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Comparison of various types of ionization chambers in terms of calibration coefficients

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Introduction

The use of calibrated radiotherapy electrometers with ionization chambers, traceably to primary standards directly or through secondary standards, **is necessary and required by law for the accurate evaluation of patient radiation dose delivery in radiotherapy**.

In Poland, these measuring instruments are calibrated at the Secondary Standards Dosimetry Laboratory which is now the integral part of the Maria Sklodowska-Curie National Research Institute of Oncology in Warsaw.

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Introduction

The aim of this study was **comparison of various pieces of the most frequently used ionization chambers in Poland in terms of calibration coefficients**.

The most commonly used chambers are:

- PTW 30013;
- PTW 23343;
- PTW 30001;
- PTW 34001,
- Scanditronix-Wellhofer FC65-G;
- Scanditronix-Wellhofer PPC05.

Introduction

Characteristics of the studied cylindrical ionization chambers, based on the data provided by the manufacturers:

PTW 30013

General

Type of product	vented cylindrical ionization chamber
Application	reference dosimetry in radiotherapy beams
Measuring quantities	absorbed dose to water, air kerma, exposure
Reference radiation quality	^{60}Co
Design	waterproof, vented, guarded
Direction of incidence	radial

Materials and measures

Wall of sensitive volume	0.335 mm PMMA, 1.19 g/cm³ 0.09 mm graphite, 1.85 g/cm³
Total wall area density	56.5 mg/cm²
Dimensions of sensitive volume	radius 3.05 mm length 23.0 mm
Central electrode	Al 99.98, diameter 1.15 mm
Build-up cap	PMMA, thickness 4.55 mm

Specification

Nominal sensitive volume	0.6 cm³
Nominal response	20 nC/Gy
Long-term stability	≤ 0.5 % per year
Chamber voltage	400 V nominal ± 500 V maximal
Polarity effect at ^{60}Co	< 0.5 %
Reference point	on chamber axis, 13 mm from chamber tip
Photon energy response	≤ ± 2 % (70 kV ... 280 kV) ≤ ± 4 % (200 kV ... ^{60}Co)
Directional response in water	≤ ± 0.5 % for rotation around the chamber axis and for tilting of the axis up to ± 5°
Leakage current	≤ ± 4 fA
Cable leakage	≤ 1 pC/(Gy·cm)

PTW 30001

Volume:	0.6 cm³
Response:	2×10^{-8} C/Gy
Leakage:	$\pm 4 \times 10^{-15}$ A
Polarizing voltage:	max. 500 V
Cable leakage:	10^{-12} C/(Gy × cm)
Wall material:	PMMA($C_5H_8O_2$)$_n$
Wall density:	1.18 mg/cm³
Wall thickness:	0.45 mm
Area density:	53 mg/cm²
Electrode:	Aluminum; 1 mm ∅; 21.2 mm long
Range of temperature:	+10°C .... +40°C
Range of relative humidity:	20% ... 75%
Ion collection time:	300V:0.18ms 400V:0.14ms 500V:0.11ms

FC65-G

Features

- Waterproof
- Air ionization chamber
- Vented through waterproof sleeve
- Fully guarded
- Includes Build-up Cap, with individual factory calibration certificate and user's guide

Specifications

Cavity Volume: 0.65cm³
Cavity Length: 23.1 mm
Cavity Radius: 3.1 mm
Wall Material: Graphite
Wall Thickness: 0.073 g/cm²
Central Electrode Material: Aluminum
Waterproof: Yes

Introduction

Characteristics of the studied plane-parallel ionization chambers, based on the data provided by the manufacturers:

PTW 23343

Materials and measures:

Entrance foil	0.03 mm PE (polyethylene CH_2), 2.76 mg/cm^2
Protection cap	0.87 mm PMMA, 1.19 g/cm^3, 0.4 mm air
Total window area density	106 mg/cm^2, 1.3 mm (protection cap included)
Water-equivalent window thickness	1.06 mm (protection cap included)
Sensitive volume radius	2.65 mm, depth 2 mm
Guard ring width	< 0.2 mm

Specification

Type of product	vented plane parallel ionization chamber
Application	absolute dosimetry in high-energy electron beams
Measuring quantity	absorbed dose to water
Reference radiation quality	^{60}Co
Nominal sensitive volume	0.055 cm^3
Design	waterproof with protection cap, vented
Reference point	in chamber center on entrance foil, or 1.3 mm below surface of protection cap
Direction of incidence	perpendicular to chamber plane
Nominal response	2 nC/Gy
Long-term stability	≤ 1 % per year
Chamber voltage	300 V nominal, ± 400 V maximal
Polarity effect	≤ 1 %, for electrons ≥ 9 MeV
Directional response in water	≤ ± 0.1 % for chamber, tilting ≤ ± 10°
Leakage current	≤ ± 4 fA
Cable leakage	≤ 3.5 pC/(Gy·cm)

PTW 34001

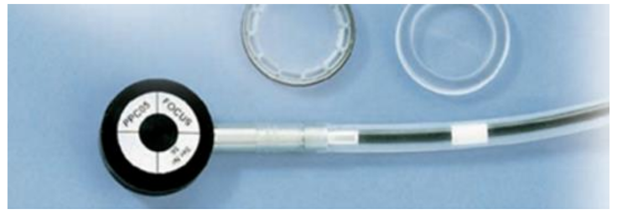
Materials and measures:

Entrance window	1.01 mm PMMA, 1.19 g/cm^3 0.02 mm graphite, 0.82 g/cm^3 0.1 mm laquer, 1.19 g/cm^3
Total window area density	132 mg/cm^2
Water-equivalent window thickness	1.29 mm
Sensitive volume	radius: 7.5 mm, depth: 2 mm
Guard ring width	4 mm

Specification

Type of product	vented plane parallel ionization chamber acc. IEC 60731
Application	reference dosimetry in high-energy electron and proton beams
Measuring quantity	absorbed dose to water
Reference radiation quality	^{60}Co
Nominal sensitive volume	0.35 cm^3
Design	waterproof, vented
Reference point	in chamber center, 1.12 mm below surface
Direction of incidence	perpendicular to chamber plane, see label 'Focus'
Nominal response	12 nC/Gy
Long-term stability	≤ 0.5 % per year
Chamber voltage	200 V nominal, ± 400 V maximal
Polarity effect	< 0.5 %
Directional response in water	≤ ± 0.1 % for chamber tilting ≤ ± 10°
Leakage current	≤ ± 4 fA
Cable leakage	≤ 1 pC/(Gy·cm)

PPC05



Outer dimensions

Chamber outer diameter: 30.0 mm
Chamber body height: 14.0 mm
Stem diameter: 8.5 mm
Stem length: 38.0 mm

Inner dimensions

Sensitive volume (nominal): 46.0 mm^3
Cylinder height: 0.6 mm
Entry window (polarizing electrode) diameter: 20.0 mm
Entry window thickness: 1.0 mm (0.176 g/cm^2)
Diameter of collecting electrode: 9.9 mm
Guard ring diameter: 17.8 mm
Guard ring width: 3.4 mm

Operational characteristics

Polarizing voltage: ±300 V (max. ±500 V)
Typical leakage current: 5 fA
Recommended pre-irradiation: 5 Gy
Typical sensitivity: 1.7 nC/Gy
Guard potential: ±300 V (max. ±500 V)
Temperature range: +15 – +35 °C
Relative humidity range: 20 % – 80 %

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Material

In this study we compared **calibration coefficients** values for ionization chambers with different serial numbers for each of the six types of ionization chambers mentioned earlier.

The calibration coefficients were measured at the Polish SSDL over a period of four consecutive years to minimize the aging effects of the ionization chambers.

Some of the ionization chambers were calibrated with more than one electrometer during the analyzed period.

The **calibration coefficients** based on standards of absorbed dose to water $N_{D, w}$ were established in ^{60}Co beam by comparing the readings of the calibrated dosimeter with the readings of the reference dosimeter in reference conditions defined in the Technical Reports Series No. 398 (IAEA, 2000).

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Methods

The following values were calculated for each group of chambers:

- the arithmetic mean value of $N_{D,\,\mathrm{w}}$;
- the median value of $N_{D,\,\mathrm{w}}$;
- the standard deviation value of $N_{D,\,\mathrm{w}}$, expressed as a percentage of the arithmetic mean value of calibration coefficients for each group of chambers;
- the ratio of the largest and the smallest calibration coefficients in each group of chambers.

Moreover, the results have been analyzed using an appropriate statistical test at a predetermined significance level: $\alpha = 0.05$.

The choice of the statistical test have been justified providing evidence that the assumptions regarding the choice of the given statistical test have been met.

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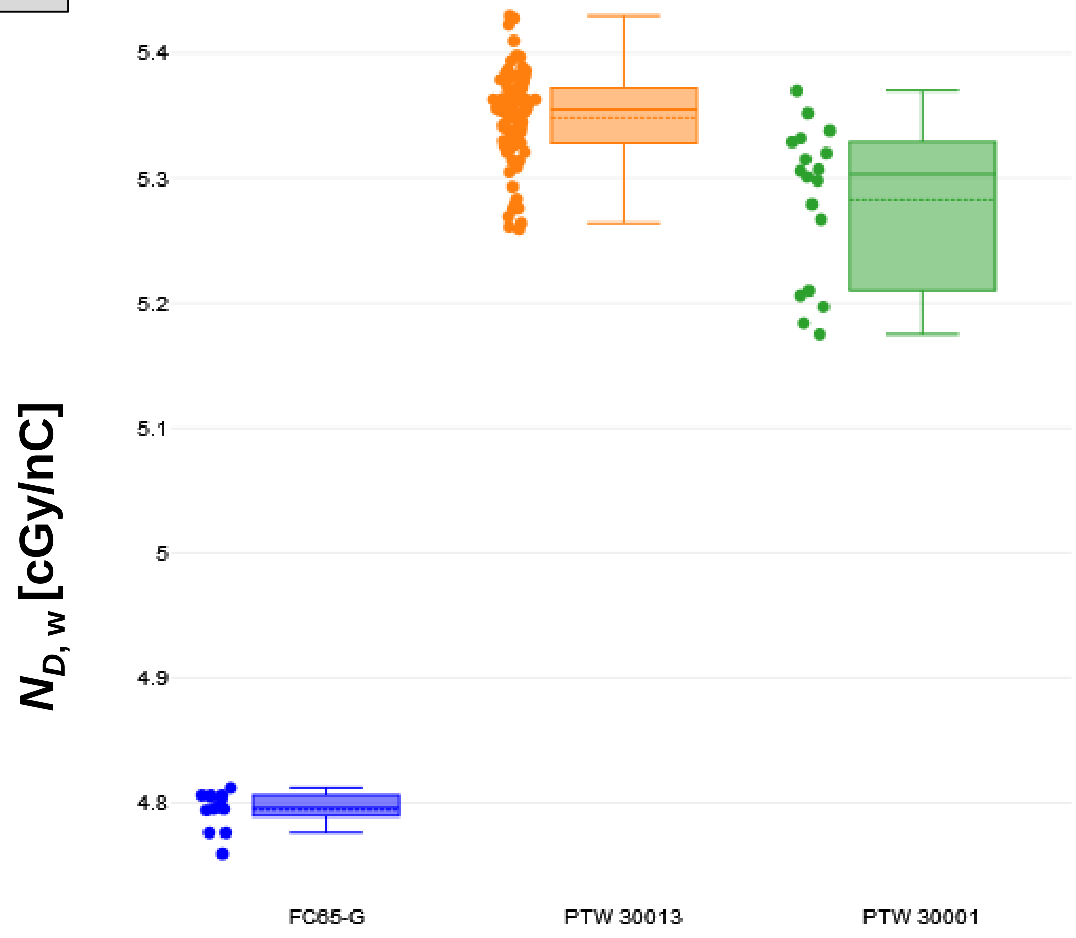
Results

Calibration coefficients for cylindrical ionization chambers

Box plot



Type of cylindrical ionization chambers

Descriptive statistics

Type of chambers	FC65-G	PTW 30013	PTW 30001
Sample size: n	13	82	18
Arithmetic mean value of $N_{D,w}$ [cGy/nC]	4.795	5.348	5.283
Median value of $N_{D,w}$ [cGy/nC]	4.796	5.355	5.303
Standard deviation value of $N_{D,w}$ [cGy/nC]	0.015	0.037	0.062
Standard deviation value of $N_{D,w}$ expressed as a percentage of the arithmetic mean value of $N_{D,w}$ [%]	0.32	0.70	1,16
Q_1 [cGy/nC]	4.759	5.328	5.210
Q_3 [cGy/nC]	4.806	5.372	5.329
$N_{D,w\ max}$ [cGy/nC]	4.812	5.430	5.370
$N_{D,w\ min}$ [cGy/nC]	4.759	5.259	5.175
$N_{D,w\ max}$ / $N_{D,w\ min}$	1.01	1.03	1.04
Outliers	4.759	5.259, 5.261	none

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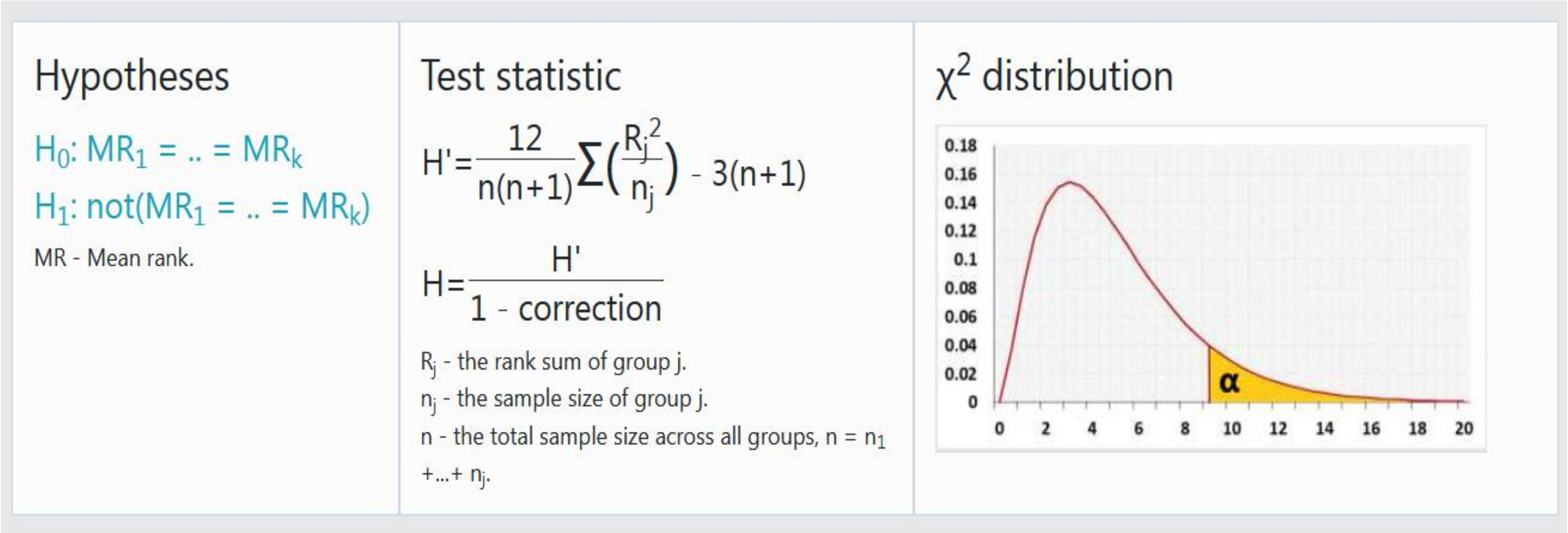
Results

Statistical analysis of the calibration coefficients for cylindrical ionization chambers

Kruskal -Wallis test followed by post-hoc Dunn's test

The Kruskal-Wallis test also called one-way ANOVA on ranks is a non-parametric test.

Target: To check if the difference between the ranks of two or more groups is significant, using a sample data. When the groups have a similar distribution shape, the null assumption is stronger and states that the medians of the groups are equal. When performing the Kruskal-Wallis test, we try to determine, if the difference between the ranks reflects a significant difference between the groups, or is due to the random noise inside each group. The Chi-square statistic is an approximation for the exact calculation.



Assumptions

- Independent samples from independent groups. One subject can't be in more than one group.
- The dependent variable is ordinal variable or continuous variable.
- Two or more groups (the independent variable is categorical variable with two or more values).

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Results

Statistical analysis of the calibration coefficients for cylindrical ionization chambers

Kruskal-Wallis test followed by post-hoc Dunn's test

Groups:	FC65-G	PTW 30013	PTW 30001
Skewness:	-1.2496	-0.4641	-0.6096
Skewness Shape:	**Asymmetrical,**	(pval=0.081)	Potentially
Excess kurtosis:	1.0027	0.3439	-0.9788
Tails Shape:	Potentially	Potentially	Potentially
Normality	0.03224	0.02157	0.05192
Outliers:	4.759	5.259, 5.261	
Median:	4.796	5.355	5.3035
Sample size (n):	13	82	18
Rank sum (R):	91	5701	649
R^2/n:	637	396358.5488	23400.0556

Normality

The normality is **not** an assumption for the Kruskal-Wallis test!

We only check the normality to know if we could use a better test (i.e. the ANOVA test).

The normality was checked based on the Shapiro-Wilk test at the significance level: $\alpha = 0.05$.

When running the Shapiro-Wilk test on the residuals, the p-value is 0.001059.

The ANOVA test is more powerful than the Kruskal-Wallis test and considered robust for moderate violation of the normality assumption.

When checking the groups with a small sample size, less than 30, two groups don't have normally distributed data (the smaller p-value is 0.0322).

The Kruskal-Wallis test is probably the correct test.

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Results

Statistical analysis of the calibration coefficients for cylindrical ionization chambers

Kruskal-Wallis test followed by post-hoc Dunn's test

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Tails Shape:	Potentially	Potentially	Potentially
Normality	0.03224	0.02157	0.05192
Outliers:	4.759	5.259, 5.261	
Median:	4.796	5.355	5.3035
Sample size (n):	13	82	18
Rank sum (R):	91	5701	649
R^2/n:	637	396358.5488	23400.0556

Significance level: $\alpha = 0.05$

The p-value equals $1.677e^{-11}$ (p-value < 0.001)

The test statistic H equals 49.62 which is not in the 95% region of acceptance: [0, 5.9915].

Since the p-value < α, H_0 is rejected.

Some of the groups' mean ranks consider to be not equal.
In other words, the difference between the mean ranks of some groups is big enough to be statistically significant.
When selecting a value from each of the groups, there are some groups with a higher probability of containing the highest value than others.

The Kruskal-Wallis H test indicated that there is a **significant difference in the *dependent variable* between the different *groups***, $\chi^2(2) = 49.62$, $p < 0.001$, with a mean rank score of 7 for FC65-G ionization chamber type, 69.52 for PTW 30013 ionization chamber type, 36.06 for PTW 30001 ionization chamber type.

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Results

Statistical analysis of the calibration coefficients for cylindrical ionization chambers

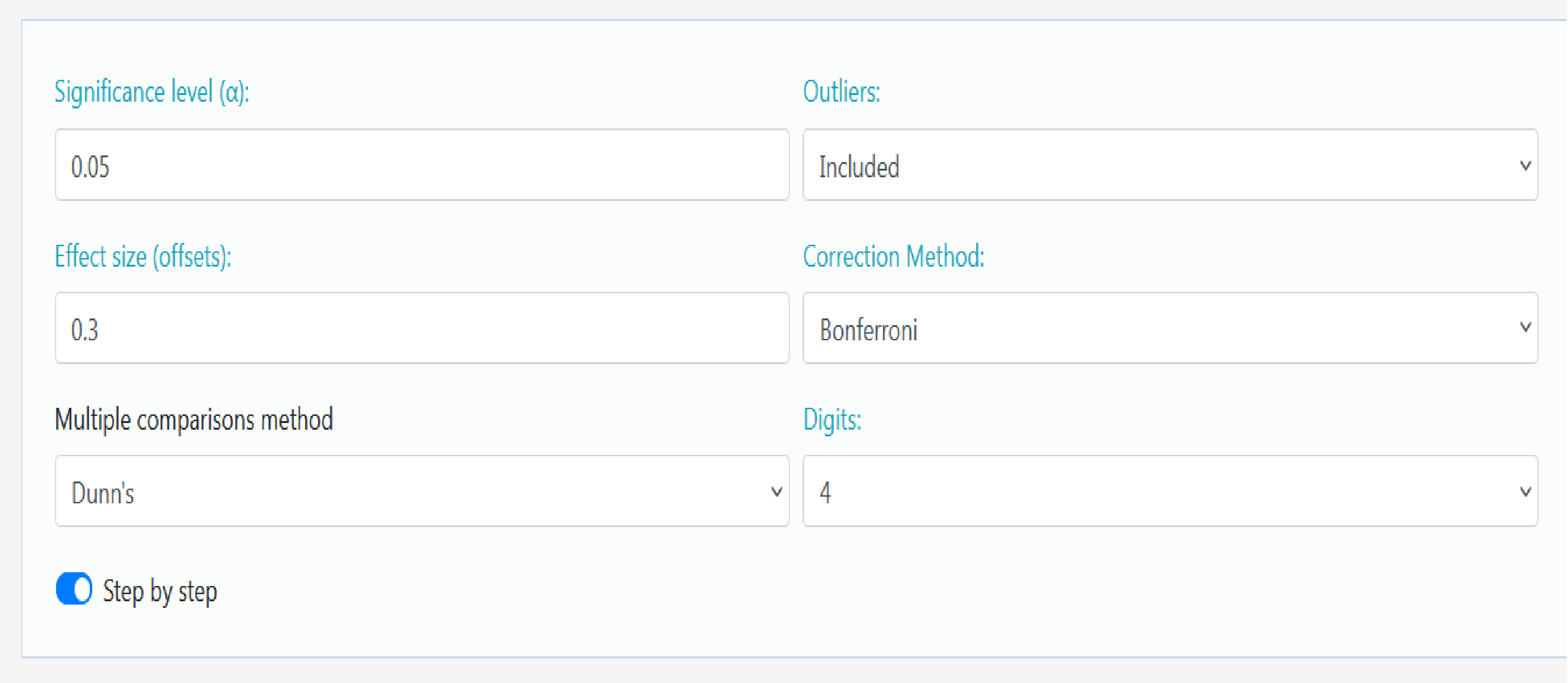
Kruskal-Wallis test followed by post-hoc Dunn's test

Multiple comparisons

Even if we know that not all the ranks are equal, we don't know which groups are not equal, hence we run a **Multiple comparisons test (i.e. Dunn's test)** to compare all the pairs. **Dunn's test** takes into consideration the total number of groups (k) even when comparing only two groups.

Pair	Mean Rank difference	Z	SE	Critical value	p-value	p-value/2
x_1-x_2	-62.5244	6.3931	9.7799	23.4123	1.625e-10	8.127e-11
x_1-x_3	-29.0556	2.4367	11.9241	28.5452	0.01482	0.007411
x_2-x_3	33.4688	3.9249	8.5273	20.4135	0.00008676	0.00004338

Group	PTW 30013	PTW 30001
FC65-G	-62.52	-29.06
PTW 30013	0	33.47



The Post-Hoc Dunn's test using a Bonferroni corrected alpha of 0.017 indicated that **the mean ranks of the following pairs are significantly different**: **x_1-x_2, x_1-x_3, x_2-x_3**, where x_1 refers to FC65-G ionization chamber type, x_2 refers to PTW 30013 ionization chamber type, x_3 refers to PTW 30001 ionization chamber type.

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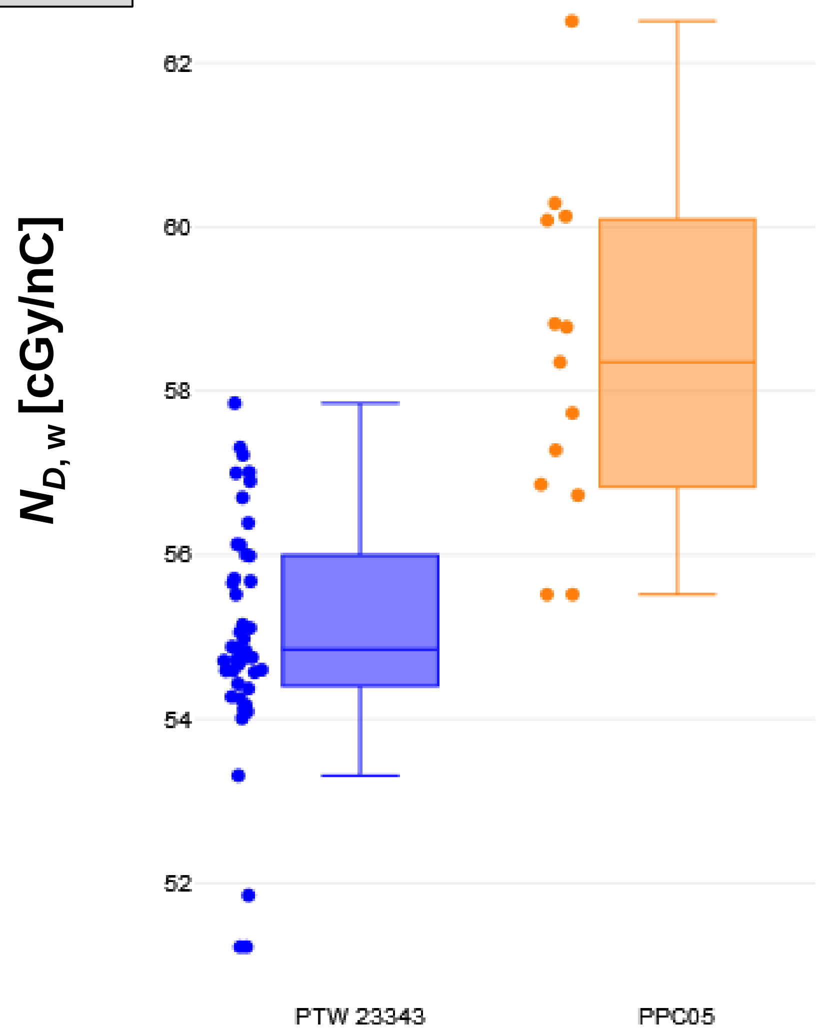
Results

Calibration coefficients for PTW 23343 and PPC05 ionization chambers

Box plot



Type of plane parallel ionization chambers

Descriptive statistics

Type of chambers	PTW 23343	PPC05
Sample size: n	44	13
Arithmetic mean value of $N_{D,w}$ [cGy/nC]	55.03	58.35
Median value of $N_{D,w}$ [cGy/nC]	54.85	58.35
Standard deviation value of $N_{D,w}$ [cGy/nC]	1.44	2.04
Standard deviation value of $N_{D,w}$ expressed as a percentage of the arithmetic mean value of $N_{D,w}$ [%]	2.61	3.50
Q_1 [cGy/nC]	54.40	56.86
Q_3 [cGy/nC]	55.99	60.08
$N_{D,w\ max}$ [cGy/nC]	57.85	62.51
$N_{D,w\ min}$ [cGy/nC]	51.22	55.52
$N_{D,w\ max} / N_{D,w\ min}$	1.13	1.13
Outliers	51.22, 51.85, 51.22	none

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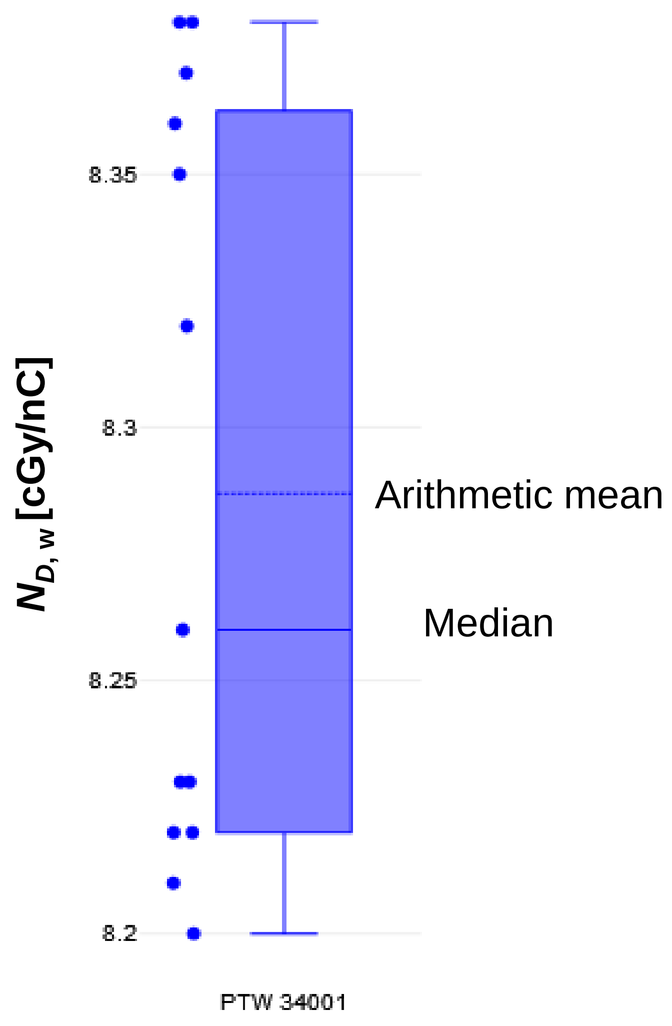
Results

Calibration coefficients for PTW 34001 ionization chambers

Box plot



Type of plane parallel ionization chambers

Descriptive statistics

Sample size: n	13
Arithmetic mean value of $N_{D,w}$ [cGy/nC]	8.29
Median value of $N_{D,w}$ [cGy/nC]	8.26
Standard deviation value of $N_{D,w}$ [cGy/nC]	0.07
Standard deviation value of $N_{D,w}$ expressed as a percentage of the arithmetic mean value of $N_{D,w}$ [%]	0.90
Q_1 [cGy/nC]	8.22
Q_3 [cGy/nC]	8.36
$N_{D,w\ max}$ [cGy/nC]	8.38
$N_{D,w\ min}$ [cGy/nC]	8.20
$N_{D,w\ max}$ / $N_{D,w\ min}$	1.02
Outliers	none

Conclusions

The obtained results indicated that **the maximum differences in the calibration coefficients of the analyzed cylindrical ionization chambers did not exceed 4%.**

For the analyzed plane parallel ionization chambers, the calibration factors may differ by more than 10%.

Therefore, it should be remembered that **the use of an ionization chamber in clinical work must always be preceded by its calibration in a competent calibration laboratory**.
This will enable measurements of the dose delivered to the patient in teleradiotherapy with the **expected accuracy**.

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Thank you for your attention.