Choice of a Suitable Dosimeter for Photon Percentage Depth Dose Measurements in Flattening Filter-Free Beams

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Abstract

The International Atomic Energy Agency Technical Reports Series-398 code of practice for dosimetry recommends measuring photon percentage depth dose (PDD) curves with parallel-plate chambers. This code of practice was published before flattening filter-free (FFF) beams were widely used in clinical linear accelerators. The choice of detector for PDD measurements needs to be reassessed for FFF beams given the physical differences between FFF beams and flattened ones. The present study compares PDD curves for FFF beams of nominal energies 6 MV, 6 FFF, 10 MV, and 10 FFF from a Varian TrueBeam linear accelerator (Varian Medical Systems, Palo Alto, USA) acquired with Scanditronix photon diodes, two scanning type chambers (both PTW 31010 Semiflex), two small volume chambers (Wellhofer CC04 and PTW 31016 PinPoint 3D), PTW 34001 Roos, Scanditronix Roos, and NACP 02 parallel-plate chambers. Results show that parallel-plate ion chambers can be used for photon PDD measurements, although for better accuracy, recombination effects should be taken into account.

Keywords: International Atomic Energy Agency Technical Reports Series-398, percentage depth dose, photon dosimetry, parallel-plate ion chamber

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Introduction

Linear accelerators with flattening filter-free (FFF) beams are becoming widespread, with Varian TrueBeam, and Elekta Versa being the most common ones since Siemens is no longer in the radiotherapy market. New radiotherapy techniques, such as volumetric modulated arc therapy and stereotactic body radiotherapy, allow the clinical use of unflattened beams. As it has been widely discussed in the literature, FFF linear accelerators have several potential advantages, including the fact that treatment times can be reduced as dose rates are much higher than the ones for flattened beams.[1-3]

The International Atomic Energy Agency (IAEA) published its Technical Reports Series-398 (TRS-398) code of practice "Absorbed Dose Determination in External Beam Radiotherapy" in 2000[4] when FFF linear accelerators were not yet in widespread clinical use. Nevertheless, this international code of practice is currently being utilized for FFF beams in different countries. The issue of whether or not corrections should be applied to the beam quality conversion factor, k_q, to account for spectral differences of unflattened beams has been discussed in the literature, using both $TPR_{20,10}$ or $PDD(10)_x$ as beam quality specifiers.[5] Some authors[6] recommend to subtract 0.5% from the beam quality conversion factor, k_q, when using $TPR_{20,10}$ as quality index but do not recommend any corrections when using $PDD(10)_x$ (0.4% being the maximum error). The National Physical Laboratory, which uses $TPR_{20,10}$ as quality index, mentions in their 2014 calibration certificates that an additional small correction factor may be required but recommends to set it to unity while more data are collected, in the meantime increasing the expanded uncertainty from 1.4% to 1.6%. The IPEM topical report 1[3] introduces a correction factor of 0.997.

IAEA TRS-398 recommends the use of parallel-plate chambers to measure photon percentage depth doses (PDDs).[4] FFF linear accelerators produce radiation profiles which are peaked on the central axis; therefore, ion chambers used to measure central axis PDDs can experience partial volume averaging,

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which could lead to an underestimation of dose.[7] Since the dimensions of a parallel-plate chamber are larger than the dimensions of typical scanning chambers, a volume averaging effect (radial beam nonuniformity correction) could have a bigger influence on parallel-plate chambers than on scanning chambers; also, recombination and polarity effects could have an influence. An investigation into these effects is necessary if recommendations to measure photon PDDs with parallel-plate chambers are to be followed for FFF beams.

AAPM TG-51 does not make any specific recommendations regarding the use of parallel-plate chambers for PDD acquisition, but since $PDD(10)_x$ is used as the quality index, the accurate determination of this value is of great importance. AAPM TG-51 addendum explicitly mentions the advantages of using a parallel-plate chamber to measure PDDs.

The aim of this paper is to assess the use of parallel-plate ion chamber for photon PDD measurements in FFF beams, in comparison with other suitable dosimeters.

Methods

Photon PDD curves for FFF beams of nominal energies 6 MV (6 FFF) and 10 MV (10 FFF) (Varian TrueBeam) were acquired with a Scanditronix photon diode, two scanning type chambers (both PTW 31010 Semiflex), two small volume chambers (Wellhofer CC04 and PTW 31016 PinPoint 3D), PTW 34001 Roos, Scanditronix Roos, and an NACP 02 parallel-plate chamber. PTW MP3 and PTW MP3-M water tanks, a PTW TANDEM electrometer, and PTW MEPHYSTO were used for all these measurements. IBA Blue Phantom 2 was also used for measurements with a second PTW Roos chamber and Scanditronix photon diodes. PDDs were measured at 100 cm source-to-surface distance (SSD), for fields of size: 5 cm × 5 cm, 10 cm × 10 cm, 20 cm × 20 cm, 30 cm × 30 cm, and 40 cm × 40 cm. PDDs were measured at all available dose rates for 6 FFF and 10 FFF as PDD curves smoothing vary with dose rate. A reference chamber (PTW Semiflex) was used for all scans to account for linear accelerator output variations, but for the diodes, where an appropriate diode was used instead.

Since there are conflicting findings in the literature about diode behavior with dose rate and energy dependence, diode measurements must be compared with ion chamber measurements. AAPM TG-106[8] does not recommend the use of diodes in large X-ray fields unless specific compensation or corrections with validated test result indicate; otherwise, our measurements in FFF beams show this diode behavior. There are also conflicting recommendations regarding PTW PinPoint 3D; according to a PTW technical note (D165.200.01/00), this chamber can be used up to a 30 cm × 30 cm field. Therefore, we restricted the use of these detectors to fields smaller or equal to 30 cm × 30 cm.

Dose-per-pulse in FFF beams is higher than for flattened ones, and this leads to higher values for ion recombination factors.[3,9-12] Since dose-per-pulse in Varian TrueBeam does not change with nominal dose rate, recombination factors do not change either. The two voltage technique was used to obtain these factors[7,13-16] for all field sizes, ion chambers, and polarities at six different depths, d_{max}, 50, 100, 150, 200, and 300 mm deep, with a PTW TANDEM electrometer and IBA CCU electrometer used for PDD scanning. All PDDs were measured for two different polarities as supplied by PTW TANDEM and IBA CCU electrometers. Recombination factors were also measured with a PTW UNIDOS E electrometer at the same depths and for the same field sizes, and yielded the same values within uncertainty estimates.

A decision was made to measure PDDs using two polarities as Sarkar *et al*.[13] reported significant differences in PDDs measured using very small ion chambers, which became larger with increasing depths. These discrepancies were found to be bigger for the smallest volume chamber, Exradin A16, but it was also significant for Wellhofer CC04, which is one of the chambers used in our study. A PTW PinPoint 3D ion chamber is also used in our study, with volume 0.016 cm,[3] which is not as small as the Exradin A16, but it is still smaller than Wellhofer CC04, making the assessment of this chamber relevant. Exradin A16 and PTW PinPoint 3D differ greatly in one relevant feature of their design, PTW PinPoint chamber is built with an aluminum electrode, while Exradin A16 has a wire electrode. Due to this fact, Exradin A16 presents an overresponse for low-energy photons, effect which increases as the number of low-energy photons increases, e.g. as field size.

To correct the raw PDDs for recombination factors at different depths, the ion recombination measurements were fitted against depth using the least squares method. All PDDs were measured at all available dose rates, ranging from 400 MU/min to 1400 MU/min for 6 FFF and from 400 MU/min to 2400 MU/min for 10 FFF. Scans were found to be smoother at higher dose rates as it has been previously reported in the literature, but no reportable discrepancies were found for none of the parameters relevant for our study.

Results

It was found that parallel-plate chambers showed the best PDD curves coincidence for both polarities, differences were below 0.1% for all depths [Figure 1], whereas cylindrical chambers could show differences up to 0.6% at 350 mm deep and a 30 cm × 30 cm field [Figure 2].

PDDs for one single polarity and different ion chambers were corrected for recombination and compared. The largest difference in PDD among different ion chambers (excluding PinPoint which was used up to 30 cm × 30 cm) was found at 350 mm deep for all field sizes, which would amount to: 0.6% for 6 FFF and 0.5% for 10 FFF for a 40 cm × 40 cm field between CC04 and PTW Roos. Differences increase with field size [Figure 3].

PDDs measured with photon diodes led to the highest difference compared with ion chamber measurements, for both energies and for all field sizes, reaching 4% difference

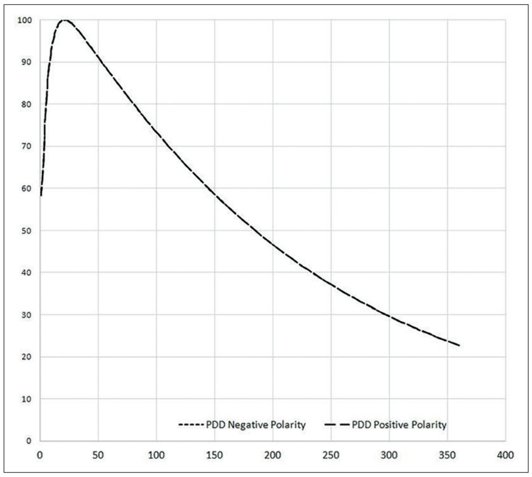

Figure 1: Percentage depth dose for a 10 FFF beam, measured with a PTW Roos parallel-plate ion chamber and both polarities. Field size 40 cm × 40 cm

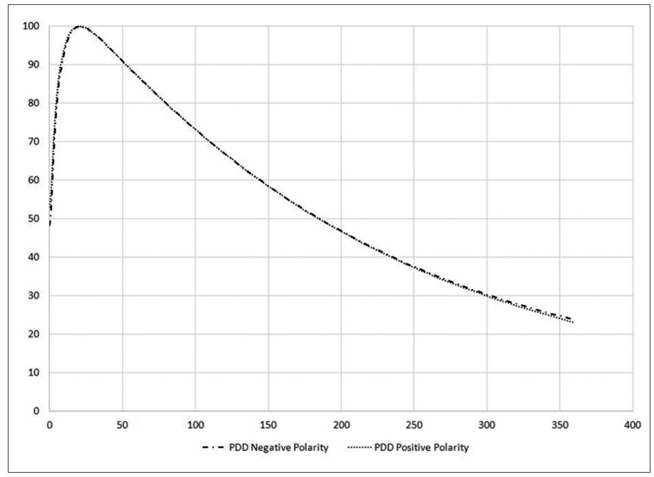

Figure 2: Percentage depth dose for a 10 FFF beam, measured with a PinPoint 3D ion chamber and both polarities. Field size 30 cm × 30 cm

with PTW Semiflex chamber for 6 FFF, 40 cm × 40 cm and 350 mm deep, diodes should be compared with ion chambers in any case. Our results show that differences increase with depth and increasing field size, what could be related to the low energy overresponse of Scanditronix diodes and PTW PinPoint 3D ion chamber. The overresponse of diodes at low energies has been extensively reported in the literature.[8] Our results are consistent with these previous findings. Discrepancies are slightly higher than the ones found for flattened beams as the spectrum is softer for FFF beams.

PDDs measured with ion chambers have a very small dependence on dose rate, unlike diodes for which differences up to 1.5% can be found at the largest field size for 6 FFF.

For absolute dosimetry purposes, IAEA TRS-398 reference conditions for the determination of absorbed dose to water are SSD = 100 cm, 10 cm × 10 cm field at 10 cm deep.[4] Hence, the accurate measurement of the value of PDD(10) is relevant. Our results show that the maximum difference in PDD(10) measured with all different ion chambers, regardless of the polarity, is 0.3% for 6 FFF measured between PTW PinPoint 3D chamber and PTW Semiflex for a 30 cm × 30 cm field. The highest difference between ion chamber PDD(10) and diode PDD(10) is 1.3%.

Once PDDs are corrected to take into account recombination effects, we found differences between corrected and uncorrected PDDs that ranged from 1.2% for PTW Semiflex ion chamber to 2.4% for PTW Roos ion chamber, 2.5% for Scanditronix Roos, all measured for a 10 FFF, 40 cm × 40 cm at 350 mm deep. The NACP ion chamber gave consistent intermediate recombination results for all field sizes. The question of whether or not all PDDs must be corrected for recombination effects is something medical physicists should judge taking into account results for their detectors and beams. We checked two PTW Roos ion chambers and one Scanditronix Roos chamber, and in the case of these chambers, the percentage difference might be too high to be neglected. At 10 cm deep in a 10 cm × 10 cm field, the differences between PDD value for recombination corrected curves and noncorrected ones range from 0.5% for the Roos chamber to 0.2% for the PinPoint 3D chamber.

The differences between PDD(10) measured with diodes and ion chamber corrected for recombination effects PDD(10) are ~1.5% for all chambers for a 30 cm × 30 cm field and 6 FFF, whereas for 10 FFF, differences are ~2%.

Conclusions

Parallel-plate chambers can be used for PDD measurements in Varian TrueBeam FFF beams, provided field sizes are large enough (at least 5 cm × 5 cm for a Roos-type ion chamber) to allow the use of parallel-plate chambers. They can be used in the case of a 10 cm × 10 cm field so that PDD(10) can be measured, and hence, absolute dose at d_{max} obtained for absorbed dose to water determination according to the TRS-398 code of practice. TRS-398 recommendations for PDD measurements can then be followed, and the determination of $PDD(10)_x$ according to TG-51 can also be carried out using this type of chamber. Parallel-plate chambers show an interesting and important property, which is a very small polarity dependence, and the smallest of all chambers included in our study. In addition, as mentioned in AAPM TG-51 addendum, they have a well-defined effective point of measurement, and they show good agreement with Monte Carlo calculations, especially in the region of dose buildup, which makes them good detectors for PDD measurements. There is one caveat though, regarding the use of parallel-plate ion chambers, i.e., correction for ion chamber recombination effects, as this type of chambers present the highest recombination effects dependence.

When obtaining recombination factors with values over 1% and noticeable variation with depth, such as the ones corresponding to PTW and Scanditronix Roos ion chambers for field sizes

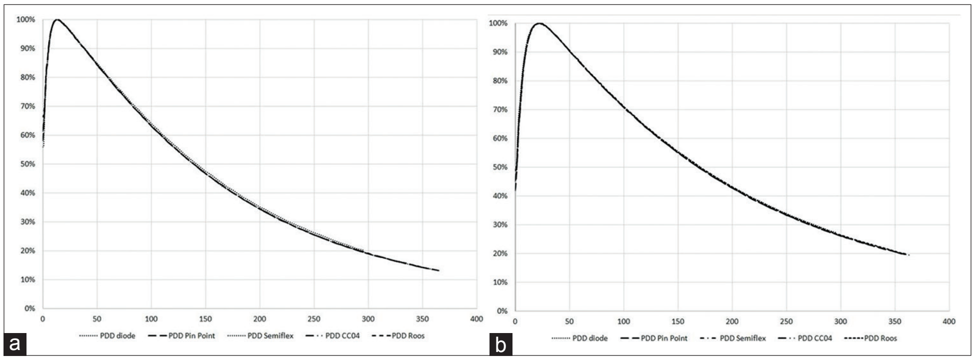

Figure 3: Percentage depth doses for a 10 × 10 field size, measured with a Photon Field Diode (PFD), 3D PinPoint ion chamber, Semiflex ion chamber, CC04 ion chamber, and PTW Roos parallel-plate ion chamber. (a) 6 FFF, (b) 10 FFF

over 20 cm × 20 cm, the use of recombination corrected PDDs might be advisable, to prevent systematic errors that could be as high as 2.5% at 350 mm deep for large field sizes. In the case of Semiflex chambers, the difference between the uncorrected and the corrected PDD is not so high; clinical judgment should be used to decide whether or not corrections must be applied with this particular chamber or with any other ion chamber included in our study.

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Conflicts of interest

There are no conflicts of interest.

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