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Evaluation of the Characteristics of Ionization Chambers Used for Commissioning in High Dose Rate Linacs

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Abstract

Introduction: Recently there has been an increased interest in high dose rate free flattening filter (FFF) linear accelerators which are used clinically in most of the advanced radiotherapy techniques such as VMAT, SRS and SBRT. From previous reports, the calculated ion recombination (P_{ion}) at FFF beams may be inaccurate as calculated from the two-voltage technique. Therefore, Pion was measured for flattened beams of 6 and10 MV and for FFF beams of 6 and 10 MV with the two voltage method and verified by Jaffe Plots.

Materials and Methods: The aim of the work is to investigate the charge collection efficiency of two ionization chambers for photon beams with flatting filter and flattening filter free of Elekta Versa HD Linac with IBA PPC05 and CC13 ionization chambers. Experimental data will be collected from Elekta Versa HD at energies of 6 MV, 10 MV, 6 MV FFF and 10 MV FFF for different field sizes at two different depths applying the two voltage method and verify it using the Jaffe Plots.

Results: After studying the effect of the voltage difference used on the value of electrical charges collected by each of the two chambers at FF and FFF beams, it was found that the effect of the applied voltage is always higher on the cylindrical chamber.

Conclusion: The results showed that the magnitude of that effect increases with both energy and dose rate and it is possible to say that as much as the active volume is small and easy to determine the effective point of measurements as in the parallel plate chamber as much as it showed a significant impact on the accuracy and stability of measurements in most of measurement conditions. Also being suitable for use in absolute measurements makes them better in non-reference or relative measurements at FFF beams.

Keywords: Flattening filter free; Ion recombination; Acceptance and commissioning and ionization chambers

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Introduction

The effect on a chamber reading of pressure, temperature, using polarizing potentials of opposite polarity, electrometer calibration and ion recombination must always be checked on commissioning [1]. The ion recombination correction is worth significant investigation and discussion since it provides a very good indication of whether a chamber is operating correctly [2-4]. The standard technique for determining the Pion correction is the two-voltage technique as mentioned at the American Association of Physicists in Medicine Task Group (TG) 51 protocol [5] and the International Atomic Energy Agency's Technical Reports Series No. 398 protocol (TRS-398) [1] by measuring charge produced by the ion chamber when two different voltages are applied to the detector.

The ion recombination correction factor, Pion, is used to correct the incomplete signal col-lection of charge in an ionization chamber cavity due to the recombination of ion pairs either formed by separate ionizing particle tracks or by a single ionizing particle track [1,6].

According to the TG 51 protocol Pion is determined using the two-voltage method (using high voltage [VH] and low voltage [VL] that produce measured ionization readings MH and ML, respectively) and should not exceed 1.05 [5]. For pulsed beams, Pion is described by equation:

$$P_{ion}(V_H) = \frac{1 - V_H / V_L}{M_{raw}^H / M_{raw}^L - V_H / V_L}$$

The main purpose of the FFF X-rays is to provide higher dose rates for treatments. FFF X-rays from Elekta Versa HD can deliver 1400 MU/minute for 6 MV X-rays and 2400 MU/minutes for 10 MV X-rays. Higher dose rates have clinical benefits in organ motion management [7]. Clinically in most of the advanced radiotherapy techniques such as VMAT, SRS and SBRT treatments, large MUs are often required and FFF X-ray beams can deliver these large MUs in a much shorter time. So, it is crucial to measure the pion correction factor for the high dose rate FFF beams as well as traditional flattened beams to determine if the existing two-voltage method is appropriate for FFF beams or not [6,8].

Another technique used by several authors [2,4,9] to verify the results of the simple two voltage method recommended in TG-51 [2,5,10,11] is by determining the recombination correction by plotting 1/reading against 1/applied voltage referred to as a Jaffé plot and extrapolating to infinite voltage.

Materials and Methods

This work was done by using the Versa HD linac which is capable of delivering 6 MV, 6 MV FFF, 10 MV, 10 MV FFF photon beams. Measurements of Pion were made using the two-voltage method based on the TG 51 protocol with voltages of -300 V and -150 V for two ionization chamber namely thimble ionization chamber IBA CC13 (14005, Germany) and parallel plate ionization chamber IBA PPC05 (885, Germany). The collected charge from 200 MU was measured for the two voltages. Measurements were made using IBA water tank Blue Phantom² with a scanning range of 48 × 48 × 41 cm^3 at a source-to-surface distance of 100 cm. The field sizes were 10 × 10 cm^2 and 40 × 40 cm^2 for photon beams. Pion was measured for photon beam energies of 6, 10 MV FF and 6,10 MV FFF at depths of Dmax (1.5 cm for 6 MV and 2.3 cm for 10 MV) and D10 (depth of 10 cm).

Table 1 P_{pol} for parallel plate chamber PPC05 and thimble chamber CC13.

Energy	6 MV	10 MV	6 MVFFF	10 MVFFF	Mean
PPC05	1.000121	1.000113	1.00072	1.00009	1.0002
CC13	1.00026	1.000478	1.00023	1.000408	1.0003

Finally, the recombination correction was verified by plotting the inverse of the chamber reading (1/Q) as a function of the inverse of the polarizing voltage (1/V) (Jaffé-plots) for each chamber and all the energies. The collected charge from 200 MU was measured as a function of chamber voltage which varied between -100 and -300. The effect of the variation in applied reference voltage on the collective charge for that the produced ionization were measured at four different voltages (- 300 V, -150 V, -120 V and -100 V). The measured value was extrapolated to 1/V = 0 to estimate the recombination effects at -300 V. and then Jaffé-plot recombination factors were compared to the Pion values determined with the two-voltage method values.

Results

The comparison between the two ionization chambers was performed in three steps: first, the effect of polarizing voltage on the absolute collective charge which called polarity effect (Ppol), where the ionization was collected at the reference voltage -300 and at the opposed voltage +300. Second, the effect of the variation in applied reference voltage on the collective charge which called ion recombination (Pion) for that the produced ionization were measured at four different voltages.

Third, the two chambers were used to perform some selected nonstandard or relative measurements to evaluate practically the outcome of the two chambers on the quality of relative data commissioning.

Polarity effect (Ppol)

The results showed that the effect of the polarity Ppol on the parallel plate ionization chamber PPC05 was 0.02% whereas for the Thimble ionization chamber CC13 the effect was 0.03% **(Table 1)**.

For the ion recombination (P_{ion}), as described in the previous section material and methods the two-voltage method was used to determine the ion recombination and the two-voltage uncertainty assignment is based on the difference between the expected value from the Jaffe Plot theory and the value measured by the two-voltage method. For the photon beams examined in this study, the mean measured Pion values of the parallel plate ionization chamber PPC05 are presented in **Tables 2 and 3** for the 6, 10, 6 FFF and 10 FFF MV X-ray beams for field sizes 40 × 40 cm^2 and 10 × 10 cm^2 with depths of 10 cm (D_{10}) and depth of maximum dose (D_{max}) by the two voltage technique and Jaffe plot method. The depth of maximum dose for 10 MV and 6 MV are 2.3 cm and 1.5 cm respectively. The

Table 2 P_{ion} Parallel plate chamber PPC05 for field size 40 × 40 cm^2 at depths D_{max} and D_{10}.

Energy	6 MV		10 MV		6 MV FFF		10 MV FFF	
Depth cm	D_{10}	D_{max}	D_{10}	D_{max}	D10	D_{max}	D_{10}	D_{max}
P_{ion}	1.0007	1.004	1.003	1.0021	1.0025	1.0044	1.0017	1.0019
Jaffe plot	0.9981	0.9991	1.0358	0.9951	0.9814	0.993	0.9869	0.996

Table 3 P_{ion} parallel plate chamber PPC05 for field size 10 × 10 cm^2 at depths D_{max} and D10.

Energy	6 MV		10 MV		6 MV FFF		10 MV FFF	
Depth cm	D10	D_{max}	D_{10}	D_{max}	D_{10}	D_{max}	D_{10}	D_{max}
P_{ion}	1.005	1.0031	1.0056	1.001	1.008	1.0037	1.0012	1.0037
Jaffe plot	0.992	0.9988	0.9921	0.9929	0.9946	0.9967	0.9965	0.9964

results showed a very small variation of P_{ion} with both differences in energies dose rate and depths. Although there was a difference between the two calculation methods therefore this deviation was no more than 0.4% (± SD 1.6%) over the measured beams for each energy. It is worth mentioning here that for the reference field size 10 × 10 cm^2 the results were the same as the large one 40 × 40 cm^2 with slight differences between the two calculation methods 0.8% (± SD 0.4%) over the measured beams for each energy.

For cylindrical or thimble ionization chamber CC13, **Tables 4 and 5** show the mean measured Pion values at 6, 10, 6 FFF and 10 FFF MV X-ray beams for field sizes 10 × 10 cm^2 and 40 × 40 cm^2 with depths D_{10} cm and D_{max} by the two voltage technique and Jaffe Plot method.

The mean value for Pion at the two field sizes were 1.7% and 2.1% respectively. Unlike the parallel plate chamber, the thimble one showed a large effect with reduced voltages and so the variations between the two techniques were 2.3% (± SD 1.1%) and 2% (± SD 0.8%) respectively over the measured beams for each energy. Also, the thimble chamber results showed that there was no specific behavior with a change in the depths.

The uncertainty in the ion chamber readings (the spread between the three readings that comprised each measurement point) was <0.3% for the parallel plate chamber against 0.9% for the thimble ionization chamber. In addition to, different setups the uncertainty of the positioning was 0.5%.

Discussion

High voltage effect

In this study, we focused on the effect of the difference in the applied voltage on the efficiency of the collection of ions generated in the two ion chambers at a range of energies used in radiotherapy as well as in the different measurement conditions to clarify which ones will appear sturdier than the others. After studying the effect of the voltage difference used on the value of electrical charges collected by each of the two chambers, it was found that the effect of the applied voltage P_{pol} is always higher on the thimble chamber (CC13) for all energy except for 6 MV FFF. The results also showed that the magnitude of that effect increases with both energy and dose rate. Looking at all the results, it is possible to say that the small size of the active volume of the parallel plate chamber and its geometry that makes it easy to determine its effective point have a significant impact on the accuracy and stability of measurements in most of measurement conditions. Also being suitable for use in absolute measurements makes them better in relative measurements.

Linear behavior (Jaffe plots)

The Jaffe plots for all FF and FFF beams were plotted to verify the validity of the Pion values measured with the two voltage technique. The inverse of the chamber reading (1/Q) as a function of the inverse of the polarizing voltage (1/V) were obtained for each chamber for all the energies with different field sizes and different sizes as shown in **Figures 1-4**. The results of the Jaffe plots method as appeared in the following **Figures 1-4** are highly compatible with the two-voltage method where that the linear relation between the ion chamber reading and the voltage is very little for the parallel plate chamber in comparison with the CC13 thimble chamber. Even that the values of Pion from Jaffe plots agreed within 0.5% with the two voltage technique Pion.

Non-reference dosimetry

Percentage depth dose and beam profiles: Percentage depth dose and beam profile were measured by using the two types ionization chambers **Figures 5-10**. Although the two chambers results were close to each other, the parallel plate chamber was better in the results of the surface dose in comparison with the

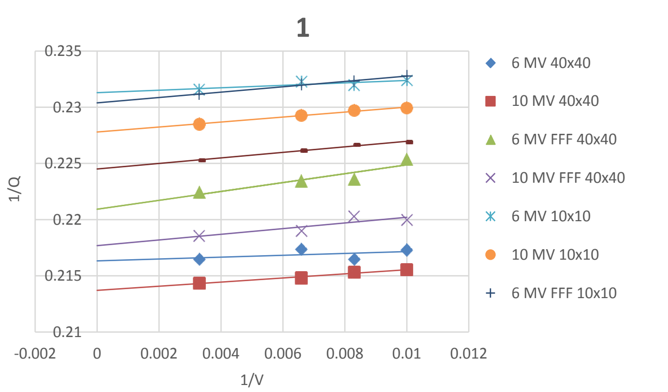

Figure 1 Jaffe plot for PPC05 at D_{max} for 40 × 40 cm^2 and 10 × 10 cm^2 FS for different energies.

Table 4 P_{ion} thimble ionization chamber CC13 for field size 10 × 10 cm^2 at depths D_{max} and D_{10}.

Energy	6 MV		10 MV		6 MV FFF		10 MV FFF	
Depth cm	D_{10}	D_{max}	D_{10}	D_{max}	D_{10}	D_{max}	D_{10}	D_{max}
P_{ion}	1.0128	1.0044	1.0153	1.0097	1.013	1.0166	1.0172	1.003
Jaffe plot	0.9927	0.9939	0.9893	0.9928	0.9881	0.9708	0.9877	0. 9901

Table 5 P_{ion} thimble ionization chamber CC13 for field size 40 × 40 cm^2 at depths D_{max} and D_{10}.

Energy	6 MV		10 MV		6 MV FFF		10 MV FFF	
Depth cm	D_{10}	D_{max}	D_{10}	D_{max}	D_{10}	D_{max}	D_{10}	D_{max}
P_{ion}	1.0037	1.006	1.0093	1.012	1.011	1.0165	1.011	1.021
Jaffe plot	0.9946	0.9953	0.9898	0.9937	0.9868	0.9852	0.9896	0.9901

2019
Vol.4 No.1:1

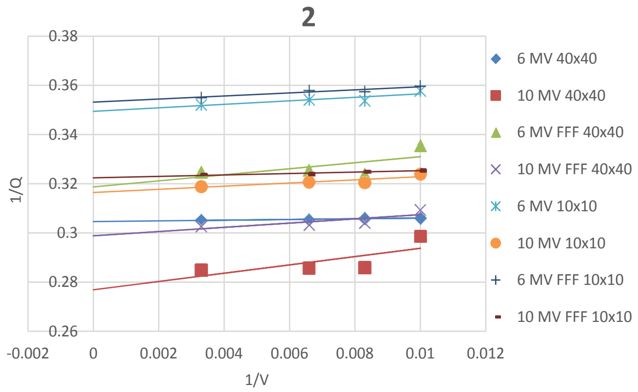

Figure 2 Jaffe plot for PPC05 at D_{10} for 40 × 40 cm² and 10 × 10 cm² FS for different energies.

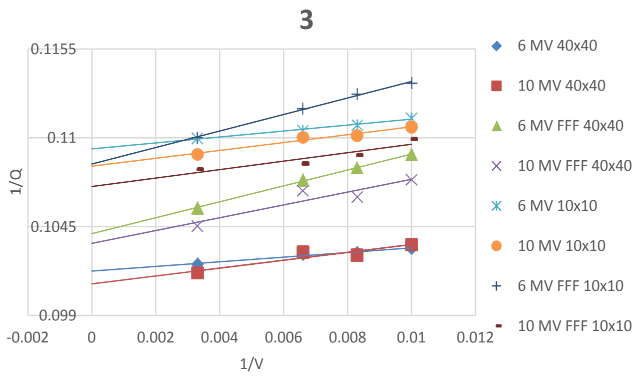

Figure 3 Jaffe plot for CC13 at D_{max} for 40 × 40 cm² and 10 × 10 cm² FS for different energies.

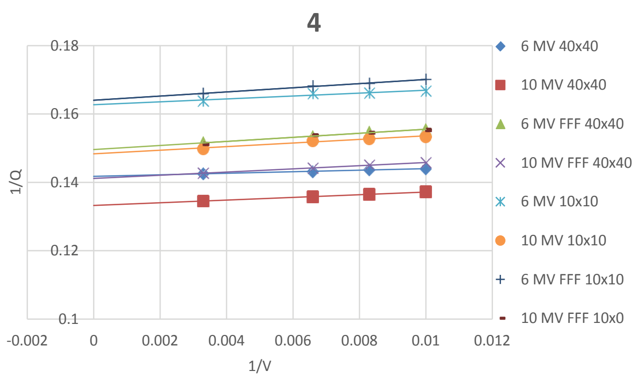

Figure 4 Jaffe plot for CC13 at D_{10} for 40 × 40 cm² and 10 × 10 cm² FS for different energies.

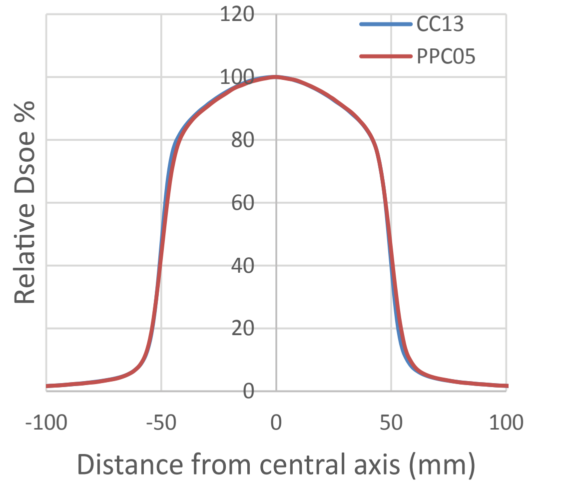

Figure 5 Y-axis profile for 10 MV FFF beam at 10 × 10 cm² FS.

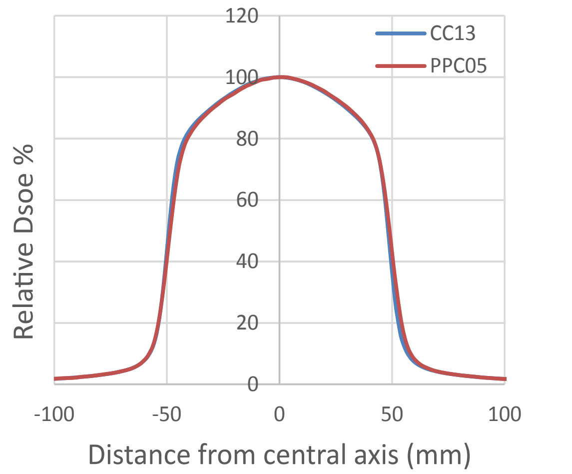

Figure 6 X-axis profile for 10 MV FFF beam at 10 × 10 cm² FS.

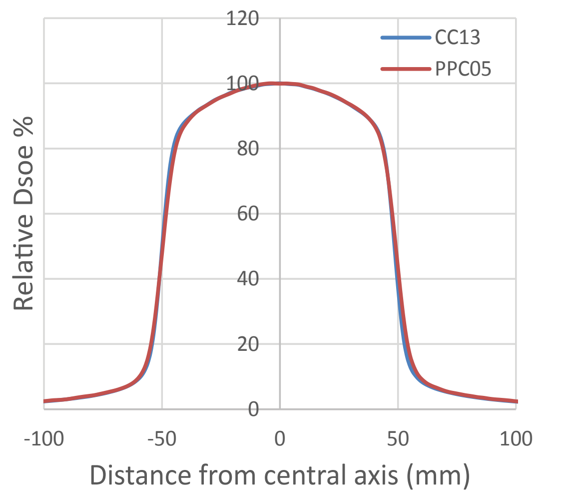

Figure 7 Y-axis profile for 6 MV FFF beam at 10 × 10 cm² FS.

published data (ICRU-25) [12]. Those results confirm what was adopted by the IAEA protocols 381 [13] and 398 [1] and the IAEA hand book that plane-parallel chambers are recommended for relative measurements of depth- ionization distributions and beam profiles in photon beams. The desirable chamber properties for this purpose are essentially the same as those for electron radiation. For beam profile **Figures 5-10** the parallel plate chamber showed better symmetry than the CC13 chamber.

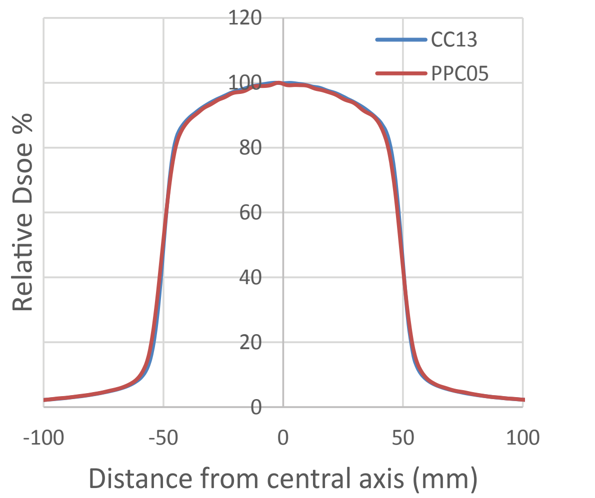

Figure 8 X-axis profile for 6 MV FFF beam at 10 × 10 cm^2 FS.

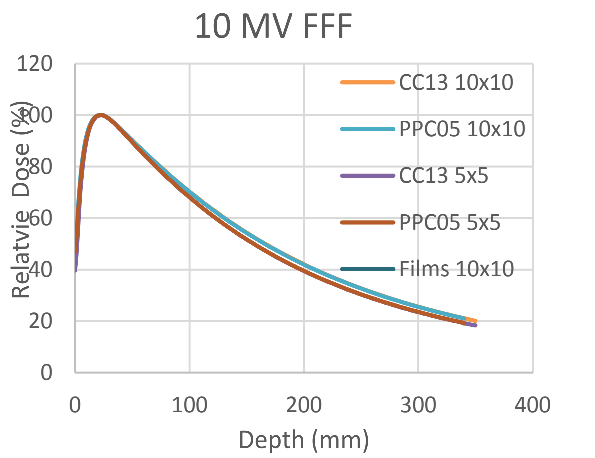

Figure 9 PDD for 10 MV FFF beam at 10 × 10 cm^2 and 5 × 5 cm^2 FS.

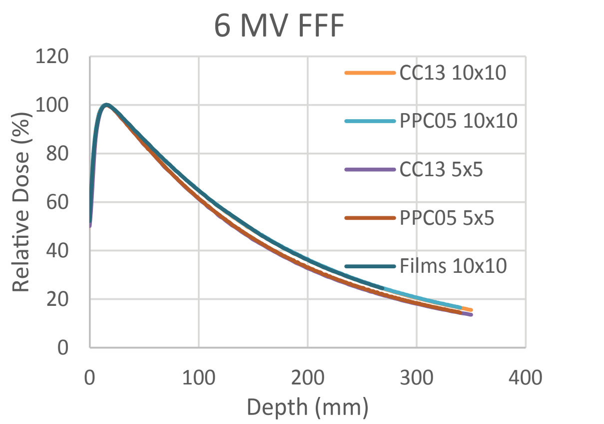

Figure 10 PDD for 6 MV FFF beam at 10 × 10 cm^2 and 5 × 5 cm^2

The highly defined chamber dimensions were important in order to ensure that taking the effective point of measurement to be at the center of the front surface of the air cavity is a reasonable approximation, independent of beam quality and measuring depth and this is an essential advantage in comparison with thimble chambers (CC13). This is especially important for measurements under non equilibrium conditions at shallow depths in the build- up region, where even larger ratios of guard ring width to cavity height could be advantageous.

For PDD measurements, parallel plate ionization chambers with the effective point of measurement placed at nominal depth are recommended. IAEA experts [8] recommend the use of a parallel-plate chamber during acceptance testing and data collection for linear accelerators used in radiotherapy, and that most, if not all, manufacturers of ionization chamber detectors used for that purpose recommend the use of small cylindrical or thimble ionization chambers for relative dose measurements. For most plane-parallel ionization chambers recommended in this report the in-scattering and wall backscattering perturbation effects are assumed to be relatively insensitive to the measuring conditions [14,15]. The same criteria for the position of the effective point of measurement as for absolute measurements is recommended, where the effective point (P_{eff}) is positioned at the inner side of the front wall of the air cavity for all depths. According to Pion results when relative depth ionization curves are measured with CC13 ion chamber the variation in the collection efficiency due to voltage variations and at different depths must be considered.

The reference to recommending the use of a parallel plate chamber is attributed to two reasons: the first is the small active volume, which results in the very accurate dose measurements in the parts where there is a significant change in the level of radiation such as the construction area from the phantom surface to the maximum dose point (buildup region) and the shadow area at the side ends of the field size (penumbra region). The second reason is the ease and accuracy of determining the point of influence (the effective point of measurement) of the parallel plate ionization chamber.

Conclusion

After studying the effect of the voltage difference used on the value of electrical charges collected by each of the two chambers, it was found that the effect of the difference in the applied voltage is always higher on the cylindrical chamber than the parallel plat chamber. The results also showed that the magnitude of that effect increases with both energy and dose rate. Looking at all the results, it is possible to say that the small size of the active volume and easy to determine the effective point of the parallel plat chamber has a significant impact on the accuracy and stability of measurements in most of measurement conditions. Also being suitable for use in absolute measurements makes them better in relative measurements. According to these results we can recommend the parallel plate ion chamber for non-reference or relative measurements (percentage depth dose and beam profile).

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