

The development of a cylindrical phantom for nanoDot™ calibration with multiple beam angles

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ARTICLE INFO

Article history:

Received 27 October 2023

Accepted as revised 22 December 2023

Available online 10 January 2024

Keywords:

Calibration factor, calibration phantom, nanoDot™, OSLD calibration

ABSTRACT

Background: The nanoDot™ dosimeter, an optically stimulated luminescent dosimeter (OSLD), is compact and precise, ideal for various applications like radiation dosimetry. The nanoDot™ requires calibration before use with the detector alignment perpendicular to the central beam axis. It exhibits angular dependence that may impact the calibration factor, requiring the fabrication of a specific cylindrical phantom for the calibration procedure.

Objective: This study aimed to develop a cylindrical phantom for nanoDot™ calibration to facilitate dose measurements in composite fields with various beam angles and to evaluate the nanoDot™ calibration factors for different plans.

Materials and methods: The cylindrical phantom was constructed using cast nylon material to accommodate the nanoDot™ or a cylindrical ionization chamber (IC). The novel phantom underwent validation for physical characteristics, including dimensions, density, and uniformity. Validation for the calibration factor, using cylindrical phantom (CF_{cylin}) under standard conditions with a 10x10 cm² field size at 10 cm depth was conducted with 6 MV X-rays, comparing it with calibration factor using slab solid water phantoms (CF_{solid}). The CF_{cylin} for different numbers of beams were determined and validated against a reference IC in various planning conditions. Furthermore, angular correction factors were determined for their application in the single-beam calibration factor.

Results: The cylindrical phantom had dimensions of 20 cm in diameter and 30 cm in length, a density of 1.145 g/cm³ and good uniformity. As a result of single beam, the CF_{cylin} agreed well with CF_{solid} , showing a difference of -0.069%. The CF_{cylin} increased with the number of beams, ranging between 1.179 and 1.242. Additionally, the angular correction factor increased as the number of beams increased, peaking at 1.058 with 9 beams. When comparing the results to the IC, it was observed that with an increase in the number of beams to 4 beams, the single-beam calibration factor exhibited a variation of more than 2%. However, when applying the CF_{cylin} specific to the number of beams or correcting for the angular correction factor, the dose differences between nanoDot™ and IC measurements were within 2%.

Conclusion: The developed cylindrical phantom is suitable for nanoDot™ calibration under single beam angle and in composite fields with various beam angles. The new calibration factors for specific numbers of beams allow for accurate dose measurements using nanoDot™, thus reducing the dose difference from the IC to acceptable levels. Further studies should investigate its application in clinical situations.

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doi: 10.12982/JAMS.2024.022

E-ISSN: 2539-6056

Introduction

The nanoDot™ (Landauer Inc., Glenwood, IL, USA) is a type of optically stimulated luminescent dosimeter (OSLD) commonly utilized in point dosimetry for radiation

therapy applications.¹⁻⁶ It is employed for in vivo dosimetry to determine organ doses during irradiation, such as for the skin⁷⁻¹⁰ and eye lens.¹¹ The nanoDot™ offers several advantages, including its small size and repeatable readout, making it a preferred choice for in vivo dosimetry.^{11,12} However, being a passive dosimeter, it requires calibration before use.

Calibrating the nanoDot™ to determine the calibration factor before using it for measurements is essential. This factor is necessary for converting the measured signals into accurate radiation doses. The calibration factor for the luminescence dosimeters should be established through a cross calibration with a calibrated ion chamber, ideally under reference conditions, to ensure traceability.¹³ Therefore, this calibration is conducted under reference conditions by comparing the nanoDot™ reading (the value obtained after reading the nanoDot™ with the reader) to an ionization chamber (IC) measurement taken at the central axis with a gantry angle of 0 degrees, using a standard solid water phantom. However, this calibration factor may not be suitable when there is gantry angle variation, as in Intensity-modulated radiation therapy (IMRT) techniques, due to the angular dependence of the nanoDot™, which can affect the measured signal. Previous research discovered that the nanoDot™ exhibited significant angular sensitivity when exposed to photon beams. Specifically, when subjected to incident photon beams parallel to the dosimeter's plane, the nanoDot™ response was 4% lower at 6 MV and 3% lower at 18 MV compared to the response observed when exposed to incident beams perpendicular to the dosimeter's plane.¹⁴

In a preliminary study, the calibration factor for the nanoDot™ was determined using a standard method (single beam angle, perpendicular to detector) with solid water phantom (CF_{solid}).¹⁵ This process involved comparing the nanoDot™ reading obtained from the reader with an ionization chamber (IC) measurement taken at the central axis, with a gantry angle of 0 degrees and a source-to-axis distance (SAD) of 100 cm, using slab solid water phantoms. Subsequently, these factors were applied to nanoDot™ measurements to determine the dose in the eye lens and thyroid in a phantom for an IMRT plan in head and neck cancer. The results indicated that the dose variation between the nanoDot™ and the treatment planning system (TPS) exceeded 6%. This discrepancy may be attributed to the angular dependence of the nanoDot™. Therefore, calibrating the nanoDot™ in composite fields, a treatment technique where multiple radiation beams or fields are combined to deliver a dose to a target volume (isocenter), may increase the accuracy of dose measurements in multiple beams techniques.

To the best of our knowledge, a phantom for nanoDot™ calibration has not been established, and the calibration factor for different beam angles has not been studied. Therefore, the objective of this study was to develop a cylindrical phantom for nanoDot™ calibration in composite fields with various beam angles. This phantom is designed to accommodate both OSLD nanoDot™ and ionization chamber devices for calibration under the same

conditions. The calibration factors for the nanoDot™, determined using the developed cylindrical phantom (CF_{cylin}), were validated through dose measurements against an ionization chamber.

Materials and methods

Phantom fabrication

The calibration phantom was designed with the concept of maintaining a constant depth for all angles, which led to the selection of a cylindrical phantom. The detector, either the nanoDot™ or the PTW 30010 Farmer ionization chamber (PTW, Freiburg, Germany) with a 0.6 cm³ volume, can be precisely inserted into the center of the phantom at the intended 10 cm depth by changing the detector holder rod. Cast nylon, with a density of 1.14 g/cm³, was selected as the material for constructing the phantom due to its ease of construction and cost-effectiveness.¹⁶

The cylindrical rod for embedding the detector, with a 3 cm diameter and a length of 30 cm, was designed to accommodate both types of detectors. During use, it is inserted into the center of the cylindrical phantom.

The phantom was fabricated from cast nylon 6 with a density of 1.14 g/cm³. The material composition of cast nylon 6 typically includes polyamide 6 (nylon 6), additives (such as plasticizers, stabilizers, lubricants, and pigments), and fillers, depending on the application and desired properties. The specific formulation can vary among manufacturers. In the fabrication of the phantom, the raw material of cast nylon 6, formed through the casting process with dimensions large enough to lathe the phantom to 20 cm in diameter and 30 cm in length, was shaped using CNC (Computer Numerical Control) technology to create a cylindrical phantom. Subsequently, the central hole of the cylindrical phantom was drilled using a Radial Drilling machine. The cylindrical rod of detector holder for nanoDot™ and IC was also fabricated using a similar process.

Phantom characteristics

Dimensions and density were determined, with density calculated using Equation 1. Subsequently, CT numbers and the uniformity of the phantom were evaluated using computed tomography images obtained from the Philips CT simulator Brilliance Big Bore (Philips Medical Systems, Bothell, Washington, United States).

$$\text{density (g/cm}^3\text{)} = \frac{\text{mass (g)}}{\text{volume (cm}^3\text{)}} \quad (1)$$

Uniformity was assessed by measuring the Hounsfield units (HU) in 5 regions of interest (ROI) at both a central and four peripheral positions within a transverse CT phantom image. Appropriate uniformity should exhibit a difference of no more than 5 HU between these positions¹⁷ this work is currently focused on quality assurance (QA).

Determination of nanoDot™ sensitivity correction factor

The sensitivity correction factor for the nanoDot™ accounts for corrections needed due to non-uniformity in

readings among detectors within the same batch. Ideally, all detectors should yield identical dose measurements, but individual detectors may exhibit sensitivity differences. Consequently, these variations in sensitivity are corrected using a factor known as the “sensitivity correction factor” ($k_{\text{sensitivity}}$).

For each individual nanoDot™, this correction factor was calculated by determining the ratio of the average reading from all detectors (M_{avg} in cGy) in the same batch to its own reading (M in cGy), as shown in Equation 2.

$$k_{\text{sensitivity}} = \frac{M_{\text{avg}}}{M} \quad (2)$$

For sensitivity correction factor determination, 100 nanoDot™ detectors were irradiated with a 1 Gy dose of 6MV X-ray beam at a source-to-axis distance (SAD) of 100 cm, a depth of 10 cm, and a field size (FS) of 20x20 cm². The Clinac 2100 (Varian Medical Systems, Palo Alto, CA, USA) was employed in this study. Subsequently, the sensitivity correction factor for each nanoDot™ was determined using Equation 2. Any nanoDot™ with a sensitivity

correction factor exceeding $\pm 5\%$ was excluded, and only detectors with sensitivities close to 1 were utilized in the next experiment.

Evaluation of phantom

The evaluation of the developed phantom for nanoDot™ calibration involved comparing the calibration factors of nanoDot™ OSLDs obtained using a custom-made cylindrical phantom (CF_{cylind}) to those obtained through calibration with a Solid Water™ phantom (Gammex RMI, Middleton, WI, USA) - CF_{solid} . The comparison was conducted under reference conditions, involving a single beam of 10x10 cm², 100 cm SAD, and 10 cm depth, as illustrated in Figure 1.

This study utilized nanoDot™ dosimeters in conjunction with the microStar OSL reader (Landauer, Inc., Glenwood, IL, USA). The dosimeter, based on aluminum oxide doped with carbon ($\text{Al}_2\text{O}_3:\text{C}$), features a disk-shaped active volume measuring 4 mm in diameter and 0.3 mm in thickness. It is enclosed within a light-tight plastic cassette with dimensions of 10 mm × 10 mm × 2 mm.

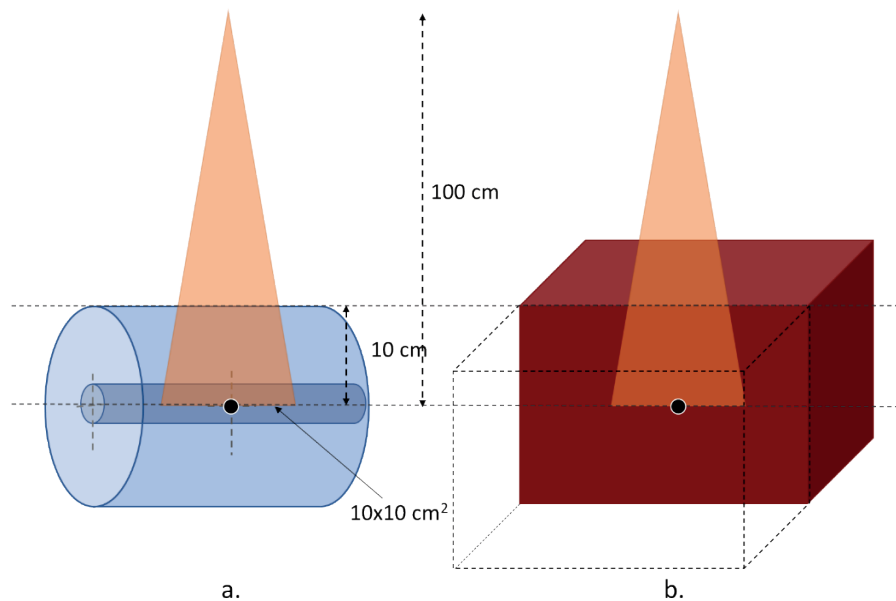


Figure 1. Comparison of the setup geometry for calibration factor determination between (a) a developed cylindrical phantom, and (b) a standard solid water phantom.

The effect of angular variation on calibration factor

Determination of calibration factor (CF_{clin})

The determination of the CF_{clin} was carried out using a cylindrical phantom with a single beam at gantry 0 degrees, perpendicular to the dosimeter. Additionally,

multiple beams, specifically 5, 7, and 9 beams, were employed for this purpose. In the configuration with multiple beams, the radiation beams were adjusted at equal-angle intervals, starting from 0 degrees, as depicted in Figure 2.

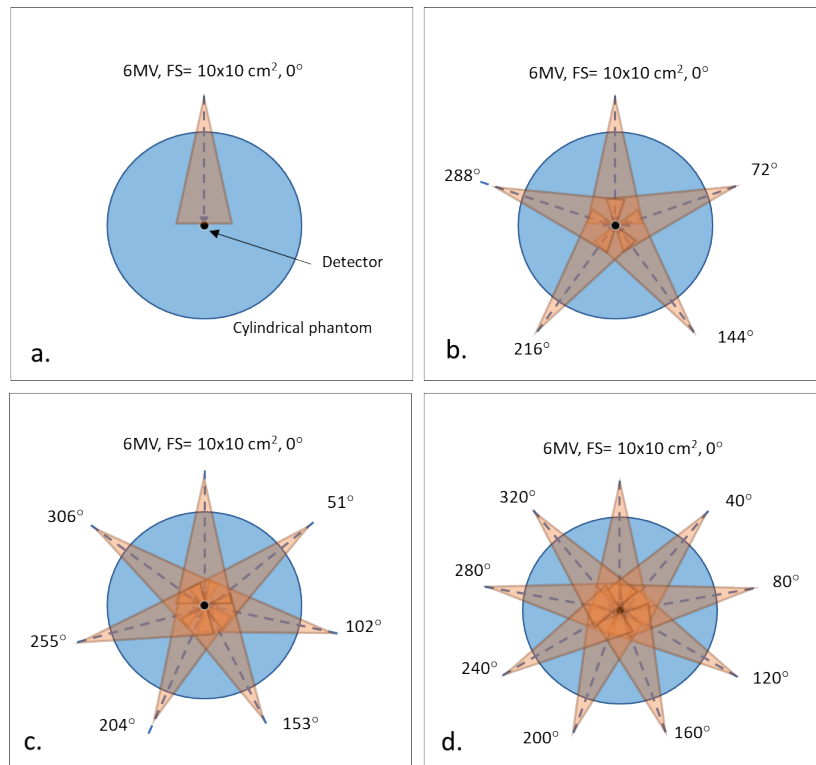


Figure 2. Illustration of the arrangement of radiation beams for a single beam (a), 5 beams (b), 7 beams (c), and 9 beams (d).

All of these beams were irradiated with field size of 10x10 cm², and the measurement depth was set at SAD of 100 cm with a depth of 10 cm, delivering 1 Gy of 6 MV x-ray radiation at the isocenter. The center of each

detector was positioned at the isocenter, as depicted in Figure 3a. The nanoDot™ measurements were repeated three times, using one detector each time, for each beam condition to assess experimental variation.

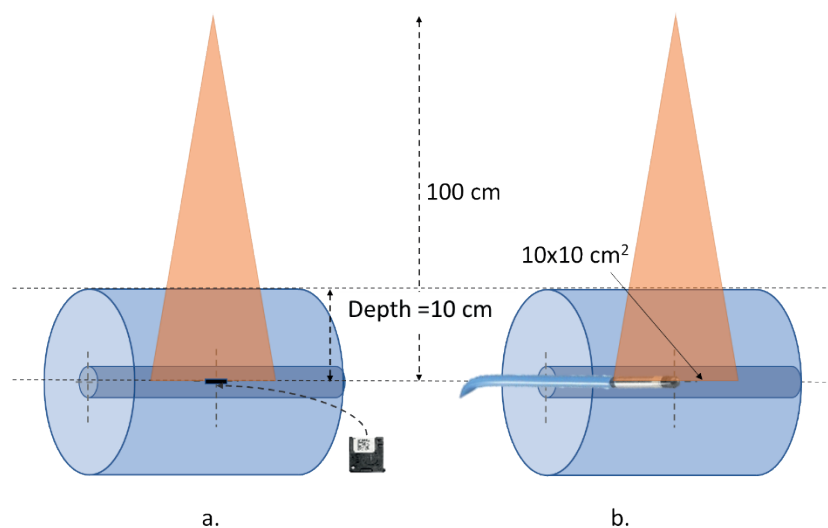


Figure 3. Illustration of setup geometry of nanoDot™ and ionization chamber for calibration factor (CF_{cylin}) determination

The reference dose was measured using a 0.6 cm³ ionization chamber following the TRS 398 protocol¹⁸ under the same conditions as the nanoDot™, with a dose of 1 Gy of 6 MV x-ray, as shown in Figure 3b.

After irradiation, the nanoDot™ readings were analyzed using the MicroStar reader. The readings were repeated three times to calculate the average for each detector. Subsequently, the averages of the three measurements were used to determine the calibration factor, as calculated by Equation 3.

$$\text{Calibration factor} = \frac{D_{IC}}{M_{OSLD}} \quad (3)$$

where D_{IC} is the absorbed dose measured by ionization chamber (cGy) and M_{OSLD} is the nanoDot™ reading with sensitivity correction (cGy).

Because the nanoDot™ exhibits angular dependence, the calibration factor also depends on the orientation of the nanoDot™ relative to the beam angle. As illustrated in Figure 2, the number of beams is associated with beam angles in different directions. As the number of beams increases, the beam angles vary. Correcting each beam angle individually may be complex in practical implementation, so employing the concept of the number of beams could assist in manual correction for this purpose. Therefore, in this study, the angular correction

factors, denoted as ' k_{angle} ', were determined and related to the number of beams. The k_{angle} was calculated as the ratio of the calibration factor for any number of beams ($CF_{cylin,angle}$) to the calibration factor at a single beam with gantry angle 0 degrees ($CF_{cylin,1beam}$), as shown in Equation 4. This factor accounts for variations in the number of beams.

$$k_{angle} = \frac{CF_{cylin,angle}}{CF_{cylin,1beam}} \quad (4)$$

For the implementation of k_{angle} to correct changes in the number of beams, the equation to calculate the dose from nanoDot™ was formulated by multiplying the single-beam calibration factor with k_{angle} .

Validation of calibration factor (CF_{cylin}) of nanoDot™

To validate the calibration factor of the nanoDot™, dose measurements were conducted in various conditions (as shown in Table 1), comparing the results obtained with the nanoDot™ and an ionization chamber. These conditions included open fields of 5x5 cm² and 15x15 cm² at a depth of 8 cm using a 30x30x30 cm³ solid water phantom. Additionally, validation was performed for two parallel opposing beams and four fields in a 5x5 cm² configuration, using a cylindrical phantom at a depth of 10 cm. In all cases, a 1 Gy dose was delivered to the isocenter.

Table 1. Plan parameters for the validation of calibration factors (CF_{cylin}).

Plan	Phantom	Planning		
A	Solid water	Depth 8 cm, SAD 100 cm, Gantry 0 degrees	1 beam	FS 5x5 cm ²
B	Solid water		1 beam	FS 15x15 cm ²
C	Cylindrical	AP and PA parallel opposing, SAD 100 cm	2 beams	FS 5x5 cm ² , depth 10 cm, SAD 100 cm
D	Cylindrical	4 field box, SAD 100 cm	4 beams	FS 5x5 cm ² , depth 10 cm, SAD 100 cm

Note: FS: field size

The nanoDot™ measurements were repeated three times, utilizing one detector each time, for each beam condition. Each nanoDot™ reading was individually multiplied by the sensitivity correction factor and then averaged across all repeated measurements. The nanoDot™ readings were analyzed by the reader under the same conditions, as described in Section 4.2. The doses measured with the nanoDot™ (D_{OSLD} in cGy) were calculated using Equation 5.

$$D_{OSLD} = M_{OSLD} \times CF \quad (5)$$

where M_{OSLD} (cGy) represents the nanoDot™ reading multiplied by the sensitivity correction factor ($M \times k_{sensitivity}$) and averaged for all repeated measurements, CF is the nanoDot™ calibration factor. The calibration factors for both single and multiple beams were applied to calculate the dose using Equation 5. Additionally, the doses measured with the nanoDot™ were also calculated by implementing the k_{angle} to the calibration factor in the single beam ($CF_{cylin,1beam}$), as shown in Equation 6.

$$D_{OSLD} = M_{OSLD} \times CF_{cylin,1beam} \times k_{angle} \quad (6)$$

Subsequently, the dose measured with the nanoDot™ was compared to the measurement obtained by the 0.6 cm³ ionization chamber following the TRS 398 protocol, calculating the percentage difference using Equation 7.

$$\% \text{difference} = \frac{(D_{OSLD} - D_{IC})}{D_{IC}} \times 100 \quad (7)$$

where D_{OSLD} represents the dose determined by the nanoDot™ (cGy), while D_{IC} represents the dose determined by the ionization chamber (cGy). A percentage difference within 2% is considered acceptable according to the TRS 430 recommendation.¹⁹

Statistical analysis

Mean and standard deviation (SD) were employed to describe the data. The %difference was used to compare the dose between nanoDot™ and IC measurements.

Results

Developed phantom

The cylindrical cast nylon phantom, with dimensions of 20 cm in diameter and 30 cm in length, incorporates

a cylindrical plug measuring 3 cm in diameter and 30 cm in length for embedding the detectors (nanoDot™ and 0.6 cm³ ionization chamber), as shown in Figure 4.

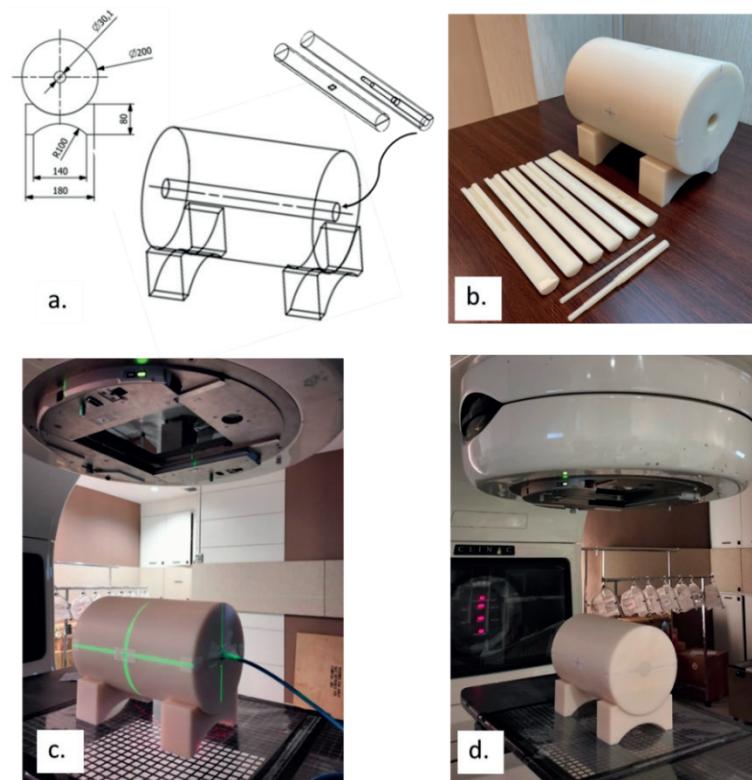


Figure 4. The novel cylindrical phantom for nanoDot™ calibration factor determination: (a) Phantom drawing, (b) fabricated phantom with a different detector plug, (c) a phantom with an 0.6 cm³ IC, and (d) a phantom with nanoDot™ embedded.

Physical characteristics of phantom

The exact dimensions were 20 cm in diameter and 30 cm in length, with a weight of 10.8 kg and a volume of 9,420 cm³. The calculated density was 1.145 g/cm³. The HU at the center were 100.4 ± 4.6 , and at the periphery, they were 102.2 ± 4.5 , 100.8 ± 4.5 , 102.7 ± 4.5 , and 102.0 ± 4.1 HU, as shown in Figure 5. The results demonstrated good uniformity in HU values throughout the phantom, with

differences not exceeding ± 5 HU, in accordance with IAEA HHS No. 19 guidelines.¹⁷ For comparison with the HU value of the solid water phantom, the mean HU value of the cylindrical phantom with cast nylon material was 101.62 ± 0.98 HU, while the solid water phantom provided a value of 27.26 ± 0.09 HU. The difference in HU between the two materials, attributed to the density of nylon, was higher than that of the solid water phantom (1.03 g/cm³).²⁰

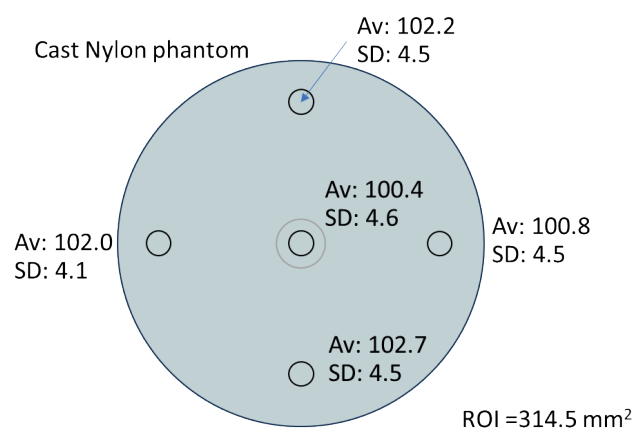


Figure 5. The image of a cylindrical phantom showing the location of the region of interest (ROI) used to determine HU values.

Sensitivity correction factor of nanoDot™

Figure 6 illustrates sensitivity correction factors for 100 nanoDot™ detectors. The mean and SD of sensitivity correction factors of all detectors was 1.00 ± 0.023 , with a coefficient of variance of 2.26%. The sensitivity correction

factor of each nanoDot™ detector was applied to correct the dose determination. The nanoDot™ detectors with a correction factor greater than $\pm 5\%$ were excluded from this study.

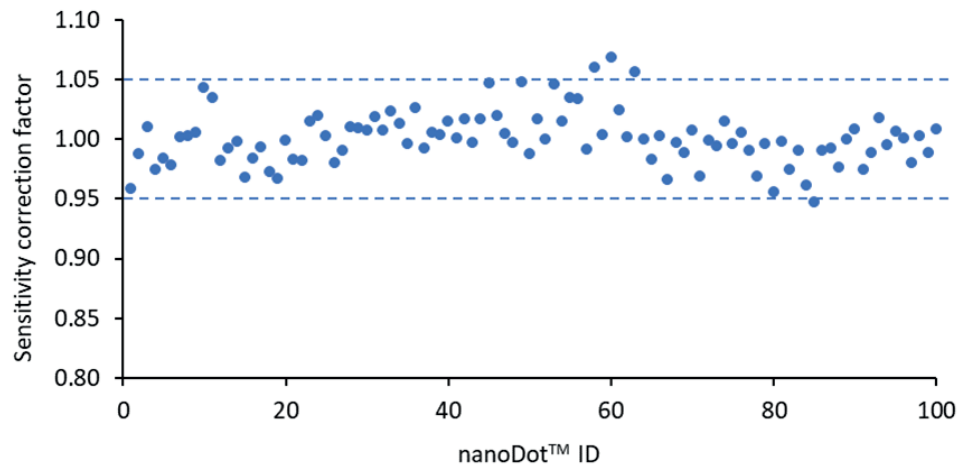


Figure 6. Sensitivity correction factors of 100 nanoDot™ detectors.

Evaluation of cylindrical phantom

The calibration factor of the developed phantom (CF_{cylin}) was 1.1785, and the calibration factor of the solid water phantom (CF_{solid}) was 1.1793, as shown in Table 2.

The results demonstrate good agreement, with a difference of -0.069%. Therefore, the cylindrical phantom is suitable for the nanoDot™ calibration factor.

Table 2. Calibration factors of nanoDot™ from solid water phantom (CF_{solid}) and the newly developed (CF_{cylin}).

Phantom	Dose of IC (cGy)	nanoDot™ reading (cGy) ^a	Calibration factor	Difference
Solid water	100.20	84.96	1.1793	-0.069 %
Cylindrical phantom	100.32	85.12	1.1785	

Note: IC: ionization chamber, ^aaveraged from 3 nanoDot™ detectors

The effect of angular variation on calibration factor (CF_{cylin})

The average nanoDot™ readings from the single and multiple beams (new method) compared to the dose

from the ionization chamber are illustrated in Figure 7. As the number of beams increased, the nanoDot™ readings decreased. Therefore, the CF_{cylin} values were adjusted according to the number of beams.

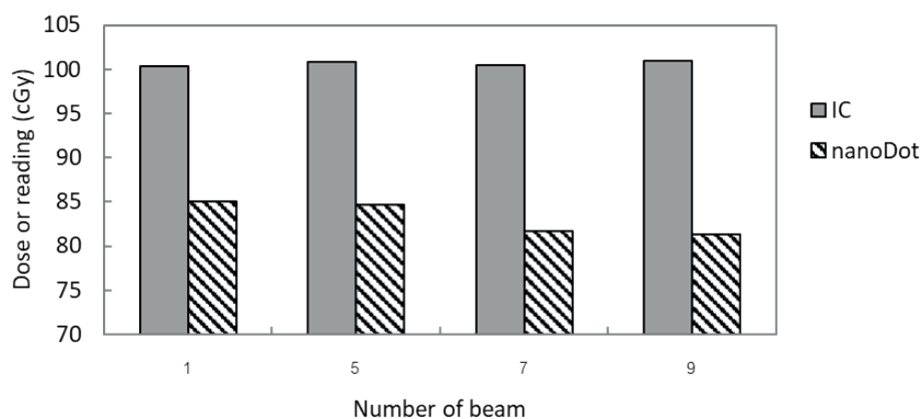


Figure 7. Comparison of doses from the ionization chamber (IC) and the average reading of nanoDot™ for different numbers of beams using the cylindrical phantom.

The calibration factors determined from the cylindrical phantom for single and multiple beams are shown in Figure 8. The results indicate that the calibration factor increased as the number of beams increased, ranging within a calibration factor from 1.179 to 1.242. The relationship between the calibration factors and the number of beams follows the polynomial equation (Equation 8) with an R^2 value of 0.9287.

$$CF = 0.0008x^2 + 0.0005x + 1.1759 \quad (8)$$

where CF is the calibration factor, and x is the number of beams.

The angular correction factors, influenced by the number of beams, are depicted in Figure 9. These values can be applied to nanoDot™ measurements, as shown in Equation 6.

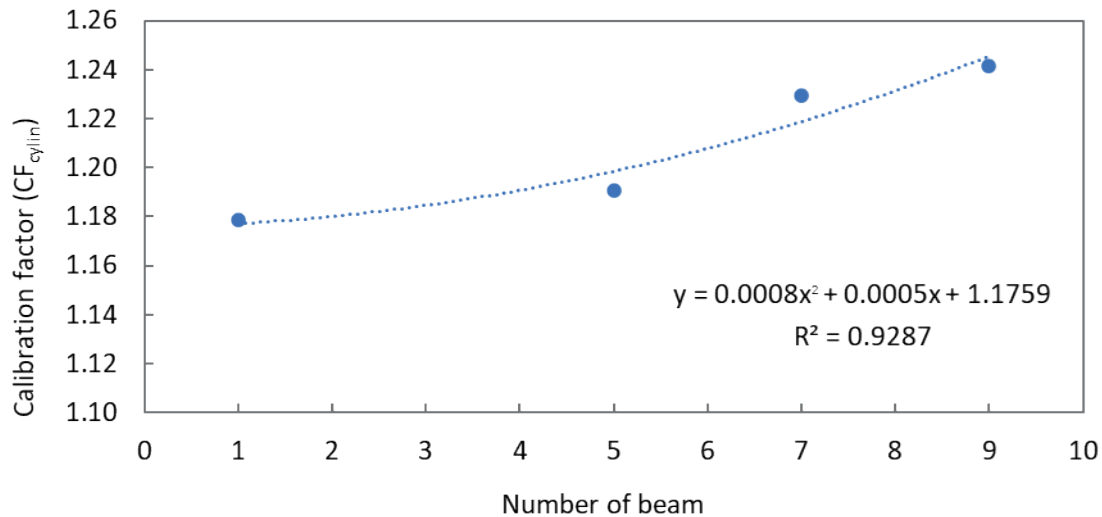


Figure 8. The relationship between calibration factors determined using the cylindrical phantom (CF_{cylind}) and the number of beams (second-order polynomial equation).

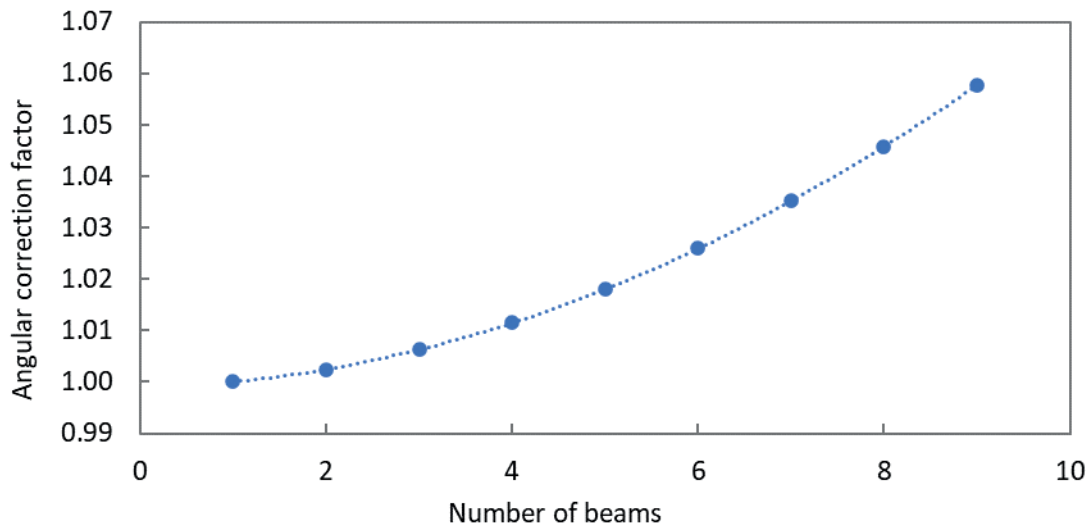


Figure 9. The relationship between the angular correction factor and the number of beams (Second-order Polynomial Equation) using the cylindrical phantom.

Validation of calibration factor of nanoDot™

The results showed that the nanoDot™ measurements for the 4-field plan (Plan D) exhibited the largest deviation from the IC when compared to the single-beam and

2-beam plans (Plan A, B, and C). The difference in Plan D slightly exceeded 2%, while the differences in the other plans remained within 2% (as shown in Table 3).

Table 3. The comparison involves doses determined from the calibration factor determined using cylindrical phantom, including the single-beam calibration factor (CF_{1beam}), new calibration factors using the fitting equation (CF_{poly}), and that of correction for angular correction factor, against those measured by the ionization chamber.

Plan	Dose (cGy)				%difference		
	Ionization chamber	nanoDot™			nanoDot™ vs Ionization chamber		
		CF_{1beam}	CF_{poly}	$CF_{1beam} \times k_{angle}$	CF_{1beam}	CF_{poly}	$CF_{1beam} \times k_{angle}$
A	100.60	99.37	99.37	99.37	-1.23	-1.23	-1.23
B	100.76	100.74	100.74	100.74	-0.02	-0.02	-0.02
C	100.40	99.85	99.98	100.10	-0.54	-0.42	-0.30
D	100.37	98.34	99.38	99.47	-2.02	-0.98	-0.90

CF_{1beam} : single-beam calibration factor with 0 degrees gantry angle, CF_{poly} : calibration factor from polynomial equation,

$CF = 0.0008x^2 + 0.0005x + 1.1759$ (x = number of beams), $CF_{1beam} \times k_{angle}$: single-beam calibration factor multiplied by angular correction factor.

When applying the calibration factor based on the number of beams, the percentage difference in Plans C and D decreased. There was no notable difference between applying the calibration factor from the polynomial equation (Equation 8) and correcting for the number of beams ($CF_{1beam} \times k_{angle}$). Therefore, the angular correction factor (k_{angle}) can be utilized for clinical applications in various situations, as determined in this study. However, by incorporating the k_{angle} value from this study, the nanoDot™ calibration factor of single beam should still be determined specifically at the user institute.

Discussion

This study utilized cast nylon to create the phantom. Previous research also employed cast nylon for CT dosimetry phantoms, demonstrating its viability as an alternative for CTDI measurement.¹⁶ Intang A *et al.* demonstrated the suitability of cast nylon phantoms for SRS end-to-end testing using an alanine dosimeter.²¹ The cylindrical nylon phantom in this study had a density of 1.145 g/cm³, comparable to the work of Sookpeng S *et al.*¹⁶. Despite its density being higher than that of water (1 g/cm³) and solid water phantom (1.03 g/cm³), it did not affect the determination of the calibration factor. The calibration factor for the developed phantom (CF_{cylind}) closely matched that of solid water phantom (CF_{solid}), with a percentage difference of -0.069%.

A cylindrical cast nylon phantom proved beneficial for multiple beam determinations, for which the slab water phantom was found unsuitable. Consequently, this study designed the phantom with a cylindrical shape. However, the cylindrical shape was hard to set up due to its easy rotation. Hence, improvements in the design of the alignment marker were necessary for practical application. Another advantage of the cylindrical nylon phantom designed in our study is the reproducibility of the nanoDot™ setup. This is attributed to the cylindrical plug designed for embedding the detector, specifically designed to match the dimensions of the nanoDot™,

with the center of the sensitive volume of the nanoDot™ aligned with the center of the cylindrical phantom. This feature facilitates an easier, more accurate, and more reproducible setup compared to using a slab solid water phantom.

Typically, calibration factors of nanoDot™ were determined using a solid water phantom at a reference depth, such as 10 cm, with the nanoDot™ oriented perpendicularly to the beam in reference condition, and then compared with IC measurements. For practical applications, this calibration factor was utilized for dose measurements with nanoDot™. However, clinical irradiation often involves beams coming from non-perpendicular directions, as previous studies have demonstrated that nanoDot™ responses are highly dependent on the angular of the incident beam.¹⁴ This angular effect leads to a reduction in measurement signals. Therefore, our study aimed to investigate this effect when applying nanoDot™ for dose measurements in plans with multiple beam angles. The calibration factor required adjustment to account for the angular aspect, and an angular correction factor was applied to the single-beam calibration factor, as illustrated in Equation 6. This study did not provide the calibration factor specifically for individual gantry angles because it is challenging to correct in practice. Instead, we adapted the calibration factor for the composite field with multiple beam angles, as used in IMRT. For future studies, exploring the calibration factor for arc therapy configurations, such as VMAT, may be useful. The results showed that adjusting the calibration factor for specific numbers of beams improved dose measurements with nanoDot™, reducing the percentage difference from 2.02% to less than 1% (Table 3).

It's worth noting that the calibration factor is also influenced by the beam quality and the reader system of the detector. The calibration factors derived from this study are specific to our setup and not be directly applied in other hospitals or with different reader systems. To extend these findings to other institutions, the values

were determined. Calculations using Equation 6, along with the calibration factor obtained from the standard method with single beam under reference condition, can be employed to determine doses with the nanoDot™. With values, there is no need to determine the calibration factor for different numbers of beams. This approach may be particularly useful for institutions lacking access to a cylindrical phantom and can reduce the time needed for calibration factor determination.

For future research, we recommend investigating the application of nanoDot™ in clinical settings, such as in intensity-modulated radiation therapy (IMRT) and volumetric modulated arc therapy (VMAT) techniques. Additionally, exploring organ doses outside the irradiation beam should be a subject of further investigation.

Limitation

The limitation of this study is the lack of investigation in clinical applications. While the validation of the new calibration was performed for single, two and four-field plans, higher numbers of beams and modulated beams have not been investigated.

Conclusion

The new cylindrical phantom is suitable for determining the nanoDot™ calibration factor, obtaining a calibration factor comparable to the standard solid water phantom. Another implication of the cylindrical phantom is its suitability for multiple-beam measurements, which is appropriate for angular-dependent studies. The calibration factors are dependent on the number of beams. The calibration factor specific to the number of beams or the angular correction factor improves dose measurements using the nanoDot™ and aligns with ionization chamber measurements, showing a difference of less than 2%.

Conflict of interest:

None

Funding

The research was funded by the Faculty of Allied Health Science, Naresuan University, for the Budget Year 2023, under Contract Number AH-66-01-002.

Acknowledgements

We sincerely thank our undergraduate students for analyzing the nanoDot™ reading.

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