems, comparing methods, providing additional confidence to customers, validating measurement uncertainty, to mention a few. There are several standards available that provide details about the organization and types of intercomparisons and statistical methods for the evaluation of results [7, 8].

Intercomparisons in metrology of ionizing radiation are organized to demonstrate consistent dosimetry in all fields of application. They enable assessment of the quality of dosimetry service and identification of discrepancies as well as initiation of steps to resolve the discrepancies. Several types of intercomparisons are being organized in this field – intercomparisons based on thermo luminescent dosimeters (TLD), intercomparisons based on calibration of transfer instruments (typically ionization chambers), but also direct comparisons [9]. For a particular calibration laboratory, it is of great importance to participate in all available intercomparisons. There is evidence that discrepancies identified during TLD intercomparisons do not always correlate with discrepancies identified by means of ionization chambers [10, 11]. Another important point is that radiotherapy ionization chambers are still being calibrated in terms of both dose to water and air kerma free-in-air. It is important that calibration laboratories participate in intercomparisons for both quantities, because the methodologies are different [12].

MATERIALS AND METHODS

Calibration and measurement capabilities of SSDL-VINS

Radiation beam qualities used in the SSDL-VINS are generated using 6 ^{60}Co sources, 3 ^{137}Cs sources and X-ray generator Philips MG-320, according to ISO standard 4037-1 and IEC standard 61267:2006 [13, 14]. These sources enable dose rates ranging from background level to 20 Gy/h for S-Co radiation quality and from 12 Gy/h to 6 mGy/h for S-Cs. The X-ray generator is capable of producing the X-ray qualities used in all three fields of application (radiation protection, diagnostic radiology and radiation therapy) between 40 kV and 320 kV, as presented in tab. 1.

In addition to dosimetry quantities listed in tab. 1, calibrations are also performed in terms of operational quantities – personal dose equivalent and ambient dose equivalent, where the reference dose values are obtained by multiplying reference air kerma value by conversion coefficients available from standard ISO 4037-3 [16] and IAEA SRS 16 [3]. Therefore, the appropriate comparisons performed in terms of air kerma are used to validate the methods of calibration in terms of operational quantities.

Methodology of the organized intercomparisons

Intercomparisons discussed in this paper fall in two categories – postal TLD intercomparisons and ionization chamber calibration intercomparisons. A postal TLD intercomparison is performed by distributing TLD to all participating laboratories. TLD are irradiated with a pre-set dose and returned to the comparison coordinator together with background TLD for reading. The readings are compared with the reference value. This type of intercomparisons has been used to evaluate the performance of SSDL for over 30 years

Table 1. Overview of relevant calibration and measurement capabilities of VINS-SSDL

Field of application	Secondary standard	Calibrated in terms of	Radiation qualities [13, 14]	Standard	Expanded uncertainty, $k = 2$
Radiation therapy	PTW 30012 s/n* 172, 0.6 cm^3	K_a**	S-Co	IAEA TRS 277 [15]	1.1 %
Radiation therapy	PTW 30012 s/n 172, 0.6 cm^3	K_a	T1 - T4 (100 kV-250 kV)	IAEA TRS 277 [15]	2.1 %
Radiation therapy	PTW 30012 s/n 172, 0.6 cm^3	D_w***	S-Co	IAEA TRS 398 [4]	1.2 %
Radiation protection	PTW 32002 s/n 311, 1 dm^3	K_a	S-Co, S-Cs	IAEA SRS 16 [3]	1.8 %
Radiation protection	PTW 32002 s/n 310, 1 dm^3	K_a	N-40, N-60, N-100, N-200 (40 kV-200 kV)	IAEA SRS 16 [3]	1.8 %
Radiation protection	PTW 32003 s/n 126, 10 dm^3	K_a	S-Co, S-Cs	IAEA SRS 16 [3]	1.8 %
Diagnostic radiology	Exradin Magna A650, s/n D082611, 3 cm^3	K_a	RQR2-RQR10 (40 kV-150 kV)	IAEA TRS 457 [1]	2.2 %

* s/n – serial number, ** K_a – air kerma free in air; *** D_w – absorbed dose to water

[17], but also to evaluate the dosimetry services of radiotherapy centers [18, 19].

In case of chamber calibration intercomparisons, transfer ionization chambers are sent to each participating laboratory for calibration. Usually, ionization chambers are returned to the intercomparison co-ordinator several times during the comparison cycle for interim re-calibrations and check. Calibration coefficients obtained by comparison participants are compared with the reference value. This type of intercomparisons is also used to compare primary standards [20].

SSDL-VINS participated in intercomparisons in the fields of radiation protection, radiation therapy and diagnostic radiology. Reference values were determined by using secondary standards – ionization chambers, calibrated in terms of air kerma – free in air and in terms of absorbed dose to water. Secondary standards are calibrated in IAEA dosimetry laboratory, which provided traceability to the primary standard.

Intercomparisons organized by IAEA/WHO

IAEA/WHO is the main provider of intercomparisons for VINS-SSDL. In total, VINS-SSDL participated in 10 intercomparisons in the last 7 years. Reference values were determined either by IAEA dosimetry laboratory or by BIPM, and the participants included primary and secondary standard laboratories in IMS. These intercomparisons were in the fields of radiation protection and radiation therapy, and will be grouped by beam quality and application for an easier survey.

In the year 2014, VINS-SSDL participated in two chamber calibration intercomparisons – for calibrations in terms of air kerma free in air and absorbed dose to water. Radiation therapy chambers of farmer type were circulated to the participants, and the calibrations were performed in S-Co quality. Calibrations in VINS-SSDL were performed according to IAEA TRS 277 [15] (air kerma free-in-air) and IAEA TRS 398 [4] (absorbed dose to water). The experimental setup was as in [12]. Secondary standard PTW 30012 s/n 172 was used.

VINS-SSDL participated in 6 postal TLD audits for radiotherapy level dosimetry between 2009 and 2014. Three of these intercomparisons were performed in S-Co quality and three in 6 MV quality. All intercomparisons were in terms of absorbed dose to water. Reference values of absorbed dose to water were determined by secondary standard PTW 30012 s/n 172, according to IAEA TRS 398 [4].

Two TLD audits were organized for radiation protection level calibrations. Both audits were performed for S-Cs radiation quality. Reference values of air kerma free-in-air were determined by secondary standard PTW 32002 s/n 311 according to IAEA SRS 16 [3].

Intercomparisons organized by EURAMET

Intercomparisons in the field of diagnostic radiology were organized between March 2011 and June 2012 within project EURAMET 1177. A total of 22 laboratories participated. Calibrations in VINS-SSDL were performed during October 2011. X-ray beams were produced by X-ray unit Philips MG 320.

Three transfer instruments were circulated between laboratories for intercomparison – two commercial KAP-meters (kerma area product meters) [1], and one ionization chamber – 3 cm^3 Magna A650. It is important to note that KAP-meter calibrations are not within the scope of accreditation of VINS-SSDL, but the reference values of dose rate are measured by ionization chamber Magna A650 traceable to a primary standard. Calibrations were performed in 5 radiation qualities, RQR3, RQR5, RQR6, RQR8 and RQR9. VINS-SSDL performed calibrations in all 5 radiation qualities and all calibrations were performed according to IAEA TRS 457 [1]. However, measured HVL (half value layer) for RQR3 deviates by 10 % from IEC 61267 [14] HVL values and it is not possible with current equipment to achieve better agreement because of high inherent filtration. RQR5 and RQR6 also deviate from the standard but are within acceptable limits.

Participants' calibration factors were compared to the weighted means of the calibration factors obtained by participating primary laboratories – comparison reference value (CRV) and the comparison result was denoted with *R*. *R* value of 1 represents complete agreement between a calibration factor and CRV.

Bilateral intercomparison

VINS-SSDL and SCK-CEN (Studiecentrum voor Kernenergie – Centre d'Étude de l'Énergie Nucléaire) organized a series of intercomparisons in the year 2014. Among these, two intercomparisons were performed with farmer type chamber (used in radiation therapy) and two with1– liter radiation protection chamber – spring campaign and autumn campaign. Farmer chambers were calibrated only in S-Co radiation quality, while the 1-liter chambers were calibrated in S-Co, S-Cs, N60, and N200 qualities.

Results were considered acceptable if the absolute value of z-score was lower than 2 as shown in eq. (1), where Z is Z score, X_1 and X_2 are calibration coefficients of comparison participants and u_1 and u_2 are combined and expanded measurement uncertainties (k = 2). The used equation was modified from reference [8], to take into account the fact that the uncertainties were expanded.

$$Z \quad \left|\frac{X_1 \quad X_2}{\frac{1}{2}\sqrt{u_1^2 \quad u_2^2}}\right| \quad 2 \qquad (1)$$

RESULTS AND DISCUSSION

Intercomparisons organized by IAEA/WHO

Results of the intercomparisons organized by IAEA are given either as the ratio of measured and reference value or as the deviation of measured value from the reference value. Acceptance criteria are given in following tables in last column and results should be checked against the criteria.

VINS-SSDL results in the intercomparisons performed using ionization chambers are presented in tab. 2. Measurement uncertainties are reported as expanded measurement uncertainties ($k = 2$).

Results of the TLD postal audits for radiotherapy level are presented in tab. 3. Irradiations were performed in S-Co and 6 MV radiation qualities. Results were reported by VINS-SSDL with a measurement uncertainty of 1.2 % ($k = 2$).

Results of the TLD postal audits for radiation protection level are presented in tab. 4. Irradiations were performed in S-Cs radiation quality. Results were reported by VINS-SSDL with a measurement uncertainty 1.8 % ($k = 2$).

Results show that in each of the 10 intercomparisons organized by IAEA/WHO, VINS-SSDL results were well within the acceptance criteria. This confirms that the equipment and procedures employed in the laboratory, as well as the staff training and capabilities are adequate for calibrations in fields of radiation protection and radiotherapy.

Intercomparisons organized by EURAMET

VINS-SSDL results are shown in tab. 5.

Transfer instrument testing showed that KAP-meters calibration factors depend on irradiated area, dose rate and radiation quality. Magna A650 calibration factor depends only on radiation quality, and the dependence is less pronounced than in the case of KAP-meters. Due to this fact, comparison results were corrected for the differences of the influence quantities between the participating laboratories and CRV.

Table 2. Results of chamber calibration intercomparisons in S-Co radiation quality

Chamber	Quantity	VINS-SSDL result	Reference value	VINS-SSDL/reference value*	Acceptance criteria
Farmer type	K_a	43.95 0.48 mGy/nC	44.10 ± 0.35 mGy/nC	0.995	0.985-1.015
Farmer type	D_w	48.11 0.58 mGy/nC	48.15 ± 0.48 mGy/nC	0.998	0.985-1.015

*Participant and intercomparison provider stated traceability to different primary standards, and the correction is applied: 1/1.0018 for K_a and 1/1.0016 for D_w

Table 3. Results of postal TLD audits for radiotherapy level dosimetry

Year of irradiation	Radiation quality	VINS-SSDL stated dose	IAEA measured dose	Relative deviation	Acceptance criteria
2009	S-Co	2.00 Gy	1.97 Gy	1.6 %	3.5 %
2010	6 MV	2.00 Gy	2.00 Gy	0.1 %	3.5 %
2011	S-Co	2.00 Gy	1.99 Gy	0.7 %	3.5 %
2012	6 MV	2.00 Gy	2.02 Gy	–1.1 %	3.5 %
2013	S-Co	2.00 Gy	2.01 Gy	–0.3 %	3.5 %
2014	6 MV	2.00 Gy	2.02 Gy	–1.3 %	3.5 %

Table 4. Results of postal TLD audits for radiation protection level dosimetry

Year of irradiation	Radiation quality	VINS-SSDL stated dose	IAEA measured dose	VINS-SSDL/reference value	Acceptance criteria
2008	S-Cs	5.00 mGy	5.24 mGy	0.96	0.93-1.07
2013	S-Cs	5.00 mGy	5.10 mGy	0.98	0.93-1.07

Table 5. Results of EURAMET diagnostic radiology intercomparison

Radiation quality	KAP-meter 1		KAP-meter 2		Magna A650	
	R	$R_{corrected}$	R	$R_{corrected}$	R	$R_{corrected}$
RQR3	1.612	1.061	1.122	0.984	1.020	1.020
RQR5	1.072	1.045	1.125	1.070	1.021	1.021
RQR6	1.033	1.029	1.114	1.077	1.019	1.019
RQR8	1.023	1.023	1.111	1.083	1.014	1.014
RQR9	1.013	1.013	1.114	1.095	1.013	1.013

Therefore, VINS-SSDL results are divided into two sets – reported results (R) and corrected results ($R_{\text{corrected}}$).

KAP-meter calibration factors were reported by VINS-SSDL with combined and expanded measurement uncertainties (k = 2) between 12 % and 14 %, with the exception of KAP-meter 1 calibration in RQR3 quality (20 %). Several conclusions can be drawn when corrected and uncorrected results from Table 5 are compared. In case of KAP-meters, the difference is minimal or non-existent for highly filtered qualities. However, there is a big difference in the case of RQR3, and to some extent in case of RQR5. The large difference in the case of RQR3 is due to the fact that this quality could not be achieved according to standard due to the technical problems. It is evident that the corrected results are in much better agreement with CRV than uncorrected, but also that 9 out of 10 results are larger than 1. This means that the reference value of kerma area product is overestimated, which suggests that there might be a systematic effect that is unaccounted for.

The analysis of the results, together with the review of the procedure and equipment in VINS-SSDL has shown several shortcomings. Already mentioned HVL differences from IEC standard greatly influence the results for lightly filtered X-ray qualities which especially shows in case of RQR3 for KAP-meter 1, due to the instrument's inferior energy dependence. This is the main reason for the difference between reported and corrected values. Unfortunately, the only way for improvement is to replace the X-ray unit, which is a long and costly process. Another problem was recognized in the measurement set-up. A home-made collimator was not of a sufficient quality and its dimensions were not known with required accuracy. It is the most probable cause of the mentioned systematic effect. Collimator-to-focus distance and collimator angle with respect to beam axis influence the beam size, but these quantities were not easy to measure with the current equipment and the measurement uncertainty was hard to estimate. VINS-SSDL has taken measures to improve on all the mentioned points. High inherent filtration of X-ray unit remains the main problem, which should be solved by acquiring a new unit.

Magna A650 intercomparison results show that the deviations between VINS-SSDL calibration coefficients and CRV are between 1.3 % and 2.1 %, while the reported expanded measurement uncertainties (k = 2) were between 3.2 % and 3.4 %. Corrections are applied only for radiation quality. In all cases the correction factor for VINS-SSDL is equal to 1 – even for lightly filtered qualities. Although the results were acceptable, VINS-SSDL reference chamber was recalibrated in IAEA dosimetry laboratory after the intercomparison. Calibration set-up, working procedures and quality assurance/quality control (QA/QC) procedures were improved.

Intercomparison with SCK-CEN

Results of comparisons are shown in tabs. 6 and 7. Similarly to the already presented intercomparisons organized by IAEA/WHO, these comparisons were in the fields of radiation therapy and radiation protection. The difference was only in radiation qualities used. VINS-SSDL and SCK-CEN intercomparison covered N-60, N-200 and S-Co radiation qualities for radiation protection, which were not covered by IAEA/WHO comparisons, as well as S-Cs radiation quality.

All results show a satisfactory agreement between calibration factors provided by participating laboratories, therefore no special action is required. The results are relevant because both laboratories are externally accredited and both laboratories are designated institutes in CIPM-MRA.

Table 6. Farmer type 0.6 cc chamber intercomparisons in S-Co radiation quality

Campaign	Quantity	Z score	Acceptance criteria
Spring	K_a	–0.873	$\|Z\|$ 2
Spring	D_w	–0.622	$\|Z\|$ 2
Autumn	D_w	–0.800	$\|Z\|$ 2

Table 7. PTW model 32002 1l chamber intercomparisons in terms of air kerma free-in-air

Campaign	Radiation quality	Z score	Acceptance criteria
Spring	N60	0.120	$\|Z\|$ 2
Spring	N200	0.352	$\|Z\|$ 2
Spring	S-Cs	–0.122	$\|Z\|$ 2
Spring	S-Co	–0.332	$\|Z\|$ 2
Autumn	N60	–0.381	$\|Z\|$ 2
Autumn	N200	0.580	$\|Z\|$ 2
Autumn	S-Cs	0.000	$\|Z\|$ 2
Autumn	S-Co	–0.532	$\|Z\|$ 2

CONCLUSIONS

Intercomparisons in fields of radiation therapy and radiation protection showed that VINS-SSDL has continuity of good results that can satisfy the strict acceptance criteria. This confirms that the equipment, radiation sources, QA/QC procedures as well as staff training are adequate for maintaining good calibration services.

Intercomparisons in the field of diagnostic radiology exposed several shortcomings in VINS-SSDL. Although the results for calibrations in terms of air kerma free-in-air were acceptable, lightly filtered radiation qualities were not established according to standard, due to evident technical problems. Additionally, the analysis of intercomparison of KAP-meters showed that the results could be most easily improved by improving positioning system and by acquiring new collimators. The proposed improvements were implemented shortly after the first intercomparison results were available.

Several future intercomparisons are already scheduled for the following years and VINS-SSDL will continue to participate in all available comparisons. It would be beneficial for many laboratories if the number of chamber calibration intercomparisons, especially key intercomparisons, increased. This is especially important for the field of diagnostic radiology, but also for some radiation qualities in other dosimetry fields.

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AUTHOR CONTRIBUTIONS

The manuscript was written by M. Z. Živanović and critically reviewed by O. F. Ciraj-Bjelac. Figures were prepared by M. Z. Živanović and K. S. Karadžić. All authors analyzed and discussed the results and reviewed the manuscript. Intercomparisons were performed by Dj. R. Lazarević, O. F. Ciraj-Bjelac, M. Z. Živanović, S. J. Stanković, and S. M. Ćeklić. The theoetical analysis was carried out by Dj. R. Lazarević, O. F. Ciraj-Bjelac, and M. Z. Živanović.

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ИНТЕРКОМПАРАЦИЈЕ КАО ВАЖАН ЕЛЕМЕНТ ОСИГУРАЊА КВАЛИТЕТА У МЕТРОЛОГИЈИ ЈОНИЗУЈУЋЕГ ЗРАЧЕЊА

Интеркомпарације представљају важне активности које се спроводе да би се осигурало да су услуге које лабораторије за еталонирање пружају крајњем кориснику у складу са међународно прихваћеним стандардима. Интеркомпарације у дозиметрији јонизујућег зрачења углавном спадају у два типа – поштанске интеркомпарације са термолуминисцентним дозиметрима и интеркомпарације са јонизационим коморама. У овом раду приказана су оба типа интеркомпарација, као и резултати седам година учешћа у таквим интеркомпарацијама. Такође, у току анализе интеркомпарација, откривено је неколико проблема чије је решавање размотрено.

Кључне речи: дозиметрија, метрологија, интеркомпарација, осигурање квалитета