COMPARISON OF CALIBRATION FACTORS FOR FIELD-CLASS DOSIMETERS

by

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Scientific paper
https://doi.org/10.2298/NTRP2202103Z

This paper presents a comparison performed between two calibration laboratories in several radiation qualities, using dosimeters of varying quality as transfer instruments. The goal of this work was to investigate the viability of using field-class dosimeters for official comparisons and to determine if the calibration factors for field-class dosimeters are comparable between calibration laboratories within the stated measurement uncertainties.

The results of the comparison were acceptable for high-quality electronic personal dosimeters in all radiation qualities, and such dosimeters could be used as transfer instruments. On the other hand, comparison results for low-quality dosimeters were often not acceptable, either due to pronounced energy dependence, low stability, or both. Such instruments are unreliable even under well-defined laboratory conditions, and their use in routine measurements may cause doubt in official data or influence public opinion. This problem is often hidden because many dosimeters are calibrated or verified only in ^{137}Cs beams, where the deviations are the smallest. The largest differences are found for low-energy X-ray radiation qualities, where many dosimeters have significant overresponse.

Key words: dosimetry, comparison, energy dependence, stability, calibration, ambient dose equivalent, personal dose equivalent

INTRODUCTION

Operational dosimetry is of great importance for managing external exposures to ionizing radiation. Three operational quantities that were defined in International Commission on Radiation Units and Measurements (ICRU) report 51 [1] are recommended by International Commission on Radiological Protection (ICRP) [2] and are used in most countries: personal dose equivalent, ambient dose equivalent, and directional dose equivalent. The first two are commonly used for photon radiation, which is the focus of this paper, while the latter is used for weakly penetrating radiation.

Radiation protection dosimeters can be classified as active (provide direct readout) or passive (do not provide direct readout and can operate without a power source), and are based on many different technologies, producing dosimetry data of different quality [3]. Dosimeter characteristics, such as the energy dependence of the response, greatly influence the uncertainty of operational measurements. Even though several International Electrotechnical Commission (IEC) standards give requirements for different types of dosimeters [4-6], which in practice limit the uncertainty, there are many dosimeters in use that have inferior metrological properties. In some cases, dosimeter response variations can be much greater than the limits of variation defined in the standards [7, 8]. This is partly due to the fact that the type testing is a long and expensive process, and that complete extensive type testing is available only in a very small number of specialized facilities, *e. g.* Physikalisch-Technische Bundesanstalt, Germany [9], as well as that type approval is not mandatory in all countries where radiation protection dosimeters are regularly used (*e. g.* Serbia or Bosnia and Herzegovina) or not mandatory for all end-users (*e. g.* non-governmental networks). Many countries require regular calibrations or verifications of dosimeters, which is of paramount importance for quality assurance in operational dosimetry, but calibrations are often performed for one radiation energy or a limited range of energies.

In this paper, the results of a comparison of calibration factors for field-class dosimeters are pre-

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sented. The comparison was organized in this way to investigate two questions. First, are calibration factors for field-class dosimeters in different laboratories comparable, considering measurement uncertainty and appropriate statistical tests? This question is especially important for low-quality dosimeters and low photon energies. Possible differences in calibration factors can cause doubt in calibration data.

Second, can field-class dosimeters be used as transfer instruments for comparisons between calibration laboratories, and if yes, under which conditions? Such comparisons typically use high-quality ionization chambers as transfer instruments, both for comparisons in terms of air kerma and terms of operational quantities [10-13]. These comparisons are long, expensive, and complicated, due to the use of sensitive, bulky, and costly equipment (ionization chambers and electrometers). The use of field-class dosimeters would make the comparisons between calibration laboratories easier and could increase the availability of comparisons. To the best knowledge of the authors, this is the first time that the results of such an exercise are published.

SELECTION OF FIELD-CLASS DOSIMETERS

The selection of dosimeters for comparison was performed to sample both high-quality and low-quality field-class dosimeters. Dosimeter quality is most apparent by examining the energy dependence of the response. In this paper, it was considered that a dosimeter is of high quality if it meets the requirements of the relevant IEC standard for the examined property and that it is of low quality in case it does not meet the requirements.

Considering electronic personal dosimeters (EPD), several studies have shown that most of them fulfill the requirements of the IEC 61526:2010 standard [5] within a wide range of photon energies [14-18]. This corresponds with the limits of variation of the dosimeter response with a photon energy between +67 % and –29 %, compared to the reference radiation quality – usually ^{137}Cs (radiation quality code S-Cs [19]). These limits of variations apply to the changes in both angle and energy [5], but angular dependence of dosimeter response is not examined here.

The situation with ambient dosimeters is different: while many professional dosimeters show good performance, in compliance with the relevant standards, some of them exhibit poor energy dependence or fail other tests [20]. Some detectors used by end-users as ambient dosimeters are purpose-built for contamination measurements or search for lost sources, and dose indication (if available) is only of secondary importance [21]. Low-cost dosimeters, which in most cases have inferior metrological properties (*e. g*., overresponse at low energies of several hundred percent due to poor energy compensation) and are rarely calibrated or tested, are often used by laymen or in non-governmental networks [7, 22]. Such unreliable and unchecked measurement data are often available online to the general public and can cause unsubstantiated fear, which is especially important in case of radiological or nuclear emergencies when confidence in official data and decisions can be critical. Low-cost dosimeters are sometimes also used by professionals, as evidenced by the calibration requests received by the authors of this study.

Finally, passive dosimeters are used for both ambient and individual monitoring. Extensive tests on different types of dosimeters used by specialized professional technical services have shown a similar situation as with active dosimeters: some dosimeter types have properties corresponding with the standard requirements, while others can have inferior metrological properties. In the most extreme case, an overresponse of more than 800 % was recorded at low energies for thermoluminescent dosimeters used as ambient dosimeters [8, 23-25].

Based on the previous discussion and based on the available field-class dosimeters and their manufacturers' specifications, four field-class dosimeters were selected: one EPD and one ambient dosimeter which meet IEC requirements [4, 5] regarding energy dependence (marked EPD and AD1 in the following text), and two ambient dosimeters that do not meet the IEC requirements. One of the latter is occasionally used by professionals in Serbia, as evidenced by the authors (marked AD2) and one is used in non-governmental networks (marked AD3). Passive dosimeters were not used for this comparison. Basic information about the selected dosimeters is presented in tab. 1.

In addition, an ionization chamber of the quality typically used for comparisons was included in the comparison (marked IC). The rationale for including the ionization chamber was to check whether the discrepancies between calibration factors for field-class dosimeters (if any) are due to the dosimeters themselves or possible errors of the calibration laboratories for one or more radiation qualities.

Table 1. Field-class dosimeters selected for comparison

Dosimeter	Reference radiation quality	Energy dependence of the response (manufacturers' specifications)
EPD	S-Cs	17 keV to 1.5 MeV, response deviation 20 %
AD1	S-Cs	60 keV-1.3 MeV, response deviation between +67 % and –29 %*
AD2	S-Cs	Detects gamma radiation from 30 keV**
AD3	N/A	Detectable energy range: 0.1-3.0 MeV**

* energy dependence is provided graphically in technical specifications, **no statement regarding deviations

METHODS

The comparison was performed in two calibration laboratories, Vinča Institute of Nuclear Sciences (VINS) and the Institute of Metrology of Bosnia and Herzegovina (IMBIH).

All calibrations and tests were performed according to International Organization for Standardization (ISO) standard ISO 4037 [19, 26, 27]. The ionization chamber was calibrated in terms of air kerma, free-in-air. The electronic personal dosimeter was calibrated in terms of personal dose equivalent, using a standard ISO slab phantom. Ambient dosimeters were calibrated in terms of ambient dose equivalent, free-in-air.

Energy dependence of dosimeter response was investigated before the comparison in VINS, in collimated fields of ^{60}Co (S-Co), ^{137}Cs, and X-ray radiation qualities from the N-series. The properties of the used radiation qualities are presented in tab. 2.

Radiation quality S-Co was not used for the comparison, because it was not available in both calibration laboratories. The calibrations were performed first in VINS, then in IMBIH, and finally again in VINS to check dosimeter stability. The results of the last calibration are marked "VINS2".

Field-class dosimeters were calibrated using methods that are routinely used for such equipment in respective laboratories. In the case of ^{137}Cs, both laboratories used a reference radionuclide source unit (known radiation field calibration method) [28], *i.e.*, sources are calibrated using a secondary standard and reference values are calculated taking into account source decay and calibration distance. In the case of X-ray radiation qualities, IMBIH used the substitution method without a monitor chamber, and VINS used a reference monitor chamber (*i.e.*, the monitor chamber is calibrated by using a secondary standard for specified source-detector distance and field size) [28].

The ionization chamber was calibrated using the substitution method [28], which is used in official comparisons and which provides the best measurement uncertainty. The third calibration of IC was performed in VINS using the methods for field-class dosimeters, to check if there is a significant difference between the substitution method and methods used for field-class dosimeters (other than the increased measurement uncertainty). Methods used for field-class dosimeters rely on several approximations and presumptions (dose rate is assumed to follow inverse square law, scattered radiation is neglected, spectral changes with distance are neglected, and good reproducibility of the setup is assumed…). A comparison of the calibration results obtained for IC in the first and second calibration in VINS checks the validity of these assumptions and therefore checks if the calibration methods are implemented correctly.

Table 2. Radiation qualities used for comparison. Data are taken from ISO 4037-1 [19], actual values in calibration laboratories differ within the limits defined by the standard

Radiation quality	X-ray tube voltage [kV]	Mean energy [keV]	1st HVL at 2.5 m [mm]
N-40	40	33,3	2.63 Al
N-60	60	47,9	0.235 Cu
N-80	80	65,2	0.580 Cu
N-100	100	83,3	1.09 Cu
N-120	120	100	1.67 Cu
N-150	150	118	2.30 Cu
N-200	200	165	3.92 Cu
S-Cs	–	662	–
S-Co	–	1250	–

One dose rate was chosen for each field-class dosimeter in the part of the measurement range where good measurement statistics can be achieved, but no significant non-linearity is noticed. The dose rate was kept as constant as possible for all radiation qualities and in all three calibrations. Small deviations from the selected dose rate are not expected to influence the overall conclusions of the comparison exercise. The following dose rates were selected: 6 mSvh^{-1} for EPD, 500 Svh^{-1} for AD1, and 150 Svh^{-1} for AD2 and AD3.

The comparison results were evaluated by calculating Z-score according to eq. 1

$$Z \quad \frac{|N_{\mathrm{H1}} \quad N_{\mathrm{H2}}|}{0.5\sqrt{U_1^2 \quad U_2^2}} \tag{1}$$

where Z represents the Z-score, N_{H1} and N_{H2} are calibration factors (IMBIH and VINS in the graphs in the *Results and discussion* section, respectively), and U_1 and U_2 are the corresponding measurements uncertainties, with coverage factor $k = 2$. The Z-scores below 2 were considered acceptable and above 3 as not acceptable. The values between 2 and 3 were considered *warning* values. Dosimeter stability was evaluated in the same way, based on two calibrations in VINS.

The measurement uncertainty was evaluated according to usual procedures. Examples can be found in the comparison report for VINS [13], which is corresponding to the uncertainty budget for calibrations in terms of air kerma. Calibration methods for field-class dosimeters include additional uncertainty components, most importantly uncertainty of the conversion coefficient from air kerma to operational quantities, the uncertainty of using different calibration distances (in the case of radionuclide sources), the uncertainty of field inhomogeneity, and uncertainty components arising from the use of reference monitor chamber (energy dependence of the response of the monitor chamber, reproducibility of the measurement setup, *etc*.). Correlations in measurement uncertainty between laboratories were not evaluated but are expected to be small. VINS and IMBIH have traceability to the same primary laboratory, but the contribution of the reference chambers' calibration factors' uncertainty to the overall uncertainty is small. Principal uncertainty components are not correlated.

RESULTS

Energy dependence of dosimeter response was investigated before the comparison and is shown in fig. 1. The IC and EPD show excellent performance, with maximum deviations of the response of 8 % and 20 % over the whole energy range, compared to the reference radiation quality. The AD1 does not perform according to specifications within the rated energy range, with a maximum deviation of –48 % (N-80 radiation quality). Therefore, this specific unit of the dosimeter is not according to IEC standard requirements [4]. Finally, dosimeters AD3 and AD4 show maximum deviations of +336 % and +422 %, respectively.

Comparison results for the ionization chamber are presented in fig. 2. Results of the comparison are satisfactory for all radiation qualities, with *Z*-scores below 0.75. Such good agreement is expected for comparisons between calibration laboratories and VINS previously achieved similar results participating in a key comparison [13]. The third measurement was made using the calibration method for field dosimeters. The agreement between the third calibration and the first two is excellent, showing that the method for field-class dosimeters is equivalent to the substitution method, with an expected increase in the measurement uncertainty. It should be noted that IC stability is very good, compared to other dosimeters, and therefore it was not considered.

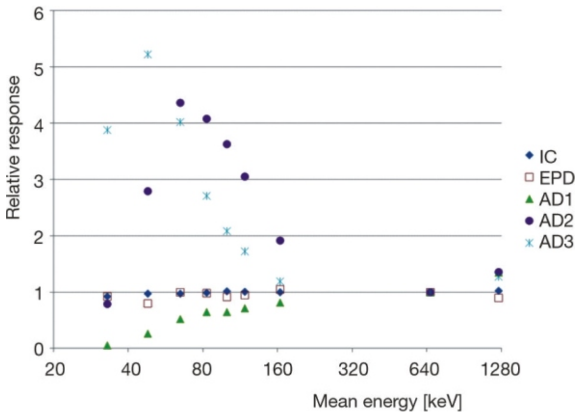

Figure 1. Relative energy response of dosimeters used in the comparison (normalized to S-Cs)

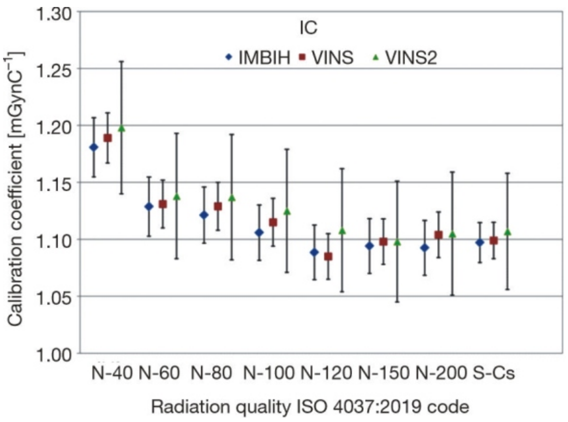

Figure 2. Comparison results for ionization chamber calibration in terms of air kerma free in the air

Comparison results for field-class dosimeters are shown in fig. 3.

In the case of EPD, all *Z*-scores were acceptable and comparable to *Z*-scores for IC, with the maximum value below one. Results of the stability test are also good, and no significant differences were found.

Dosimeter AD1 has a relatively flat energy dependence of the response in the rated energy range, compared to the other two ambient dosimeters, but the *Z*-score values are larger than two for almost all radiation qualities. The only acceptable result was for S-Cs radiation quality, with a *Z*-score value of 0.03, three results were in the warning category of the statistical test, and two were not acceptable (N-80 and N-150). The third measurement showed that the dosimeter has good stability, so the differences between calibration factors are most likely due to the differences in X-ray spectra. Radiation qualities below 60 keV (below N-80) are not in the measurement range of this dosimeter and were not included in the comparison.

The largest *Z*-scores were obtained for AD2, which is a dosimeter based on a non-compensated Geiger-Müller tube. The only acceptable result was recorded for S-Cs radiation quality, with *Z*-score for other radiation qualities being as high as 5.6. The third calibration was in several cases significantly different than the first calibration (even for S-Cs), suggesting bad stability. Thus, the reason for the poor results, in this case, is a very pronounced energy dependence of the response, as well as bad long-term stability.

Finally, results for AD3 are surprisingly good, even though the dosimeter has a very pronounced energy dependence of the response, similar to AD2. The only non-acceptable Z-test result is for N-40 radiation quality. The third measurement shows good stability during the comparison.

DISCUSSION

Comparison results suggest that at least some high-quality active field-class dosimeters can be used as transfer instruments for comparisons between calibration laboratories. It is important to stress that comparisons in terms of operational quantities do not automatically validate the calibration capabilities for air

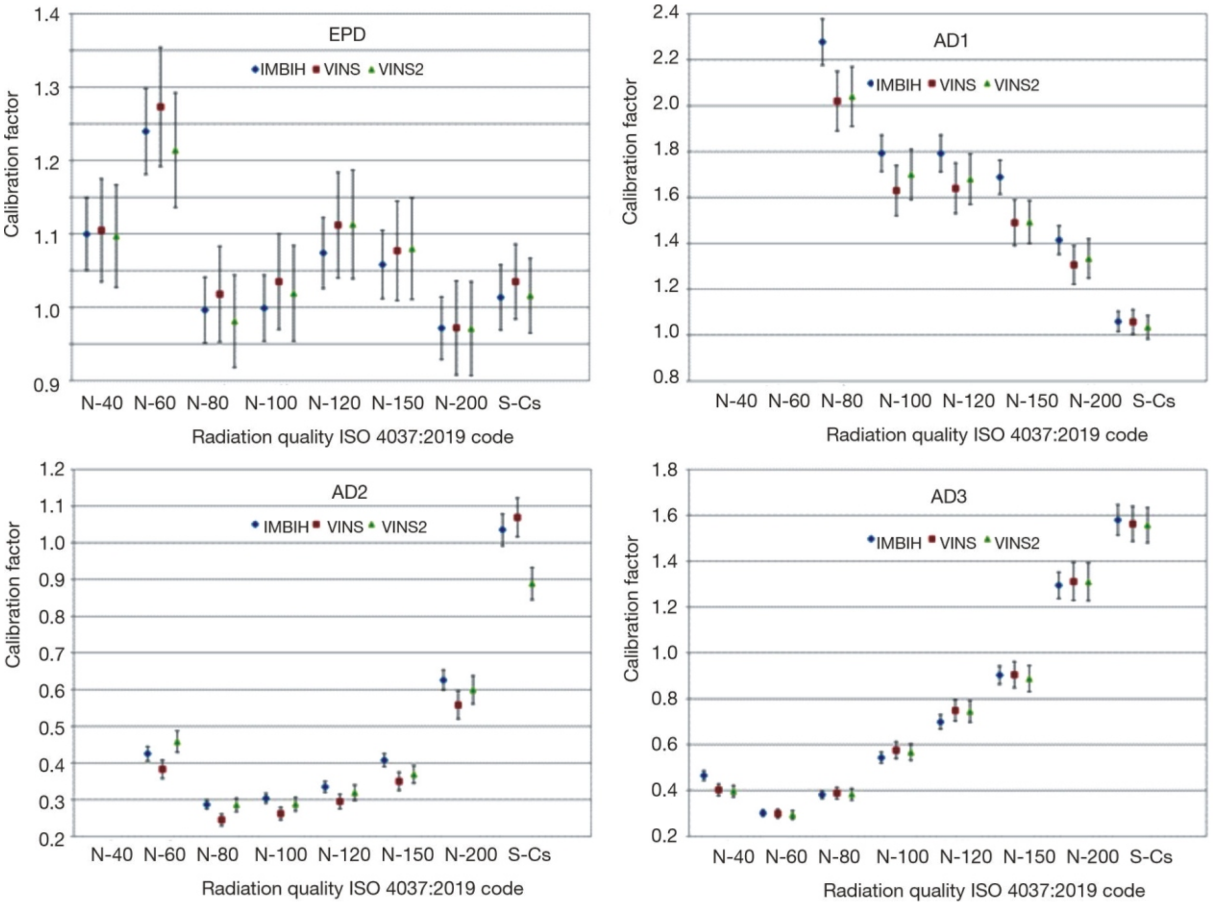

Figure 3. Comparison results for field-class dosimeters calibration in terms of personal dose equivalent (EPD) and ambient dose equivalent (AD1, AD2, and AD3)

kerma, because of the large differences in measurement uncertainty. High-quality passive dosimeters are already used for calibration laboratory audits by the International Atomic Energy Agency (in terms of air kerma) [29].

The most significant dosimeter property that should be evaluated before using field-class dosimeters as transfer instruments is long-term stability, which can cause significant differences between calibration factors. This effect can be addressed by performing several calibrations or tests before the comparison, and estimating the uncertainty due to long-term stability, which can be considered when calculating Z-scores (*e. g.*, by increasing measurement uncertainty). In case of significant instability, dosimeters cannot be used for comparisons. This problem can arise even for dosimeters that are type-approved because there is no requirement in the IEC standards to test long-term stability, so it should always be checked [4, 5].

Pronounced energy dependence (or more precisely, rate of change of dosimeter response in the vicinity of the chosen radiation quality) can also affect comparison results. Low-cost, low-quality or special purpose dosimeters are especially prone to pronounced energy dependence. As was seen in the case of AD1, even in cases when the dosimeter fulfills IEC requirements according to specifications, specific units of dosimeter type can be outside of specifications (*e. g.*, due to damage, aging, or other reasons). The reason for discrepancies in calibration factors is the fact that radiation qualities, although nominally the same (regarding the spectra) differ between laboratories. X-ray radiation qualities are strongly dependent on and defined by X-ray tube voltage, filtration thickness, and material and other parameters, but the differences are relatively small considering the ISO 4037 standard requirements [19]. Differences in radionuclide radiation qualities are even smaller. These small differences are not significant when using high-quality instruments, but in the case of pronounced energy dependence, even small differences in spectra can cause large changes in calibration factors. For example, for AD2, the response increases around 250 % between subsequent radiation qualities, N-40, and N-60, see fig. 1. The differences in calibration factors do not arise in all cases, because there are several random effects in play. For example, the energy dependence of the response of a specific dosimeter can be relatively flat in the vicinity of one radiation quality, but still be very steep in the vicinity of another radiation quality, or between radiation qualities. Also, the magnitude of spectral differences between laboratories is randomly distributed, so it is different for different radiation qualities and different pairs of laboratories. Finally, spectral differences are also a function of time. For example, small variations in X-ray tube voltage on different time scales (even during single exposure) cause spectral changes, as well as tube aging, movement or replacement of filters, use of different radiation distances, *etc.*

From the point of view of the end users, good comparability of calibration factors can be expected for high-quality instruments, but the comparability is not guaranteed for low-quality dosimeters. Lack of comparability can cause doubt in the results provided by the calibration laboratories or cause other problems – e. g., a testing laboratory can fail in comparison, even when measurements are done in well-characterized radiation fields. This further means that low-quality instruments have a high probability of producing erroneous results, even when calibrated in radiation qualities of similar energy to the intended use, which could influence public confidence in official data and decisions in case of radiological or nuclear events. The impact of poor energy dependence is even bigger when performing measurements in unknown radiation fields.

Comparability is worse for low-energy X-rays than for higher photon energies. In the case of S-Cs, the results are acceptable for all four dosimeters. There are several reasons for that: first, the spectra of ^{137}Cs sources do not depend strongly on laboratory setup, second, the energy dependence of conversion coefficient from air kerma to the operational dosimetry quantity is very small in this region [26], and third, the energy dependence of dosimeter response is usually small in the region around 662 keV, as can be seen from fig. 1 and the recent research [3, 7, 14, 20, 21]. The common practice of calibrating or verifying field-class dosimeters in only one radiation quality (S-Cs) can therefore conceal the problem that is discussed in this paper. If type test data are absent, or dosimeter specifications are not dependable, relying only on ^{137}Cs radiation field for calibration or verification can cause exceptionally high measurement uncertainties (or measurement errors) in real unknown poly-energetic fields.

The effects of energy dependence (based on type tests or calibration results) and long-term stability (based on stability checks performed by the user) should be included in the uncertainty budgets for field measurements.

Finally, a question arises what action should be taken by calibration laboratories when asked to calibrate low-quality instruments. Calibrations using regular procedures may produce dubious results, even for stable instruments, as demonstrated by this research. One solution can be to increase the overall measurement uncertainty to reflect the changes in instrument sensitivity within the permissible variations of energy spectra for the reference radiation quality – because there is an inherent uncertainty in the definition of the radiation qualities. Another solution can be to refuse to calibrate low-quality instruments or instruments that are non-compliant with relevant IEC standards.

The research presented in this paper has several limitations. The number of dosimeters that were used is relatively small, and only one field-class dosimeter was IEC-compliant. Only two laboratories participated in the comparison. Stability checks of field-class dosimeters were based on two measurements. Further research should include more high-quality dosimeters, with more rigorous testing and extended long-term stability checks. Such research will help to produce well-defined requirements for field-class dosimeters to be used as transfer instruments in comparisons. At this moment it is not clear if such requirements would coincide with relevant IEC standards, or if they would be stricter, but at least the requirement for long-term stability should be included.

This comparison was performed only with active dosimeters but considering the pronounced energy dependence of the response of some types of passive dosimeters [8, 23], the conclusions can also be applied to them.

CONCLUSIONS

Field-class dosimeters can be used as transfer instruments for comparisons between calibration laboratories, providing that their long-term stability and energy dependence of the response are satisfactory. Low-quality dosimeters cannot be used for this purpose, because the comparability between calibration laboratories cannot be guaranteed, even when the laboratories meet the requirements of the relevant standards and have good performance in official comparisons. Additional work is needed to determine the exact criteria for transfer instruments, *i. e.*, to draw the border between high-quality and low-quality dosimeters. Requirements that are given by appropriate IEC standards can be used as a starting point.

Dosimeters with pronounced energy dependence of the response or bad long-term stability, which are used by nonprofessionals and even by professionals in some cases, can produce erroneous results and can cause doubt in the results provided by calibration laboratories or by official authorities. Calibration factors obtained by different calibration laboratories for such dosimeters are often not comparable. This problem rarely presents in S-Cs radiation quality, which is commonly used for comparisons, calibration, and verification, which stresses the importance of using additional radiation qualities. This is especially important for dosimeters that do not have type testing data and which are used for measurements in fields with low photon energies.

Future work is planned to address some questions that arose during the work presented in this paper. There is not much data on the long-term stability of field-class dosimeters, and this question is important for operational measurements. Another question is the uncertainty budget for measurements using field-class dosimeters in different scenarios, including known and unknown radiation sources. Finally, a further comparison of field-class dosimeters under realistic field conditions and laboratory conditions is planned, to extend this study.

ACKNOWLEDGMENT

This research was performed within the project 17RPT01 DOSEtrace. This project has received funding from the EMPIR programme co-financed by the Participating States and from the European Union's Horizon 2020 research and innovation programme.

AUTHORS' CONTRIBUTIONS

M. Z. Živanović designed the study. Measurements and data analysis were performed by all authors. The first draft of the paper was produced by M. Z. Živanović. Figures were prepared by M. V. Djaletić. All authors reviewed the manuscript, discussed the results, and provided valuable comments and suggestions.

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Received on April 20, 2022
Accepted on July 12, 2022

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ПОРЕЂЕЊЕ КАЛИБРАЦИОНИХ ФАКТОРА ЗА ОПЕРАТИВНЕ ДОЗИМЕТРЕ

У овом раду представљена је интеркомпарација између две лабораторије за еталонирање у неколико квалитета зрачења, користећи дозиметре различитог квалитета као трансфер инструменте. Циљ овог рада био је да се истражи оправданост коришћења оперативних дозиметара у званичним интеркомпарацијама, као и да се испита да ли су калибрациони фактори за оперативне дозиметре у различитим лабораторијама за еталонирање упоредиви у оквиру мерне несигурности.

Резултати интеркомпарације били су прихватљиви за лични дозиметар високог квалитета у свим квалитетима зрачења и такви дозиметри су погодни за трансфер инструменте. С друге стране, резултати за дозиметре ниског квалитета често су били неприхватљиви, због лоше енергетске зависности, лоше стабилности или због оба разлога. Овакви инструменти непоуздани су чак и у добро дефинисаним лабораторијским условима и њихово коришћење у рутинским мерењима може изазвати сумњу у званичне податке или утицати на јавно мнење. Овај проблем често је прикривен због тога што се многи дозиметри еталонирају или оверавају само у пољима ^{137}Cs, где су одступања најмања. Највеће разлике проналазе се за нискоенергетске X-зраке, где многи дозиметри имају значајно повећање осетљивости.

Кључне речи: дозиметрија, интеркомпарација, енергетска зависност, стабилност, еталонирање, амбијентални дозни еквивалент, лични дозни еквивалент