

DEVELOPMENT AND VALIDATION OF REFERENCE WORKPIECES FOR DETERMINING THE ACTIVE VOLUME OF IONIZATION CHAMBERS

Marta Rępańska, Tomasz Kowaluk, Piotr Tulik, Adam Woźniak✉

Warsaw University of Technology, Faculty of Mechatronics, Institute of Metrology and Biomedical Engineering, ul. Boboli 8, 02-525 Warsaw, Poland (✉ adam.wozniak@pw.edu.pl)

Abstract

The article presents the development and validation of reference workpieces for determining active volume of ionization chambers used in radiation dosimetry. Accurate determination of active volume is essential for precise measurements of absorbed dose in radiotherapy and radiation protection. Therefore, sixteen reference sets made of graphite and PA6 aluminium alloy, featuring different geometries and nominal volumes, were designed and manufactured. The volumes of the reference sets were determined based on high-precision coordinate measurements of their geometric features. Measurements were conducted independently in two laboratories to ensure verification and comparability of the results. Measurement uncertainties were evaluated using the sensitivity analysis method. The obtained expanded uncertainties met the stringent requirements for reference standards in metrology. Good agreement between the results obtained in both laboratories was confirmed using conformity assessment criteria. The developed reference sets can be used for calibration and validation of X-ray computed tomography methods in dimensional metrology.

Keywords: ionization chamber, volume measurement, radiation dosimetry, reference workpieces, measurement uncertainty, dimensional metrology, X-ray tomography.

1. Introduction

Ionization chambers are widely used in dosimetry, particularly in radiotherapy and radiation protection. These are gas detectors that utilize the phenomenon of gas ionization within the detector's active volume [1]. They also play a key role in realization of absorbed dose standards for different radiation fields. For example, the international code of practice for radiotherapy dosimetry defines procedures for dose determination using ionization chambers [2], while the *International Commission on Radiation Units & Measurements* (ICRU) report provides fundamental physical data and recommendations for ionizing radiation dosimetry [3]. Additionally, international comparisons of national standards confirm the importance of ionization chambers in maintaining measurement traceability and consistency, as demonstrated in key comparisons of air-kerma and absorbed dose standards [4,5]. The applicability of graphite ionization chambers as primary or transfer standards has also been discussed in the literature [6].

The ionometric method, which uses ionization chambers, allows for absolute determination of the absorbed dose value by measuring the charge generated in the ionization process of the gas contained in the active volume of the chamber. The accuracy of this method depends on several correction factors and physical constants, among which the determination of the chamber's active volume is one of the most significant contributors to measurement uncertainty. General requirements for uncertainty in radiotherapy dosimetry are discussed in [7], while recent studies highlight the impact of ionization chamber design and characterization on dosimetric accuracy [8,9].

A significant problem in determining the active volume of an ionization chamber is the inability to use standard methods for measuring the geometry, such as CMMs. These are closed structures, where physical measurement of internal components is impossible. X-ray computed tomography has been identified as a suitable technique for dimensional metrology of complex internal structures [10], with further studies demonstrating its industrial applicability [11]. The use of X-ray tomography to determine the active volume of ionization chambers requires development of reference measurement workpieces. Correct volume determination will depend on the proper definition of the threshold value between air and material [12].

The accuracy of determining the absorbed dose depends directly on the accuracy of measuring the internal volume of the ionization chamber. Errors in determining the volume of ionization chambers should not exceed 0.1%, in accordance with the guidelines specified in the project regulations [13], for which the reference workpieces of active volume of ionization chambers presented in this article were developed.

2. Reference workpieces of ionization chambers

As part of the research, 16 ionization chamber workpieces were constructed – eight chambers made of graphite and eight chambers made of aluminium alloy, varying in terms of geometry (volume), shape, and wall thickness (5 mm, 3 mm, and 2.5 mm). Figure 1 shows some of the manufactured workpieces, while Fig. 2 highlights the geometric features necessary to determine the volume, designated as V_k .

The chambers were made of POCO EDM-3 graphite, the same material used to manufacture ionization chambers by the *Central Office of Measures* (GUM). POCO EDM-3 graphite is a material designed for precision machining, characterized by high strength and well-defined technical parameters confirmed by the manufacturer's quality certificate, which is particularly important when constructing ionometric standards for dosimetry applications. High-purity graphite is widely used in ionization chamber construction due to its favourable physical and dosimetric properties, such as good electrical conductivity and chemical stability. It is applied both in commercial chambers and in specialized designs intended for reference standards.

The other material is PA6 aluminium alloy, which is easy to machine and provides high strength and dimensional stability. Aluminium and its alloys are also commonly used in ionization chambers due to their good electrical conductivity and stable interaction with ionizing radiation. Additionally, PA6 exhibits radiographic properties similar to pure aluminium, making it suitable for applications in X-ray computed tomography.

The nominal numerical values of the geometric parameters of the graphite and aluminium chambers are presented in Table 1.



Fig. 1. Examples of reference workpieces of ionization chambers: a) graphite, b) PA6 aluminium alloy.

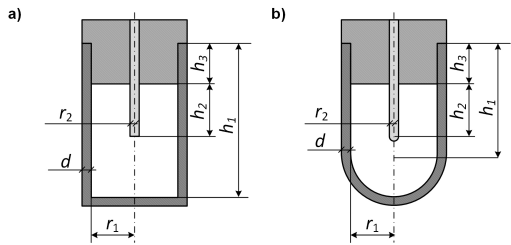


Fig. 2. Designation of geometric features of graphite and aluminium alloy chambers: a) geometry I (cylindrical), b) geometry II (thimble).

Table 1. Summary of geometric parameters of chambers made of graphite and PA6 aluminium alloy.

Designation <i>G</i> (graphite) / <i>A</i> (aluminium)		Nominal parameters						
		V_k	d	r_1	r_2	h_1	h_2	h_3
		cm ³	mm					
$V_{kG_5_60}$	$V_{kA_5_60}$	60	5	20	1.5	58	10	10
$V_{kG_3_60}$	$V_{kA_3_60}$	60	3	20	1.5	58	10	10
$V_{kG_5_30}$	$V_{kA_5_30}$	30	5	15	1.5	52.9	10	10
$V_{kG_3_30}$	$V_{kA_3_30}$	30	3	15	1.5	52.9	10	10
$V_{kG_5_10}$	$V_{kA_5_10}$	10	5	10	1.5	42.5	10	10
$V_{kG_3_10}$	$V_{kA_3_10}$	10	3	10	1.5	42.5	10	10
$V_{kG_2.5_0.5}$	$V_{kG_2.5_0.5}$	0.5	2.5	3.75	1.25	16	10	3.6
$V_{kG_2.5_0.5_II}$	$V_{kG_2.5_0.5_II}$	0.5	2.5	3.75	1.25	16	10	3.6

3. Estimation of ionization chamber volumes along with measurement uncertainty

The volumes of the chambers V_k were determined based on the measurements of geometric features, shown illustratively in Fig. 2a, using the equation:

$$V_k = \pi [r_1^2 (h_1 - h_3) - r_2^2 \cdot h_2], \quad (1)$$

while for the chambers shown schematically in Fig. 2b) from the equation:

$$V_k = \pi \left[r_1^2 (h_1 - h_3) - r_2^2 \cdot h_2 + \frac{2}{3} (r_1^3 - r_2^3) \right]. \quad (2)$$

The determined values of the volume of graphite and aluminium chambers along with the measurement uncertainties (given as expanded uncertainties for the coverage factor $k = 2$ and the coverage probability $\gamma = 95.45\%$) determined in the laboratory of Warsaw University of Technology (Politechnika Warszawska) – marked with the index PW – V_{k_PW} and in an external laboratory (Laboratory of Coordinate Metrology of Cracow University of Technology (Politechnika Krakowska) – marked with the index PK – V_{k_PK}) are presented in Table 2 and Table 3.

The volume values of the reference workpieces of ionization chambers, obtained from the two laboratories and summarized in Tables 2 and 3, were additionally assessed for consistency of measurement results (assuming that the results obtained from PK are reference results). For this purpose, the E_n number was used, which is one of the parameters listed in the PN-EN ISO/IEC 17043 [14] standard used to assess compliance in proficiency testing. The E_n number, in relation to the analyzed example, can be described by the following relationship:

$$E_n = \frac{V_{k_PW} - V_{k_PK}}{\sqrt{U_{V_{k_PW}}^2 + U_{V_{k_PK}}^2}}, \quad (3)$$

where: V_{k_PW} and V_{k_PK} denote the values of the ionization chamber volumes determined based on the results obtained at PW and PK, respectively, while $U_{V_{k_PW}}$ and $U_{V_{k_PK}}$ denote the corresponding measurement uncertainties. The agreement of the measurement results expressed by the number E_n occurs when $|E_n| \leq 1$.

Table 2. Summary of volumes of the graphite chambers along with measurement uncertainties.

Designation	Nominal value	Measurement results PK		Measurement results PW		$ E_n $
		Calculated value	Measurement uncertainty	Calculated value	Measurement uncertainty	
		V_{k_PK}	$U_{V_{k_PK}}$	U_{k_PW}	$U_{V_{k_PW}}$	
		cm ³				—
$V_{kG_5_60}$	60	60.0352	0.0038	60.0434	0.0076	0.96
$V_{kG_3_60}$	60	60.0160	0.0038	60.0205	0.0076	0.54
$V_{kG_5_30}$	30	30.0490	0.0025	30.0496	0.0050	0.10
$V_{kG_3_30}$	30	30.0552	0.0025	30.0572	0.0050	0.35
$V_{kG_5_10}$	10	10.0142	0.0013	10.0151	0.0025	0.30
$V_{kG_3_10}$	10	10.0146	0.0013	10.0161	0.0025	0.51
$V_{kG_2.5_0.5}$	0.5	—	—	0.49877	0.00026	—
$V_{kG_2.5_0.5_II}$	0.5	—	—	0.49813	0.00023	—

Table 3. Summary of volumes of the PA6 aluminium alloy chambers along with measurement uncertainties.

Designation	Nominal value	Measurement results PK		Measurement results PW		$ E_n $
		Calculated value	Measurement uncertainty	Calculated value	Measurement uncertainty	
		V_k_{PK}	$U_{V_k_{PK}}$	$U_{k_{PW}}$	$U_{V_k_{PW}}$	
		cm ³				—
$V_{kA_5_60}$	60	60.0959	0.0038	60.0956	0.0076	0.04
$V_{kA_3_60}$	60	59.9815	0.0038	59.9759	0.0076	0.67
$V_{kA_5_30}$	30	30.0900	0.0025	30.0865	0.0050	0.63
$V_{kA_3_30}$	30	30.0920	0.0025	30.0869	0.0050	0.92
$V_{kA_5_10}$	10	10.0167	0.0013	10.0153	0.0025	0.50
$V_{kA_3_10}$	10	10.0154	0.0013	10.0145	0.0025	0.34
$V_{kA_2.5_0.5}$	0.5	—	—	0.45662	0.00025	—
$V_{kA_2.5_0.5_II}$	0.5	—	—	0.47248	0.00022	—

3.1. Estimation of uncertainty of volume measurement $\mathbf{V}_k$ – measurements of geometric features at PW

The volume of the chamber (marked as V_k) was determined based on measurements of features such as circle radii (r_1, r_2) and distances (h_1, h_2, h_3) which are marked illustratively in Fig. 2. Measurements of features: r_1, r_2, h_1, h_2 and h_3 were performed on a coordinate measuring machine located at the Institute of Metrology and Biomedical Engineering, Warsaw University of Technology. The measurements were performed in a controlled ambient temperature (20 ± 1) °C, on a Carl Zeiss Accura coordinate measuring machine, with a current calibration certificate issued by ZEISS. To estimate the uncertainty of coordinate measurements of features: r_1, r_2, h_1, h_2 and h_3 , a sensitivity analysis method was used, referring to two types of features: circle radius and distance [15, 16]. The uncertainty of the circle radii r_1, r_2 appearing in equation (1) on the chamber volume was determined in the same way. In the sensitivity analysis method, the principle of determining the measurement uncertainty treats coordinate measurement as an indirect measurement based on the mathematically minimal number of points. Based on this and the general equation for the radius of a circle in vector notation:

$$r = \frac{|AB| \cdot |AC| \cdot |BC|}{2|AB \times AC|} \quad (4)$$

designating the coordinates (x, y, z) of circle points A, B and C as: $A(x_1, y_1, z_1)$, $B(x_2, y_2, z_2)$, $C(x_3, y_3, z_3)$, and the lengths of vectors: $AB(a, b, c)$, $AC(d, k, f)$, $CD(g, h, j)$, we obtain the equation for measuring the radius of a circle in scalar notation:

$$r = \frac{\sqrt{(a^2 + b^2 + c^2)} \cdot \sqrt{(d^2 + k^2 + f^2)} \cdot \sqrt{(g^2 + h^2 + j^2)}}{2\sqrt{(bf - ck)^2 + (cd - af)^2 + (ak - bd)^2}}. \quad (5)$$

Equation (5) was adopted as the equation for measuring the radii r_1, r_2 , based on which the chamber volume V_k was determined. In the next step, based on (5), the sensitivity coefficients c_i were determined as partial derivatives of the equation for measuring the output quantity (generally designated as Y) with respect to the input quantities X_i , which is described by the general known relationship.

For the radius measurement (5), in which there are $N = 9$ input quantities described by standard uncertainties denoted as u_i , the combined standard uncertainty u_r of the radius measurement r will be described by:

$$u_r = \sqrt{\sum_{i=1}^9 (c_i u_i)^2}. \quad (6)$$

The standard uncertainties u_i of individual input quantities were determined based on the Maximum Permissible Error (according to ISO 10360, in μm) described by the equation:

$$E_{MPE} = 1.7 + L/333, \quad (7)$$

where L expressed in mm corresponds to the difference in the coordinates of a pair of points. It was assumed that the machine errors were described by normal distribution, which was verified by checking the error distribution from the machine calibration certificate.

The uncertainty of the distance h_1 , h_2 and h_3 measurements was estimated analogously. Assuming the distance $h = |AB|$, determined based on the coordinates of the pair of points A and B, designated as: $A(x_1, y_1, z_1)$, $B(x_2, y_2, z_2)$ and $AB(a, b, c)$ respectively, we obtain the distance measurement equation in scalar notation:

$$h = \sqrt{a^2 + b^2 + c^2}. \quad (8)$$

The sensitivity coefficients of the input quantities h_1 , h_2 and h_3 and their corresponding standard uncertainties were determined in the same way as in the case of the radius measurement.

The estimated value of r_1 was the determined radius of the cylinder, obtained by measuring the circle, typically in a dozen or so cross-sections (the number of cross-sections depended on the chamber geometry), with several dozen measurements on each cross-section, with points evenly distributed around the circumference. To estimate the uncertainty of determining the radius r_1 , an appropriate number of 3-point sets (evenly distributed around the circumference) were selected from the set of points for each cross-section, and the uncertainty of the circle radius was determined for each cross-section using sensitivity analysis. The differences in radius uncertainty values were verified both for points from a single cross-section and between cross-sections. The differences in the obtained values were negligible (nm levels), while the uncertainty of the radius r_1 was selected as the highest value of all determined values.

The radius of the cylinder measured was used as an estimate of r_2 (electrode radius). Due to the geometry of the measurement, fewer cross-sections were used (than was the case for measuring the chamber's internal diameter) as well as the number of measurements on each cross-section, with points evenly distributed around the circumference. To estimate the uncertainty in determining the radius r_2 , 3-point sets were selected from the set of points for each cross-section, similarly to the one for r_1 , and the uncertainty in the circle radius was determined for each. The greatest value of all determined values was chosen as the uncertainty in determining the radius r_2 .

A sample table of the radius measurement uncertainty budget is presented below, with an example for determining the chamber's internal radius, Table 4.

The analogy presents an example Table 5 of the uncertainty budget for determining distances, an example for distance h_1 .

The combined uncertainty of the volume measurement determined from (1) is described by:

$$u_{V_k} = \sqrt{\sum_{i=1}^5 \left(\frac{\delta V_{k1}}{\delta X_i} u_i \right)^2}. \quad (9)$$

The summary of the determined estimates of individual input quantities for the measurement of an example chamber with a volume of $V_{kG_2.5_0.5}$, their standard uncertainties and sensitivity coefficients is presented in Table 6.

Table 4. Example of the uncertainty budget table for the r_1 radius measurement.

Quantity	Estimate		Standard uncertainty	Probability distribution	Sensitivity coefficient	Uncertainty contribution
X_i	x_i		$u(x_i)$		c_i	$u_i(r_1)$
a	5.76781	mm	0.572 μm	normal	0.15724	0.090 μm
b	−3.17870	mm	0.569 μm	normal	0.28532	0.162 μm
c	−0.00010	mm	0.567 μm	normal	−0.00009	−0.001 μm
d	5.35259	mm	0.572 μm	norma	0.17430	0.099 μm
k	3.38956	mm	0.570 μm	normal	−0.27524	−0.157 μm
f	−0.00160	mm	0.567 μm	normal	0.00004	0.001 μm
g	−0.41522	mm	0.567 μm	normal	−0.03600	−0.020 μm
h	6.56827	mm	0.573 μm	normal	0.56942	0.326 μm
j	−0.00150	mm	0.567 μm	normal	−0.00013	−0.001 μm
r_1	3.75504	mm				0.00042 mm

Table 5. Example of the uncertainty budget table for the height measurement h_1 .

Quantity	Estimate		Standard uncertainty	Probability distribution	Sensitivity coefficient	Uncertainty contribution
X_i	x_i		$u(x_i)$		c_i	$u_i(r_1)$
a	0.00109	mm	0.57 μm	normal	0.0001	0.00004 μm
b	−0.00172	mm	0.57 μm	normal	−0.0001	−0.00006 μm
c	15.99120	mm	0.58 μm	normal	1.000	0.583 μm
h_1	15.99120	mm				0.583 μm

Table 6. Example volume uncertainty budget table $V_{kG_2.5_0.5}$ (PW measurements).

Quantity	Estimate		Standard uncertainty	Probability distribution	Sensitivity coefficient	Uncertainty contribution
X_i	x_i		$u(x_i)$		c_i	$u_i(r_1)$
r_2	1.24617	mm	0.37 μm	normal	−78.716	−0.029 mm^3
r_1	3.7511	mm	0.42 μm	normal	292.084	0.123 mm^3
h_1	15.9912	mm	0.58 μm	normal	44.205	0.026 mm^3
h_2	10.0532	mm	0.58 μm	normal	−4.879	−0.003 mm^3
h_3	3.5984	mm	0.57 μm	normal	−44.205	−0.025 mm^3
$V_{kG_2.5_0.5}$	498.772	mm^3				0.132 mm^3

Assuming that the input quantities are not significantly correlated, the expanded uncertainty of the determined volume (for $k = 2$, $\gamma = 95.45\%$) can be written as:

$$U_{kG_2.5_0.5} = k \cdot u(V_{kG_2.5_0.5}) = 0.264 \text{ mm}^3 \quad (10)$$

and the final measurement result:

$$V_{kG_2.5_0.5} = (0.49877 \pm 0.00026) \text{ cm}^3. \quad (11)$$

3.2. Estimation of the uncertainty of volume measurement $\mathbf{V}_{\mathbf{k}}$ – measurements of geometric features at PK

To verify the obtained measurement results for the graphite and aluminium chambers, measurements of characteristics: r_1 , r_2 , h_1 , h_2 and h_3 were performed at an external laboratory – the Coordinate Metrology Laboratory of Tadeusz Kościuszko Cracow University of Technology, which is a PCA-accredited calibration laboratory according to PN-EN ISO/IEC 17025:2018-02 [17]: accreditation number AP-132. The measurements were performed on a Leitz Hexagon PMM12106 coordinate measuring machine. Based on the obtained results, the volume of the ionization chambers was determined using (1). Based on the uncertainty of the measurements of the characteristics given in the above-mentioned certificates, a measurement uncertainty budget was developed, Table 7. In analogy to (6), sensitivity coefficients were determined, and the combined standard uncertainty was estimated, according to (9).

Table 7. Example volume uncertainty budget table $V_{kG_5_60}$ (PK measurements).

Quantity	Estimate	Standard uncertainty	Probability distribution	Sensitivity coefficient	Uncertainty contribution
X_i	x_i	$u(x_i)$		c_i	$u_i(r_1)$
r_2	1.49890 mm	0.30 μm	normal	-422.086	-0.127 mm ³
r_1	20.00972 mm	0.30 μm	normal	6038.294	1.811 mm ³
h_1	58.02381 mm	0.30 μm	normal	1257.858	0.377 mm ³
h_2	44.81768 mm	0.30 μm	normal	7.058	0.002 mm ³
h_3	9.99592 mm	0.30 μm	normal	1257.858	0.377 mm ³
$V_{kG_5_60}$	60095.94 mm ³				1.89 mm ³

Assuming that the input quantities are not significantly correlated, the expanded uncertainty of the determined volume (for $k = 2$, $\gamma = 95.45\%$) can be written as:

$$U_{kA_5_60} = k \cdot u(V_{kA_5_60}) = 3,78 \text{ mm}^3 \quad (12)$$

and the final measurement result:

$$V_{kA_5_60} = (60.0959 \pm 0.0038) \text{ cm}^3. \quad (13)$$

The results of measuring the volume of graphite and aluminium chambers determined in analogy to the example discussed were summarized in the tables: Table 2 and Table 3 and marked with the index “PK”.

4. Conclusions

The designed and manufactured reference workpieces considered as master artifacts for precise *computer tomography* (CT) measurement of active volume of ionization chambers used in radiation dosimetry. Relative errors in ionization chamber volume measurement should not exceed 0.1%, according to the design assumptions [13]. According to the golden rule of metrology, reference ionization chambers should have an uncertainty ten times smaller. The obtained calibration uncertainty values (U_{cal}) for all constructed standards are summarized in Table 8. The calibration uncertainty of the eight constructed ionization chamber standards meets the assumptions of the reference chambers, i.e., $U_{cal} < 0.01\%$, and they were distinguished in Table 8.

The lower uncertainty values for chamber geometry measurements obtained at the external laboratory may be the result of both the use of a different CMM and the adopted procedure of estimating measurement uncertainty. When selecting PK as the reference laboratory, it was expected that more accurate measurement results would be obtained, based on the laboratory's declared *calibration and measurement capability* (CMC), as specified in its scope of accreditation.

Table 8. Summary of the obtained values of relative uncertainty of the standards: chambers made of graphite and PA6 aluminium alloy.

Nominal volume	Graphite		PA6 aluminium alloy	
	Obtained relative calibration uncertainty U_{cal}			
	Lab. PK	Lab. PW	Lab. PK	Lab. PW
cm ³	%	%	%	%
60	0.006	0.013	0.006	0.013
60	0.006	0.013	0.006	0.013
30	0.008	0.017	0.008	0.017
30	0.008	0.017	0.008	0.017
10	0.013	0.025	0.013	0.025
10	0.013	0.025	0.013	0.025
0.5	—	0.053	—	0.055
0.5	—	0.047	—	0.047

Acknowledgements

The research has been co-funded from the state budget from research project INFOSTRATEG7/0003/2023: “Metrological Platform for Volumetry in Computer Tomography” (Metrologiczna Platforma Wolumetrii w Tomografii Komputerowej) of The National Centre for Research and Development in Poland.

References

- [1] Attix, F. H., & Roesch, W. C. (Eds.). (1966). *Radiation Dosimetry: vol. 2: Instrumentation*. Academic Press.
- [2] International Atomic Energy Agency. (2000). Absorbed dose determination in external beam radiotherapy: An international code of practice for dosimetry based on standards of absorbed dose to water (Technical Reports Series No. 398). IAEA. Vienna. https://www.paho.org/sites/default/files/TRS398_scr.pdf

- [3] International Commission on Radiation Units and Measurements. (2016). *Key Data for Ionizing-Radiation Dosimetry: Measurement Standards and Applications* (ICRU Report No. 90). ICRU. https://doi.org/10.1093/jicru_ndw029
- [4] Kessler, C., Burns, D., Knyziak, A., Szymko, M., & Derlaciński, M. (2021). Key comparison BIPM.RI(I)-K1 of the air-kerma standards of the GUM, Poland and the BIPM in 60 Co gamma radiation. *Metrologia*, 58(1A), 06011. <https://doi.org/10.1088/0026-1394/58/1a/06011>
- [5] Kessler, C., Roger, P., Niedzialek, W., Derlaciński, M., & Buliński, K. (2025). Comparison BIPM.RI(I)-K6 of the standards for absorbed dose to water of the GUM, Poland and the BIPM in accelerator photon beams. *Metrologia*, 62(1A), 06003. <https://doi.org/10.1088/0026-1394/62/1a/06003>
- [6] Szymko, M., Knyziak, A., & Derlaciński, M. (2022). Graphite ionization chamber as an ionometric standard of absorbed dose to water for Co-60 gamma radiation. *Measurement*, 194, 110928. <https://doi.org/10.1016/j.measurement.2022.110928>
- [7] International Atomic Energy Agency. (2016). *Accuracy Requirements and Uncertainties in Radiotherapy*, (Human Health Series No. 31), IAEA, Vienna. https://www-pub.iaea.org/MTCD/Publications/PDF/P1679_HH31_web.pdf
- [8] Wołowiec, P., Tulik, P., Stemplowska, J., Buliński, K., Niedzialek, W., Szymko, M., Zaczek, K., Derlaciński, M., Kowaluk, T., & Braziewicz, J. (2025). Verification of the performance of the experimental ionization chamber for determination of absorbed dose to water for high-energy photon beams using Monte Carlo calculation. *Reports of Practical Oncology & Radiotherapy*, 30(2), 138–146. <https://doi.org/10.5603/rpor.105856>
- [9] Wołowiec, P., Niedzialek, W., Szymko, M., Tulik, P., Zaczek, K., Stemplowska, J., Buliński, K., & Braziewicz, J. (2025). Enhancing dosimetry accuracy: Characterization and verification of an experimental cylindrical graphite ionization chamber for dosimetry of therapeutic photon beams in reference conditions. *Polish Journal of Medical Physics and Engineering*, 31(2), 158–163. <https://doi.org/10.2478/pjmpe-2025-0018>
- [10] Kruth, J., Bartscher, M., Carmignato, S., Schmitt, R., De Chiffre, L., & Weckenmann, A. (2011). Computed tomography for dimensional metrology. *CIRP Annals*, 60(2), 821–842. <https://doi.org/10.1016/j.cirp.2011.05.006>
- [11] De Chiffre, L., Carmignato, S., Kruth, J., Schmitt, R., & Weckenmann, A. (2014). Industrial applications of computed tomography. *CIRP Annals*, 63(2), 655–677. <https://doi.org/10.1016/j.cirp.2014.05.011>
- [12] Kowaluk, T., & Wozniak, A. (2017). A new threshold selection method for X-ray computed tomography for dimensional metrology. *Precision Engineering*, 50, 449–454. <https://doi.org/10.1016/j.precisioneng.2017.06.020>
- [13] Regulations of the INFOSTRATEG VII project. <https://www.gov.pl/web/ncbr/vii-konkurs-infostrateg-na-projekty-zamawiane>
- [14] International Organization for Standardization. (2023). ISO/IEC 17043:2023: Conformity assessment – General requirements for the competence of proficiency testing providers. ISO. <https://www.iso.org/standard/80864.html>
- [15] Płowucha, W. (2018). Evaluation of coordinate measurement uncertainty by sensitivity analysis – theoretical background. *Mechanik*, 11, 953–956. <https://doi.org/10.17814/mechanik.2018.11.168>
- [16] Jakubiec W. (2007) Analityczne wyznaczanie niepewności pomiaru we współrzędnościowej technice pomiarowej. Bielsko-Biała: Wydawnictwo Akademii Techniczno-Humanistycznej, (in Polish).

- [17] International Organization for Standardization. (2017). ISO/IEC 17025:2017: General requirements for the competence of testing and calibration laboratories. ISO. <https://www.iso.org/standard/66912.html>



Marta Rępańska obtained her M.Sc. degree in quality engineering from Warsaw University of Technology (WUT) in 2005. There, she also obtained her PhD in mechanical engineering in 2019. She is currently employed as an assistant professor at the Institute of Metrology and Biomedical Engineering, WUT. Her scientific interests include coordinate measurement metrology, focusing on probes for machine tools and issues related to estimation of measurement uncertainty and reliability.



Piotr Tulik D.Sc. (Dr hab.) in the field of biomedical engineering – 2020, Ph.D. in biocybernetics and biomedical engineering – 2008, Warsaw University of Technology (WUT), Poland. He is currently a professor at the Faculty of Mechatronics at Warsaw University of Technology. His research focuses primarily on dosimetry of mixed radiation fields; radiation protection, with particular emphasis on medical procedures involving ionizing radiation; and the development of dosimetric standards

based on ionometric methods.



Tomasz Kowaluk A graduate of the Faculty of Mechatronics at Warsaw University of Technology, he earned his M.Sc. in Engineering in 2011 and his Ph.D. in 2016. He is currently an assistant professor at the Institute of Metrology and Biomedical Engineering, Faculty of Mechatronics, Warsaw University of Technology. His research interests include industrial computed tomography and coordinate measurement techniques.



Adam Woźniak Full Professor – 2017, D.Sc. (Dr hab.) – 2011, Ph.D. – 2002, Warsaw University of Technology (WUT), Poland. From 2005 to 2006 he was a visiting professor with the Department of Mechanical Engineering, École Polytechnique de Montréal, Canada. He is currently a professor at WUT. He teaches and conducts research in coordinate metrology. He has authored or coauthored 3 books and over 200 papers. Since 2020 he has been a Vice-Rector of WUT.