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Gabon results for the 2018 IAEA regional intercomparison exercise on measurements of the personal dose equivalent $H_p(10)$ in photon fields and additional tests

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ABSTRACT

The study provides the overall results of the national individual monitoring service in Gabon obtained during the 2018 International Atomic Energy Agency Africa region intercomparison exercise on measurements of the personal dose equivalent $H_p(10)$ in photon fields. The dosimetry system tested was the microStar InLight dosimetry system (Landauer, Inc., USA). The results were assessed using the trumpet curve. Requirements for photon energy, linearity, coefficient of variation and mixed irradiations were also assessed against IEC 62387 standard. The reader stability, zero dose, recording levels and the ability of the dosemeter to act as a crude energy spectrometer for low energy photons were evaluated as well. The results for reader stability were in line with the manufacturer' specifications, and the photomultiplier tube count measurements relative to the dark current and the built-in ^{14}C radioactive source passed the chi-square test proposed. Monthly and quarterly recording level and zero dose values were calculated to be 0.057 ± 0.003 mSv, 0.05 ± 0.01 mSv and 0.110 ± 0.001 mSv, respectively. The overall results obtained during the 2018 intercomparison exercise met the requirement for overall accuracy (trumpet curve). For the dose equivalent, photon radiation energy and angle of incidence ranges tested, the results for coefficient of variation, energy dependence and mixed irradiations met the corresponding IEC 62387 standard requirements. The results for linearity were considered satisfactory with respect to the corresponding IEC 62387 standard requirement. The method proposed to estimate workplace low photon energies provided better results than the system algorithm. This study has demonstrated that the national individual monitoring service can provide a reliable and consistent accurate dosimetry service to its customers.

1. Introduction

Since its establishment in 2012, the Individual Monitoring Service (IMS) of the General Directorate of Radiation Protection and Nuclear Safety (DGRSN), Ministry of Mines, Energy and Water Resources, in Gabon, has involved itself in participating in regional intercomparison exercises for individual monitoring of external exposure from photon radiation (Arib et al., 2014; Ondo Meye et al., 2017, 2018a). The 2018 International Atomic Energy Agency (IAEA) regional intercomparison, organized by IAEA in cooperation with the Nuclear Research Centre of Algiers (CRNA) through its Secondary Standard Dosimetry Laboratory (SSDL) under the framework of RAF9057 project, “Strengthening National Capabilities on Occupational Radiation Protection in Compliance with Requirements of the new International Basic Safety Standards”, was the fifth participation of the DGRSN's IMS in a regional intercomparison exercise. Twenty one IMSs from nineteen African countries took part in the latter intercomparison exercise. The aim of the DGRSN's IMS in participating in intercomparison exercises is to externally assess, on a regular basis, the consistency of its measurement procedures and laboratory practice so as to achieve a more accurate dosimetry service.

Traditionally in intercomparison exercises, including those organized by IAEA and the European Radiation Dosimetry Group (EURADOS), the performance requirement used to assess the results produced by IMSs has been limited to the trumpet curve as it accounts for the overall accuracy of the dosimetry systems assessed (Arib et al., 2014; Nuclear Research Centre of Algiers, 2016; Nuclear Research Centre of Algiers, 2018; International Atomic Energy Agency, 1999; International Atomic Energy Agency, 2007; Figel et al., 2014). Although this choice is practical, it would be more relevant to assess

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Table 1
InLight model 2 dosemeter (XA case type) filtration.

Filter	Reading position	Filtration (front) mg/cm^2	Filtration (back) mg/cm^2	Primary use
OW (open window)	E1	30	108	Beta response
PL (plastic)	E2	298	284	Beta characterization Photon response
Al (Aluminium)	E3	398	384	Photon characterization
Cu (copper)	E4	568	554	Photon response and characterization

dosimetry systems of the participating IMSs using specific performance requirements for photon energy and angle of incidence, linearity, coefficient of variation and mixed irradiations. Additionally to the trumpet curve, this study assessed Gabon results using specific performance requirements for photon energy, linearity and mixed irradiations using the standard IEC 62387 (International Electrotechnical Commission, 2012). A test of coefficient of variation, more strict than that described in IEC 62387 standard as it does not allow outliers, was also used.

In the literature, different methods for determining the recording level have been proposed. References (Ondo Meye et al., 2017; International Atomic Energy Agency, 2018) have proposed a theoretical approach that takes into account the monitoring period. This method may be considered as limited as it is not based on measurements. Moreover, Reference (Ondo Meye et al., 2017) also proposed an experimental method of determining the lower limit of Detection (considered as the recording level) based on the intercept of the linearity curve. Here also the approach may be seen as limited as only one energy (^{137}Cs) was used. References (Ondo Meye et al., 2017; Yukihara and McKeever, 2011) proposed a statistical approach, based on readings of blank dosemeters (freshly annealed dosemeters). The recording level determined using this approach may be seen as related to the instrumental (reader) background and not to the natural background radiation. The method proposed in reference (Landauer, 2009) is more rigorous as it accounts for several energies and natural radiation background. The limitation associated with this method is that it may not be suitable for IMSs with limited resources. The present study proposes a statistical approach that takes into account natural radiation background and that is based on the fact that it is rare to observe outcomes that exceed three standard deviations from the mean natural radiation dose.

In general, the assessment of the stability of readers of InLight dosimetry systems is carried out following the manufacturer's specifications (Musa et al., 2017, 2018). This study went beyond that by also using control charts and counting statistics for that purpose.

The main aim of the study was to demonstrate the capability of the dosimetry system, an OSL microStar InLight system (Landauer, Inc., USA), of the DGRSN's IMS to measure the personal dose equivalent $H_p(10)$ in photon (gamma- and X-ray) fields.

2. Materials and methods

2.1. Materials

The dosimetry system considered is an InLight dosimetry system (Landauer, Inc., USA). It is designed to assess personnel exposure to beta particles (energy response: 250 keV - 1 MeV; angular response: ± 45°) and photons (energy response: 5 keV - 20 MeV; angular response: ± 60°) using optically stimulated luminescence (Yukihara and McKeever, 2011; Landauer, 2009; InLight®, 2009). The system consists of personal passive dosemeters, a reader, a high intensity light annealer and a software installed on a personal computer.

2.1.1. Reader

The reader under consideration is the portable InLight microStar (32.7 cm width × 23.2 cm depth × 10.9 cm height (Yukihara and McKeever, 2011; InLight®, 2009), serial number 11040681, date of installation, April 2012). The OSL readout of each detector is performed using an array of 38 green LEDs (532 nm wavelength) operated in continuous wave - optically stimulated luminescence (CW - OSL) mode during about 1 s. All the 38 LEDs are used for the stimulation of low doses (strong beam) whereas only 6 LEDs are used for high doses (weak beam). The dose range is evaluated prior to the measurement using one LED and the cut - off point is an adjustable parameter.

2.1.2. Dosemeters

The dosemeter considered comprises a case and a slide. The latter contains 4 detector elements of Al_2O_3: C cut into round pieces of ~ 5 mm in diameter sandwiched between two layers of polyester for a total thickness of 0.3 mm. The detectors are located in read positions 1 (E_1), 2 (E_2), 3 (E_3) and 4 (E_4). When the slide is inside the case, each detectors is positioned behind different filters providing different radiation attenuation conditions (Yukihara and McKeever, 2011; Landauer, 2009) (Table 1). The signal from each OSL detector is used in conjunction with a dose algorithm to evaluate different dosimetric quantities ($H_p(10)$, $H_p(0.07)$ and $H_p(3)$). This dose algorithm inherently uses individual calibration factors.

2.1.3. Irradiation facility

The dosemeters were irradiated at the CRNA's SSDL using a ^{137}Cs gamma irradiator of OB6 type, an ELDORADO 78 ^{60}Co therapy level irradiation unit and a Philips x-ray machine.

2.2. Methods

2.2.1. Intercomparison procedure

At the end of January 2018, IAEA, through the RAF9057 project, made an announcement for the organization of the 2018 regional intercomparison exercise to its member states from Africa region. IMSs wishing to participate completed and submitted to the IAEA a questionnaire for the participation in the exercise. IAEA and the organizing SSDL then sent the intercomparison instructions to the participating laboratories. Thereafter, the latter prepared and sent a total of 45 dosemeters to the CRNA's SSDL. The preparation phase mainly consisted of annealing 33 field dosemeters (used to monitor occupationally exposed workers) and 12 control dosemeters (used for transport and natural background radiation dose measurement). After the dosemeters were received, the SSDL performed their irradiation. Once the irradiation phase ended up, the dosemeters were sent back to the participating IMSs where they were read out. Then, the reading results were transmitted to the organizing SSDL. Finally, the SSDL sent the true dose values to the participating IMS laboratories. The intercomparison results were handled by the CRNA's SSDL and IAEA as confidential data. The identity of IMSs was not disclosed.

2.2.2. Reader stability

For quality control purposes, the stability of the reader regarding its instrumental background is regularly checked twice a week. In addition, the stability of the reader is also controlled before dose measurements are performed. The stability of the reader is evaluated from three photomultiplier tube (PMT) count measurements relative to the dark current (DRK), the built-in ^{14}C radioactive source (CAL) and the

Fig. 1. Sets of dosemeters used to measure monthly and quarterly natural radiation background doses in the DGRSN's IMS laboratory (left). Packages and box sent to the organizing SSDL (right). In particular, the 6 transport and radiation background dosemeters fixed on each face of the box are shown.

light beam (LED). These three PMT count measurements were collected during the whole period of the intercomparison exercise, from the preparation of the dosemeters to their read out after they had been irradiated. Usually the stability of the reader is assessed in terms of the fluctuation of DRK, CAL and LED counts which must lie within the manufacturer's recommended limits (DRK count < 30; CAL and LED counts within ± 10% of the mean). This study goes beyond that. Control charts and counting statistics are also used to assess the stability of the reader.

Control charts use warning limits (given by mean ± 2×standard deviations) and action limits (given by mean ± 3×standard deviations) beyond which investigations and corrective actions must be taken.

Counting statistics was applied to DRK and CAL counts as it is well known that dark current is Poisson distributed and that the decay of a radionuclide is rigorously described by the binomial distribution. In practice, Poisson and Gaussian distributions are suitable approximations to the binomial distribution. The procedure followed was simple. First, one checks that the data and Poison or Gaussian distributions are similar, then a chi-square test is used to provide a numerical measure for comparison of the observed and expected fluctuations. The following probability

$$\Pr(\chi_{\upsilon}^2 \geq \chi_{\upsilon,data}^2) \tag{1}$$

is calculated. χ_{υ}^2 is the variable of the chi-square distribution with $\upsilon = n - 1$ degrees of freedom, n is the number of measurements (sample size) and $\chi_{\upsilon,data}^2$ is the value of χ_{υ}^2 calculated from the data. Very low probabilities (less than 0.02) indicate abnormally large fluctuations (usual type of malfunction) in the data. Very high probabilities (greater than 0.98) indicate abnormally small fluctuations (Knoll, 2000).

2.2.3. Zero dose, recording levels and natural radiation background dose

The zero dose is the reader background dose due to PMT dark counts, electronic noise, stimulation light leakage, etc (Yukihara and McKeever, 2011). It is evaluated using blank (annealed) dosemeters. About 200 measurements were taken using 20 dosemeters. For each detector E_i, $i = \{1,2,3,4\}$, the zero dose value was determined in terms of counts as the mean value of the measurements taken. This value was then divided by the product $S_i \times CF_i$ of the sensitivity and reader calibration factor relative to the detector position i to obtain the zero dose value in units of mSv. The zero dose value associated with the dosemeter was finally obtained by taking the average of the zero dose values of the fours detectors E_i.

In applications, for most probability distributions, it is rare to observe outcomes that exceed three standard deviations from the mean in either direction (Turner et al., 2012). This is confirmed by the Chebyshev's inequality

$$\Pr(X - \mu \geq k\sigma) = \Pr(X \geq \mu + k\sigma) \leq \frac{1}{k^2} \tag{2}$$

where X denotes a random variable having a probability distribution with finite mean μ and variance σ^2, k is a positive constant. This relationship can be applied to any probability distribution. Therefore, the radiation dose above three standard deviations from the mean natural radiation background dose might be due to the radiation exposure being evaluated. The critical level, L_C, of dose is thus given by

$$L_C = \mu_B + 3\sigma_B \tag{3}$$

where μ_B and σ_B are respectively the mean natural radiation background dose and the associated standard deviation. The probability that the radiation background dose will be greater than L_C does not exceed $1/3^2 = 11\%$.

In practice, the radiation background dose is removed from the total measured dose to obtain a net dose. This can be seen as translating the radiation background distribution from μ_B to the origin.

If we assume that the radiation background is normally distributed, then the probability that the radiation background dose is greater than L_C is given by

$$\Pr(D_B \geq L_C) = \Pr\left(Z \geq \frac{L_C - \mu_B}{\sigma_B}\right) = \Pr(Z \geq 3) = 0.13\% \tag{4}$$

where D_B is the radiation background dose, $Z = (D_B - \mu_B)/\sigma_B$ is the standard normal variable and $\mu_B = 0$. In the case where the number of measurements $n < 30$, the Student's t-distribution should be used in place of the normal distribution.

In practice, the critical level (decision threshold) is taken as the recording level as it determines whether a measured dose is significantly different from the radiation background dose.

In addition to the 12 dosemeters used to measure the transport and natural radiation background dose, two sets of 10 dosemeters were used to determine monthly and quarterly radiation background doses in the DGRSN's IMS laboratory (Fig. 1). This was done to obtain natural background doses typical for monthly and quarterly monitoring periods in order to determine recording levels corresponding to these monitoring periods. The box sent to the CRNA's SSDL contained 3 packages for linearity, energy dependence and blind tests. 2 transport and background dosemeters were added in each package. The remaining 6 dosemeters were fixed on each face of the box (Fig. 1). Because of their repartition in box, the dosemeters may be differently exposed to natural background radiation and x-ray screening beams. In this regard, the difference in the mean values of the transport and radiation background doses measured at the surfaces of the box and in the packages inside the box was assessed using the following *(1-α) %* confidence interval:

$$\bar{X} - \bar{Y} - t_{\upsilon,\alpha/2}\sqrt{\frac{S_x^2}{n_1} + \frac{S_y^2}{n_2}} < \mu_x - \mu_y < \bar{X} - \bar{Y} + t_{\upsilon,\alpha/2}\sqrt{\frac{S_x^2}{n_1} + \frac{S_y^2}{n_2}} \quad (5)$$

where $\bar{X}$ and $\bar{Y}$ are respectively the sample mean values for dosemeters at the surfaces of the box and inside the box, μ_x and μ_y are the corresponding true mean values, S_x^2 and S_y^2 are the corresponding sample variances, n_1 and n_2 are the number of measurements used to compute $\bar{X}$ and $\bar{Y}$, respectively; $t_{\upsilon,\alpha/2}$ is the quantity with υ degrees of freedom that cuts off an area of size $\alpha/2$ to the right under the Student *t*-distribution; υ is obtained using the Satterthwaite's approximation.

2.2.4. Irradiation procedure

The dosemeters were irradiated at the surface of an ISO slab phantom (International Organisation for Standardization, 1999) using values of dose rates calculated from the measured air kerma determined with the SSDL reference instrument. These irradiations were performed as follows:

- Irradiations using the ^{137}Cs source to dose values varying from 0.4 to 8 mSv in normal incidence (linearity verification - dosemeters irradiated in groups of 3);
- Irradiations at the fixed dose of 2 mSv using three X - ray qualities (N-60, N-80, N-150) and S–Cs (energy response - dosemeters irradiated in groups of 3);
- Irradiations with S–Co quality and mixed qualities (N-60 + S–Cs) at different doses (20 and 6 mSv, respectively) and in normal incidence (Blind test - dosemeters irradiated in groups of 3).

2.2.5. IAEA performance requirement

In intercomparison exercises, IAEA has traditionally used the trumpet curve as this performance requirement accounts for overall accuracy (Arib et al., 2014; Nuclear Research Centre of Algiers, 2016; Nuclear Research Centre of Algiers, 2018; International Atomic Energy Agency, 1999; International Atomic Energy Agency, 2007). Although the requirements for photon energy, linearity, coefficient of variation, mixed irradiations are included in the trumpet curve, it is of a great importance to test a dosimetry system using specific performance requirements. For this purpose, the standard IEC 62387 (International Electrotechnical Commission, 2012) was used accordingly.

2.2.6. Linearity and coefficient of variation

According to IEC 62387 standard, the test of the coefficient of variation shall be performed together with the linearity test. The procedure followed here and that given in IEC 62387 are part of the same test procedure developed in reference (Brunzendorf and Behrens, 2006). The author suggests to use the test procedure presented in IEC 62387 for a number of data points greater than 5. Another reason to use the test procedure presented in this study was to demonstrate the performance of the dosimetry system used as this test is more strict since it does not allow outliers (the test procedure given in IEC 62387 allows 2 non consecutive outliers).

The statistical fluctuations of the indicated value shall fall below $c \times limit$ where *limit* is given in IEC 62387 standard and *c* is a parameter computed using the formula given in reference (Brunzendorf and Behrens, 2006).

Regarding linearity, the performance requirement given in IEC 62387 standard was strictly followed: the dosemeters are irradiated at known dose equivalents and the variation of the response due to the change of the dose equivalent shall not exceed the values given in the standard. This requirement is met only if the appropriate relationship given in the standard is valid.

2.2.7. Photon energy

IEC 62387 standard requirement was followed: the variation of relative response due to a change of radiation energy within the rated ranges shall not exceed the value given for $H_p(10)$ in the standard. The above requirement is met if, for every radiation quality, the appropriate inequality found in the standard is valid.

Also in this study, the ability of the dosemeter to act as a crude energy spectrometer for low energy photons was assessed(Landauer, 2009; Yukihara and McKeever, 2011). Specifically, the ability of the ratio E_1/E_4 (count in position 1/count in position 4) to determine low photon energy was evaluated.

2.2.8. Response to mixed irradiations

In this test, the indicated value evaluated by the dosimetry system is compared to the corresponding indicated value calculated for each detector element E_i, $i = \{1, 2, 3, 4\}$, using counts from each detector and the evaluation algorithm. The IEC 62387 standard requirement states that the relative response to mixed irradiations shall be within the range of response weighted with the respective dose values.

In the present study, mixed irradiations using 2 radiations qualities *K* and *L* (N-60 and S–Cs) were simulated by combining the counts $E_{K,i}$ and $E_{L,i}$ for each detector element $i = \{1, 2, 3, 4\}$. The mean indicated value for the detector element *i*,

$$\bar{H}_{m,K+L} = K_{K,i} \times \frac{\bar{E}_{K,i}}{S_i \times CF_i} + K_{L,i} \times \frac{\bar{E}_{L,i}}{S_i \times CF_i}, \quad (6)$$

for the mixed irradiation condition $K + L$ with the conventional true dose $H_{t,K+L} = H_{t,K} + H_{t,L}$ was calculated. $H_{t,K}$ and $H_{t,L}$ are conventional true doses corresponding to energies *K* and *L*, respectively, $K_{K,i}$ and $K_{L,i}$ are, respectively, correction factors for the detector element *i* and energies *K* and *L* determined using data from previous intercomparison exercises, $\bar{E}_{K,i}$ and $\bar{E}_{L,i}$ are the mean counts registered by detector element *i* for energies *K* and *L*, S_i and CF_i are the sensitivity and the reader calibration factor for detector *i*, respectively. The mean relative response given by

$$r = \frac{\bar{H}_{m,K+L}}{H_{t,K+L}} \times \frac{H_{t,ref}}{\bar{H}_{m,ref}} \quad (7)$$

was assessed using the same relationship than for the performance requirement for photon energy but by using the weighted responses $r_{\min,w}$ and $r_{max,w}$ instead of $r_{\min}$ and r_{max}:

$$r_{min,w} = \frac{r_{min,K}\cdot H_{t,K} + r_{min,L}\cdot H_{t,L}}{H_{t,K} + H_{t,L}}\,;\; r_{max,w} = \frac{r_{max,K}\cdot H_{t,K} + r_{max,L}\cdot H_{t,L}}{H_{t,K} + H_{t,L}} \quad (8)$$

where $r_{min,K}$ and $r_{max,K}$ are minimum and maximum relative responses for energies *K* and *L*, respectively, given in the standard.

In this study the combination of N-60 and S–Cs with the ratio 2/4 for a total delivered dose of 6 mSv was used: N-60 (2 mSv), S–Cs (4 mSv); S–Cs (2 mSv), N-60 (4 mSv). As in the 2018 intercomparison exercise a 4 mSv dose irradiation using N-60 quality was not performed separately, this condition was simulated by multiplying by 2 the counts registered by each detector element for the 2 mSv dose irradiation using the same radiation quality, which was carried out in the exercise (taking advantage of the well known additive properties of Al_2O_3:C - based OSL detectors (Perks and Passmore, 2006)).

3. Results and discussion

3.1. Reader stability

38 samples of size $n = 10$ were taken for each PMT count type (DRK, CAL or LED), meaning that 380 measurements were collected in total for each of them. For each sample, almost all the data points were within the warning limits. No data points went beyond the action limits. This latter fact is in line with the assumption made earlier that it is rare to observe outcomes that exceed three standard deviations from the mean in either direction. For CAL measurement, it was noticed that, depending on the sample mean and variance, the ± 10% of the mean

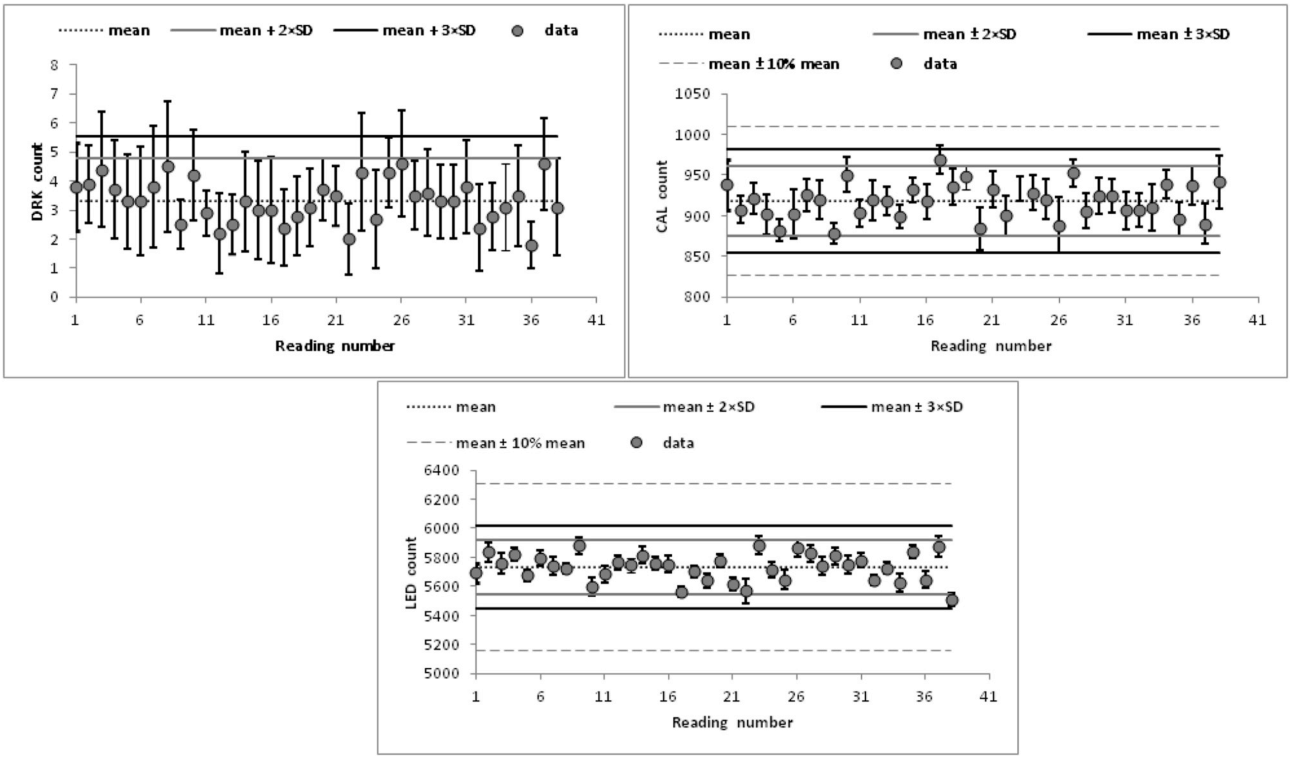

Fig. 2. Results for the mean of mean values of PMT DRK, CAL and LED counts.

limits recommended by the manufacturer were either narrower or wider than the action limits. For the LED measurement, the manufacturer's recommended limits were always significantly wider than the action limits. The highest DRK count value measured was 11. Fig. 2 shows the results for the mean of sample mean values for each PMT count type. The values of standard deviation used to compute warning and action limits are respectively 0.73, 21.36 and 94.94 for DRK, CAL and LED counts. The large majority of the data points are within the warning limits. However, in some cases, particularly for DRK count, one can see that a small part of the confidence interval (given by $\bar{x} \pm (t_{9,0.025}/\sqrt{10}) \times SD$ where $t_{9,\,0.025}$ is a coverage factor for a two sided confidence level of 95% from a Student's t-distribution) associated with the data point is outside the permitted upper limit of variation. This means that there is a possibility that the true value lies outside the limit. The probability that such an event occurs is weak (assuming a normal distribution of the data).

Figs. 3 and 4 show the distributions of DRK and CAL counts for all the 380 measurements collected, respectively. One can see that the data distribution is similar to the normal or Poison distribution. The chi-square test was then successfully applied to each sample ($n = 10$)

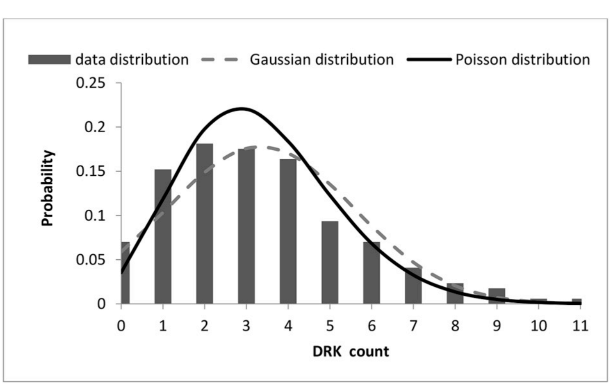

Fig. 3. Distribution of DRK counts for all the 380 measurements collected.

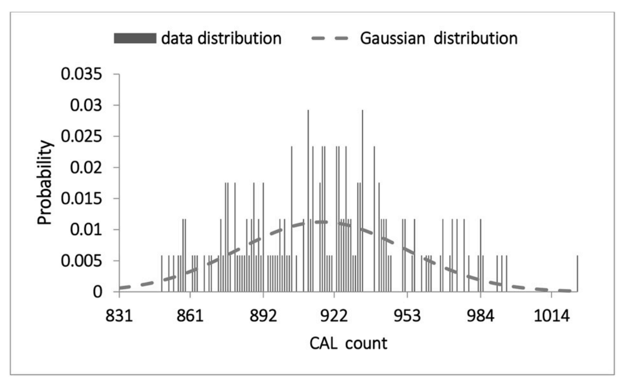

Fig. 4. Distribution of CAL counts for all the 380 measurements collected.

collected. As an example, the chi-square test applied to the DRK and CAL count samples collected just before the dose measurements for the 2018 intercomparison exercise were performed lead to the probabilities $\Pr(\chi^2 \geq 10.42) = 0.32$ and $\Pr(\chi^2 \geq 9.59) = 0.38$, respectively. Because these probabilities were neither very large nor very small, it was concluded that the test is passed (the observed fluctuations in DRK and CAL counts are random and consistent with Poisson distribution: the reader counting system is operating properly). Reference (Ondo Meye et al., 2018b) came to the same conclusion by using a two-tailed chi-square test applied to CAL counts.

The additional tests used in this study to assess reader stability, particularly control charts, may be considered more efficient in determining abnormalities in the counting system than the manufacturer's recommended limits since it has been shown that these limits are in general wider than action limits. In the case where data points are outside the action limits, investigation will be carried out and corrective actions will be taken more quickly.

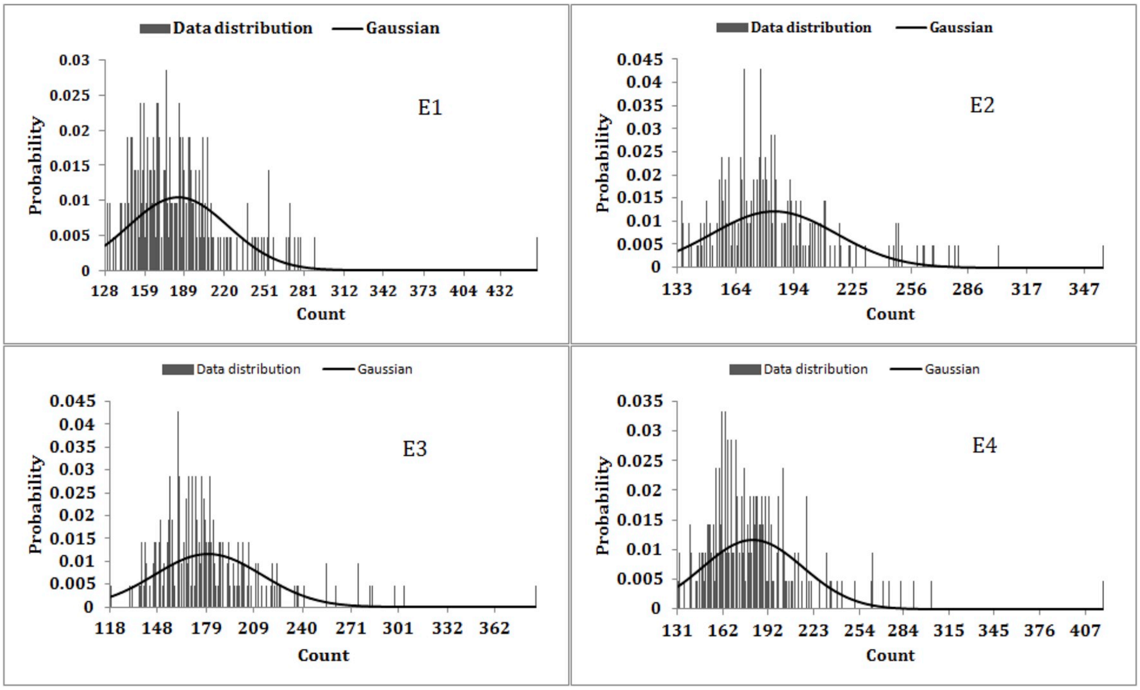

Fig. 5. Zero dose distribution for each detector position E_1, E_2, E_3 and E_4.

3.2. Zero dose and recording levels

Fig. 5 shows the distributions of zero dose for each detector position $i = \{1, 2, 3, 4\}$. It is observed that they are nearly normally distributed. Table 2 gives the zero dose values associated with each detector element. The zero dose value associated with the dosemeter, average of these four values, is also given.

Table 3 lists results for transport and natural radiation background dose. Results for monthly and quarterly local natural radiation background doses are also provided. The monthly radiation background dose was measured each month during three months using 10 dosemeters. The quarterly radiation background dose was measured during one quarter using 10 dosemeters. The results show that the transport and radiation background dose is clearly much greater than the quarterly local radiation background dose. This may be due to the fact that the transport and background dose accounts for the local natural radiation background within the organizing SSDL (accumulated in the dosemeters during about 86 days, i.e., three months), cosmic radiation (the relevant components being electrons and photons) at commercial aircraft altitudes (typically 6100–12200 m (International Atomic Energy Agency, 2018)), scanning processes at the airport, and so on, whereas the monthly and quarterly local background doses account only for the natural background radiation within the DGRSN's IMS laboratory, typical of natural background radiation encountered in workplaces in Libreville (capital city of Gabon). It is worth mentioning that the mean local radiation background dose in the DGRSN's dosimetry laboratory, 2.00 ± 0.07 µSv/d, is in agreement with the value (2 µSv/d) of the conventional true value of the natural radiation given in IEC 62387 standard.

The distribution of the transport and radiation background dose at the surfaces of and within the transport box suggested that the dosemeters were uniformly irradiated by natural radiation and x-ray scanning machines at airports. That is the reason why the mean background and transport dose was computed using all the 12 dosemeters. This can be demonstrated statistically using Equation (5). $\bar{X} = 0.327\, mSv$ and $S_x = 0.037\, mSv$ are the mean value of the $n_1 = 6$ background and transport doses measured at the surfaces of the transport box and the associated standard deviation, respectively. $\bar{Y} = 0.298\, mSv$ and $S_y = 0.050\, mSv$ are, respectively, the mean value and the associated standard deviation ($n_2 = 6$) of background and transport doses measured within the box. The 95% confidence interval of $\mu_w = \mu_x - \mu_y$ is [-0.029 mSv, 0.045 mSv]. Since 0 is included in this interval, there is 95% confidence that the transport and background dose (true) mean values at the surfaces of and within the transport box are the same. This result can be further confirmed using statistical hypothesis testing. The null and alternative hypotheses are respectively H_0: $\mu_w = \mu_x - \mu_y = 0$; H_1: $\mu_w \neq 0$. The test statistic is $t = (\bar{w} - 0)/(s_w/\sqrt{n})$ where $W = X - Y$, $\bar{w} = 0.028\, mSv$, $s_w = 0.061\, mSv$ and $n = 6$; the significance level is $\alpha = 0.05$. Since the $p - value = 0.31 > \alpha$, the null hypothesis is not rejected.

Table 4 lists the monthly and quarterly recording levels of the dosimetry system. The recording level of the system corresponding to the intercomparison period is also listed. It is observed that the recording level for the intercomparison exercise period is lower than all the delivered doses. It is believed that the value of this recording level would have been significantly lower if more dosemeters, e.g. $n = 30$, were employed to measure the transport and radiation background dose. The quarterly recording level is a little bit lower than the monthly recording

Table 2
Zero dose values, in mSv, associated with each detector element E_i, $i = \{1, 2, 3, 4\}$ and with the dosemeter. The statistical uncertainty associated with each value was calculated using $(t_{n-1}/\sqrt{n})s$ where t_{n-1} is the Student's t-value for a two sided 95% confidence interval, s is the sample standard deviation and n is the sample size ($n = 210$).

	E_1	E_2	E_3	E_4
	0.111 ± 0.003	0.109 ± 0.002	0.109 ± 0.003	0.109 ± 0.003
Dosemeter	**0.110 ± 0.001**			

Table 3
Transport and natural radiation background, monthly and quarterly local natural radiation background doses in mSv for each detector element E_i, $i = \{1, 2, 3, 4\}$ and with the dosemeter. The statistical uncertainty associated with each value was computed as for the zero dose.

	Transport and natural radiation background dose			
	E_1	E_2	E_3	E_4
	0.33 ± 0.03	0.33 ± 0.02	0.34 ± 0.03	0.32 ± 0.03
Dosemeter	**0.33 ± 0.01**			
	Monthly local natural radiation background			
	E_1	E_2	E_3	E_4
	0.056 ± 0.007	0.054 ± 0.007	0.055 ± 0.007	0.050 ± 0.007
Dosemeter	**0.054 ± 0.004**			
	Quarterly local natural radiation background			
	E_1	E_2	E_3	E_4
	0.19 ± 0.01	0.18 ± 0.01	0.18 ± 0.01	0.17 ± 0.01
Dosemeter	**0.18 ± 0.01**			

Table 4
Recording levels in *mSv* for monthly, quarterly and the intercomparison exercise periods.

	Intercomparison exercise period			
	E_1	E_2	E_3	E_4
	0.14	0.12	0.13	0.15
Dosemeter	**0.14 ± 0.02**			
	Monthly period			
	E_1	E_2	E_3	E_4
	0.055	0.060	0.057	0.054
Dosemeter	**0.057 ± 0.003**			
	Quarterly period			
	E_1	E_2	E_3	E_4
	0.49	0.55	0.62	0.39
Dosemeter	**0.05 ± 0.01**			

level. This is due to the fact that the statistical fluctuation in the natural radiation background is less for a quarterly period than for a monthly period. This latter result is in contradiction with references (Ondo Meye et al., 2017; International Atomic Energy Agency, 2018) as they suggest a quarterly recording level (three times) greater than the monthly recording level. However, the recording levels determined in this study is in agreement with the monthly LLD interval determined using the experimental approach described in (Ondo Meye et al., 2017).

3.3. Intercomparison overall results, coefficient of variation, linearity

Fig. 6 presents overall results (net values and mean net values) for all the tests that were performed during the 2018 intercomparison exercise. It is observed that all the points are within the trumpet curve. Since 95%, i.e., 19 of 20, of the data points shall fall within the trumpet curve, then the dosimetry system passed all the tests carried out as 100% of the points are within these acceptance limits. This is in agreement with results obtained for the previous IAEA regional intercomparison exercises (Ondo Meye et al., 2018a).

Results for the coefficient of variation are shown in Fig. 7. The dotted line represents the required limit given in IEC 62387 standard. The latter limit is multiplied by c to obtain $c \times limit$ (solid line). $c = 1.4298$ ($n = 3$, $w = 5$). Since all the data points are well below the limit (the data point that seems to lie on the limit is in fact very close, 0.97 times the limit, but below the limit), the coefficient of variation requirement is fulfilled. These results are better than those shown in reference (Ondo Meye et al., 2018a) where two consecutive outliers were observed in the region of the recording level. This might be due to the fact that the test in that study was limited to check whether measured coefficients of variation were below the specified limit given in IEC 62387 without taking into account improvement of the test as described in this study.

Fig. 8 shows the results for linearity test. All the data points are within the recommended limits. Since either the confidence intervals

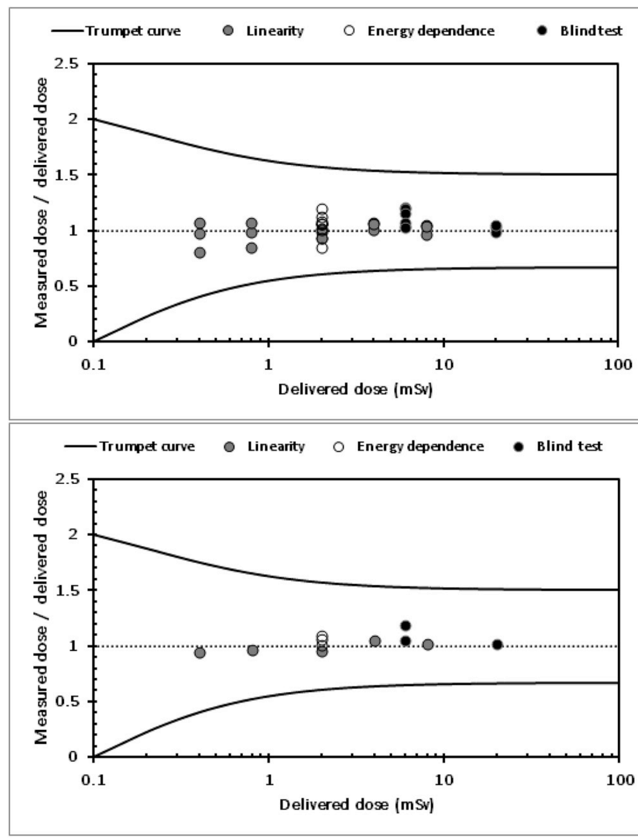

Fig. 6. Overall results, net values (top) and mean net values (bottom), for all the tests performed during the 2018 IAEA intercomparison exercise.

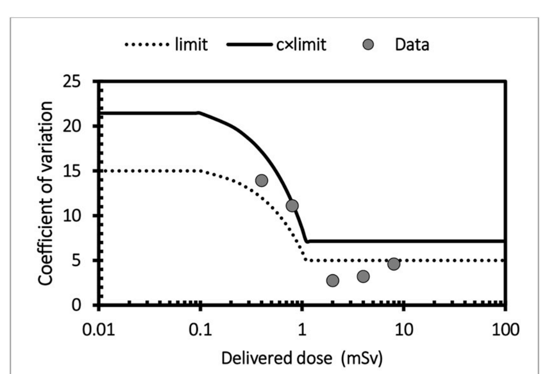

Fig. 7. Results for the coefficient of variation test.

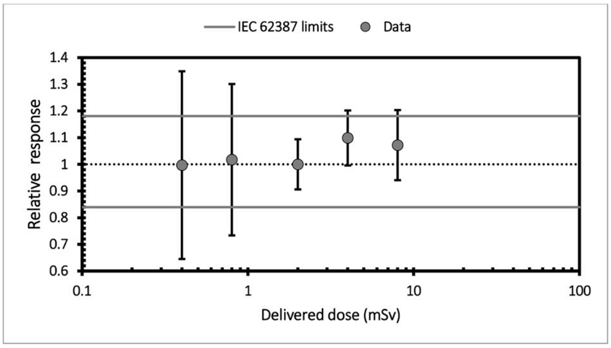

Fig. 8. Results for the linearity test.

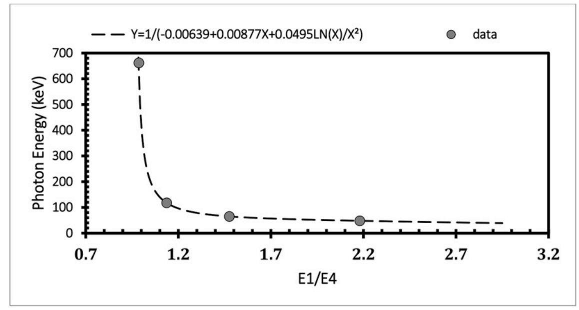

Fig. 9. Photon mean energy in function of the ratio E_1/E_4.

associated with the data points include the permitted limits of variation or only part of the confidence intervals is outside the permitted upper limit, then the results are considered satisfactory with respect to IEC 62387 requirement for linearity.

Since parts of the statistical uncertainty associated with the first two data points are outside the permitted limits, then there is a possibility that the true values lie outside the limits in either direction. An assumption is made that the data are normally distributed. Since the number of measurements $n = 3 < 30$, the Student's *t*-distribution should be used. The probability that the true value lies beyond the limits is $\Pr(t < (r_{min} - \overline{r})/(s/\sqrt{n})) + Pr(t > (r_{max} - \overline{r})/(s/\sqrt{n})$, where $\overline{r}$, s, r_{min} and r_{max} are the mean relative response, its associated standard deviation, the lower and upper limit relative responses, respectively. One finds 17% and 12% for the first and second data points, respectively.

For the last two data points, since part of the statistical uncertainty is outside the permitted upper limit, then there is a possibility that the true values lie above the upper limit. The probability that the true value lies above the upper limit is $Pr(t > (r_{max} - \overline{r})/(s/\sqrt{n})$. One finds 3% for these two data points. To decrease the probability that a true value lies outside the permitted limits, the number *n* of measurements should be increased.

The linearity results obtained in this study are comparable to those obtained in reference (Ondo Meye et al., 2017). It is observed that statistical uncertainty is an issue in both cases, especially in the region of the recording level. The number of dosemeters should be significantly increased in future intercomparison exercises to reduce the statistical uncertainty. For instance, the expanded uncertainty associated with a mean dose equivalent would have been reduced to less than half of that obtained in this study if a number $n = 6$ dosemeters were used ($((t_{5,0.025}/\sqrt{6})/(t_{2,\,0.025}/\sqrt{3}) = 0.42$ and the sample standard deviation for 6 dosemeters is expected to be smaller than that for 3 dosemeters). It is also important to mention that this statistical uncertainty issue would not have been detected if the trumpet curve was used as the only performance requirement since the concern would have been to check whether 95% of the data points fall within the permitted limits.

3.4. Energy dependence, response to mixed irradiations

It has been noticed, from data of different intercomparison exercises, that the microStar system algorithm, described in reference (Landauer, 2009) and based on the ratio E_3/E_4 (counts measured under the aluminium filter/counts measured under the copper filter), provides an estimate of low photon energies with errors up to more than + 70%. The algorithm proposed in this study, based on the ratio E_1/E_4 (counts measured under the open window/counts measured under the copper filter), provides a better estimate of low photon energies. Fig. 9 presents the graph of photon energy in function of the ratio of E_1/E_4. The choice of the ratio E_1/E_4 was made because it is already used in an internal procedure to correct for overexposure from low energy photons (Ondo Meye et al., 2018a, 2018b). More generally, it is a common practice to use the ratio between the signal from the same material in the open window position and behind a high energy photon attenuation filter (e.g. Cu filter) to determine the mean energy of the photon field (Yukihara and McKeever, 2011). Low energy photons will be more attenuated by the filter than high energy photons resulting in a ratio between the signals from the detectors in the two positions that is energy dependent. This ratio can then be used to determine the mean energy of the photon radiation field. Since for photon energies beyond 100 keV the response is nearly independent of energy (Yukihara and McKeever, 2011; Landauer, 2009), this ratio is more appropriate for estimating low photon energies. Table 5 compares low photon mean energies estimated by the dosimetry system and by the method used in this study for the 2016 IAEA intercomparison exercise. It clearly shows that the proposed method provides a better estimate of low photon energies (maximum error < 14%) than the dosimetry system algorithm (maximum error = 74%). Similar results were obtained by applying this method to a small sample of workplace data from the medical sector and the results were in agreement with typical energies (< 150 keV (Yukihara and McKeever, 2011)) encountered in diagnostic radiology (Table 6).

Results for energy dependence are shown in Fig. 10. The radiation qualities used were N-60 (energy: 48 keV; delivered dose: 2 mSv; angle: 0°), N-80 (energy: 65 keV; delivered dose: 2 mSv; angle: 0°), N-150 (energy: 118 keV; delivered dose: 2 mSv; angle: 0°), S–Cs (energy: 662 keV; delivered dose: 2 mSv; angle: 0°) and S–Co (energy:1250 keV; delivered dose: 20 mSv; angle: 0°). All the data points are within the required limits. It is therefore concluded that, for normal incidence and photon radiation energies tested, the IEC 62387 standard requirement for photon energy is met. These results are better than those obtained in reference (Ondo Meye et al., 2018a) where it was observed that parts of the statistical uncertainties were outside the permitted limits for some

Table 5
Comparison of low photon mean energy (in keV) estimated by the dosimetry system and by the method used in this study for the 2016 IAEA intercomparison (the dosemeters were irradiated in groups of 4).

Intercomparison code	Estimated energy (system)	Estimated energy (this study)	true energy
E11	59	47	48
E12	60	47	48
E13	59	47	48
E14	58	48	48
E21	83	62	65
E22	83	65	65
E23	82	61	65
E24	85	67	65
E31	149	99	100
E32	174	93	100
E33	141	100	100
E34	124	86	100

Table 6
Comparison of low photon mean energy (in keV) estimated by the dosimetry system and by the method used in this study for a small sample of workplace data from the medical sector.

Measurement number	Estimated energy (system)	Estimated energy (this study)	E1/E4
M1	114	68	1.42
M2	90	62	1.54
M3	80	60	1.60
M4	83	60	1.59
M5	76	59	1.62
M6	73	60	1.59
M7	129	83	1.27
M8	90	66	1.45
M9	148	76	1.32
M10	86	68	1.42

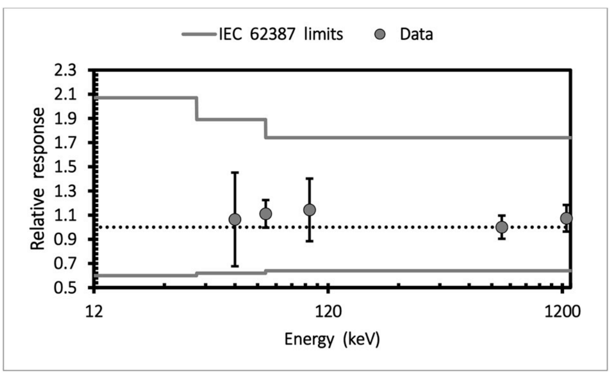

Fig. 10. Result for energy dependence test.

Table 7
Mean relative response for each detector E_i, $i = \{1, 2, 3, 4\}$, to simulated mixed irradiations (normal incidence) using radiation qualities N-60 (2 mSv) and S–Cs (4 mSv), and S–Cs (2 mSv) and N-60 (4 mSv) (dose ratios 2/4).

S–Cs (2 mSv) + N-60 (4 mSv)				Limits	
E_1	E_2	E_3	E_4	Lower	Upper
1.22 ± 0.12	1.16 ± 0.08	1.21 ± 0.09	1.21 ± 0.12	0.70	1.72
S–Cs (2 mSv) + N-60 (4 mSv)					
				Limits	
E_1	E_2	E_3	E_4	Lower	Upper
1.30 ± 0.11	1.22 ± 0.09	1.28 ± 0.09	1.27 ± 0.12	0.70	1.77

data points. This might be due to the fact that photon radiation angles of incidence other than normal incidence were used in that study and that the number n of dosemeters for the angular dependence test was limited to 2.

For each detector located at position $i = \{1,2,3,4\}$ the relative response to the simulated mixed irradiations of dosemeters (sample size $n = 3$) were calculated. The radiation qualities N-60 (energy: 48 keV; delivered dose: 2 mSv; angle 0°) and S–Cs (energy: 662 keV; delivered dose: 4 mSv; angle 0°), and S–Cs (energy: 662 keV; delivered dose: 2 mSv; angle 0°) and N-60 (energy: 48 keV; delivered dose: 4 mSv; angle 0°) were used. The ratio of the total delivered dose was 2/4 for each case. The weighted limits were calculated to be 0.70 and 1.72, and 0.70 and 1.77, respectively. All the calculated relative responses were within these limits, ranging from 1.16 to 1.26 and 1.21 to 1.33, respectively. The mean relative responses for each detector at position $i = \{1,2,3,4\}$ are given in Table 7. All the values are within the limits. It is thus concluded that the IEC 62387 requirement for mixed irradiations is fulfilled.

4. Conclusion

The study was mainly aimed at presenting Gabon results obtained during the 2018 IAEA African region intercomparison exercise on measurements of the personal dose equivalent $H_p(10)$ in photon fields. The reader stability results were very satisfactory regarding manufacturer's requirements, control charts and chi-square test. The computed monthly and quarterly recording level and zero dose values were 0.057 ± 0.003 mSv, 0.05 ± 0.01 mSv and 0.110 ± 0.001 mSv, respectively. The overall results obtained during the exercise met the requirement for overall accuracy. For the dose equivalent, photon radiation angle of incidence and energy ranges tested, the results for coefficient of variation, energy dependence and mixed irradiations demonstrated that the corresponding IEC 62387 standard requirements were fulfilled. The results for linearity were considered satisfactory with respect to the corresponding IEC 62387 standard requirement. It is expected that increasing significantly the number of dosemeters will improve the results. The method proposed to estimate workplace low photon mean energies provided more accurate results than those provided by the system algorithm.

Finally, the 2018 IAEA regional intercomparison exercise showed the consistency of the measurement procedures of the DGRSN's IMS, thus demonstrating very good laboratory practice.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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