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Publication date:
2014

Document Version
Publisher's PDF, also known as Version of record

Citation (APA):
Beierholm, A. R., Behrens, C. F., Sibolt, P., Rønde, H. S., Biancardo, S. B. N., Aznar, M. C., ... Andersen, C. E. (2014). Reference dosimetry and small-field dosimetry in external beam radiotherapy: Results from a Danish intercomparison study. DTU Nutech. (DTU-Nutech-R; No. 8(EN)).

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DTU-Nutech-8(EN)

Edited by A.R. Beierholm, C.F. Behrens, P. Sibolt, H.S. Rønde, S.B.N. Biancardo, M.C. Aznar, J.B. Thomsen, L. Præstegaard, L. Nyvang, H.L. Riis, K.M. Pedersen, J. Helt-Hansen and C.E. Andersen

December 2014

DTU Nutech
Center for Nukleare Teknologier

Danish Cancer Society

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ISBN 978-87-995321-8-6

Group Reg. No.:
DTU-Nutech-8(EN)

Sponsorship:
This work was supported by the Danish Cancer Society (R40-A1902) and CIRRO – Center for Interventional Research in Radiation Oncology, supported by the Lundbeck Foundation. The work was partly carried out within the EMRP: “Metrology for radiotherapy using complex radiation fields” (HLT09). The EMRP is jointly funded by the EMRP participating countries within EURAMET and the European Union.

Front page:

Example of experimental setup at one of the participating radiotherapy clinics. A small-volume ionization chamber is positioned in a large water phantom and irradiated with a 6 MV photon beam from a medical linear accelerator.

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Content

Reference dosimetry and small-field dosimetry in radiotherapy: A comparison study from six Danish radiotherapy clinics

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Abstract

A comparison of dosimetry methods at different clinics can be used as a means to uncover systematic uncertainties in ra-diotherapy. To assess the current status of reference dosimetry and small-field dosimetry in clinical practice, a collaborative comparison study involving several dosimetry methods was performed by DTU Nutech at six Danish clinics. The first part of the intercomparison regarded the consistency of reference dosimetry. Absorbed dose to water under reference conditions was measured using a Farmer ionization chamber, and was found to agree within 1 % with the daily dose checks obtained routinely at each clinic. The second part of the study concerned the accuracy of small-field dosimetry and dose calculations. The geometric size of small fields down to 1 cm x 1 cm was measured using radiochromic film. Minor discrepancies were seen between the nominal field sizes set by the collimators and the measured field sizes, although one clinic showed field dimensions that were down to 21 ± 3 % smaller than expected. Small-field correction factors were estimated for a PinPoint chamber and a diamond detector using a fibre-coupled organic scintillator as reference, after correcting for volume averaging. The corrections were found to be within 2 % down to the 1 cm x 1 cm field size. Output factor measurements performed with the three detectors were compared with the commissioning beam data originally acquired by the individual clinics using their own detectors and protocols, and with dose calculations performed using the treatment planning systems. Measured output factors agreed within 3 % with commissioning beam data and within 2 % with dose calculations for small MLC-defined fields. The study demonstrated (i) consistency of reference dosimetry and small-field dosimetry on a national level, and (ii) clinical applications of fiber-coupled plastic scintillators. The study also demonstrated that the estimation of detector-specific correction factors in small fields is consistent among clinics and linac models, supporting the robustness and usefulness of the proposed IAEA formalism for detector-specific correction factors for non-reference fields.

1. Introduction

It is generally recommended that audits and multi-institutional intercomparison studies between radiotherapy clinics are performed by independent institutions on a regular basis in order to identify systematic errors in radiotherapy. Two recent studies have regarded reference dosimetry and treatment verification in Sweden(1) and accuracy of treatment planning systems (TPS) in Portugal(2). A small-field postal audit was recently carried out in Spain and Portugal using thermoluminescent dosimeters(3), showing deviations larger than 5.0 % between prescribed and delivered dose for 4 of the 13 investigated clinics. Another recent investigation performed by the Radiological Physics Center(4) in the USA compared measured small field multi-leaf collimator (MLC) output factors with TPS-calculated values at several American clinics, aiming at providing a standard beam data set for small-field output factors.

Different clinics generally employ different methods for acquiring beam data, with variable attention towards small-field measurements depending on what treatment modalities are being used at the particular institution. Dosimetry in small radiotherapy fields is however highly influenced by the detectors used. The International Atomic Energy Agency (IAEA) has introduced a formalism for dosimetry in small and non-reference fields(5), but there is still little consensus among clinics on which detectors that are optimal for small-field dosimetry. Small-field dosimetry comparisons are also complicated by the fact that the determination of the size of a small field is controversial(6). Careful calibration of the collimators is also important, since e.g. a 1 mm error in a 1 cm x 1 cm field setting can result in a 2-4 % error in the measured dose or output factor(7).

A comparison of dosimetry methods at different clinics can be used as a means to quantify systematic uncertainties. This research study presents a collaborative dosimetric intercomparison, involving all six independent Danish radiotherapy clinics at the time of the study. The study seeks to contribute to ensuring high quality of dosimetry at Danish clinics, and describes how a set of detectors can be used to assess dosimetric accuracy in situations relevant to modern radiotherapy aimed for small-field delivery. The study also describes how novel dosimetry methods, based on fibre-coupled organic scintillators, can contribute to such intercomparisons. The study has been performed by the Center for Nuclear Technologies, Technical University of Denmark (DTU Nutech) in collaboration with the Danish National Institute for Radiation Protection (SIS). Both institutions are non-clinical and they work within the field of metrology. The comparison study involves measurements of essential dosimetric parameters, obtained using commercial detectors as well as in-house scintillator detectors. The results obtained during the study have been compared with TPS dose calculations, and with measurements previously performed by the physicists at each clinic as part of routine quality assurance (QA) procedures and beam data acquisition for TPS commissioning.

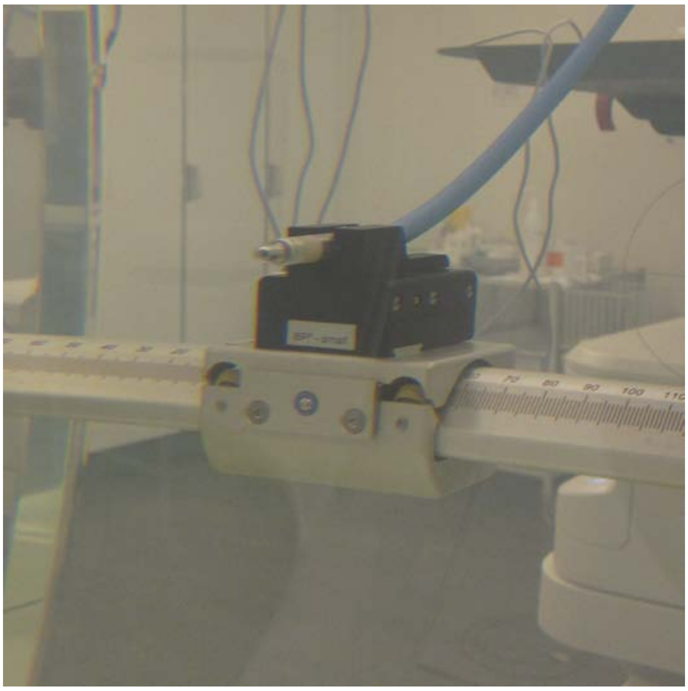
The main objective of this study was twofold: i) to assess the consistency in reference dosimetry among clinics, and ii) to assess the agreement between measured and TPS calculated dose in small fields.

2. Materials and methods

The comparison study was performed at six Danish radiotherapy clinics; each designated a letter from A to F. Measurements were carried out using a single linear accelerator (linac) at each clinic. The investigated linacs were one Elekta Versa HD, one Elekta Synergy, three Varian TrueBeams (TBs) and one Varian TrueBeam STx (TB STx). The comparison study involving all six clinics was limited to 6 MV photon beams, with the linac gantry and gantry head at 0º rotation. The same set of detectors was used for the measurements performed at all participating clinics: i) a Scanditronix-Wellhöfer FC65-G Farmer ionization chamber, ii) a PTW 31014 PinPoint ionization chamber, iii) a PTW 60003 diamond detector, iv) an in-house developed fiber-coupled organic scintillator, and v) Gafchromic EBT2 radiochromic film. All point detector measurements were made in water, using the clinics own scanning water phantoms with three-dimensional positioning control, while film measurements were carried out in plastic slab phantoms. The detectors were in all cases irradiated with the detector axis perpendicular to the beam central axis, as this was normal practice at most of the participating clinics.

Table 1. Overview of detectors used and measurements performed during the study.

Detector	Measurement session	Measurement	Investigated field size
IBA FC65-G Farmer, 0.65 cm^2	Reference dosimetry	Reference dose to water	10 cm x 10 cm
DTU ME40 Scintillator dosimetry system	Reference dosimetry	Dose per pulse	10 cm x 10 cm
	Small-field dosimetry	Output factors (beam data comparison)	1 cm x 1 cm to 10 cm x 10 cm
		Output factors (TPS comparison)	2 cm x 2 cm to 10 cm x 10 cm
PTW 60003 Diamond	Small-field dosimetry	Output factors (beam data comparison)	1 cm x 1 cm to 6 cm x 6 cm
		Output factors (TPS comparison)	2 cm x 2 cm to 6 cm x 6 cm
PTW 31014 PinPoint, 0.0015 cm^2	Small-field dosimetry	Output factors (beam data comparison)	2 cm x 2 cm to 10 cm x 10 cm
		Output factors (TPS comparison)	2 cm x 2 cm to 10 cm x 10 cm
Gafchromic EBT2 film	Small-field dosimetry	Field size	1 cm x 1 cm to 3 cm x 3 cm



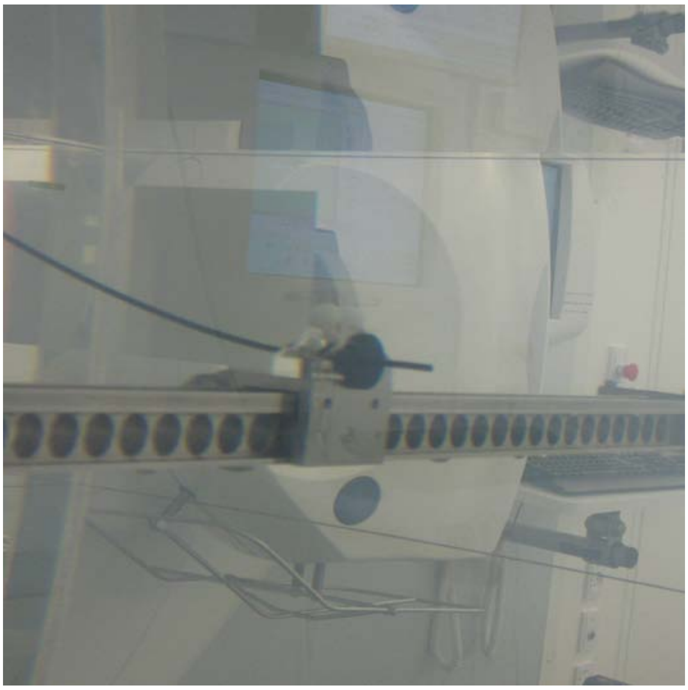


Fig. 1. Examples of measurement setups at two different clinics. Upper picture: PTW 31014 Pin-Point chamber positioned in an IBA Blue Phantom 2 water phantom, irradiated using a Varian TrueBeam. Lower picture: Fibre-coupled organic scintillator and custom-made adapter, positioned in a PTW MP3 water phantom and irradiated using an Elekta Versa HD. The detectors were in all cases aligned with the beam central axis using the in-room lasers; for the small-field measurements, the alignment was furthermore fine-tuned by scanning for the maximum signal in the crossplane and inplane directions.

2.1. Reference dosimetry

The measurements regarding reference dosimetry concerned i) dose per pulse and ii) dose under reference conditions. For each measurement, 100 monitor units (MU) were delivered at nominal dose rates of 400-600 MU/min. Reference conditions for irradiations were defined by a source to axis distance (SAD) setup: 10 cm x 10 cm collimator setting, 10 cm depth and 90 cm source to surface distance (SSD). The investigated linacs and the traceability of dose to water to a primary standard are listed in table 2 for each clinic. Except for clinic E, the reference dose to water was traceable to calibrations in Co-60 beams with beam quality correction factors (k_Q) applied in the respective 6 MV linac beams. In the case of clinic E, the dose-to-water calibration had been performed in a 6 MV linac beam at the primary standard laboratory, meaning that the calibration factor did not need to be corrected for differences in beam quality between the primary standard and the user beam.

2.1.1. Dose per pulse

Measurements of dose per pulse under reference SAD conditions were performed using a custom dosimetry system based on a fibre-coupled organic plastic scintillator detector. This was done to study and compare the dose rate stability of the investigated linacs. The scintillator detector (sensitive volume of 1 mm diameter, 2 mm length) was made in-house, and the radiation-induced light from the detector was read out with per-pulse resolution using the ME40 hardware developed by DTU Nutech(8,9). The detailed time resolution of the scintillator measurements allowed for an in-depth investigation of the variations in instantaneous dose rate encountered throughout the study. During measurement, the ME40 system was connected to the synchronization and target signals from the linac. This was done to perform dose measurements synchronized with the linac pulses and measure the target current directly, in order to monitor linac output fluctuations during measurements. For Varian linacs, the ME40 was connected to the “SYNC” and “TARGET” outputs, while for the Elekta linacs “ST” and “MI” were used. The parasitic light generated in the optical fiber itself was chromatically suppressed using an out-of-field calibration method(8,10). Five consecutive measurements were performed with the scintillator in the field and with the fiber going across the field, respectively. Cross-calibration with respect to absorbed dose to water was performed against the Farmer chamber under reference conditions in the respective linac beams.

Table 2. Overview of investigated linacs and of the institutes responsible for the calibration of secondary standards instruments with traceability to a primary standard for each clinic, including the beam quality used for calibration.

Clinic	Linac	Dose-to-water traceability
A	Elekta Versa HD	SIS/NPL[a,b] (Co-60)
B	Elekta Synergy	SIS/NPL (Co-60)
C	Varian TB STx	SSM/BIPM[c,d] (Co-60)
D	Varian TB	SIS/NPL (Co-60)
E	Varian TB	NPL (6 MV)
F	Varian TB	SIS/NPL (Co-60)

[a] National Institute of Radiation Protection (SIS), Herlev, Denmark.
[b] National Physical laboratory (NPL), London, Great Britain.
[c] Swedish Radiation Safety Authority (SSM), Stockholm, Sweden.
[d] Bureau National des Poids et Mesures (BIPM), Sèvres, France.

2.1.2. Dose to water under reference conditions

A Scanditronix-Wellhöfer FC65-G Farmer ionization chamber was used for measuring reference dose to water. The charge signals from the chamber were acquired using a Keithley 6517B electrometer configured for floating input, with a bias voltage of +300 V to the central electrode. Prior to the measurement sessions, the entire assembly of Farmer chamber, cable and electrometer was calibrated against a secondary standard at SIS. The calibration was performed in a Co-60 beam using a Best Theratronics Gammabeam X200 research irradiator. The dose rate of the beam had been determined with an ionization chamber whose calibration was traceable to a primary standard at the National Physical Laboratory (NPL) in London. The reproducibility of the calibration was verified after the comparison measurements at the various clinics had been performed.

An Ahlborn Almemo 2690 instrument, equipped with two FD A612-SA pressure sensors and two 26908A temperature sensors, was used to monitor the water temperature and the ambient pressure at regular intervals during the measurement sessions, to apply corrections for ambient conditions. Recombination corrections were applied using the two-voltage method(11). Polarity correction factors were not measured, but were expected to be negligible in the investigated beams(12). Beam quality correction (k_Q) factors were linearly interpolated from the calculated values listed in TRS-398(11), using measurements of tissue-phantom ratios at 10 cm and 20 cm depth.

2.2. Small-field dosimetry

The measurements regarding small-field dosimetry concerned i) measured field size for small fields, ii) a comparison between measured output factors and the beam data used for TPS commissioning, and iii) a comparison between measured output factors and TPS calculated output factors for MLC-defined fields. As for the measurements concerning reference dosimetry, small-field dose measurements were performed at 90 cm SSD and 10 cm depth. The investigated linac, the detectors used for acquiring beam data for commissioning and the TPS used for dose calculation are listed in table 3 for each clinic.

2.2.1. Field size

Off-axis profiles for 1 cm x 1 cm, 2 cm x 2 cm and 3 cm x 3 cm fields were measured in solid phantoms at reference SSD and depth using radiochromic film. Gafchromic EBT2 film (Lot No. A12041005A). For the Varian linacs, the fields were collimated using the secondary jaws (MLCs fully retracted), while for Elekta linacs the fields were MLC-defined. This was done to follow the procedures used for beam data acquisition during TPS commissioning at each clinic. Three profiles were obtained for each field size, delivering a dose of approximately 7.0 Gy to each. The full width half maximum (FWHM) in the inplane and crossplane directions were subsequently determined from the dose profiles and used as a measure of field size. After irradiation and self-developing for approximately 36 hours, the film pieces were scanned using an Epson Perfection 4990 Photo scanner in transmission mode (150 dpi resolution and 24 bit colour scale). The profiles were subsequently acquired in RisøScan software(13) using the red colour channel to acquire the optical density values. The relationship between optical density and absorbed dose was established using a four-degree polynomial fit to a densitometric curve obtained using 15 pieces of film irradiated from 0.0 Gy to approximately 8.0 Gy. The scanned profile images were converted from response profiles to dose profiles using the established densitometric calibration curve.

Table 3. Overview of investigated linacs, detectors used for measuring output factor beam data for commissioning, and the TPSs and dose calculation algorithms used by each clinic.

Clinic	Linac	Detectors used for commissioning beam data (output factors)	TPS / dose calculation
A	Elekta Versa HD	PTW 31010 Semiflex chamber (2 cm x 2 cm to 40 cm x 40 cm)	Pinnacle 9.2 (CC)[a]
B	Elekta Synergy	Scdx-Wellhofer IC28 (4 cm x 4 cm to 40 cm x 40 cm)	Oncentra 4.3 (CC)
C	Varian TB STx	PTW 60017 E diode (1 cm x 1 cm to 4 cm x 4 cm); PTW 31010 Semiflex chamber (3 cm x 3 cm to 40 cm x 40 cm)	Eclipse 11.0 (AAA)[b]
D	Varian TB	PTW 31014 PinPoint chamber (2 cm x 2 cm to 4 cm x 4 cm); Scdx-Wellhofer IC15 chamber (4 cm x 4 cm to 40 cm x 40 cm)	Eclipse 10.0 (AAA)
E	Varian TB	PTW 60003 Diamond detector (1 cm x 1 cm to 5 cm x 5 cm); Scdx-Wellhofer RK chamber (3 cm x 3 cm to 40 cm x 40 cm)	Eclipse 10.0 (AAA)
F	Varian TB	Sun Nuclear EDGE diode (3 cm x 3 cm to 5 cm x 5 cm); Scdx-Wellhofer FC65-G chamber (5 cm x 5 cm to 40 cm x 40 cm)	Eclipse 10.0 (AAA)

[e] Collapsed Cone (CC).
[f] Anisotropical Analytical Algorithm (AAA).

2.2.2. Output factors: Comparison with commissioning beam data

Output factors measurements concerned square field settings with side lengths of 1 cm, 2 cm, 3 cm, 4 cm, 5 cm, 6 cm, 8 cm and 10 cm. As for the field size measurements, the fields were jaw-defined on Varian linacs and MLC-defined on Elekta linacs, in accordance with the respective procedures for beam data acquisition. Three different detectors were used and compared for output factor measurements: the PTW 31014 PinPoint ionization chamber, the PTW 60003 diamond detector, and the in-house developed plastic scintillator detector.

The PTW 31014 PinPoint chamber is a small-volume ionization chamber commonly used for measurements in small fields. In this study, the PinPoint was used for measuring output factors for fields from 2 cm x 2 cm to 10 cm x 10 cm size, as 2 cm x 2 cm is the minimum recommended field size as stated by the manufacturer.

Solid state detectors based on natural diamonds have previously been considered a suitable choice for small-field dosimetry, quoted to require minimal corrections[(14)]. The PTW 60003 detector used in this study (5.6 mm^2 sensitive area, 0.34 mm sensitive volume thickness) was used for measuring output factors for 1 cm x 1 cm to 6 cm x 6 cm fields. To correct for field size dependence, the diamond measurements were renormalized (Daisy-chained) to those of the PinPoint chamber at the intermediate 4 cm x 4 cm field setting. The diamond detector was pre-irradiated with a dose of 10-20 Gy prior to each measurement session. The diamond detector was corrected for its dose per pulse dependence using recombination-corrected Farmer chamber readings and the relationship given by Fowler[(15)], using an exponential correction factor that had been experimentally determined prior to this study.

Fiber-coupled organic plastic scintillator detectors have been hypothesized to be essentially perturbation-free in small fields. This hypothesis has been supported by Monte Carlo calculations[(16)] as well as by experiments[(8,17,18,19)], and scintillator detectors have recently been used for determining correction factors for commercial detectors in small fields[(18,19)]. Furthermore, a commercial scintillator detector has recently become available from Standard Imaging Inc[(20)]. The scintillator detector described previously was used for measuring output factors for all investigated fields from 1 cm x 1 cm to 10 cm x 10 cm. A recent IAEA study showed small-field correction factors for scintillator detectors being close to 1 relative to alanine measurements[(21)].

Prior to the measurements, the PinPoint, diamond and scintillator detectors were aligned with the beam central axis by scanning in the crossplane and inplane directions in 0.2 mm increments. The charge signals from the PinPoint and diamond were acquired using the Keithley 6517B electrometer. For the PinPoint, the electrometer was configured for floating input with a bias voltage of +300 V applied to the central electrode, while the diamond detector was used with the electrometer in grounded input configuration with a +100 V bias to the outer electrode.

The output factors were measured in a randomized order, alternating back and forth between small and large collimator settings in order to include the contribution from collimator positioning uncertainties in the total measurement uncertainty[21]. Each output factor was defined as the average of three to five readings, normalized to the 10 cm x 10 cm reference field. Volume averaging corrections were applied to the measurements for the three smallest fields. Volume averaging corrections for the PinPoint, diamond and scintillator were estimated by averaging the measured dose over an area around the central axis corresponding to the detector dimensions, using the crossplane and inplane profiles obtained using the radiochromic film during field size measurements. The measured output factors were also corrected for differences between nominal and measured field sizes by linear interpolation of the detector readings. Following the formalism by Alfonso[5] and the methodologies of Ralston et al[18] and Morin et al[19], the scintillator measurements were used to estimate $k_{Qmsr,Qref}^{fmsr,fref}$ correction factors for the PinPoint and diamond, for the four investigated linac models.

The measured output factors were compared to the ones previously obtained by each clinic as part of beam data acquisition for TPS commissioning. As shown in table 2, two clinics had commissioned their TPS down to 1 cm x 1 cm field size, while the remaining clinics had commissioned their TPS down to 2 cm x 2 cm, 3 cm x 3 cm or 4 cm x 4 cm. For clinics C, D and E, beam data had been measured at another SSD and depth. These data were therefore calculated at the reference SAD setup using the TPS dose calculation engine.

2.2.3. Output factors: Comparison with TPS calculations

The comparison with TPS calculations concerned MLC-defined square fields with side lengths of 2 cm, 3 cm, 4 cm, 6 cm and 10 cm. The same set of detectors was used as for the commissioning beam data comparison: The PinPoint chamber and scintillator was used for all five field sizes while the diamond was only used up to the 6 cm x 6 cm field size due to field size dependence giving erroneous readings for larger fields. For measurements using the Varian linacs, the secondary jaws were fixed at 10 cm x 10 cm. Each measurement was repeated three times and normalized to the 10 cm x 10 cm reference field size.

3. Results and discussion

3.1. Reference dosimetry

3.1.1. Dose per pulse

The ME40 scintillator dosimetry system was used to independently monitor the linac output through measurements of the target current. For the entire duration of each clinic visit (typically two days), linac target current fluctuations amounted to 0.7 % (1 SD) or less. The uncertainty on the target current measurements was not evaluated, and the correlation between target current and linac output was not quantified. However, it has been verified previously that the target current measurements can be used as a surrogate for linac output and dose per pulse[(8)]. Fig. 2 shows pulse-resolved scintillator measurements for individual irradiations under reference SAD conditions for each clinic in three situations: i) the total irradiation, ii) at beam-on (transient), and iii) during beam-on after the beam has fully stabilized (plateau). For each panel, five consecutive irradiations are displayed to visualize the measurement-to-measurement variability. The number of delivered pulses per MU is seen to be very stable for the newer linac models (Versa HD, TB, TB STx). The different linac models are seen to differ in the shape as well as duration of the transient phase, where different servo systems are being employed to stabilize the dose per pulse after beam-on. As such, the TB and TB STx exhibit transient phases of approximately 0.5 s, while the Versa HD takes 4 seconds and the Synergy takes 6 seconds for the dose rate to stabilize. Variations in the transient behavior are also evident between consecutive irradiations, as is most clearly seen in the measurements for clinics C and F. The variation in delivered dose during the transient phase is corrected for by the monitor ionization chambers, ensuring that enough radiation pulses are delivered to reach the specified number of MU. However, the dose rate stability might influence the accuracy and precision of small-MU deliveries, as in small IMRT segments.

3.1.2. Dose to water under reference conditions

For all clinics, the reference dose to water was measured and compared with the nominal dose to which the linac had been calibrated, corrected for changes in linac output relative to the time of calibration. Table 4 lists the uncertainties associated with the reference dose measurements, while all values of measured and nominal doses are listed in table 5 for all clinics. The measured dose values exhibited a mean deviation of -0.04 % (0.7 % SD) from the nominal dose values, and the largest deviation was 1.0 ± 1.4 %. In the case of clinic E, the ionization chamber used to calibrate the linac had been calibrated directly in a 6 MV beam at a primary standards laboratory (other clinics used Co-60 calibrations from secondary standards laboratories and calculated k_Q factors, see Table 2). It was not possible from this study to conclude whether this more favorable calibration methodology lead to significant changes in the delivered dose, as the observed deviation of 1.0 % was within measurement uncertainties. Previous investigations performed by clinic E have however indicated that calibration in a 6 MV beam leads to a change of approximately 0.7 % in the delivered dose, with a considerable decrease in uncertainty due to the circumvention of k_Q determination.

Table 4. Estimated relative uncertainty components for the measurements performed.

Quantity	**Relative uncertainty (%)**
Dose-to-water calibration coefficient traceable to NPL (Co-60)	0.8
Estimation of k_Q factor from TRS-398 (6 MV)	1.0
Reproducibility of setup and repeated measurements	0.5
Combined standard uncertainty (reference dose to water)	**1.4**
Scintillator calibration (removal of stem effect)	0.5
Reproducibility of setup, positioning and repeated measurements	0.5
Field size correction	0.3
Volume averaging correction	0.3
Combined standard uncertainty (small-field output factors)	**0.8**
Combined standard uncertainty ($k_{Qmsr,Qref}^{fmsr,fref}$ correction factors)	**1.1**

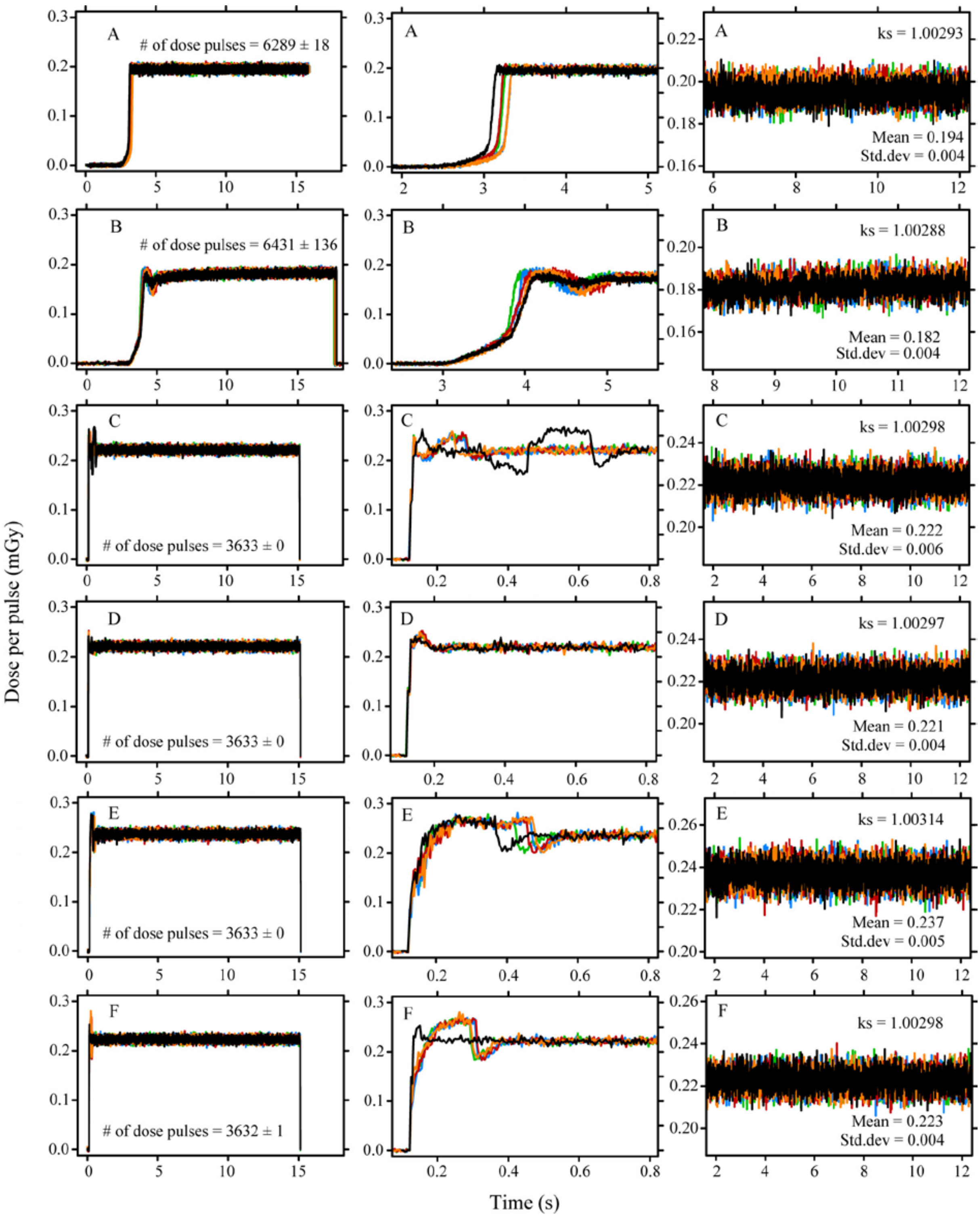


Fig. 2. Measurements of dose per pulse for the total irradiation (left), in the beam-on transient (middle) and in the plateau phase (right) for all clinics A-F. Each panel shows five consecutive 100 MU irradiations under reference conditions, in the order black (first), green (second), blue (third), red (fourth) and orange (fifth). The mean and standard deviation of the dose per pulse are given for the background and plateau.

Table 5. Comparison between measured and nominal reference dose to water per 100 MU. Measurement uncertainties (1 SD) are within 1.4 %.

	A	B	C	D	E	F
Measured dose (Gy)	0.993	0.997	0.798	0.796	0.853	0.808
Nominal dose (Gy)[a]	1.003	1.000	0.797	0.799	0.845	0.805
Difference (%)	-1.0	-0.3	0.1	-0.4	1.0	0.4

[a] Corrected for linac output fluctuations.

3.2. Small-field dosimetry

3.2.1. Field size

Measured field dimensions and collimator settings for the three smallest fields are listed in table 6. The relative differences between measured field width and collimator setting were largest for the smallest field. For the two investigated Elekta machines, the MLC-defined fields were generally wider in the crossplane direction than in the inplane direction. This was believed to be an interplay effect between the set square field profile and the MLC interleaf leakage. Clinic D showed the largest discrepancy of roughly 1 mm in both crossplane and inplane directions, for the smallest jaw-defined field resulting in a field area being 20.8 ± 2.8 % smaller than expected. The discrepancies were consistent for all three field settings, suggesting a calibration offset of the collimator jaws. For the remaining clinics, measured field size differed from set field size by as much as 9.6 ± 5.7 %.

3.2.2. Output factors: Comparison with commissioning beam data

Uncertainties associated with output factor measurements are listed in table 4. Volume averaging corrections for the scintillator and diamond in the 1 cm x 1 cm field, and for the PinPoint in the 2 cm x 2 cm field, are listed in table 7. The largest correction amounted to 0.9 %. Volume averaging was found to be negligible in fields larger than 1 cm x 1 cm for the scintillator and diamond, and in fields larger than 2 cm x 2 cm for the PinPoint. Table 8 shows measured output factors for the beam data comparison, corrected for detector volume averaging and measured field size. For clinic D, the field size corrections were as large as 2.2 % due to the 0.9 cm x 0.9 cm actual field size. For the remaining clinics, the field size corrections were within 0.7 %. Table 9 shows diamond and PinPoint $k_{Qmsr,Qref}^{fmsr,fref}$ correction factors relative to the scintillator readings. The detectors differ by 1.8 % for the 1 cm x 1 cm field size and by 1.2 % for the 2 cm x 2 cm field size. The differences amount to 2.2 % for 1 cm x 1 cm and 0.7 % for 2 cm x 2 cm when concerning the contribution from other factors than volume averaging. The differences between detectors for small fields may be due to mass density effects, as argued by Scott et al(23). The accuracy of the corrections should ideally be confirmed by comparison with Monte Carlo simulations. Such a comparison was however outside the scope of this study. Correction factors reported in the literature, although performed for different linac models and collimators, are nevertheless comparable to the values estimated in this study(24,25,26). The scintillator correction factors published by Azangwe(22) concerned a specific linac and collimation device, and were therefore not applied in this study. The IAEA study nevertheless confirmed that scintillator detectors can be used for small-field output factor measurements with an uncertainty within approximately 2.0 %.

Table 6. Comparison between set and measured small field sizes. Uncertainties due to collimator positioning variability were approximately 0.4 mm for Elekta linacs and 0.2 mm for Varian linacs.

Collimator setting (cm)	Direction	Measured FWHM (cm)					
		Elekta (MLC fields)		Varian (jaw fields)			
		A	B	C	D	E	F
1.00	Crossplane	1.06	1.13	0.98	0.90	1.03	1.01
	Inplane	1.00	0.97	1.04	0.88	0.92	0.94
2.00	Crossplane	2.07	2.07	1.98	1.91	2.05	2.02
	Inplane	2.01	1.96	2.02	1.85	1.90	1.92
3.00	Crossplane	3.05	3.08	3.00	2.93	3.06	3.03
	Inplane	3.04	2.98	3.03	2.85	2.91	2.93

Table 7. Estimated volume averaging correction factors for each detector in the smallest field used. Uncertainties are within 0.3 % (1 SD).

Collimator setting (cm)	Detector	Volume averaging correction factor					
		Elekta (MLC fields)		Varian (jaw fields)			
		A Versa	B Synergy	C TB STx	D TB	E TB	F TB
1 x 1	Scintillator	1.003	1.003	1.002	1.007	1.003	1.003
1 x 1	Diamond	1.004	1.004	1.004	1.009	1.005	1.005
2 x 2	PinPoint	1.004	1.004	1.005	1.005	1.004	1.005

Table 8. Measured output factors for the beam data comparison, corrected for volume averaging and field size. Measurement uncertainties are within 0.8 % (1 SD).

Collimator setting (cm)	Detector	Measured output factor					
		Elekta (MLC fields)		Varian (jaw fields)			
		A Versa	B Synergy	C TB STx	D TB	E TB	F TB
1 x 1	Scintillator	0.688	0.680	0.690	0.681	0.694	0.688
	Diamond	0.697	0.695	0.696	0.695	0.702	0.701
2 x 2	Scintillator	0.800	0.806	0.800	0.798	0.796	0.798
	Diamond	0.798	0.806	0.797	0.797	0.796	0.796
	PinPoint	0.798	0.801	0.797	0.792	0.797	0.793
3 x 3	Scintillator	0.845	0.846	0.838	0.838	0.836	0.838
	Diamond	0.842	0.847	0.837	0.838	0.836	0.836
	PinPoint	0.843	0.846	0.837	0.835	0.836	0.837
4 x 4	Scintillator	0.878	0.879	0.870	0.870	0.867	0.869
	Diamond	0.877	0.881	0.870	0.869	0.867	0.868
	PinPoint	0.877	0.881	0.870	0.869	0.867	0.868
5 x 5	Scintillator	0.905	0.905	0.900	0.895	0.897	0.898
	Diamond	0.903	0.906	0.898	0.896	0.896	0.897
	PinPoint	0.902	0.904	0.899	0.895	0.896	0.897
6 x 6	Scintillator	0.930	0.929	0.925	0.922	0.923	0.924
	Diamond	0.929	0.932	0.926	0.925	0.924	0.925
	PinPoint	0.927	0.930	0.924	0.922	0.923	0.923
8 x 8	Scintillator	0.969	0.968	0.966	0.966	0.966	0.966
	PinPoint	0.967	0.969	0.967	0.966	0.967	0.967

Table 9. Estimated diamond and PinPoint $k_{Qmsr,Qref}^{fmsr,fref}$ correction factors, obtained for the beam data comparison measurements. The corrections have been estimated with reference to the volume averaging-corrected scintillator readings. Uncertainties are within 1.1 % (1 SD).

Collimator setting (cm)	Detector	$k_{Qmsr,Qref}^{fmsr,fref}$ correction factor relative to scintillator					
		Elekta (MLC fields)		Varian (jaw fields)			
		A Versa	B Synergy	C TB STx	D TB	E TB	F TB
1 x 1	Diamond	0.991	0.982	0.995	0.988	0.993	0.987
2 x 2		1.003	0.999	1.003	1.002	1.000	1.003
3 x 3		1.004	0.999	1.002	1.001	1.000	1.002
2 x 2	PinPoint	1.006	1.010	1.009	1.012	1.004	1.011
3 x 3		1.002	1.000	1.001	1.004	1.000	1.002

The comparison with the commissioning beam data is shown in fig. 3, where the output factors measured using each detector (corrected for volume averaging and field size) are compared with the output factors used for TPS commissioning at each clinic. Agreement within 1.1 % is generally seen for field settings from 10 cm x 10 cm to 3 cm x 3 cm. For the 2 cm x 2 cm setting, agreement is within 1.4 % for all clinics. For clinics C and E, where small-field commissioning had been performed using respectively an unshielded diode and a diamond detector, measurements and beam data agree within respectively 2.7 % and 3.2 %. These differences might have been slightly enhanced by the dose calculation model, which was used to calculate from the 95 cm SSD, 5 cm depth setup to 90 cm SSD and 10 cm depth.

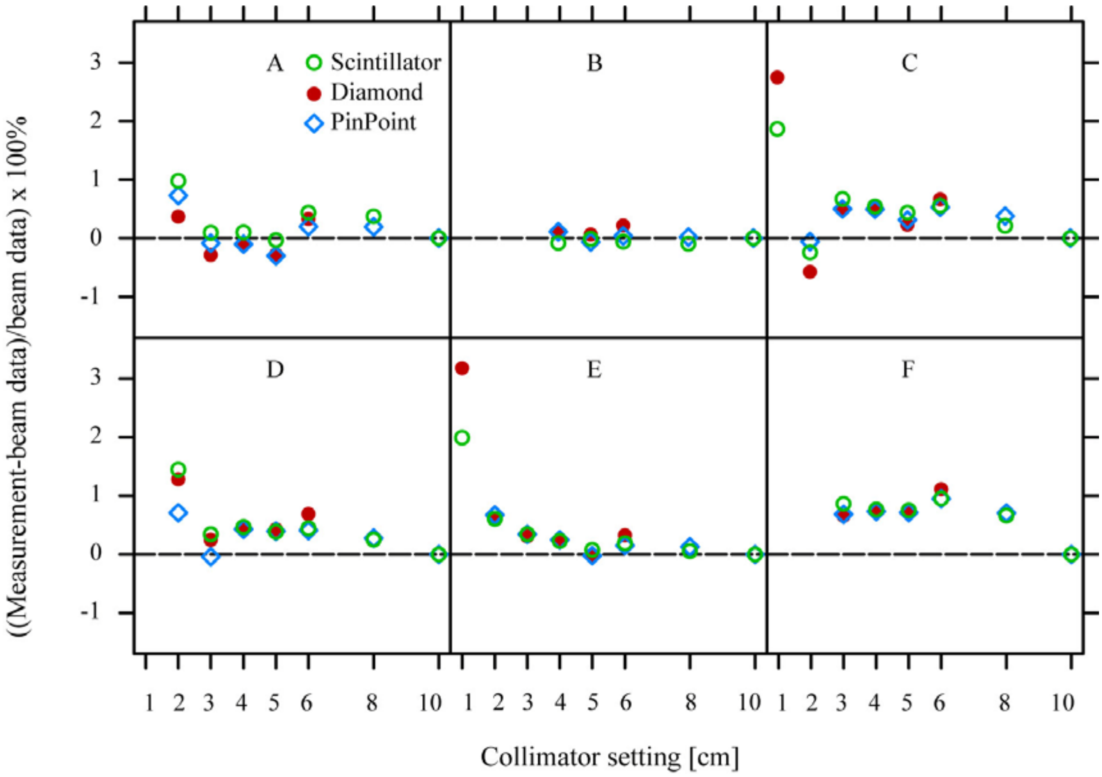


Fig. 3. Comparison between measurements and the beam data used by each clinic for TPS commissioning. Data are shown for the scintillator (open circles), diamond detector (closed circles) and PinPoint chamber (open diamonds). Measurement uncertainties (1 SD) are within 0.8 %.

3.2.3. Output factors: Comparison with TPS calculations

Percentage differences between measurements and TPS calculations are seen in fig. 4 for MLC-defined square fields. Detector correction factors for the 2 cm x 2 cm and 3 cm x 3 cm MLC-defined fields on Varian machines were not estimated, but were expected to be comparable to the ones presented in table 8 within the 1.1 % uncertainty. A volume averaging correction of 1.004 was applied to PinPoint measurements for the 2 cm x 2 cm field, based on the mean value obtained from the six corresponding values listed in table 6. This was considered a good approximation due to the small spread (0.1 % SD) of the estimated corrections. TPS calculation uncertainties were not evaluated, but were assumed to be within 0.5 %. Agreement between the measurements and the TPS calculations is generally within 1.9 %. An interesting observation is that the observed differences for the three Varian TBs (D-F) deviate by no more than 0.5 % despite of the different ways the TPS had been commissioned. This indicates that small-field dose calculation is not influenced by whether or not beam data for small fields have been included in the commissioning data set, at least for this linac-TPS combination down to a field setting of 2 cm x 2 cm.

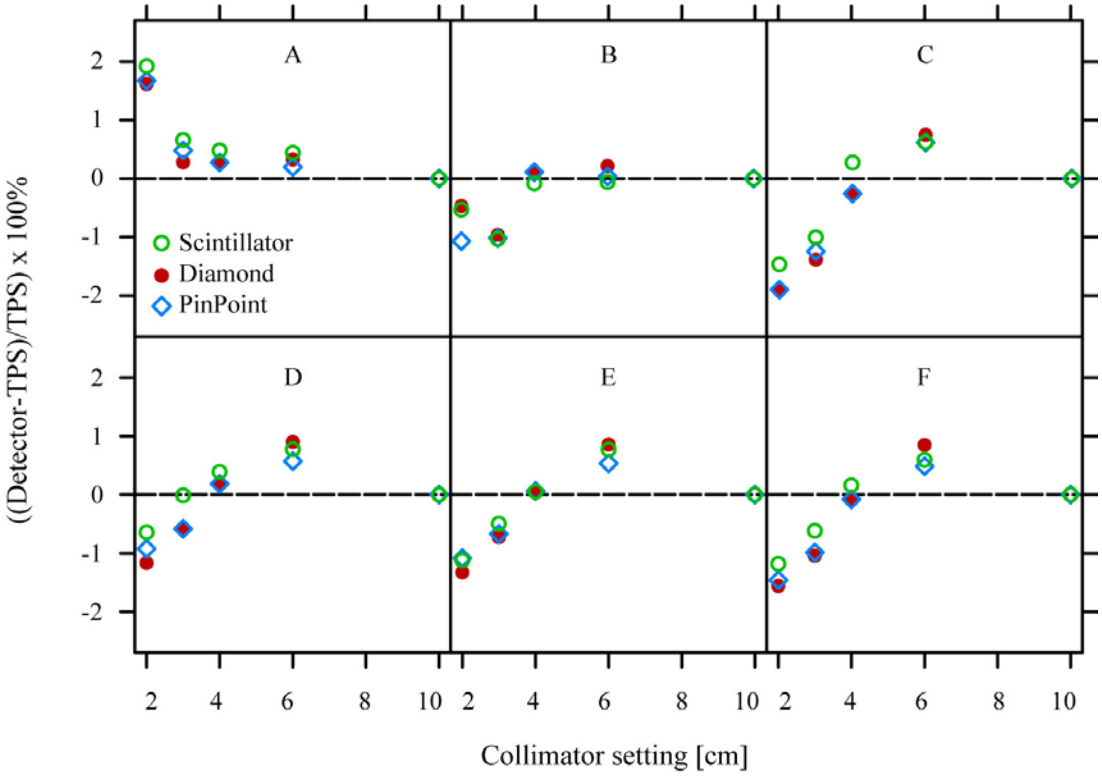


Fig. 4. Differences between measurements and TPS calculations for MLC-defined fields. Data are shown for the scintillator (open circles), diamond detector (closed circles) and PinPoint chamber (open diamonds). Measurement uncertainties (1 SD) are within 0.8 %.

4. Conclusions

Comparative dose measurements performed at all major Danish radiotherapy clinics have been presented. For all clinics, measurements of dose under reference conditions agreed with expected values within 1.0 %. The study did not uncover any significant differences in the reference dose among the clinics, despite the fact that different methodologies had been used for linac dose calibration. At the time of the study, five clinics had their reference ionization chambers calibrated in Co-60 beams with subsequent estimation of generic k_Q factors ,while one clinic had its reference chamber calibration directly traceable to a 6 MV beam at NPL, circumventing the need of a beam quality correction. A follow-up study on the dosimetric implications of different calibration methods would however prove highly relevant.

An in-house developed dosimetry system based on a fiber-coupled organic scintillator was used to visualize variations in dose rate behavior for four different linac models on a dose per pulse scale. The scintillator was also used to estimate correction factors for a PinPoint chamber and a diamond detector in small fields, revealing discrepancies within 2.2 % between the three detectors. Agreement between FWHM and collimator settings for small fields was within 6.0 % for four clinics, while two clinics showed field sizes that were respectively 9.6 % larger and 20.8 % smaller than expected. The largest discrepancy was however not expected to influence clinical dose delivery since small jaw-defined fields are not used during treatment at the particular clinic.

Output factor measurements agreed within 3.2 % with the beam data used for commissioning the TPS at each clinic. For MLC-defined fields, measurements agreed with TPS calculations within 1.9 %. It was not possible to assess whether the inclusion of small-field beam data in the TPS commissioning did influence the calculation accuracy for field settings down to 2 cm x 2 cm. At the present time, a minimal MLC setting of 2 cm x 2 cm is used during most IMRT treatments. However, the general tendency in radiotherapy is going towards more conformal treatments and the use of smaller fields; for instance, the Elekta Versa HD has been developed with the aim of stereotactic treatments. It is therefore expected that all clinics will put a higher emphasis on fields smaller than 2 cm x 2 cm in the future. This emphasizes that detectors used for acquiring small-field beam data are chosen carefully if the beam data are to be the basis of TPS calculated dose distributions in treatments involving small fields.

This study has demonstrated (i) consistency of reference dosimetry and small-field dosimetry on a national level, and (ii) clinical applications of fiber-coupled plastic scintillators. Furthermore, the study indicates that the estimation of detector-specific correction factors in small fields is consistent among clinics and linac models. This supports that the proposed IAEA formalism[(5)] for detector-specific correction factors for non-reference fields is both robust and useful for practical clinical measurements of small-field output factors.

Acknowledgements

This work was supported by the Danish Cancer Society and CIRRO – Center for Interventional Research in Radiation Oncology, supported by the Lundbeck Foundation. Part of this work was carried out within the EMRP project "Metrology for radiotherapy using complex radiation fields" (HLT09). The EMRP is jointly funded by the EMRP participating countries within EURAMET and the European Union.

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Appendix: Additional measurements

During the experimental sessions at some of the participating clinics, some additional measurements concerning flattening filter free (FFF) beams were performed. The FFF beam measurements were at the time of the study limited to clinics C, D, E and F. The measurements concerned the beam modalities 6 MV FFF and 10 MV FFF, and where performed in the same manner as for the 6 MV measurements, as described in the Materials and Methods section. The FFF measurements performed using the scintillator were corrected for energy dependence of the calibration coefficients using the values reported by Beierholm et al(25). This correction was negligible for 6 MV FFF but amounted to 0.8 ± 0.1 % for 10 MV FFF.

Reference dosimetry

The dose per pulse characteristics for 6 MV FFF and 10 MV FFF beams for the investigated linacs were comparable to the observations made by Beierholm et al(9). At the time of the study, only one of the investigated clinics (E) had completed absolute calibration of FFF beams. Measurements of reference dose to water performed using the scintillator where included for comparison with the Farmer chamber values. As described in the Materials and Methods section, the scintillator had in all cases been cross-calibrated with the Farmer chamber at 6 MV. Discrepancies in measured dose between scintillator detectors and ionization chambers have however been reported at other beam qualities(25), and it was therefore relevant to evaluate the magnitude of these discrepancies for FFF beams at the four investigated clinics.

The measured dose values are reported in table 9. The differences between the scintillator and Farmer measurements for 6 MV FFF amount to a mean value of -0.8 ± 0.1 %, while for the 10 MV FFF measurements the differences exhibit a mean value of 0.3 ± 0.2 %. These numbers agree well with the discrepancies reported earlier(25) (-1.2 ± 0.2 % difference for 6 MV FFF, 0.4 ± 0.1 % difference for 10 MV FFF). In the case of clinic E, the reference dose for 6 MV FFF measured using the Farmer chamber differ from the clinic nominal value by 1.0 %, while the scintillator measurement differs by 0.2 %. For 10 MV FFF, the differences from the clinic nominal value amount to 1.8 % for the Farmer chamber and 2.4 % for the scintillator.

Table 9. Comparison between measured and nominal reference dose to water per 100 MU. Measurement uncertainties (1 SD) are within 1.4 %.

Beam modality	Quantity	Dose (Gy)			
		C	D	E	F
6 MV FFF	Farmer measurement	0.808	0.804	0.832	0.799
	Scintillator measurement	0.802	0.797	0.825	0.792
	Nominal value (clinic)[a]			0.824	
10 MV FFF	Farmer measurement	0.868	0.902	0.873	0.897
	Scintillator measurement	0.870	0.902	0.878	0.898
	Nominal value (clinic)[a]			0.857	

Small-field dosimetry

Measured output factors for 6 MV FFF and 10 MV FFF where corrected for detector volume averaging and field size discrepancies as described in section 2.2.2. These corrections were comparable to the corrections obtained for 6 MV beams with negligible differences. The corrected output factor measurements are listed in table 10 for 6 MV FFF and in table 11 for 10 MV FFF. The corrected scintillator, diamond and PinPoint measurements are seen to agree within 1.1 % for 6 MV FFF and within 2.1 % for 10 MV FFF.

Estimated small-field correction factors are listed in table 12 and 13 for the diamond and PinPoint relative to the scintillator. As is the case for the 6 MV values, the largest differences are seen for the smallest investigated field size (1 cm x 1 cm for the diamond, 2 cm x 2 cm for the PinPoint). For 6 MV FFF, these differences are within 1.5 % while for 10 MV FFF they are within 1.7 %. It must again be emphasized that careful Monte Carlo simulations and further experiments should be performed to validate the observed corrections. However, the results show that differences between the three investigated detectors can be expected to be within 1.7 % when used for field sizes down to 1 cm x 1 cm for FFF beams.

A comparison between the corrected output factor measurements and the beam data used for TPS commissioning is shown in figure 5 for 6 MV FFF and in figure 6 for 10 MV FFF. The comparison was limited to clinics C and E, which had completed beam data acquisition at the time of the study. For 6 MV FFF, agreement between measurements and beam data is within 2.8 % for 1 cm x 1 cm and within 2.2 % for larger fields. For 10 MV FFF, agreement is within 3.1 % for 1 cm x 1 cm and within 1.0 % for larger fields.

Table 10. Measured output factors for 6 MV FFF beams, corrected for volume averaging and field size. Measurement uncertainties are within 0.8 % (1 SD).

Collimator setting (cm)	**Detector**	**Measured output factor**			
		C TB STx	**D TB**	**E TB**	**F TB**
1 x 1	Scintillator	0.713	0.707	0.720	0.712
	Diamond	0.705	0.714	0.717	0.717
2 x 2	Scintillator	0.814	0.815	0.814	0.815
	Diamond	0.806	0.808	0.807	0.808
	PinPoint	0.809	0.809	0.811	0.809
3 x 3	Scintillator	0.853	0.855	0.852	0.854
	Diamond	0.847	0.850	0.847	0.849
	PinPoint	0.849	0.852	0.849	0.850
4 x 4	Scintillator	0.883	0.885	0.883	0.883
	Diamond	0.880	0.882	0.879	0.881
	PinPoint	0.880	0.882	0.879	0.881
5 x 5	Scintillator	0.910	0.909	0.910	0.911
	Diamond	0.908	0.907	0.907	0.909
	PinPoint	0.907	0.907	0.907	0.908
6 x 6	Scintillator	0.933	0.933	0.935	0.935
	Diamond	0.934	0.935	0.934	0.936
	PinPoint	0.932	0.931	0.931	0.932
8 x 8	Scintillator	0.972	0.971	0.972	0.972
	PinPoint	0.972	0.970	0.970	0.971

Table 11. Measured output factors for 10 MV FFF beams, corrected for volume averaging and field size. Measurement uncertainties are within 0.8 % (1 SD).

Collimator setting (cm)	**Detector**	**Measured output factor**			
		C TB STx	**D TB**	**E TB**	**F TB**
1 x 1	Scintillator	0.692	0.675	0.683	0.683
	Diamond	0.700	0.689	0.693	0.693
2 x 2	Scintillator	0.838	0.835	0.834	0.835
	Diamond	0.835	0.835	0.834	0.834
	PinPoint	0.831	0.827	0.828	0.827
3 x 3	Scintillator	0.890	0.893	0.888	0.890
	Diamond	0.889	0.894	0.889	0.889
	PinPoint	0.888	0.891	0.888	0.887
4 x 4	Scintillator	0.919	0.920	0.917	0.918
	Diamond	0.919	0.920	0.918	0.919
	PinPoint	0.919	0.920	0.918	0.919
5 x 5	Scintillator	0.940	0.938	0.939	0.940
	Diamond	0.940	0.939	0.939	0.940
	PinPoint	0.940	0.939	0.939	0.940
6 x 6	Scintillator	0.956	0.956	0.955	0.957
	Diamond	0.959	0.959	0.957	0.959
	PinPoint	0.957	0.955	0.956	0.957
8 x 8	Scintillator	0.981	0.981	0.981	0.981
	PinPoint	0.982	0.981	0.982	0.982

Table 12. Estimated diamond and PinPoint $k_{Qmsr,Qref}^{fmsr,fref}$ correction factors for 6 MV FFF beams. The corrections have been estimated with reference to the volume averaging-corrected scintillator readings. Uncertainties are within 1.1 % (1 SD).

Collimator setting (cm)	**Detector**	**$k_{Qmsr,Qref}^{fmsr,fref}$ correction factor relative to scintillator**			
		C TB STx	**D TB**	**E TB**	**F TB**
1 x 1	Diamond	1.015	1.000	1.009	0.997
2 x 2		1.011	1.009	1.009	1.009
3 x 3		1.007	1.007	1.006	1.006
2 x 2	PinPoint	1.011	1.012	1.008	1.012
3 x 3		1.005	1.004	1.004	1.004

Table 13. Estimated diamond and PinPoint $k_{Qmsr,Qref}^{fmsr,fref}$ correction factors for 10 MV FFF beams. The corrections have been estimated with reference to the volume averaging-corrected scintillator readings. Uncertainties are within 1.1 % (1 SD).

Collimator setting (cm)	**Detector**	**$k_{Qmsr,Qref}^{fmsr,fref}$ correction factor relative to scintillator**			
		C TB STx	**D TB**	**E TB**	**F TB**
1 x 1	Diamond	0.992	0.989	0.991	0.990
2 x 2		1.003	1.000	0.999	1.002
3 x 3		1.001	0.998	0.999	1.001
2 x 2	PinPoint	1.014	1.014	1.007	1.017
3 x 3		1.003	1.001	1.000	1.003

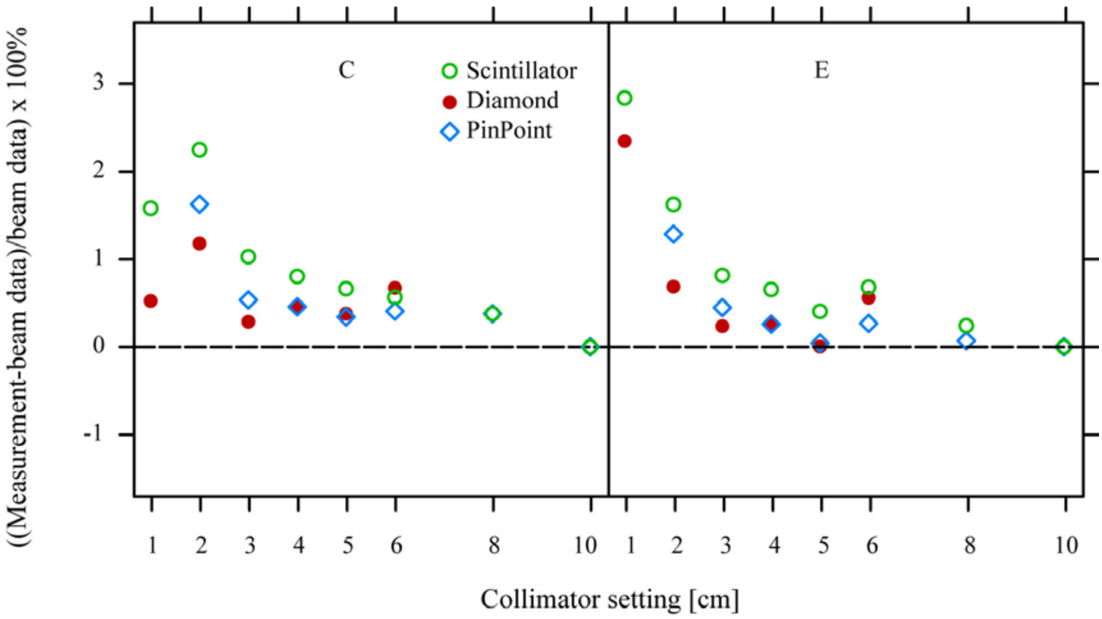

Fig. 5. Comparison between measurements and the beam data used by clinics C and E for TPS commissioning for 6 MV FFF beams. Data are shown for the scintillator (open circles), diamond detector (closed circles) and PinPoint chamber (open diamonds). Measurement uncertainties (1 SD) are within 0.8 %.

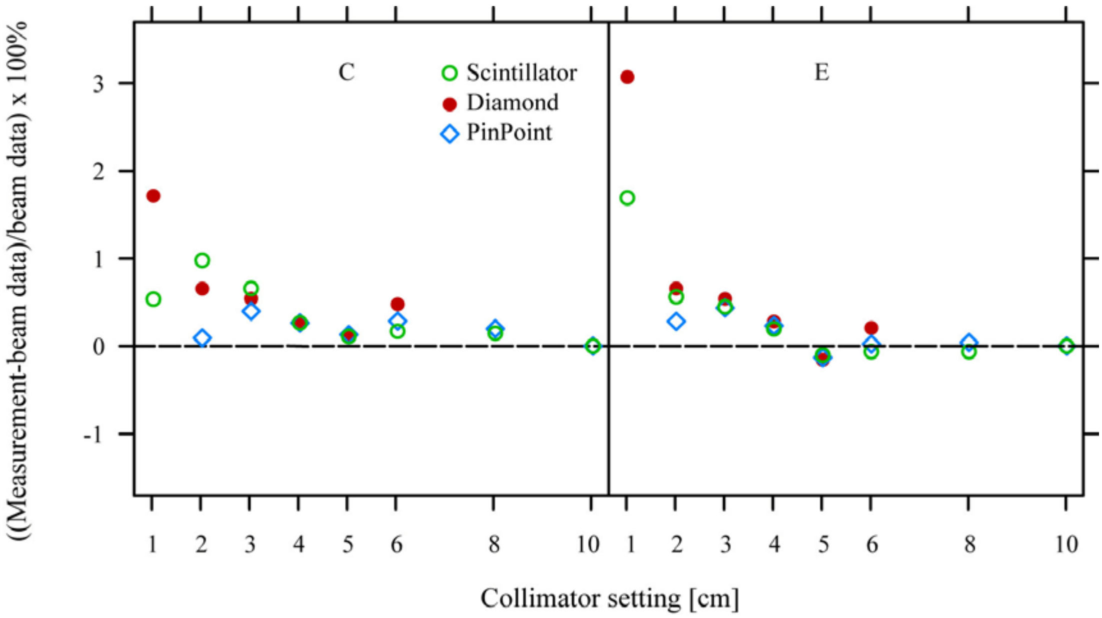

Fig. 6. Comparison between measurements and the beam data used by clinics C and E for TPS commissioning for 10 MV FFF beams. Data are shown for the scintillator (open circles), diamond detector (closed circles) and PinPoint chamber (open diamonds). Measurement uncertainties (1 SD) are within 0.8 %.

The Center for Nuclear Technologies (DTU Nutech) at the Technical University of Denmark is the Danish center of competency for nuclear technologies. With roots in research in the peaceful use of nuclear power, DTU Nutech works with the applications of ionizing radiation and radioactive substances for the benefit of society.

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