PRECISION AND RELIABILITY: CALIBRATION COEFFICIENTS AND LONG-TERM STABILITY ANALYSIS OF RADIOTHERAPY DOSIMETERS CALIBRATED BY SSDL, NUKLEAR MALAYSIA

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ABSTRACT: One of the main objectives of the Secondary Standard Dosimetry Laboratory (SSDL) in radiotherapy dosimetry is verifying the radiation dose provided to patients is accurate and meets globally recognised standards. Properly calibrating the therapy dosimeters used in the radiotherapy centres is the first step the SSDL must take to ensure this goal is attained. This study analyses the calibration coefficients and long-term stability of therapy dosimeters calibrated by Nuklear Malaysia's SSDL. The dosimeters were calibrated in the absorbed dose to water using 60Co gamma rays, following the procedure described in IAEA TRS No. 398 and IAEA TRS No. 469. Two hundred therapy dosimeters from 33 radiotherapy centres were evaluated for the percentage deviation of the calibration coefficients provided by the SSDL and the manufacturer. Furthermore, the variation in calibration coefficient and the long-term stability of therapy dosimeters from 2011 to 2021 were examined. The percentage deviation of calibration coefficients between the SSDL and manufacturers found that most (82%) user dosimeters were within the IAEA's acceptance limit of ± 1.5%. Overall, the stability of calibration coefficient values ranged between 33.25% and -27.24%, with an average of 0.03%. As predicted, only 15% of the therapy dosimeters fulfill the criteria for long-term stability of 0.5%. In conclusion, proper maintenance and annual calibration of therapy dosimeters are very important to improve accuracy, minimise measurement uncertainty, and thus reduce the likelihood of errors in radiotherapy dosimetry.

KEYWORDS: *Absorbed dose to water; calibration coefficient; long-term stability; radiotherapy dosimeter; SSDL.*

1.0 INTRODUCTION

According to the Malaysia National Cancer Registry Report, the number of newly diagnosed cancer cases in the nation has significantly increased over the previous five years [1]. Between 2012 and 2016, breast, colorectal, and lung cancers have been the most frequently reported cancers, with males having a lifetime risk of 1 in 10 and females of 1 in 9. Overall, there were 48,639 new cancer cases recorded in Malaysia in 2020, according to the World Health Organization, and the cancer incidence in Malaysia is expected to double by 2040 [2]. With the rising prevalence of cancer, the demands for radiotherapy will be rising and thus require the establishment of high-quality and safe radiotherapy [3]. There are currently 35 radiotherapy centres in the country, of which 7 are government hospitals, and 28 are private facilities [4]. One government-funded radiotherapy service is delivered through a contract with a private institution. In total, there are 92 radiation therapy modalities, including 58 medical linear accelerators, 19 brachytherapy, 7 intra-operative radiotherapy (IORT), 5 tomotherapy and 1 cyberknife [5]. One of the fundamental objectives of the Secondary Standards Dosimetry Laboratory (SSDL) in radiotherapy dosimetry is to confirm that the dose given to patients undergoing radiation treatment is accurate and consistent with the acceptance level of ± 5%, as stipulated in the International Commission on Radiation Units and Measurements (ICRU) Report 24 [6]. Subsequently, the first step to achieving this goal is to deliver traceable calibrations of radiation-measuring instruments used in radiotherapy centres.

The SSDL of the Malaysian Nuclear Agency (Nuklear Malaysia) plays its prime function as the National Centre for Radiation

Metrology. Regarding this, the SSDL provides calibration services for calibrating radiation-measuring instruments used in various fields, including diagnostic radiology, radiation therapy, and radiation protection. These services have been accredited with the Malaysian Standard (MS) ISO/IEC 17025 [7] under the Laboratory Accreditation Scheme of Malaysia (SAMM No.: 275) since 2004 [8]. In Malaysia, the calibration of radiation-measuring instruments is required in compliance with the regulations under the Laws of Malaysia, including the Atomic Energy Licensing Act 1984 (Act 304), Occupational Safety and Health Act 1994 (Act 514) and the National Measurement System Act 2007 (Act 675). Generally, the regulations specified under these laws seek to ensure the accuracy of measurement and thereby contribute to the goal of radiation safety and protection for workers, patients, and members of the public. Apart from domestic services, SSDL also has the trust of private companies abroad to serve calibration services. By 2023, various companies from Brunei Darussalam, Indonesia, India, Philippines, Singapore, Thailand, and the United Arab Emirates have received calibration services from the SSDL.

Two publications have reported on the accuracy and stability of the therapy dosimeters used in Malaysian radiotherapy centres. The first study by [9] evaluated the calibration coefficients for 29 therapy dosimeters belonging to 16 radiotherapy centres calibrated using a ^{60}Co beam in the SSDL for seven years (2004 to 2010). The findings of the study showed that the calibration coefficients for the dosimeters are reliable for measuring patient dose and do not vary over time. These results were in agreement with the study of 38 therapy dosimeters used in 14 Polish radiotherapy centres [10]. The second study presented the analysis of calibration coefficients for 33 therapy dosimeters from 24 Malaysian radiotherapy centres calibrated from 2004 to 2012 [11]. The results are contrary to the previous research, as the study indicates that there were systematic errors in the calibration coefficients over these periods of observations for various models of therapy dosimeters. The relatively large sample size of calibration coefficients (6474 dosimeters) obtained from the three accredited dosimetry calibration laboratories (ADCLs) operating in the United States, [12] revealed that the calibration coefficients for older dosimeters are more variable than those manufactured more recently. There are consistent findings for these studies, which found a significant dispersion of calibration coefficients of particular therapy dosimeters due to manufacturing differences [10]–[12].

This present work highlights the latest data on therapy dosimeters from Malaysian radiotherapy centres calibrated at the SSDL from 2011 to 2021. The purposes of this work are: (i) to observe the availability of calibrated therapy dosimeter in the SSDL; (ii) to compare the deviation of the calibration coefficient in terms of absorbed dose to water provided by the SSDL and manufacturer; (iii) to investigate the variation of the calibration coefficients of therapy dosimeters over a certain period concerning different manufacturers; and (iv) to examine the long-term stability of these therapy dosimeters after being calibrated several times from 2011 to 2021.

2.0 METHODOLOGY

2.1 Calibration of Radiation Therapy Dosimeters

Therapy dosimeters from various radiotherapy centres (user dosimeters) were calibrated in the SSDL in terms of the absorbed dose to water in ^{60}Co gamma rays, type Eldorado 8 (Nordion, Ottawa, Canada). The determination of the absorbed dose to water was performed according to the Technical Report Series (TRS) No. 398 provided by the International Atomic Energy Agency (IAEA) [13]. The user dosimeters were calibrated against the SSDL working standard dosimeter (SSDL dosimeter) in accordance with the calibration procedure of the IAEA TRS No. 469 [14]. In all measurements, both dosimeters were positioned accurately at 5 g/cm^2 depth in water phantom with a 10 cm × 10 cm field size at the water phantom surface, and a source-surface distance (SSD) of 80 cm (Figure 1). The dosimeter reference point was ensured to be placed accurately at the central axis of the radiation beam. Laser lights were utilised as a guide to ease the dosimeter alignment. The water tank, with a dimension of 300 mm × 300 mm × 300 mm, was used to provide a full scatter radiation condition. To meet the IAEA Code of Practice for ^{60}Co irradiation, the water tank with a window dimension of 100 mm × 100 mm × 2 mm for the horizontal beam was used [13]. A protective sleeve was utilised for the non-waterproof dosimeters. This sleeve was designed with a 2 mm thickness to allow the dosimeter to reach thermal equilibrium with the water in less than 10 minutes and a 2 mm air gap to allow the chamber air pressure to quickly reach the ambient air pressure. The water tank and waterproof sleeve were made of polymethylmethacrylate (PMMA) with a density of 1.19 g/cm^3.

The SSDL dosimeter used in the calibration has traceability to the SSDL reference standard dosimeter, which was sent for recalibration at the IAEA Dosimetry Laboratory every three years. The periodic stability checks of the SSDL reference and working standard dosimeters were performed every four months using the ^{90}Sr source. These checks are necessary to maintain confidence in the performance of the SSDL dosimeters between calibration intervals.

Figure 1: Set-up for therapy dosimeter calibrations in terms of absorbed dose to water

Before irradiating the user dosimeter, the current absorbed dose to water rate of SSDL standard dosimeter was calculated from the value established at a reference date, taking into account the radioactivity decay of the ^{60}Co source using Equation (1).

$$\dot{D}_c = \dot{D}_r \, e^{\frac{-0.693t}{T_{1/2}}} \quad (1)$$

Where $\dot{D}_c$ and $\dot{D}_r$ indicate the current and reference absorbed dose to water rate from the ^{60}Co source, t is a time difference (in days) between two dose rate measurements and $T_{1/2}$ is a half-life of the ^{60}Co source with 1925.20 ± 0.25 d [15].

The calibration was carried out in a controlled environment with a room temperature between 23°C ± 5°C, relative humidity between 20%

and 70%, and normal atmospheric pressure to ensure reproducible results. These parameters were measured prior to and post irradiations using a traceably calibrated thermometer, hygrometer, and barometer. The thermometer was inserted well into the water phantom and hygrometer, while the barometer was placed at the control panel. The dosimeters were allowed to warm up for at least 30 minutes to ensure stability and acclimatise the dosimeter to the ambient conditions. In addition, the dosimeter's polarising potential, leakage, and radiation-induced leakage currents were verified. The leakage should be less than 0.1% of the current (nC) during measurements [14]. At least five readings were taken for each dosimeter, and the calculated standard deviation of the reading was ensured to be less than 0.1% for the SSDL dosimeter and less than 0.2% for the user dosimeter. Using the reference of temperature, T = 20 °C, and atmospheric pressure, P = 101.325 kPa, the correction for temperature and pressure was calculated. The result of calibration in terms of the absorbed dose to water calibration coefficient, $N_{D,w}$ in mGy/nC was determined as the ratio of the absorbed dose to water rate in mGy/s obtained from the SSDL working standard dosimeter, and the reading of the user dosimeter in nC/s. The calibration results are valid for 12 months [16].

2.2 Analysis of calibration coefficient provided by the SSDL and manufacturer

Typically, the client sends the new therapy dosimeter to the SSDL for calibration along with the calibration certificate provided by the manufacturer. Using this information, the percentage deviation of the calibration coefficient between SSDL and the manufacturer was calculated using Equation 2. The IAEA has set an acceptance limit of 1.5% for the results of these comparisons [14]. Considering the measurement uncertainty in the SSDL, users with results outside the limit of 2% will be not issued the calibration certificate. They were also advised to take further action to resolve the discrepancy.

$$Deviation\ (\%) = \frac{N_{D,w}(SSDL)\ -\ N_{D,w}(manufacturer)}{N_{D,w}(manufacturer)} x\ 100 \qquad (2)$$

2.3 Analysis of calibration coefficients of therapy dosimeters over years

The variation of the calibration coefficients of therapy dosimeters over a particular time for different manufacturers was investigated. The stability of a therapy dosimeter was determined by comparing the calibration coefficient from the subsequent calibration, $N_{(D,w)i}$ to the calibration coefficient from the previous calibration, $N_{(D,w)i-1}$. The equation used to calculate the stability of the calibration coefficient is shown in Equation 3. The dosimeters that were first-time calibrated in the SSDL will be not included in the calculation. According to IAEA Report 469 [14], the stability check of the calibration coefficient should not be changed more than around 0.3% from the value assigned at the most recent calibration. If not, the dosimeter should be sent for repair and/or recalibration as soon as possible.

$$Stability\ check\ (\%) = \frac{N_{(D,w)_i} - N_{(D,w)_{i-1}}}{N_{(D,w)_{i-1}}} x\ 100 \tag{3}$$

Where i denotes a subsequent calibration of the total number of calibrations.

2.4 Analysis of long-term stability of user dosimeter

The long-term stability of user dosimeters was examined based on their calibration coefficients for the absorbed dose of water, $N_{D,w}$ in ^{60}Co gamma radiation. In this work, the long-term stability was estimated for each dosimeter as a mean calibration coefficient over the total period of the calibration service in SSDL. The long-term stability, $\bar{\delta}_{N(D,w)}$ was determined using the following Equations 4 and 5 [10].

$$\bar{\delta}_{N(D,w)} = \frac{1}{\tau}\sum_{i=1}^{n-1}\left(\frac{\left|N_{(D,w)_{i+1}} - N_{(D,w)_i}\right|}{N_{(D,w)_1}}\right) \tag{4}$$

Where

$$\tau = \sum_{i=1}^{n-1}(t_{i+1} - t_i) \tag{5}$$

The i-th index represents subsequent calibrations out of a total of n calibrations. In equation 4, the modulus of changes of $N_{(D,w)}$ between subsequent calibrations, relative to the first $N_{(D,w)1}$ value, is summed and divided by a period, τ which is the sum of time intervals between the subsequent calibrations. The calibration coefficient should be stable within 0.5% over many years [14]. The correlation between long-term stability with the: (i) year of calibration; and (ii) manufacturer of the dosimeter was further assessed using the IBM SPSS Statistics Version 27.

3.0 RESULTS AND DISCUSSION

3.1 Distribution of calibrated therapy dosimeter

From 2011 to 2021, the SSDL received approximately 90 therapy dosimeters per year from 33 radiotherapy centres, including 23 private, 6 government, and 4 university hospitals. As seen in Figure 2, there was a significant increment in the number of dosimeters calibrated in the SSDL from 2011 to 2020. It is most likely due to the increased number of radiation centres in Malaysia throughout these times. The highest number of 133 dosimeters calibrated was recorded in 2020, with 122 (92%) dosimeters sent for recalibration and 11 (8%) dosimeters calibrated for the first-time. Even during the period of the COVID-19 pandemic from 2019 to 2021, we found that the return rate of dosimeters for recalibration was considered high within these periods. This situation described the medical physicist's awareness of the need to provide accurate radiotherapy to treat patients in a high-quality and safe manner. However, in 2021, as predicted, the number of dosimeters calibrated declined as a result of the Ministry of Health Malaysia’s decision to extend the validity of calibration certificates to 60 days after the expiry date during the COVID-19 pandemic’s Movement Control Order.

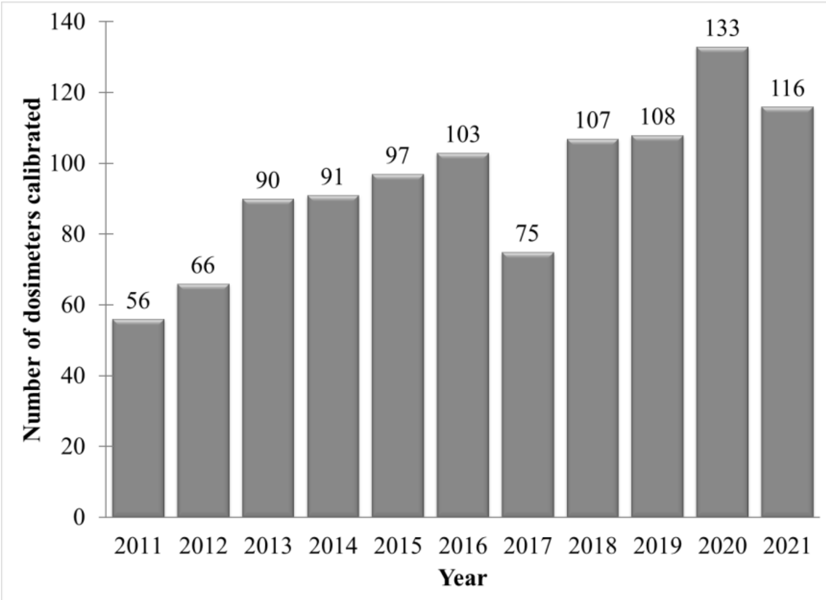

Figure 2: The number of therapy dosimeters calibrated from 2011 to 2021

Each radiotherapy centre generally has at least one therapy dosimeter to be used in routine linac quality assurance. From Figure 3, 21 radiotherapy centres have less than 6 therapy dosimeters, 9 have between 6 to 10 therapy dosimeters, and 4 have more than ten therapy dosimeters. The latter were government hospitals (3) and hospital universities (1) that we understand have many linacs installed and also a high workload for treatment and research activities. Therefore, they require several types of therapy dosimeters to support their work.

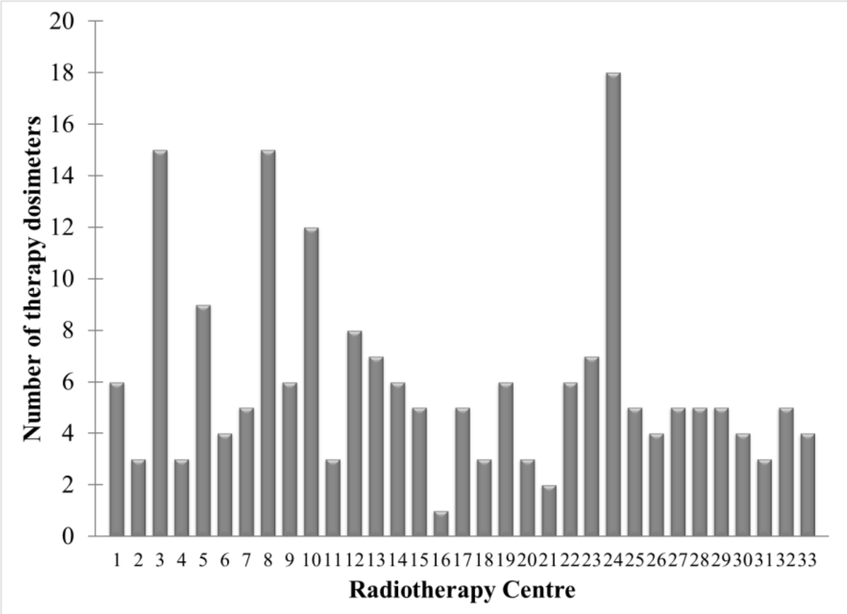

Figure 3: Number of therapy dosimeters belonging to Malaysian radiotherapy centres

3.2 Percentage deviation of SSDL and manufacturer calibration coefficients

Table 1 presents the results of the percentage deviation of calibration coefficients between the SSDL and manufacturer for user dosimeters that were first-time calibrated in the SSDL from 2010 to 2021. Most of the user dosimeters (82%) were within the IAEA's acceptance limit of ± 1.5%, while the Exradin dosimeters showed excellent results with all the dosimeters being within the acceptance limit. The user dosimeters manufactured by the PTW demonstrated that 88% of the dosimeters were within the acceptance limit, followed by NE and IBA manufactured dosimeters with 82% and 70%, respectively. These results revealed the crucial importance of calibration at local SSDL for the newly purchased therapy dosimeters before they were used in the radiotherapy centres [16]. Furthermore, Malaysia's high seasonal humidity compared to manufacturer countries may cause a significant relative response, particularly in an ionisation chamber with a hygroscopic wall [17]. A total of 170 calibration certificates (85%) were issued for the first-time calibration, and the remaining 30 dosimeters failed to get the certificate because they exceeded the SSDL's acceptance limit of ± 2%.

Table 1: The percentage deviation of calibration coefficients between the SSDL and manufacturer for user dosimeters that were first-time calibrated in the SSDL from 2010 to 2021

Manufacturer	Number of therapy dosimeters that were first-time calibrated in the SSDL from 2010 to 2021	Number of therapy dosimeters within the percentage deviation of SSDL and manufacturer calibration coefficients		
		± 1.5%[1]	± 2.0%[2]	> ±2.0%
Exradin	19	19	19	-
IBA	83	58	62	21
NE	6	5	5	1
PTW	92	81	84	8
Total	200	163	170	30

[1] IAEA's acceptance limit of ± 1.5%

[2] SSDL's acceptance limit of ± 2%

The study discovered the highest deviation between the SSDL and manufacturer calibration coefficients was given by the IBA dosimeter, at 130%. However, the result for this dosimeter was improved to 1.89% in the following year after corrective action was taken by the user. Overall, 10 dosimeters were observed to have better results within ± 2% deviation in the second-year calibration. In contrast, the remaining dosimeters pushed the results outside the limit. The low radioactivity (3.2 TBq on 14 December 2022) of the ^{60}Co source used in the calibration was identified as one of the causes of this discrepancy. For convenience, the activity of the source should be sufficient to produce an air kerma rate of not less than 0.1 Gy/min at a distance of 1 m [14]. In addition, a few user dosimeters with technical specifications were not sensitive enough to detect the low radiation dose produced by the ^{60}Co source. To address this issue, the SSDL received a new ^{60}Co source with sufficient radioactivity this year (80.97 TBq on 18 August 2022).

3.3 Variation of calibration coefficient over years

The ratios of the calibration coefficient from the subsequent calibration, $N_{(D,w)i}$ to the calibration coefficient from the previous calibration, $N_{(D,w)1-1}$ for the therapy dosimeter calibrated in the SSDL from 2012 to 2021 is presented in Figure 4. The PTW manufactured dosimeters appeared to be the highest number of dosimeters within the IAEA's acceptance limit of ± 0.3% with 33 dosimeters (42%), followed by IBA and Exradin dosimeters with 24 (33%) and 2 (17%). However, all NE dosimeters were observed to be outside the acceptable limit. Overall, the stability of calibration coefficient values ranged between 33.25% and -27.24%, with an average of 0.03% (Table 2). These findings support the significant dispersion of calibration coefficients of particular therapy dosimeters due to manufacturing differences i.e. different types of dosimeters were constructed with different chamber dimensions. [12] and [10] reported a similar trend in their studies. The calibration coefficients of PTW 30013 and NE 2571 dosimeters exhibit the least variable, followed by the Exradin A12 calibration coefficients, while the Exradin A1SL revealed the most variation among calibration coefficients [12]. Significant dispersion of calibration coefficients of particular plane-parallel chambers was observed due to more complex chamber construction than cylindrical chambers [10].

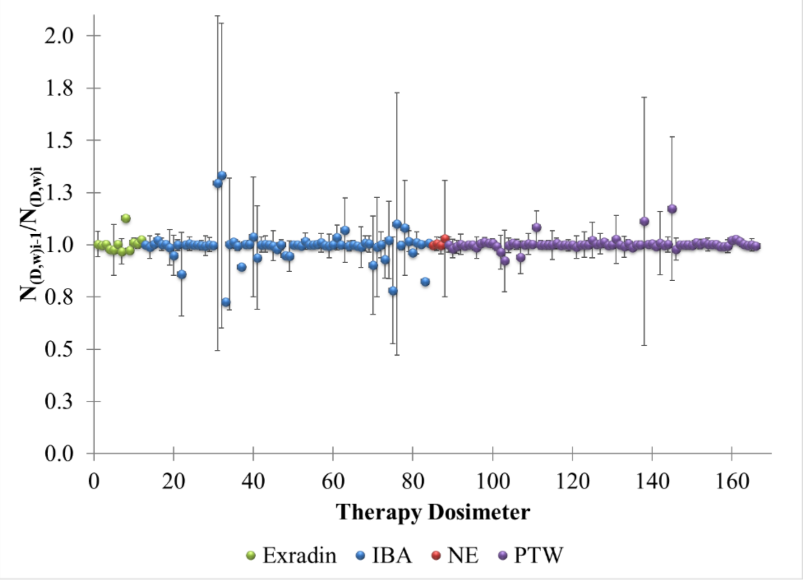

Figure 1: Ratio of the calibration coefficient from the subsequent calibration, $N_{(D,w)i}$ to the calibration coefficient from the previous calibration $N_{(D,w)i-1}$ for therapy dosimeter calibrated in the SSDL from 2012 to 2021. Error bars represent the standard deviation of the ratio

Table 2: The stability of calibration coefficients of therapy dosimeters for different manufacturers calibrated in the SSDL from 2012 to 2021

Manufacturer	Number of therapy dosimeters	Stability of calibration coefficients (%)			
		Mean	Std. Dev.	Min.	Max.
Exradin	12	0.57	4.20	-3.14	12.84
IBA	72	-0.47	7.82	-27.24	33.25
NE	4	0.71	1.61	-0.41	3.05
PTW	78	0.37	2.91	-7.69	17.31
Total	166	0.03	5.63	-27.24	33.25

It has appeared that some dosimeters have outlying calibration coefficients for a certain year of calibration, as depicted by the large error bars (Figure 5).

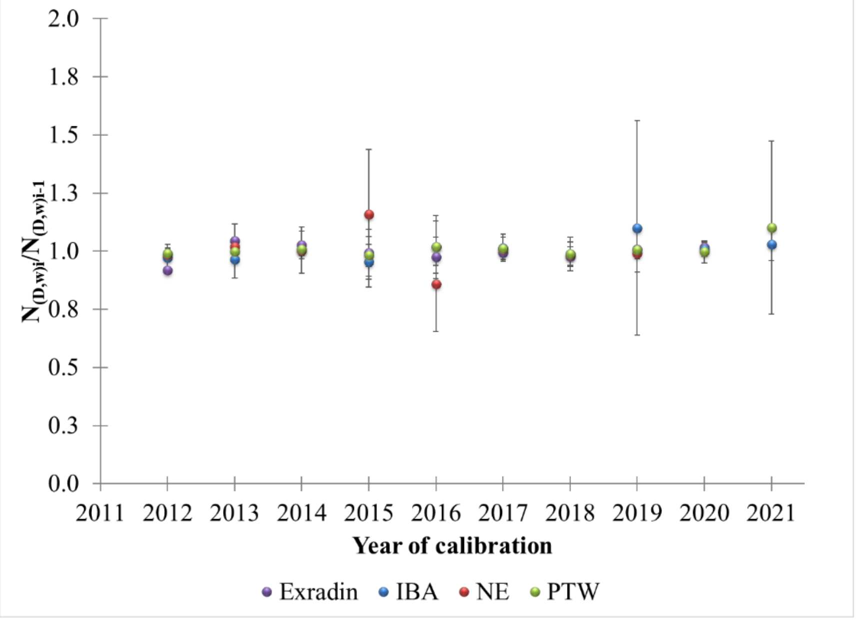

Figure 5: Variation of the ratio of the calibration coefficient from the subsequent calibration $N_{(D,w)i}$ to the calibration coefficient from the previous calibration $N_{(D,w)i-1}$ for different dosimeter manufacturers from 2012 to 2021. Error bars represent the standard deviation of the ratio

These errors most likely arise from improper handling, storage, transportation and use of the dosimeters that may result in the damage or broken of the dosimetry system. When the case was identified, additional tests were performed by the SSDL (e.g., recalibrating the dosimeter and testing the chamber with other electrometers or connecting cables). If the problem is unsolved, the abnormal behaviour was reported to the client and an investigation with the dosimeter manufacturer may need to be initiated. These findings demonstrate the importance of performing a periodic intermediate check (e.g. every month) for each calibrated dosimeter to confirm the consistency of response which could introduce confidence about the reading given in the validity calibration period [14], [18]. Moreover, these control procedures are essential either to decide whether the recalibration interval can be maintained, prolonged, or reduced or to take other appropriate corrective actions [19].

3.4 Long-term stability of user dosimeters

In Figure 6, the frequency histogram of the long-term stabilities obtained for the dosimeters is presented. As predicted, the majority (85%) of the therapy dosimeters did not fulfil long-term stabilities within the acceptance limit of 0.5%. This discrepancy could be explained by the dosimeter response drift over time heavily used and the influence of the environment during the handling, storage, transportation, and use of the dosimeters. The mean, standard deviation, minimum, and maximum of long-term stabilities calculated for different manufacturers of dosimeters are presented in Table 3. Overall, the values ranged between 0.03% and 29.83%, with an average of 3.64%. A wide range of values between 0.84% and 17.70% were obtained for NE dosimeters indicating a significant variation in long-term stabilities.

Inspection of Shapiro-Wilk, normal Q-Q plot and box plot statistics suggested that the assumption of normality was not supported for each of the three conditions. Therefore, Spearman's rank correlation, a non-parametric test, was computed to assess the relationship between long-term stability with: (i) the year of calibration; and (ii) the manufacturer of the dosimeter. The results found that there was a negative correlation between long-term stability with the year of calibration, $r(164) = -0.081$, $p = 0.302$. The small rho coefficients, r of -0.081, denote weak relationships, and the p-value of more than 0.05 shows evidence that there was no statistically significant correlation between these two variables. The results were supported by [10], who reported no trend of increase or decrease in the results throughout the observation. The same result was found for the relationship between long-term stability and dosimeter manufacturer, $r(164) = -1.47$, $p = 0.058$. These findings confirm the opinion that the therapy dosimeters should be calibrated every year, taking into account the unsatisfactory long-term stability of the dosimeters.

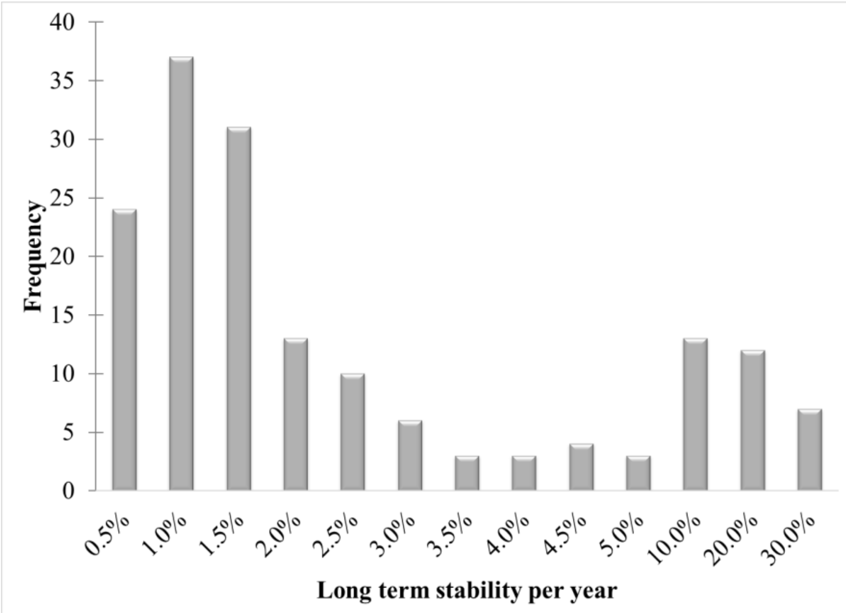

Figure 6: Distribution of the long-term stability of therapy dosimeters after calibrating several times from 2011 to 2021

Table 2: Long-term stability for different manufacturers of the therapy dosimeter

Manufacturer	Number of therapy dosimeters	Long-term stability (%)			
		Mean	Std. Dev.	Min.	Max.
Exradin	12	2.45	3.13	0.03	10.41
IBA	72	4.84	6.61	2.01	29.83
NE	4	5.55	8.18	0.84	17.79
PTW	78	2.62	4.68	0.08	26.89
Total	166	3.64	5.68	0.03	29.83

4.0 CONCLUSIONS

In conclusion, we have shown that there was a significant increment in the number of dosimeters calibrated in the SSDL from 2011 to 2021. The comparison between calibration coefficients provided by the SSDL and manufacturer demonstrates a good agreement where the majority of the user dosimeters are within the IAEA's acceptance limit of ± 1.5%. In contrast, the results of calibration coefficients and long-term stability of therapy dosimeters over these periods for different manufacturers are not satisfied with the IAEA's acceptance limit of ± 0.3% and 0.5%, respectively. Assessment of long-term stability yielded no statistically significant correlation between the year of calibration and the manufacturer of the dosimeter. The findings exhibit a clear preference for maintaining proper care and annual calibration of the therapy dosimeters.

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