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PAPER

On dosimetric characteristics of detectors for relative dosimetry in small fields: a multicenter experimental study

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Abstract

Objective. In this multicentric collaborative study, we aimed to verify whether the selected radiation detectors satisfy the requirements of TRS-483 Code of Practice for relative small field dosimetry in megavoltage photon beams used in radiotherapy, by investigating four dosimetric characteristics. Furthermore, we intended to analyze and complement the recommendations given in TRS-483. *Approach*. Short-term stability, dose linearity, dose-rate dependence, and leakage were determined for 17 models of detectors considered suitable for small field dosimetry. Altogether, 47 detectors were used in this study across ten institutions. Photon beams with 6 and 10 MV, with and without flattening filters, generated by Elekta Versa HD^{TM} or Varian TrueBeam^{TM} linear accelerators, were used. *Main results*. The tolerance level of 0.1% for stability was fulfilled by 70% of the data points. For the determination of dose linearity, two methods were considered. Results from the use of a stricter method show that the guideline of 0.1% for dose linearity is not attainable for most of the detectors used in the study. Following the second approach (squared Pearson's correlation coefficient r^2), it was found that 100% of the data fulfill the criteria $r^2 > 0.999$ (0.1% guideline for tolerance). Less than 50% of all data points satisfied the published tolerance of 0.1% for dose-rate dependence. Almost all data points (98.2%) satisfied the 0.1% criterion for leakage. *Significance*. For short-term stability (repeatability), it was found that the 0.1% guideline could not be met. Therefore, a less rigorous criterion of 0.25% is proposed. For dose linearity, our recommendation is to adopt a simple and clear methodology and to define an achievable tolerance based on the experimental data. For dose-rate dependence, a realistic criterion of 1% is proposed instead of the present 0.1%. Agreement was found with published guidelines for background signal (leakage).

1. Introduction

In 2017 the International Atomic Energy Agency (IAEA) and the American Association of Physicists in Medicine (AAPM) jointly published the TRS-483 Code of Practice: 'dosimetry of small static fields used in external beam radiotherapy; an International Code of Practice for Reference and Relative Dose Determination' (Technical Report Series No. 483) (Palmans *et al* 2018, Das *et al* 2021). One of the goals of this CoP was to improve and unify the methodology for dosimetry in small photon fields used in external beam radiotherapy. The publication of this important document was triggered by the rapid development and adoption of radiotherapy techniques such as intensity modulated radiotherapy, volumetric arc therapy, stereotactic radiosurgery and stereotactic body radiotherapy globally.

Before and after the publication of TRS-483, many experimental and theoretical studies were published, aiming to improve the dosimetry of small fields. Most of those studies were oriented towards the investigation of field output factors and detector-specific output correction factors determined by and for a variety of different detector models (Sauer and Wilbert 2007, Alfonso *et al* 2008, Dieterich and Sherouse 2011, Czarnecki and Zink 2013, Azangwe *et al* 2014, Papaconstadopoulos *et al* 2014, Gonzalez-Lopez *et al* 2015, Francescon *et al* 2017, Casar *et al* 2019, 2020, Méndez and Casar 2021, Méndez *et al* 2021). Less attention was paid to the analyzes of detectors' inherent dosimetric characteristics (IEC 60731 2011, Azangwe *et al* 2014, Laub and Crilly 2014, Lárraga-Gutiérrez *et al* 2015, Reggiori *et al* 2017, Wesolowska *et al* 2017, Akino *et al* 2020, Walter *et al* 2020, Patallo *et al* 2021, Shaw *et al* 2021).

To address this need, we initiated a multicenter experimental study involving ten radiotherapy centers, with a focus on the investigation of four dosimetric characteristics of a large number of detectors. Short-term stability, dose linearity, dose-rate dependence, and leakage were analyzed for 47 detectors representing 17 different detector models, including ionization chambers, diodes, and micro-diamond detectors. Detectors were selected such that they have small physical dimension and small active volume. They were therefore suitable for geometrical high-resolution measurements. All of them are considered appropriate detectors for small field dosimetry (Palmans *et al* 2018). In addition to their geometrical adequacy, these detectors have to fulfill several dosimetric requirements, for which TRS-483 provides guidance.

In this work, by investigating four dosimetric characteristics mentioned above, we aimed to verify whether the selected detectors satisfy the requirements of TRS-483 for relative small field dosimetry. Furthermore, we intend to complement the recommendations given in TRS-483 in the event its requirements might be considered too rigorous, or the particular verification methodology is not sufficiently defined. The methods of evaluation chosen for this study were considered to be common practice amongst clinical medical physicists in their routine work, without requiring complex laboratory equipment.

To the best of our knowledge, this is the first study to investigate dosimetric characteristics of a large number of different detector models suitable for small field dosimetry in a multicentric environment, using a single experimental protocol.

2. Methods and materials

Short-term stability, dose linearity, dose-rate dependence, and leakage were determined for 17 models of detectors considered suitable for small field relative dosimetry (table 1). These included seven models of ionization chamber, nine models of diodes, and a diamond detector. In this multicentric collaborative study, at least two complete sets of data were collected for each model of detector (table 1), following a standard protocol for this investigation. Altogether, 47 detectors were used in this study across ten institutions.

All measurements, with the exception of leakage measurements, were performed in 3D computer-controlled water phantoms, IBA Blue Phantom (IBA Dosimetry, Schwarzenbruck, Germany) or PTW MP3 tank (PTW, Freiburg, Germany), using reference class electrometers PTW Unidos or IBA Dose 1. The nominal polarizing voltage was applied to ion chambers while no voltage was applied to semiconductor diodes and diamond detector following the manufacturer's recommendations. The measurements were performed in the center of the square radiation field of size 4×4 cm^2, defined by either MLC and jaws (Elekta) or jaws only (Varian), using an isocentric set-up, a depth of 10 cm (effective point of measurements), and a gantry angle of 0° (SSD = 90 cm). These were considered to be experimental reference conditions for this study. The center of the reference radiation field was defined at the midline of full width half maximum beam profiles, determined by the in-line and cross-line scans at the measurement depth of 10 cm. In this study, 6 and 10 MV photon beams, with (WFF) and without (FFF) flattening filters, generated by Elekta Versa HD^{TM} (Elekta AB, Stockholm, Sweden) or Varian TrueBeam^{TM} (Varian Medical Systems, Palo Alto, CA) linear accelerators, were used. To minimize potential signal fluctuations originating from linear accelerator (linac) output variation, an ionization chamber (IC) having a sufficiently large cavity volume (PTW Semiflex or IBA CC13) was used as a reference detector. This

Table 1. Summary of basic characteristics and properties of the detector models included in this study.

Ionization chambers

Detector model	#[a]	Cavity volume [cm^3]	Cavity length/radius [mm]	Wall material	Wall thickness [g/cm^2]	Central electrode
IBA CC003 nanoRazor	2	0.003	/1.0[b]	C552	0.176	Graphite
IBA CC01	3	0.01	3.6/1.0	C552	0.088	Steel
IBA CC04	2	0.04	3.6/2.0	C552	0.070	C-552
PTW 31006	3	0.015	5.0/1.0	PMMA + Graphite	0.085	Steel
PTW 31014	3	0.015	5.0/1.0	PMMA + Graphite	0.085	Aluminium
PTW 31016 PinPoint 3D	2	0.016	2.9/1.45	PMMA + Graphite	0.085	Aluminium
SI Exradin A16	2	0.007	2.4/1.2	C552	0.088	Steel

Solid state detectors

Detector model		Active volume dimensions [mm]	Sensitive material	Material density [g/cm^3]	Z_{eff}	Reference[c] point [mm]
IBA EFD diode	3	Disc, Ø 1.6 thickness 0.08	Silicon	2.33	14	1.2
IBA PFD diode	2	Disc, Ø 1.6 thickness 0.08	Silicon	2.33	14	1.2
IBA Razor diode	2	Disc, Ø 0.6 thickness 0.02	Silicon	2.33	14	0.8
IBA SFD diode	3	Disc, Ø 0.6 thickness 0.06	Silicon	2.33	14	0.8
PTW 60008 Diode P	3	Disc, Ø 1.2 thickness 0.03	Silicon	2.33	14	2.0
PTW 60012 Diode E	4	Disc, Ø 1.2 thickness 0.03	Silicon	2.33	14	0.8
PTW 60017 Diode E	2	Disc, Ø 1.2 thickness 0.03	Silicon	2.33	14	1.3
PTW 60018 Diode SRS	2	Disc, Ø 1.2 thickness 0.25	Silicon	2.33	14	1.3
PTW 60019 mD	5	Disc, Ø 2.2 thickness 0.001	Synthetic diamond	3.53	6	1.0
SNC EDGE detector	4	Square 0.8 × 0.8 thickness 0.03	Silicon	2.33	14	0.3

[a] Number of detectors of the same model but different serial number, used in the study.

[b] Detector has a spherical cavity shape.

[c] Reference point is measured from the tip of the solid-state detector, with the stem orientation parallel to the beam axis. For IBA and Sun Nuclear detectors the data represent geometrical distance, while for the PTW detectors, the data represent water equivalent thickness.

was placed in the corner of the 4×4 cm^2 radiation field approximately halfway between the linac head and water surface in the phantom. To ensure stable response of detectors, each detector was pre-irradiated with 5 Gy before every measurement session. Before and after each set of measurements, the stability of linac output was checked with Farmer model reference class IC, which was also used to verify the reference detectors short-term reproducibility. All linear accelerators used in the study had similar outputs for all beams; calibrated so that 100 MU approximately corresponds to 1 Gy in the local reference conditions according to the relevant 'dosimetry protocol' used at each Institution. During measurements, pressure and temperature were monitored, and charge readings were corrected for environmental conditions, if necessary.

The orientation of detectors with respect to the beam's central axis was consistent with the recommendations of TRS-483, for relative dosimetry in small photon beams. The orientation of ionization chambers was such that the long axis (direction of central electrode) of the chamber was oriented perpendicular to the beam central axis. Diodes and micro-diamond detectors were oriented with their stem parallel to the beam central axis, except for the SNC EDGE diode which due to its design, was positioned with its stem perpendicular to the beam central axis.

With the exception of the leakage data, the acquired data were analyzed in two ways: with and without using the signal from the reference IC. Specific measurement conditions and methodology for the four investigated characteristics of detectors are provided in the following subsections.

Finally, we grouped and analyzed the individual results collected at different centers for each particular detector model to verify whether their dosimetric characteristics satisfy the requirements stated in the TRS-483.

Verification of tolerance limits can only be assessed if the uncertainties of the acquired data are adequately low compared to the tolerance limits being evaluated. Therefore, we calculated the uncertainty for each data point through error propagation, and estimated the expected absolute uncertainty $\langle u \rangle$ ($k = 1$) associated with a data point as the median uncertainty of all data points.

2.1. Stability

For each photon beam quality, each detector was sequentially irradiated ten times with 100 MU under the experimental reference conditions mentioned above.

For 6 and 10 MV WFF beams, dose rates (DR) were $DR = 500$ MU min^{-1}. It should be noted that, strictly speaking, MU/min is a unit of repetition rate. However, we use the common term dose rate instead throughout the text.

For 6 and 10 MV FFF beams with Elekta linacs, DR was nominally 1400 and 2000 MU min^{-1} respectively.

For Varian linacs, DR was 1400 MU min^{-1} for 6 MV FFF beams, whereas it was 2400 MU min^{-1} for 10 MV FFF beams.

Stability was calculated as the coefficient of variation (relative standard deviation) (IEC 60731 2011) for a single detector and selected energy, separately for each of the participating centers, as shown in equation (1)

$$\text{Stability deviation (\%)} = 100 \cdot \frac{\sigma}{\mu}, \tag{1}$$

where $\sigma = \text{st.dev.}(M_i)$ and $\mu = \text{mean}(M_i)$. M_i was calculated as $M_i = m_i/m_{i,ref}$, if the measurements with the reference IC were considered, and $M_i = m_i$, if the measurements with reference IC were not considered. m_i and $m_{i,ref}$ represent single readings obtained with a particular detector and reference IC, respectively.

The number of analyzed data points was one for each combination of energy, detector and institution (one data point was obtained from ten consecutive readings). Since we used four different beam qualities, there were four data points altogether per single detector. This number has to be multiplied by the number of detectors with different S/N and of the same model (see table 1) to get the total number of data points being analyzed.

2.2. Linearity

Since TRS-483 CoP does not provide specific guidance or methodology for determining dose linearity, we used two different approaches for the calculation of linearity, denoted as Linearity A and Linearity B.

Dose linearity was evaluated for the following number of MUs [5, 10, 20, 30, 50, 100, 200, 300, 500, and 1000] for four available photon beam qualities.

Nominal dose rates were 500 MU min^{-1} for 6 and 10 MV WFF while for FFF beams dose rates were 1400 and 2000 MU min^{-1} for 6 and 10 MV FFF beams at Elekta linacs, while at Varian linacs dose rates were 1400 and 2400 MU min^{-1} for 6 and 10 MV FFF beams, respectively.

2.2.1. Linearity A

The formalism recommended in '*IEC* 60731 *Medical Electrical Equipment—Dosimeters with Ionization Chambers as Used in Radiotherapy*' (IEC 60731 2011) was used for the determination of the linearity metric, measuring the deviation from linearity, as

$$\text{Linearity } A(\%) = 100 \cdot \left(\frac{M_i}{M_{\text{avg}}} - 1\right) \tag{2}$$

where $M_i = m_i/m_{i,ref}$ and the index i represents a measurement for a given number (N_i) of MUs.

m_i is the ith measurement (single reading); performed for a given number (N_i) of MUs (e.g. $N_1 = 5$ MU, $N_2 = 10$ MU etc) at a particular center, for the selected detector, energy combination, and

$m_{i,ref}$ is the corresponding measurement with reference IC.

For analysis of measurements without reference IC consideration, $M_i = m_i/N_i$ was used in the equation (2), where N_i denotes the number of given MUs for the ith measurement.

M_{avg} was defined as the average value of all M_i.

Ten data points were analyzed for each combination of energy, detector, and institution. Four different beam qualities were considered, resulting in 40 data points in total per detector. This number has to be multiplied by the number of detectors with different S/N and of the same model (see table 1) to get the total number of data points being analyzed.

2.2.2. Linearity B

In the alternative approach, the correlation of the measurement's m_i and N_i (without reference chamber), and m_i and $m_{i,\text{ref}}$ (with reference chamber) is used to represent the Linearity. The Pearson's correlation coefficient (r^2) was used as a measure of linearity; the difference between this measure and the ideal value ($r^2 = 1$) for truly linear relationship quantifies the deviation from linearity. We considered that the pass criterion of 0.1% was satisfied if $r^2 > 0.999$.

2.3. Dose rate dependence

The influence of dose rate on the delivery of a reference output was investigated. The reference output was defined as that obtained for a 100 MU exposure under the experimental reference conditions.

To determine the degree of dose rate dependence, each detector and reference IC were irradiated three times in the four available photon qualities, using two different DRs; denoted as DR_{min} (minimal DR) and DR_{max} (maximal DR) as available on the specific linacs used.

For 6 and 10 MV WFF beams: dose rates were $DR_{\text{min}} = 100$ MU min^{-1} and $DR_{\text{max}} = 500$ MU min^{-1}.

For 6 and 10 MV FFF beams, DR_{min} was 100 MU min^{-1} For Elekta linacs, DR_{max} was nominally 1400 and 2000 MU min^{-1}, for 6 and 10 MV FFF beams respectively.

For Varian linacs, DR_{min} was 400 MU min^{-1} for both 6 and 10 MV FFF beams and DR_{max} was 1400 MU min^{-1} for 6 MV FFF beams, whereas it was 2400 MU min^{-1} for 10 MV FFF beams.

The degree of DR dependence DR_{dep}, on the delivery of the reference output was defined by equation (3), *based on the formalism from* '*IEC* 60731 *Medical Electrical Equipment—Dosimeters with Ionization Chambers as Used in Radiotherapy*' (IEC 60731 2011)

$$DR_{\text{dep}}(\%) = 100 \cdot \left(\frac{M_i}{M_{\text{avg}}} - 1\right), \tag{3}$$

where $M_i = m_i/m_{i,ref}$. m_i denotes the ith measurement (single data point) performed in a particular center for the selected detector, energy, and each selected DRs, while $m_{i,ref}$ are the corresponding reference IC simultaneous measurements.

If measurements with reference IC were not considered, the expression $M_i = m_i$ was used in the equation (3).

M_{avg} was defined as the average value of all relevant ratios $m_i/m_{i,ref}$, i.e. $M_{\text{avg}} = \text{mean}(m_i/m_{i,ref})$ when we included measurements with reference IC, and as the average of all values m_i, i.e. $M_{\text{avg}} = \text{mean}(m_i)$ when measurements with reference IC were not taken into account.

Three data points were analyzed for each combination of energy, detector, dose rate, and institution. Four beam qualities, each at two different dose rates were considered, resulting in 24 data points in total per detector. This number has to be multiplied by the number of detectors with different S/N and of the same model (see table 1) to get total number of data points being analyzed.

2.4. Leakage

Leakage (background signal as defined in TRS-483) was determined for all studied detectors by measurements of accumulated charge in the integral mode of the electrometer. Reference class electrometers, PTW Unidos or IBA Dose 1, were used in this part of the study. The zeroing procedure was performed before every charge measurement. Three consecutive measurements for 60 s were acquired. The magnitude of leakage was determined by equation (4) as ratio (%/Gy) of leakage to a reference output obtained under reference conditions, each acquired over 60 s. The measurement for the denominator was approximated by using data

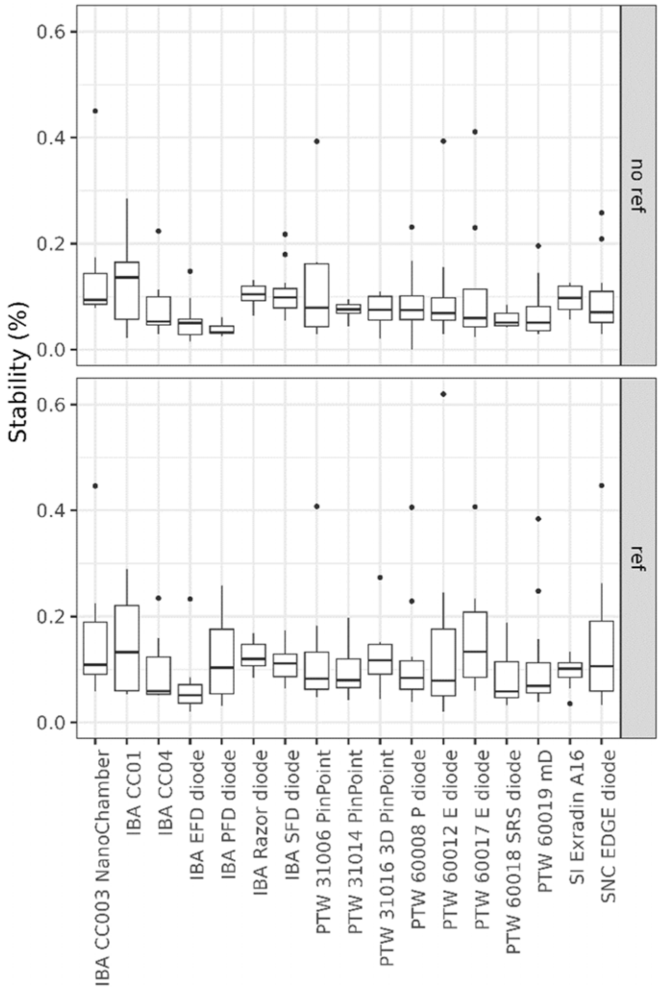

Figure 1. Short-term reproducibility (stability) for 17 detector models displayed in box plots with whiskers extending to 1.5*IQR. Two options are displayed: when reference chamber readings were taken into account (denoted as *ref*) and when those readings were not considered (denoted as *no ref*).

extracted from the stability assessment for 6 MV WFF beams which were obtained for a 100 MU exposure (corresponding to 1 Gy) at the nominal $DR = 500$ MU min^{-1}; the factor of 5 is used to simulate measurement acquisition over 60 s

$$\text{Leakage } (\%/Gy) = 100 \cdot \frac{l}{5 \cdot M}, \tag{4}$$

where l is the average value of a single background signal measurement l_i, i.e. $l = \text{mean}(l_i)$, while $M = \text{mean}(m_i)$. Measurements m_i were extracted from the data sets for stability assessment for 6 MV WFF beams obtained at the nominal $DR = 500\ MU$.

One data point was analyzed per detector. This number has to be multiplied by the number of detectors with different S/N and of the same model (see table 1) to get total number of data points being analyzed. However, for graphical presentation of the results in box plots, all three measurements for each data point are presented in the figure 4.

3. Results

Measurement results are presented in figures 1–4 in terms of distributions of values of collected data from the participating centers for the four investigated characteristics for each of the 17 detector models (47 different detectors in total). All results are rounded to two decimal places.

The distributions of measured values are displayed in box plots in which the central horizontal line signals the median value of the particular distribution, while the lower and upper hinges of the box correspond to the 25th and 75th percentiles, and therefore contain the interquartile range (IQR). The whiskers extend from the hinges to 1.5*IQR and outliers are plotted individually.

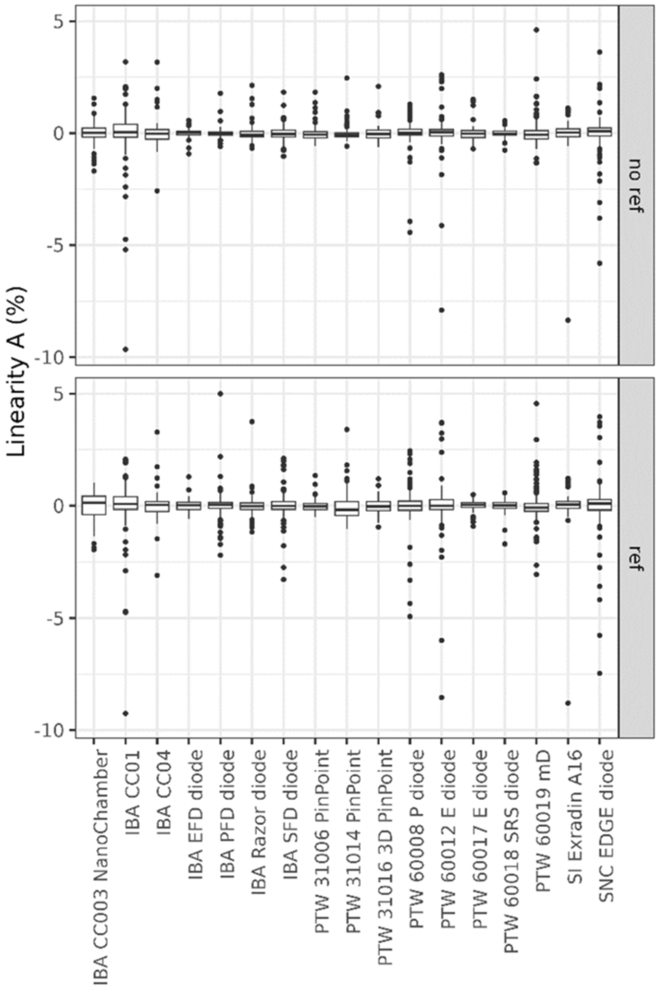

Figure 2. Data for dose linearity (Linearity A) for 17 detector models displayed in box plots with whiskers extending to 1.5*IQR. Two options are presented: when reference chamber readings were taken into account (denoted as *ref*) and when those readings were not considered (denoted as *no ref*).

Collected data for stability, dose linearity, and dose-rate dependence are presented and analyzed for two distinct approaches: when reference chamber readings were considered (denoted as *ref* in the corresponding figures) and when those readings were not considered (denoted as *no ref* in the corresponding figures). For additional information, we calculated the average values of medians for each of the investigated detector characteristics taking into consideration all examined detector models.

At this point we note, that observed outliers and, in general the non-Gaussian distribution of the obtained data, led us to the decision to present the results in box plots rather than using average values and standard deviations or uncertainties.

3.1. Short term stability

When reference IC data were considered, the median values for stability ranged from 0.05% to 0.13%. The average value of all 17 median values was 0.09% (1 STD = 0.03%). The smallest IQR was 0.03%, while the largest IQR was 0.16%.

In the case that reference IC measurements were not taken into account, the median values for stability ranged from 0.03% to 0.14%. In that case, an average value of all median values was 0.07%. The smallest IQR was 0.01%, while the largest IQR was 0.12%.

Grouped data for all investigated detectors are presented in figure 1.

3.2. Linearity

3.2.1. Linearity A

When measurements with reference IC were considered, the absolute values of median values for dose linearity range from 0.01% to 0.18%. The average value of all 17 median values was 0.05% (1 STD = 0.05%). The smallest IQR was 0.21%, while the largest IQR was 0.80%.

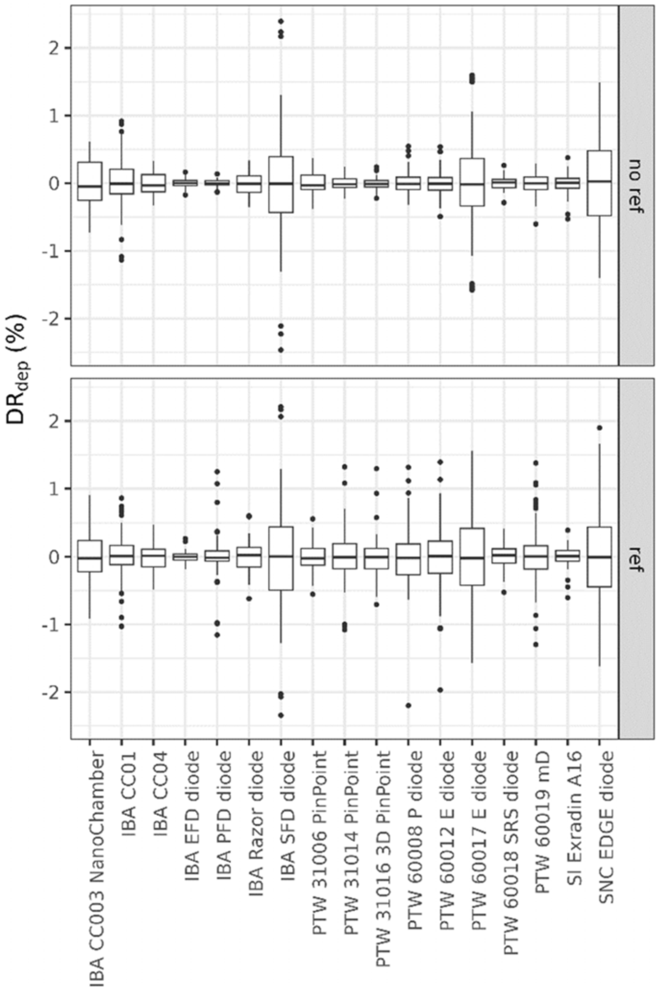

Figure 3. Data for dose-rate dependence for 17 detector models displayed in a box plot with whiskers extending to 1.5*IQR. Two options are displayed: when reference chamber readings were taken into account (denoted as *ref*) and when those readings were not considered (denoted as *no ref*).

If reference IC measurements were not taken into account, the absolute values of median values for dose linearity ranged from 0.01% to 0.09%. In that case, the average value of all median values was 0.04% (1 STD = 0.03%). The smallest IQR was 0.15%, while the largest IQR was 0.58%.

A graphical presentation of the results is shown in figure 2.

3.2.2. Linearity B

In this case, we used the Pearson's coefficient of correlation r^2 for the determination of dose linearity. Measurement results showed that $r^2 > 0.999$ for all 17 detectors for both examined data sets—with and without consideration of the reference IC data.

3.3. Dose rate dependence

Following the adopted methodology for determining dose-rate dependence, we found that the absolute values of median values ranged from 0% to 0.03%, in the case when measurements with reference IC were taken into account. The average value of all 17 median values was 0.01% (1 STD = 0.01%). The smallest IQR was 0.09%, while the largest IQR was 0.94%.

Similar results were also obtained in the case that reference IC measurements were not considered: the absolute values of median values ranged from 0.00% to 0.05%, while the average value of all median values was 0.01% (1 STD = 0.01%). The smallest IQR was 0.06%, while the largest IQR was 0.96%.

Results are shown in box plots in figure 3.

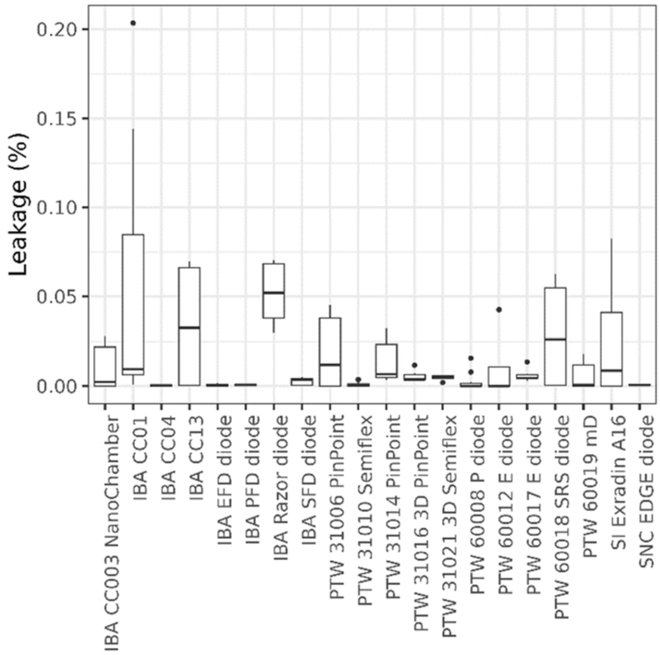

Figure 4. Data for leakage displayed in a box plot (with whiskers extending to 1.5*IQR) for each of the 17 tested detector models.

3.4. Leakage

Leakage was determined using equation (4). In this case, we had only one set of results since we did not perform measurements with reference IC. Median values ranged from 0.00% to 0.05% with an average value 0.01% (STD = 0.01%). The smallest IQR was 0%, while the largest IQR was 0.08%.

Results are shown in figure 4 as box plots.

4. Discussion

We have conducted a multicenter study to determine and evaluate the short-term stability, dose linearity, dose-rate dependence, and leakage of 17 models of detector (47 detectors) suitable for relative small field dosimetry. The primary goal of our work was to investigate whether these detectors fulfill pertinent guidelines (requirements) published in the TRS-483 CoP (Palmans *et al* 2018).

It is important to mention certain decisions in our study concerning the analysis of the results. Since the detector models were not equally represented in the analysis (refer to column 2 in table 1), differences in the inherent characteristics of the detectors may introduce bias. However, assessing the significance of the differences in dosimetric characteristics between different detectors would require a different approach involving a unique measuring institution, which was not the case in our study. For this reason, and considering the dispersion of the distributions shown in figures 1–4, we assigned equal weight to all data points in this study. Additionally, we chose to evaluate the characteristics of detectors without distinguishing between ICs and solid-state detectors. The achievable tolerances (see tables 2–4) would be slightly different if ICs were considered separately from solid-state detectors. Nevertheless, we considered all detectors equally suitable for small field dosimetry (Palmans *et al* 2018).

In general, the results presented in this work regarding detector characteristics such as short-term stability, dose linearity, and dose-rate dependence are slightly worse for measurements of output readings corrected using a reference IC than for uncorrected readings. This outcome suggests that the fluctuation of linac outputs may be very small compared to the uncertainty (noise) associated with the reference IC and the latter produces more variation in the ratio of signal to reference than the inherent variation in the signal. While this is an interesting finding and might lead one to conclude that there is no need for or benefit to using a reference IC for such measurements, we do not recommend this approach, as it is essential to consider the possibility of occasional substantial linac output variations.

In the following sections we suggest that the present data demonstrates achievable tolerances and provide recommendations for tolerance criteria that could be used in the clinics and in future Codes of Practice. These assertions are made given that the present study was a multi-center study performed by medical physicists from ten participating centers. The participants of this study represent a group that use equipment (linacs and

Table 2. Percentage of data points in bold, which fall within 0.1% tolerance for stability (TRS-483 guidance), taking into account the collected data from all 47 detectors. Other columns show the tolerances (%) t75, t90, and t95, which are fulfilled by 75%, 90%, and 95% of all collected data. Data are presented separately for two cases: when readings with reference IC were taken into account (ref IC) and when those data were ignored (no ref IC). Expected absolute uncertainties of the data points with a coverage factor $k = 1$ are $\langle u \rangle = 0.022\%$ (ref IC) and $\langle u \rangle = 0.017\%$ (no ref IC).

	Tolerance [%]			
	0.1	t75	t90	t95
Ref IC	**55.2**	0.15	0.23	0.27
No ref IC	**70.9**	0.11	0.16	0.22

Table 3. Percentage of data points in bold, which fall within 0.1% tolerance for dose linearity (TRS-483 guidance), considering collected data from all 47 detectors. The columns show the tolerances (%) t75, t90, and t95, which are fulfilled respectively by 75%, 90%, and 95% of all collected data: first part (columns 2–5), where data for 5 MU were considered and second part (columns 6–9) when the results for 5 MU were not taken into account. Data are presented separately for two cases: when data obtained with reference IC were considered (ref IC), and when we ignored those data (no ref IC). Expected absolute uncertainties of the data points with a coverage factor $k = 1$ are $\langle u \rangle = 0.097\%$ (ref IC) and $\langle u \rangle = 0.076\%$ (no ref IC).

Ref IC MU	Tolerance [%]				Tolerance [%]			
	0.1	t75	t90	t95	**0.1**	t75	t90	t95
5	**10.5**	0.99	2.19	3.94	/	/	/	/
10	**15.7**	0.66	1.16	2.06	**14.5**	0.68	1.16	2.12
20	**27.9**	0.40	0.61	0.95	**27.9**	0.41	0.65	0.97
30	**34.3**	0.27	0.48	0.77	**35.5**	0.27	0.47	0.83
50	**40.7**	0.24	0.38	0.58	**45.3**	0.19	0.29	0.36
100	**39.0**	0.26	0.46	0.79	**49.4**	0.19	0.35	0.55
200	**29.1**	0.31	0.53	0.95	**43.0**	0.24	0.37	0.60
300	**33.1**	0.30	0.66	1.09	**39.5**	0.23	0.43	0.74
500	**27.3**	0.36	0.81	1.05	**33.1**	0.29	0.50	0.84
1000	**23.3**	0.44	0.90	1.31	**25.6**	0.38	0.60	1.00
No Ref IC MU	Tolerance [%]				Tolerance [%]			
	0.1	t75	t90	t95	**0.1**	t75	t90	t95
5	**9.9**	1.06	1.99	3.70	/	/	/	/
10	**18.0**	0.45	0.93	1.35	**15.7**	0.48	0.92	1.65
20	**36.0**	0.27	0.43	0.55	**31.4**	0.28	0.44	0.55
30	**42.4**	0.22	0.33	0.46	**47.1**	0.19	0.31	0.38
50	**44.2**	0.23	0.41	0.57	**62.8**	0.14	0.23	0.29
100	**45.3**	0.25	0.41	0.63	**58.7**	0.16	0.25	0.34
200	**43.0**	0.24	0.48	0.62	**58.1**	0.16	0.27	0.41
300	**43.6**	0.23	0.45	0.62	**55.8**	0.17	0.25	0.43
500	**41.9**	0.23	0.45	0.76	**54.7**	0.18	0.30	0.50
1000	**36.6**	0.27	0.49	0.82	**41.9**	0.24	0.40	0.57

detectors) calibrated and maintained according to differing recommendations given by different national and international bodies. Whereas, single data sets should not be considered as definitive, these results represent a collection of meaningful estimates of achievable results and are therefore considered as reasonable benchmarks.

4.1. Stability

The TRS-483 guidance for stability states that the short-term detector response should be better than 0.1%. While our results are very close to the 0.1% tolerance (figure 1), this requirement has not been met by many detectors within the detector models used in the study. Less rigorous tolerance than stated in TRS-483 would be perhaps more appropriate, assuming that the investigated detectors are otherwise suitable for small field dosimetry.

Table 4. Percentage of data points in bold, which satisfies 0.1% tolerance for dose-rate dependence (TRS-483 guidance), taking into account collected data from all 47 detectors. The last three columns show the tolerances (%) t75, t90, and t95, which are fulfilled respectively by 75%, 90%, and 95% of all collected data. The 'ref IC' in the table represent data that were obtained by considering reference IC readings; the 'no ref IC' represent data acquired when reference ionization chamber data was not taken into account. Expected absolute uncertainties of the data points with a coverage factor $k = 1$ are $\langle u \rangle = 0.100\%$ (ref IC) and $\langle u \rangle = 0.078\%$ (no ref IC).

	Tolerance [%]			
	0.1	t75	t90	t95
Ref IC	**34.1**	0.39	0.78	1.08
No ref IC	**46.3**	0.25	0.50	0.88

In table 2, we show the percentage of measured data which fulfill a certain tolerance. We see that the tolerance level of 0.1% is fulfilled by 55.2% data points when reference chamber readings were considered, and 70.9% data points if the reference chamber readings were ignored.

If we accept that a reachable tolerance is the one, which is fulfilled by 90% data points (t90), we see that the corresponding tolerances are 0.23 and 0.16% (penultimate column in table 2). Therefore, it may be prudent to propose a more achievable but less stringent stability criterion of 0.25%. Such a criterion is both strict enough on the one hand and more realistic on the other considering our results.

4.2. Linearity

In the TRS-483 CoP, the guidance for dose linearity states that the detector response should be better than 0.1% over an absorbed dose range of at least three orders of magnitude. However, neither the document nor the document cited therein, *IPEM Small Field Dosimetry* (Aspradakis *et al* 2010) gives guidance or a methodology to calculate this. In addition, the origin of the 0.1% requirement remains unidentified and is not evidenced.

4.2.1. Linearity A

Following the first method (adapted IEC methodology), the present results, based on grouped data from all centers, show that our data for linearity are far from the TRS-483 CoP tolerance for dose linearity. This observation holds for all dose values from 5 to 1000 MU, as shown in table 3. We found the largest deviations for the lowest number of MUs, i.e. 5 and 10 MU, which can be attributed to the higher signal uncertainty at the lowest irradiation times.

If an acceptable tolerance is considered as one which is satisfied by 90% of all data points (denoted as t90), then the present data will suggest tolerances that range from 0.38% to 2.19% applying reference chamber corrections, and from 0.33% to 1.99% without reference chamber corrections, considering all irradiation times (number of MUs) used in our study. If measurements with 5 MU are excluded, t90 tolerances range from 0.29% to 1.16% when measurements were corrected by the reference chamber reading, and from 0.23% to 0.92% without correcting the detector reading by the reference chamber reading.

The present results suggest that a linearity tolerance of 0.1% is not achievable when the methodology described as Linearity A is followed. Based on the observed pronounced non-linearity at low doses and calculated levels of achievable linearity (t90 in table 3), it would be reasonable to adopt a less stringent criterion for dose linearity, namely around 1.0% tolerance. In addition, we suggest to exempt the lowest exposure of 5 MU (which is considered acceptable from a clinical perspective) and test the linearity over an absorbed dose range of two orders of magnitudes instead of three orders as recommended in the TRS-483 CoP.

Since many factors influence the measurements at the lowest dose below 0.1 Gy (irradiation MUs $\leqslant$ 10 MU in our case), further investigation is warranted for dose linearity for the smallest doses.

4.2.2. Linearity B

In the second approach, a less strict approach was used for the determination of dose linearity using the squared Pearson's correlation coefficient r^2. Assuming that the pass criterion of 0.1% is satisfied if $r^2 > 0.999$, the present results show that all detectors fulfill that condition even if the lowest MU data are not excluded. However, it should be noted that the r^2 approach is less sensitive than the previous methodology (Linearity A). Therefore, some detector characteristics might remain hidden.

Table 5. Percentage of data points in bold, which fall within 0.1% tolerance for leakage (TRS-483 guidance), taking into account collected data from all 47 detectors. Last three columns show the tolerances (%) t75, t90, and t95, which are satisfied respectively by 75%, 90%, and 95% of all collected data. Expected absolute uncertainties of the data points with a coverage factor $k = 1$ is $\langle u \rangle = 0.00071\%$.

Tolerance [%]			
0.1	t75	t90	t95
98.2	0.01	0.04	0.06

Table 6. Stability, linearity, and dose rate dependence for PTW 60019 mD detector model as reported by four research groups.

	Stability	Linearity	Dose rate dependence
Ciancaglioni *et al* (2012)	<0.5%	<0.5%	<0.5%
Lárraga-Gutiérrez *et al* (2015)	<0.2%	0.999 ± 0.07%[a]	<0.2%
Reggiori *et al* (2017)	<0.3%	<0.5%	<0.8%
Shaw *et al* (2021)	<0.2%	<0.5%	<0.7%

[a] To obtain the linearity, a quasi-linear equation $y = a \cdot x^b$ was used to fit the data in this study. Value b has been reported as the parameter assessing the linearity.

4.3. Dose rate dependence

Guidance given in TRS-483 stipulates that the detector's response should be better than 0.1% within the range of dose rates under which a linear accelerator operates. The present results show that all detectors exhibit low dose-rate dependence (see figure 3). Therefore, they could be considered as dose-rate independent. If it is assumed that the tolerance criterion is one that is satisfied by 90% of all data points, then a tolerance levels between 0.5% and 1.0% (see table 4) will be indicated by the presented data. However, these levels are larger than the 0.1% recommended in TRS-483 CoP. It seems reasonable to recommend tolerance levels that can be achieved experimentally for a wide range of detectors that are used in the clinical environment.

4.4. Leakage

Measured background readings were found to lie well within the TRS-483 guideline, which requires that the leakage signal should be at least three orders of magnitude lower than the detector response per Gy. Close inspection of the present results shows that 90% of all data points (t90) obtained experimentally by the 47 detectors fall within 0.04%, which is well below the 0.1% tolerance level (table 5). Hence, the present results validate the TRS-483 guidance for background signal as achievable criterion. The data also confirm the suitability of the investigated detectors for relative dosimetry in small fields.

Several experimental studies have been published in the past, where authors reported on the dosimetric characteristics of detectors suitable for small beam dosimetry. Experimental conditions, methodology, and statistical approaches differ among studies, as well as from those used in our study. Additionally, many of these studies examined only one or two detector models. Nevertheless, to facilitate a rough comparison of the previously published results with our work, we present the results of four studies for three dosimetric properties (stability, linearity, and dose rate dependence) in table 6 for the PTW 60019 mD detector—a model that has garnered considerable attention in the past decade.

5. Conclusions

Throughout the study, a criterion for tolerance for a given dosimetric characteristic (short-term stability, linearity, dose rate dependence, and leakage) was considered meaningful and achievable if 90% of all data points obtained in the present study lie within the criterion. The experimental methods chosen for the present study are simple and can be performed easily in most clinics and do not require any special laboratory equipment.

While agreement was found with published guidelines for background signal (leakage), the same was not true for the other three investigated dosimetric characteristics.

For short-term stability (repeatability), it was found that the 0.1% guideline could not be met, although the present results are very close to the specified value. Nevertheless, it is proposed that a less rigorous, but realistic, criterion of 0.25% be adopted for short-term stability.

For the determination of dose linearity, two methods were considered for the evaluation of detector response. Results from the use of a stricter method (adapted from IEC approach), show that the guideline of 0.1% for dose linearity is not attainable in the tested MU range from 5 to 1000 MU (approximately 0.05–10 Gy) for most of the detectors used in the study. This is an important finding, which implies that the published guideline might be too stringent. Following the second approach (approach based on the application of squared Pearson's correlation coefficient r^2), it was found that 100% of the data fulfill the criteria $r^2 > 0.999$, which implies that a 0.1% guideline can be considered reasonable and achievable. In the absence of any guideline for the preferred calculation methodology for the determination of linearity by TRS-483, it is not clear what method should be used for the determination of dose linearity. It is recommended that a simple practical methodology be adopted, and the associated tolerance value recommended for the determination of dose linearity.

Analysis of the present dose-rate dependence data show that 90% of the data met 1% tolerance criteria. While such a tolerance can be considered acceptable for clinical purposes, it is far from the recommended 0.1% guideline. It was found that such a strict criterion is unfeasible for most of the small field detectors included in the study. Therefore, it is recommended that a less stringent criterion of 1% (instead of 0.1%) be adopted for dose-rate dependence.

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Data availability statement

We have a large amount of data which are available upon reasonable request. The data cannot be made publicly available upon publication because they are not available in a format that is sufficiently accessible or reusable by other researchers. The data that support the findings of this study are available upon reasonable request from the authors.

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