Characterization of small active detectors for electronic brachytherapy dosimetry

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Abstract: Three active detectors, Exradin A26 chamber, IBA RAZOR Nano chamber, and PTW 60019 microDiamond, were characterized for their use in electronic BrachyTherapy (eBT) dosimetry. The detectors were calibrated in terms of air kerma using the ISO “N” (narrow) and “TW” (therapy) X-rays series from 7.5 kV to 100 kV. The responses to mono-energetic photons and their uncertainties were determined with Bayesian parameter estimation, assuming a model that incorporated smoothness via a spline function. The response functions obtained this way are consistent with 18 calibration qualities simultaneously. This approach improves on the traditional procedure of associating the response to the mean energy of the corresponding spectra. The energy responses (with uncertainties) were obtained in 0.25 keV energy steps from 6 keV to 70 keV. With differences in magnitude due to their sizes and the nature of their active volumes, the energy responses of the 3 detectors follow a similar relative behaviour. Even when the response is far from flat at low energies, i.e. below about 20 keV, the determination of reliable energy dependence curves enables the use of these detectors for dosimetry in the vicinity of eBT units. The angular dependence of the three detectors with respect to beam incidence was also measured in air in a 180° range in steps of 10° using the Zeiss INTRABEAM system (50 kV). For both energy and angular response characterization, the detectors axis were aligned in parallel with the beam axis (end-on), since this is the expected orientation in further measurements of absorbed dose distribution in water around eBT sources at PTB. This work is an effort to provide traceability for detectors and measurement procedures for the determination of 3D dose distributions as part of the ongoing European EMPIR project “Primary standards and traceable measurement methods for X-ray emitting electronic brachytherapy devices” (PRISM-eBT).

Keywords: Detector alignment and calibration methods (lasers, sources, particle-beams); X-ray detectors; Diamond Detectors

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# 1 Introduction

Electronic brachytherapy (eBT) uses miniaturized X-ray sources instead of radionuclides as an alternative in HDR (high dose rate) intracavitary and intra-operative irradiations and the treatment of skin lesions. The key factors driving eBT acceptance and fast market pace include portability of the unit, reduced shielding requirements, possibility to switch the devices off with no leakage radiation, reduced dose to treating staff, no radioactive waste, and no need to deal with regulatory issues of safety and security of radioactive sources.

The dosimetry of eBT systems rely on individual calibration tools and procedures outlined by the manufacturer, as primary laboratories do not provide calibration in terms of absorbed dose to water. The reported uncertainties in dose delivery in IORT applications for example are typically of the order of ±10−15 % (standard uncertainty, i.e. $k = 1$) [1] which are larger than clinically acceptable. Since the dosimetry procedures depend on the characteristics of particular units, it is difficult to establish standardized clinical protocols common to all of these systems and similar problems arise when conducting clinical assays involving eBT of different technologies. The lack of a dosimetry consensus limits a more extensive utilization of this treatment modality. To ensure that these systems can achieve their full clinical potential, their calibration and spatial dose distributions around the source need to be traceable to a primary standard laboratory.

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These current difficulties are being addressed in the ongoing European project “Primary standards and traceable measurement methods for X-ray emitting electronic brachytherapy devices” [2], which has the overall objective of carrying out pre-normative research on eBT to simplify and harmonise dosimetric procedures and provide metrological input to standardisation bodies. Under this framework, one of the contributions of the Physikalisch-Technische Bundesanstalt (PTB) is the characterisation of small online detectors for 3D dose distribution measurements in water and traceable dosimetry for the end user community.

In response to some of these same issues, the American Association of Physicists in Medicine (AAPM) created Task Group No. 292 — “Electronic Brachytherapy Dosimetry” [3]. Currently, there are either no formal recommendations of the AAPM for dosimetry standards, formalisms, or protocols for eBT [4], and this task group has been asked to make recommendations on a NIST-traceability source strength determination for eBT and on appropriate methods to measure and calculate dose distributions surrounding the sources, goals which are in line with the European efforts within PRISM-eBT. The TG-292 also raised the dosimetry concern of the substantial uncertainties associated with the manufacturer-provided dose rates which stem from beam hardening, detector geometry, and selection of the point-of-measurement for a given ion chamber [5]. This aims at the study of suitable detectors for absolute and relative dosimetry of eBT systems.

The abrupt fall-off in dose may result in a (highly desirable) reduced dose to the surrounding normal tissues as compared to Ir-192 sources [6]. But these advantages at the same time complicate the dosimetry. In addition to the already remarkable inhomogeneity of dose distribution characteristic of brachytherapy, there is an even sharper dose fall near eBT sources due to the low energy photon spectrum emitted. Unlike megavoltage photon beams, the higher absorption of low energy photons in water causes significant hardening of the spectrum as depth increases (even by only a few millimetres) with the resultant variation in detector’s response.

In external kV therapy, most dosimetry protocols used by calibration laboratories for soft X-rays (i.e., energies below 100 kV) are based on measurements of reference air kerma rate or source strength at 1 m distance from the source in air, later converted to absorbed dose to water at 1 cm distance in water and using the backscatter factor (TG-61 [7], NCS-10 [8], IAEA-TRS-398 [9]). For these qualities, plane parallel ionization chambers are considered the gold standard detectors due to their flat energy response.

When measuring in water, the wall of a waterproof detector absorbs most of the low energy end of the photon spectrum (below approximately 10 keV). Since low energy photons hardly reach the cavity (or the active volume) of the detector, the response in this energy region can be extremely low. Therefore, the energy dependance curve of the detector needs to be precisely determined. Furthermore, the detectors are designed to measure different eBT X-ray devices (with and without fitted clinical applicators) in a variety of photon spectra, and this also corroborates the need for detailed energy characterization.

In this study, the suitability of small active detectors to measure 3D dose distributions around electronic miniature X-ray sources was assessed. Two micro ion chambers were selected: the Exradin A26 and the IBA RAZOR Nano, and the synthetic microDiamond PTW 60019. The energy response of these detectors has been extensively investigated for megavoltage therapy but not for the low X-ray range.

The excellent behavior of the microDiamond detector for small beam dosimetry of high energy beams has led to investigations of their use for other energy ranges. For example, Damodar et
al. [10] studied the suitability of 60019 for X-ray dosimetry in the range from 50 kV to 125 kV (around the upper limit of eBTs) and concluded that the percentage depth doses measured with the 60019 generally match within 1% with MC calculation for a wide range of energies and field sizes. Butler et al. [11] characterized the active region of 60019 using kilovoltage synchrotron radiation and determined the dimensions of the active volume to be within 0.2 mm in agreement with the manufacturer’s nominal size. Khan et al. [12] studied the energy dependence (for both air-kerma and absorbed dose to water) of the PTW microDiamond 60019 in moderately filtered kilovoltage X-ray beams (M-series). They also checked for the required pre-irradiation dose, dose-rate linearity and percent depth dose. Recently, Kaveckyte et al. [13] calibrated three 60019 detectors in terms of air-kerma free in air in six X-ray beam qualities (from 25 kV to 250 kV) and compared the energy responses with MC simulations. One finding of this publication is the notable inter-detector variation of response at low energies. Although all these studies indicate the microDiamond as a candidate detector for the eBT energy range, its remarkable energy response dependence and inter detector variability in the low energy region needs further investigation.

The knowledge of the angular and energy dependance in air of active detectors at low energy X-ray beams may have a collateral interest in the dosimetry of other applications like radiobiological irradiators, where the need for standardized procedures have been identified [14, 15].

1.1 Materials and methods

1.2 The X-ray source for energy response

To investigate the energy response below 100 kV, the three detectors were calibrated using the “N” (ISO 4037-1) and “TW” (DIN 6809-4) X-ray calibration series of the PTB. The characteristics of these qualities, and international equivalence are available at the PTB website [16] and summarized in table 1. A comprehensive description of the PTB X-ray calibration qualities can be found in the compilation by Ankerhold [17].

Both “N” and “TW” series are obtained at the same facility by changing the high voltage applied to the generator and the filtration. The X-ray tube is a W anode MG165 [18]. This is a universal stationary single-pole direct voltage X-ray system with voltage range 7.5 kV to 160 kV and reproducibility of the tube current ±2 μA. The beam is shaped by apertures and circular collimators and a transmission-type monitor chamber is used to normalize the X-ray output (more details in the following section).

The spectra at the calibration distance of 30 cm (measured previously) of the “N” and “TW” series were supplied by the PTB calibration laboratory and are shown in figure 1 and figure 2 respectively. During calibration the detectors are fixed to a motorized workbench to adjust the source detector distance and to alternate the detectors in front of the radiation beam. The readings are automatically corrected by \( k_{TP} \) (no humidity correction was applied).

1.3 The X-ray source for angular response

The compact mobile X-ray unit INTRABEAM 500 XRS (Carl Zeiss Meditec AG, Jena, Germany) system [19] was used as radiation source to study the angular response. The 3 detectors under analysis in this work will be used to measure dose distribution in water around the INTRABEAM in a second phase of this research. The original concept of this miniature electron accelerator was
Table 1. Calibration qualities used for the energy characterization of detectors: the PTB “A”, i.e. ISO “N”, narrow series I108 (ISO 4037-1) and PTB “TW” therapy series (DIN 6809-4).

| Code  | Tube voltage | Added filter | 1st HVL | \(E_{\text{mean}}\) (air kerma) |
|-------|--------------|--------------|---------|--------------------------------|
|       | kV           | mm Al        | mm Cu   | mm Al | keV |
| A-7.5 | 7.5          | —            | —       | 0.02  | 6.1 |
| N-10  | 10           | 0.1          | —       | 0.05  | 8.1 |
| N-15  | 15           | 0.5          | —       | 0.16  | 11.9 |
| N-20  | 20           | 1.0          | —       | 0.35  | 15.7 |
| N-25  | 25           | 2.0          | —       | 0.67  | 19.6 |
| N-30  | 30           | 4.0          | —       | 1.18  | 23.9 |
| N-40  | 40           | 4.0          | 0.21    | 2.67  | 32.4 |
| N-60  | 60           | 4.0          | 0.60    | 5.93  | 46.9 |
| N-80  | 80           | 4.0          | 2.00    | 9.99  | 65.0 |
| N-100 | 100          | 4.0          | 5.00    | 13.10 | 84.1 |
| TW10  | 10           | —            | —       | 0.03  | 6.6 |
| TW15  | 15           | 0.05         | —       | 0.07  | 9.0 |
| TW20  | 20           | 0.15         | —       | 0.11  | 10.8 |
| TW30  | 30           | 0.5          | —       | 0.36  | 16.4 |
| TW40  | 40           | 0.8          | —       | 0.74  | 21.2 |
| TW50  | 50           | 1            | —       | 0.94  | 24.2 |
| TW70  | 70           | 4            | —       | 2.94  | 37.4 |
| TW100 | 100          | 4.5          | —       | 4.41  | 47.2 |

Figure 1. Fluence spectra of the PTB “N” calibration series (normalized to the maximum of the bremsstrahlung).

developed in 1996 by Dinsmore et al. [20], Beatty et al. [21], and Biggs and Thomson [22] and further descriptions of the INTRABEAM appear in several sources, for example, Eaton [23], Ebert [24], and Hensley [1]. Figure 3 shows the appearance of the INTRABEAM source and a local QA radiograph.
Figure 2. Fluence spectra of the PTB “TW” calibration series (normalized to the maximum of the bremsstrahlung).

Figure 3. Photo of the INTRABEAM source, and a local QA radiograph of its needle.

The electrons are accelerated at 40 or 50 kV and travel within the needle to strike a concave gold transmission target at the tip. The thickness of the gold layer has been measured at PTB to be 17 μm at the locus where the electron beam hits [25]. Thus, the emerging photon spectrum (of mean energy about 25 keV) consists of the bremsstrahlung with the superposition of gold characteristic lines. A typical dose rate at 1 cm distance in water of the INTRABEAM at 50 kV, 40 μA is 3.48 Gy/min. In preliminary irradiations, the stability of the INTRABEAM output with this technique was found to be within ±1 % for a long-term irradiation of 3 hours.

Before any irradiation a QA procedure is mandatory and for this purpose the unit uses a diode array (PDA) to verify the dynamic offset of the electron beam and another separate device (PAICH) with a PTW plane parallel 23342 ion chamber to check the output stability. The QA procedure is described in the Zeiss supplied user manual and in the report of AAPM TG-182 [26].
The needle shape of the unit allows the add-on of a variety of clinical applicators including intraoperative. To study the angular dependence, the bare needle (3.2 mm in diameter and 10 cm long) was used without additional applicators attached.

1.4 The detectors

The detectors studied are Exradin A26 (Standard Imaging, Middleton, WI, U.S.A.), microDiamond 60019 (PTW, Freiburg, Germany), and RAZOR Nano Chamber (IBA, Schwarzenbruck, Germany), see figure 4. The three detectors are robust, waterproof and have been used before to resolve high gradient dose regions. Their main characteristics are shown in table 2.

1.4.1 Exradin A26

The Exradin A26 is a fully guarded chamber designed to meet reference class criteria from IEC 60731 and TG-51 [27]. According to the manufacturer, its uniform 4.3 mm diameter spot size was conceived to reduce: a) the volume averaging effects, b) the ion recombination, c) the polarity effect, and d) the angular dependency.

1.4.2 IBA RAZOR Nano

With an active volume of 3 mm³, this chamber (also coded CC003) is the smallest ion chamber in the market at the moment of this research, which was a strong motivation to consider it. There are currently only a few publications on the IBA RAZOR Nano Chamber and its response at low kV X-ray energies. Results on the use of this detector for megavoltage small beam dosimetry have been published by Looe [28] and Wegener and Sauer [29].

Table 2. Main characteristics of the detectors according to the manufacturer.

| Characteristic                          | Exradin A26 | IBA RAZOR Nano | PTW microDiamond |
|----------------------------------------|-------------|----------------|------------------|
| Short name                             | A26         | RN             | mD               |
| Type                                    | Ion chamber | Ion chamber    | Synthetic diamond (C) |
| Density, g/cm³                          | -           | -              | 3.53             |
| Inner electrode                         | C-552, Shonka, 1.76 g/cm³ | Graphite-EDM3 |
| Outer electrode, density                | C-552, Shonka, 1.76 g/cm³ | C-552, Shonka, 1.76 g/cm³ |
| Collecting volume                       | 0.015 cm³  | 0.003 cm³      | 0.004 mm³        |
| Chamber stem, g/cm³                     | Aluminium, 2.70 | PEEK, 1.32     | -                |
| Diameter of inner electrode, mm        | 0.76        | 1.0            | -                |
| Outside diameter of shell, mm           | 4.3         | 3.0            | -                |
| Centroid of the collecting volume (from tip), mm | 1.98          | 1.4            | 1.0              |
| Inner diameter of outer electrode, mm  | 3.3         | 2              | -                |
| Shell wall thickness, mm                | 0.5         | 0.5            | -                |
| Nominal/Maximum polarizing voltage, V   | 300/1000    | 300/400        | 0/0              |
| Nominal leakage currents, fA            | 10          | 3              | -                |
| Diameter of active volume, mm           | 3.3         | 1.0            | 2.2              |
| Length of active volume, mm             | 2.24        | 2.0            | 0.001            |
| Length, mm                             | 78          | 49             | 45.5             |
| Diameter, mm                           | 6.36        | 10             | 7                |
1.4.3 PTW 60019 microDiamond detector

The microDiamond detector (PTW 60019, Freiburg, Germany) is a single crystal synthetic micro diamond detector that works on the principle of a diode with a metal/p/p+- doped diamond Schottky barrier. The concept originated at the University of Rome “Tor Vergata” laboratories. As explained by Almaviva et al. [30], a multilayered structure is obtained in a two-step precise deposition process. A diamond layer doped with boron is first obtained by chemical vapor deposition on a low-cost single crystal diamond substrate. A further diamond layer (as a sensitive layer) is later grown. The active surface is then connected with aluminum contacts. An active region of 2.23 mm in diameter × 2 μm thick was experimentally determined by Poppinga [31] et al. using the PTB 10 MeV proton microbeam facility. The PTW 60019 has been used in small-field dosimetry of high-energy photon (including stereotactic therapy) and electron beams. Its use has expanded to kV X-rays beam and even to synchrotron radiation dosimetry [32, 33]. This later application, published by Livingstone et al., resulted in a dosimetry protocol for synchrotron radiation based on this particular detector.

![Figure 4](image-url) The three detectors used in this work. From left to right: Exradin A26, IBA RAZOR Nano and PTW microDiamond (Photo and radiograph).

1.5 Response to low energy photon beams

The responses of the A26, mD 60019 and RAZOR Nano Chamber to low energy photon beams were measured in terms of air kerma. The irradiations were performed using both the narrow “N” and therapy “TW” X-ray quality series of PTB. These spectra extend from 7.5 kV to 100 kV covering the typical energy range of eBT units. The characteristics of the “N” and “TW” series used for the calibration were shown above in table 1.

A schematic view of the experimental set-up is given in figure 5. The values of air kerma free-in-air were measured by means of PTB’s primary standard for air kerma PK100 [34]. Technical data of the PK100 parallel-plate ionization chamber can be also found at the PTB website [35]. The irradiations were performed at the shortest possible distance from the source (30 cm) for a better dose rate given the relatively low response of these detectors at this energy range.

In a motorized bench, the detectors and the reference chamber were positioned in such a way to ensure the same source-detector distance when they are moved to the beam axis. As illustrated
Figure 5. Sketch of the experimental set-up for the measurement of the energy response. The bidirectional arrow indicates that any of the detectors showed at the left can be moved into the irradiation spot of the calibration X-ray keeping the same distance from the X-ray focal spot to the detector effective point of measurement.

with the arrow in figure 5, any of the detectors can be aligned to the radiation beam. So, using the same set-up, two detectors can be calibrated by switching their position in front of the beam with the reference chamber (PK-100). Although it is not usual in ion chamber calibration, the stem axis of the detectors were aligned parallel to the beam axis since this is the expected orientation in their future utilization around eBT units at PTB. As for the effective point of measurements (EPOM) of the detectors, in the absence of a better approximation for low photon energies, the recommendations of the manufacturers were taken (1.98 mm, 1.4 mm and 1 mm from the detector tip for the A26, RAZOR Nano and microDiamond respectively). The determination of the exact EPOM for this low energy range will be the subject of a future investigation.

The charge is collected by two Keysight B2987A high precision (femtoamperes) electrometers \[36\] and an in-house software controls all the steps of the experiment: (1) Change of X-ray quality, (2) movement of the selected detector to the irradiation spot, (3) beam on and off, (4) record of the readings and (5) correction of the readings.

The calibration factors of the detectors for each quality were obtained in terms of air kerma per charge in units of Gy/C and referred to standard conditions of air temperature, pressure and relative humidity of $T = 293.15$ K, $P = 101.325$ kPa and $h = 50\%$.

1.6 Determination of the energy response

For the determination of the energy response for mono-energetic photons with respect to the quantity air kerma, we had available measurements of the narrow (N) and therapy (TW) X-ray calibration series of PTB. To estimate the response curve from such measurements, it has been common practice to disregard the finite energy distribution of the photon spectra and to simply associate
each of the measured responses to the mean energy of the corresponding spectra. This approximate procedure provides a series of point data that can then be fitted to a smooth curve to estimate the required response function. The approach however is not optimal because the photon beams are not delta functions; rather, in some cases, they have long tails that extend far from the value of the mean energy of the photon spectrum (See the shape of calibration spectra in figure 1 and figure 2). Thus, this commonly used approach can lead to errors in the response functions, in particular for the energy region where the response function changes rapidly, which is a region that is of particular interest.

Thus, instead of using the procedure outlined in the previous paragraph, we used a different approach [37] based on Bayesian parameter estimation which took into consideration all the measurements of the “N” and “TW” series simultaneously, providing a total of 18 measurements for the response function. This allowed us to have a response function that is consistent with the all the measurements together with an uncertainty estimate which is provided in a natural way by the Bayesian approach.

To model the response function, we used a smooth spline function and estimated the optimal parameters of the spline using a Bayesian approach. More precisely, we used a one-dimensional radial basis function (RBF) thin plate spline (TPS) as described by Lodha and Franke [38]. This leads to a parametrized model [39] of the form:

\[
R(E) = A_1 + A_2E + \sum_{k=1}^{n} B_k (E - E_k)^2 \ln(|E - E_k|)
\]

where \(R(E)\) is the response function, \(E\) is the photon energy, \(A_1, A_2,\) and \(B_k\) are parameters that are determined from the experimental data, \(E_k\) is the value of energy assigned to the centers of the spline, and \(n\) is the number of measurements in the narrow (N) X-ray calibration series. We placed centers at each of the mean energies associated with the spectra of the (N) series.

We used the TPS parameterized model for the energy range \(6\,\text{keV} < E < 70\,\text{keV}\). While it is necessary to take into account photon energies of up to 100 keV for the analysis, we only report responses to 70 keV because the constraints on the model from the data become weaker as we approach the boundary value of 100 keV with the result that an estimation of the response above 70 keV becomes less reliable. As we expect the response to flatten out at higher energies, we have assumed in the model that the response becomes constant for \(E>75\,\text{keV}\), to prevent the onset of oscillations in the response evaluation at higher energies (which often happens in spline models as you approach a boundary or extrapolate). Below 6 keV, the information from the measurements was not strong enough to determine the shape of the response and therefore it is not reported.

The calculations were done using the software WinBUGS [40], which is well suited for the implementation of our model. The likelihood and prior distributions were chosen as follows. For each measurement \(N_k\) of a photon spectrum \(\varphi_k(E)\) belonging to the narrow (N) or therapy (TW) X-ray calibration series, the response function must satisfy the relations

\[
N_k \sim \int R(E)\varphi_k(E)\,dE
\]

where the use of the tilde (rather than an equal sign) indicates that one expects agreement only to within experimental uncertainties. This relation between counts, spectra, and response function
was used to define the likelihood function. The uncertainty in the measurements is due to counting statistics (of type A, less than 0.2%) to which we added by quadrature the contributions from additional sources of experimental uncertainty (of type B, which we estimated to be of the order of 2%). There were enough measurement counts for the Gaussian approximation to be valid. Therefore, we chose a Gaussian likelihood function for each data point. We assigned uninformative reference priors to the parameters $B_k$ of the model. For parameters $A_1$ and $A_2$, which determine the asymptotic behavior of the response (i.e., at higher photon energies), we used mildly informative priors to guide the model so it would match what is known of the response at photon energies above 50 keV from both Monte Carlo simulations and previous measurements.

The uncertainties of the responses were derived from the posterior distributions that are the outcome of the Bayesian analysis.

1.7 Angular dependence of detectors in air

Knowledge of the angular behavior of detectors helps in the selection of an appropriate one for the subsequent 3D dose distribution measurements, even though for these measurements in the water tank the detector axis will be always aligned with the radiation source (parallel orientation). To determine the angular dependence of the 3 candidate detectors, they were irradiated in air with the INTRABEAM at 50 kV. A collimator of $\Theta 10$ mm was applied to the beam in order to reduce variations in stem effects at different angles. With the aid of a rotating table, the orientation angle was changed in the range $0^\circ$ to $180^\circ$ and the charge was read with the aid of a SuperMAX™, Standard Imaging electrometer. The charge was collected for 90 s at $10^\circ$ intervals. Figure 6 shows a diagram of the experimental arrangement to measure the angular dependence of the detectors. The source, collimator and detector were aligned with the aid of a pair of lasers (front and back). A source detector distance of 145 mm was chosen for the three batches of irradiation.

![Figure 6. Diagram of the experimental set-up to measure the angular dependence of the detectors at the INTRABEAM 50 kV spectrum. The detector (at the left) is rotated around its effective point of measurement and the signal recorded every $10^\circ$ in the range ($-90^\circ$, $90^\circ$) respect to the beam axis (dimensions in mm, not to scale).](image)
2 Results

2.1 Response functions of the detectors

The response functions for the A26 chamber, for the microDiamond and for the RAZOR Nano Chamber, derived using the Bayesian approach are shown in figure 7. The range of energies studied is the same for the 3 detectors. Although the magnitude of the response differs substantially among the 3 detectors (quite different active volumes), the shape of the curves is similar. The uncertainties of the responses were derived from the posterior distributions that are the outcome of the Bayesian analysis. For all detectors, the average of the relative uncertainty over the full energy range of the response was 2% (standard deviation). This value is probably a lower limit, as changes to the model of $R(E)$ (for example, by increasing the complexity of the model by adding more parameters to it) could lead to somewhat different results.

![Figure 7](image-url)

**Figure 7.** Air kerma response (fitted splines as lines) of the Exradin A26 ion chamber (A26), IBA razor nano chamber (RN) and PTW micro-Diamond detector (mD) in the interval from 6 keV to 70 keV. The symbols (labeled “msrd”) represent the measured response at the indicated series. The right axes accounts for the response normalized to N-30 (30 kV narrow beam). The 95% coverage intervals of the fitted splines are also shown.
2.2 Detectors angular response

The angular response of Exradin A26, PTW 60019 microDiamond and IBA RAZOR Nano Chamber under INTRABEAM spectrum at 50 kV were measured in air using the experimental arrangement described previously in figure 6. The charge readings were normalized over the value of the signal when the detector is irradiated at 0° (parallel incidence). The results are shown in figure 8.

3 Discussion

As expected, the three detectors show a strong energy dependence in the very low photon energy range (below 25 keV). Due to the different size and nature of the active volumes, the energy response of the 3 detectors is obviously different in magnitude. Figure 7 shows the response of the 3 detectors, the 3 curves follow a similar behaviour, and two energy regions can be identified in the graph: 1) above approximately 25 keV the dependency is smooth and relatively flat, which is a desired behaviour for any detector and 2) the response diminishes abruptly for energies below 25 keV due to absorption in the detector wall.

![Figure 8. Angular dependence (from -90° to 90°) of the A26, RAZOR Nano and microDiamond measured in Tair. Response to the INTRABEAM at 50 kV normalized to the value at 0° (parallel incidence) with, collimated beam (Ø 1 cm) at source detector distance 145 mm.](image)

The response at qualities N-15, N-20 and N-25 (green dots in the interval from 10 keV to 20 keV in figure 7) measured for the RAZOR Nano and for the microDiamond, show some fluctuations and therefore inflexion points are observed in the response curve in this interval. This is most probably because of the materials used near the active volume of the detector or to impurities that
Figure 9. Orthogonal radiographs of the microDiamond PTW 60019. Note the asymmetry in the electric contacts near the active volume.

abruptly changes the interaction cross sections at this range due to photo-absorption edges of these materials. A physical explanation of this curious behaviour would require a better knowledge of the construction details of these two detectors. Repeating the calibration with other detectors of the same kind and/or the Monte Carlo simulation of their interaction with monoenergetic photon beams could help to clarify this apparent anomaly.

From 25 keV to 70 keV the responses of the microDiamond and the RAZOR Nano Chamber changes gradually by about 20% while the A26 chamber exhibits a more uniform energy response in this region. The responses measured at both series and associated to an average energy (location of the symbols in the graphs) are plotted for orientation. Due to the procedure followed to get the response curves (explained previously), these points do not necessarily match with the fitting, which is more evident at the lower qualities of TW because the shape of the spectra in that region: especially, the symbols for TW10 and TW15 (below 10 keV) are slightly above the curves while the symbols for TW40 and TW50 (between 20 keV and 25 keV) are located slightly below the curves. The reason is the combination of two circumstances: firstly, the rather broad energy spectra of the radiation qualities of the “TW” series compared to those of the “N” series, see figure 1, and secondly, the strong energy dependence of the responses. As outlined above, the response curves represent the responses to mono-energetic photons. As the “TW” spectra have significant contributions besides of their mean energies (symbols in the graphs) those contributions are weighted according to the energy response. I.e., for the TW10 and TW15 spectra their mean response contains significant contributions from energies to the right of their symbols with rather large responses resulting in a larger mean response compared to the corresponding response of a mono-energetic photon at their mean energy resulting the symbols placed slightly above the curves. Likewise, the TW40 and TW50 spectra contain significant contributions from energies to the left of their symbols with rather small responses resulting in a smaller mean response compared to the corresponding response of a mono-energetic photon at their mean energy resulting the symbols being slightly below the curves.

As for the angular response, the two ion chambers showed an angular variation of around 3 % (A26) and 6 % (RAZOR Nano) when the incidence angle varied from parallel (0°) to perpendicular (90°) with respect to the beam axis. The A26 exhibits a flat response over the whole range while the RAZOR Nano starts to deviate beyond 2 % for angles outside ±40°. Contrary to the active volume construction of the micro ion chambers, the geometry of the solid-state active volume of the microDiamond detector is far from spherical and a flat response in air while varying the incidence angle is not expected. We found that its response deteriorates beyond 3 % when the angle opens outside ±20° (see figure 8) and account for up to 30 % in the total angular range covered ± 90°. This is attributed to its flat (φ2.2 mm × 1 μm thick) active volume and the presence of metal contacts that disrupts the radial symmetry of the detector [41]. The position of the electric metal contacts of
the microDiamond 60019 detector can be seen in the two orthogonal radiographs of figure 9. A detail pointed out by Hartmann and Zink [42] about this detector is the different back scatter effect of electrons from the diamond substrate into the sensitive volume as the incidence angle changes.

The relatively high angular response dependence in air at the INTRABEAM X-ray quality that we measured for the microDiamond differs from similar studies conducted in water, and published, for example by Lárraga et al. [43] who found 1% deviation in the response when going from 0° to 40°, but in a completely different experimental setting of 5 cm depth in water and for megavoltage photon beam.

4 Conclusions and outlook

The Exradin A26 chamber, IBA RAZOR Nano chamber and PTW 60019 microDiamond detector have been characterized in terms of their energy and angular response to low energy X-ray beams in air. The absolute air kerma dependence was determined by calibrating the three detectors in both “N” and “TW” PTB X-ray series (18 qualities in total). The angular dependence of these detectors was measured at intervals of 10° from 0° to 180° with the INTRABEAM at 50 kV and reported relative to the aligned (0°) incidence.

From the three detectors, only the PTW microDiamond has been calibrated before in the kilovoltage range (UWADCL at M-series from 40 kV to 100 kV [12] and at Swedish SSDL from 25 kV to 250 kV [13]), but to the best of our knowledge, this is the first time in which a dosimetry laboratory publishes the X-ray energy response of the Exradin A26 and the RAZOR Nano micro chambers together with the microDiamond detector, in the range from 6 keV to 70 keV.

The Bayesian approach used in this work to determine the energy response to mono-energetic photons, that considers all the calibration qualities simultaneously, has a methodological value. The procedure can be expanded to other energy ranges and to other detectors and may lead to the creation of a detector-wise library avoiding the need of the user to re-calibrate the instrument for every new application and energy range.

The three detectors are promising candidates for 3D dose measurements in water around eBT sources. In particular, the Exradin A26 chamber exhibits an excellent angular response and a more flatter energy response to X-ray beams from above 20 keV. This conclusion may be of interest also in the dosimetry of other low energy X-ray beam applications, like radiobiological irradiators.

As mentioned earlier, the responses were determined with respect to the quantity air kerma. As in (brachy)therapy, the measurement in water is of interest, the responses to the quantity absorbed dose to water are required. For their determination, a set a detector-dependent Monte Carlo calculated correction factors are being computed which will be the subject of a subsequent study.

Even when the response is far from flat, the knowledge of a reliable energy dependence curve allows the use of these detectors in the dosimetry of low photon energies. For a measurement in water, the photon spectrum prevailing there can be estimated (by Monte Carlo calculations for example) and the overall (averaged) response obtained by its convolution with the response function for mono-energetic photons. Such a procedure would enable these detectors to be used for the dosimetry around eBT units or in other applications of low energy X-ray conventional beam (as cell culture or small animal irradiators).
The characterization of detectors suitable for electronic brachytherapy dosimetry and the further 3D dose data collection contribute to the validation, commissioning, acceptance testing and/or quality assurance of 3D brachytherapy treatment planning systems.

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Data availability statement. The program written to obtain the energy response curves of the detectors is subject to the journal open access policy and will be also available at the share point of PRISM-eBT project.

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