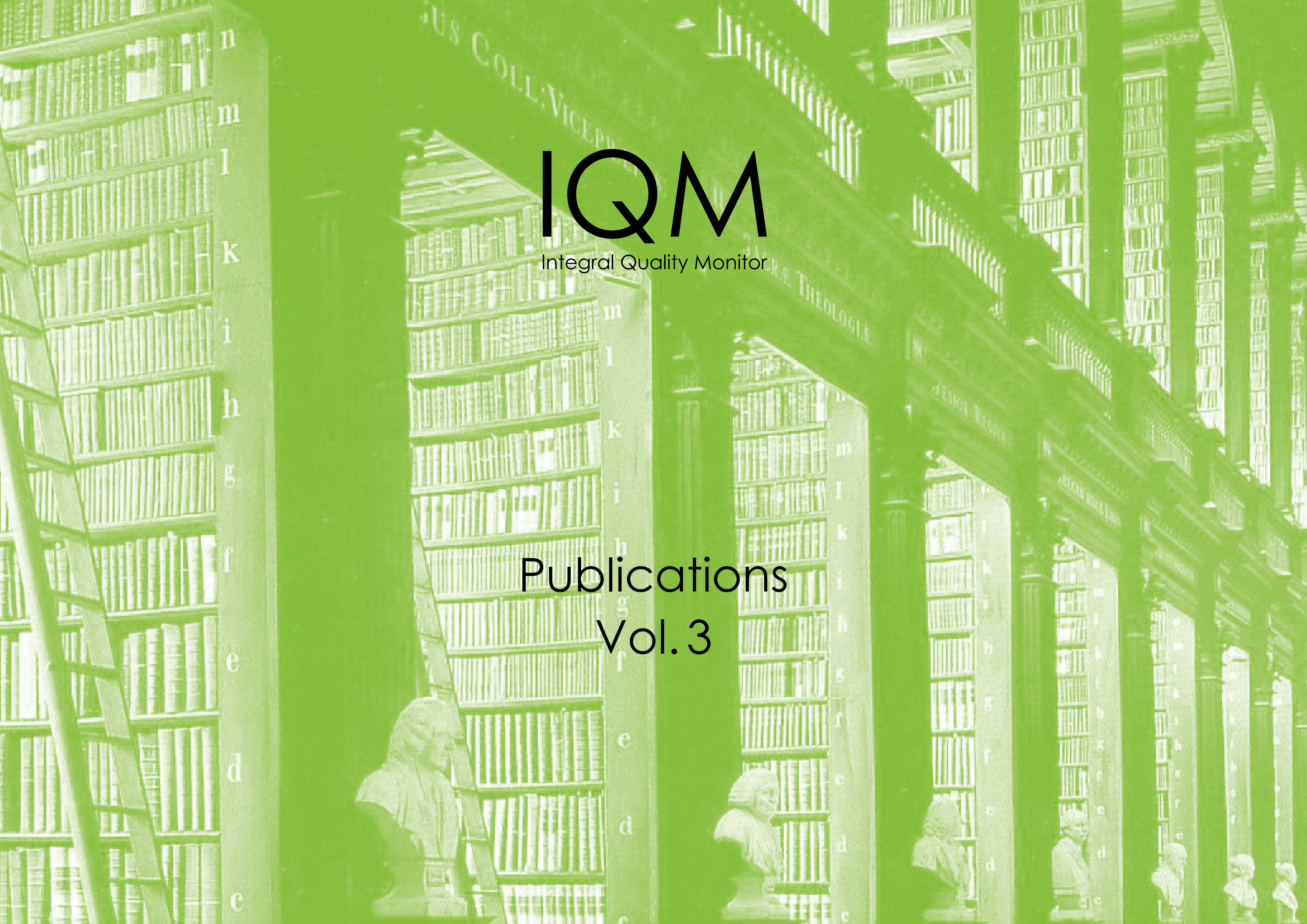

IQM

Integral Quality Monitor

Publications

Vol. 3

Ladies and Gentlemen,

Welcome to Volume 3 of the IQM Publications series.

This 3rd volume of the series is dedicated to the clinical implementation publication titled:

"Influence of the Integral Quality Monitor transmission detector on high energy photon beams: A multi-centre study"

published in the Zeitschrift für Medizinische Physik (Journal for Medical Physics, in press, available online March 21, 2017) by Dr. Bozidar Casar et al.

This article discusses the influence of the Integral Quality Monitor (IQM) transmission detector on photon beam properties.

"This study demonstrates clinically negligible changes in beam quality and surface dose for all investigated beams."

The authors evaluated data acquired at nine different Radiation Therapy centers and concluded that the magnitudes of changes which were found justify treating IQM either as energy-specific tray factors in the treatment planning system or alternatively as a set of modified output factors for each linac energy.

This article provides valuable guidance for implementing the IQM System into the clinical routine.

With best regards,

Jürgen Oellig
Managing Director, iRT Systems

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Cinzia Talamonti, Jianguo Qian, Ignasi Mendez, Denis Brojan, Bruce Perrin,
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Influence of the Integral Quality Monitor transmission detector on high energy photon beams: A multi-centre study

Zeitschrift für Medizinische Physik; Currently in press, available online March 21, 2017

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Abstract

Purpose:

The influence of the Integral Quality Monitor (IQM) transmission detector on photon beam properties was evaluated in a preclinical phase, using data from nine participating centres: (i) the change of beam quality (beam hardening), (ii) the influence on surface dose, and (iii) the attenuation of the IQM detector.

Methods:

For 6 different nominal photon energies (4 standard, 2 FFF) and square field sizes from 1 × 1 cm^2 to 20 × 20 cm^2, the effect of IQM on beam quality was assessed from the $PDD_{20,10}$ values obtained from the percentage dose depth (PDD) curves, measured with and without IQM in the beam path. The change in surface dose with/without IQM was assessed for all available energies and field sizes from 4 × 4 cm^2 to 20 × 20 cm^2. The transmission factor was calculated by means of measured absorbed dose at 10 cm depth for all available energies and field sizes.

Results:

(i) A small (0.11–0.53%) yet statistically significant beam hardening effect was observed, depending on photon beam energy. (ii) The increase in surface dose correlated with field size ($p < 0.01$) for all photon energies except for 18 MV. The change in surface dose was smaller than 3.3% in all cases except for the 20 × 20 cm^2 field and 10 MV FFF beam, where it reached 8.1%. (iii) For standard beams, transmission of the IQM showed a weak dependence on the field size, and a pronounced dependence on the beam energy (0.9412 for 6 MV to 0.9578 for 18 MV and 0.9440 for 6 MV FFF; 0.9533 for 10 MV FFF).

Conclusions:

The effects of the IQM detector on photon beam properties were found to be small yet statistically significant. The magnitudes of changes which were found justify treating IQM either as tray factors within the treatment planning system (TPS) for a particular energy or alternatively as modified outputs for specific beam energy of linear accelerators, which eases the introduction of the IQM into clinical practice.

Keywords:

Transmission detector, on-line dose monitoring, quality assurance, linear accelerator, beam hardening, IQM

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1 Introduction

Quality assurance (QA) programmes and the associated quality control (QC) procedures have become one of the most important tasks of radiotherapy during the last three decades [1–9]. The evolution of advanced radiotherapy techniques such as stereotactic radiosurgery and radiotherapy (SRS/T)[10–13], intensity modulated radiotherapy (IMRT) [14] and volumetric modulated arc therapy (VMAT) [15] has triggered new developments in the field of pre-treatment patient specific dosimetry. Various dosimetry phantoms (Delta4, MatriXX, OCTAVIUS, etc.) were introduced into clinical routine to verify the accuracy of planned dose delivery before the first radiotherapy session. However, pre-treatment plan verification is considered time consuming and is limited to a few planes. In addition, pre-treatment measurements are typically performed only once prior to the first treatment session assuming that there are no changes or errors in all sub-sequent treatment sessions. Moreover, adaptive radiotherapy approaches demand for on-line verification of dose delivery.

In the last decade several transmission detectors have been developed for on-line verification of photon beam dose that provide full field coverage and are compatible with VMAT delivery.

On-line beam monitoring systems can adequately validate the accuracy and integrity of patient plan data and detect dosimetric failures in beam delivery on time. Various systems were described in the literature, such as the DAVID system (PTW, Germany) [16,17], the Dolphin detector with the COMPASS verification software (IBA Dosimetry, Germany) [18,19] or the “magic plate” (Centre for Medical Radiation Physics, University of Wollongong, Australia) [20]. The DAVID system consists of a flat, multi-wire transmission type ionization chamber and is constructed from transparent material, the Dolphin detector uses 1513 air-vented plane parallel ionization chambers for beam verification, while the “magic plate” consists of 11 × 11 epitaxial diodes mounted on a 0.6 mm Kapton substrate. A potential disadvantage of all mentioned transmission detectors is their intrinsic limited resolution due to the characteristics of their design: limited number of wires, plane parallel ionization chambers or diodes. A common feature of the mentioned transmission detectors is that they are placed between the radiation source and the patient, allowing the beam fluence to be monitored (on-line) during the actual treatment of an individual patient.

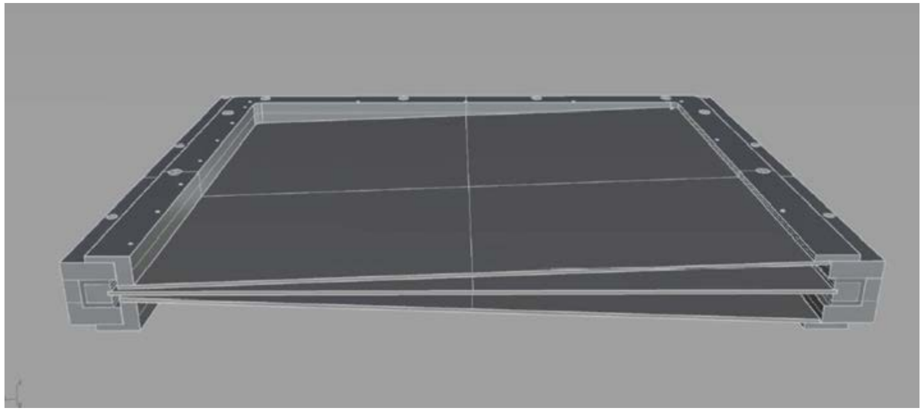

Figure 1. Schematic drawing of the IQM detector (courtesy of iRT Systems) with three electrodes: upper and lower polarizing electrodes are angled relative to the central collecting electrode, providing spatial sensitivity of the measured signals in one direction – direction of MLC leaf motion.

Recently, a multi-institutional study on quality assurance for VMAT was published [21] where authors have investigated linac specific QA based on the analysis of log files while for dosimetric measurements an ionization chamber array was used. While log file analysis is prospective tool for future QA programmes, this approach presently does not offer online verification of beam parameter accuracy during the actual treatment delivery.

A newly developed transmission detector (a prototype was designed by Islam et al. [22]), the Integral Quality Monitor (IQM, i-RT, Germany) overcomes the limitation of resolution by using an area integrating energy fluence monitoring sensor. IQM is air-vented spatially sensitive large area ion chamber with gradient response. It consists of two polarizing electrodes which are angled relative to the central collector electrode with increasing separation in the direction of MLC leaf motion (Fig. 1, courtesy of iRT Systems). The slope of the electrode separation provides high spatial sensitivity of the signal (0.5%/mm) while still keeping a small detector thickness of 3.5 cm [23–25]. All three electrodes are made of 1.5 mm thick aluminium plates to minimize absorption of the detector and to ensure the rigidity of the system. The physical sensitive area of 26.5 × 26.5 cm^2 covers the entire range of radiation fields offered by present linear accelerators. One of the main features of the IQM system is the automatic comparison of measured signals against expected signals (segment-by-segment) in real time. Expected signals are calculated from the imported treat-ment plan parameters from the TPS.

One concern about the use of transmission detectors is their effect on beam quality and the induced beam attenuation. Due to their intended daily on-line verification during patient treat-ment, characteristics of these detectors have to be thoroughly examined prior to clinical implementation. Hence, there is a potential need for new commissioning and a new beam model in the TPS.

The aim of this multi-centre study was to evaluate the influence of the IQM system on photon beam properties of linear accelerators: (i) change of beam quality (beam hardening),(ii) influence on surface dose and (iii) attenuation of the IQM detector. The influence of the IQM system on surface dose and beam quality has not yet been investigated in a systematic multi-centre study. In this present work we provide generic data for IQM's transmission factors for further clinical use.

2 Materials and methods

While a possible pronounced increase of surface dose could be a limiting factor for clinical implementation, significant beam hardening would require additional commissioning measurements prior to clinical start.

The influences of the newly designed IQM system on beam properties were studied on Elekta linear accelerators (Synergy, Precise and Versa HD) at nine different institutions following a predefined study protocol (Table 1).

Surface dose, beam quality and output factors were studied for a set of standard photon beams with flattening filters with nominal energies (6 MV, 10 MV, 15 MV and 18 MV) and for two FFF photon beams (6 MV FFF and 10 MV FFF). Percentage depth doses (PDD) were measured for 9 square radiation fields to investigate the extent and significance of the beam hardening effect: 1 × 1 cm^2, 2 × 2 cm^2, 3 × 3 cm^2, 4 × 4 cm^2, 5 × 5 cm^2, 7 × 7 cm^2, 10 × 10 cm^2, 15 × 15 cm^2, 20 × 20 cm^2, with/without the IQM attached to the linac accessory. Various small field detectors (PTW 60019 microdiamond detectors, IBA CC01 ionization chamber, IBA SFD diode, PTW Pinpoint 3D ionization chamber and Exradin A14 ionization chamber) were used for dose measurements for field sizes up to 7 × 7 cm^2, while for larger fields ranging from 4 × 4 cm^2 to 20 × 20 cm^2 ionization chambers of medium chamber cavity volumes (IBA CC13, PTW Semiflex and Exradin A1) were used. PDD data were collected at fixed source to surface distance SSD = 90 cm. Environmental conditions were recorded and their influence on the absorbed dose was taken into account as appropriate.

Along with the nominal beam energies, beam qualities $TPR_{20,10}$ were reported for all investigated beams from all participating centres.

2.1 Analysis of beam quality changes – beam hardening effect

To determine the influence of the IQM on photon beam quality, $PDD_{20,10}$ values were acquired. This approach is less sensitive to potential set-up errors of the detectors compared to the evaluation of $PDD_{10,max}$ and is also commonly used for the determination of beam quality [26,27].

In a first step, differences in beam qualities were investigated by comparing $PDD_{20,10}$ with/without the IQM attached to the linac for different square radiation fields x_i. Beam hardening effect $\delta_{Q,i,j}^{IQM}$ for the selected beam quality Q and radiation field size x_i, and participating centre j was calculated using Eq. (1)

$$\delta_{Q,i,j}^{IQM}=100\times\frac{PDD_{20,10,i,j}(IQM)-PDD_{20,10,i,j}(no\quad IQM)}{PDD_{20,10,i,j}(no\quad IQM)} \tag{1}$$

	Percentage depth dose measurements	
	Small fields	Large fields
Scanning system	3D automatic water phantom	3D automatic water phantom
Detectors	IBA CC01, PTW Pinpoint, IBA SFD, PTW diamond, Exradin A14	IBA CC13, PTW Semiflex, Exradin A1
Eff. point of detector	As defined by manufacturer	0.6 r_{cav} upstream from the ionization chamber centre
Fields [cm^2]	1 × 1, 2 × 2, 3 × 3, 4 × 4, 5 × 5, 7 × 7	4 × 4, 5 × 5, 7 × 7, 10 × 10, 15 × 15, 20 × 20
SSD [cm]	90	90
Measurement range [cm]	0–25	0–25
Direction of scans	Bottom to surface	Bottom to surface
Scan data collection [mm]	≤1	≤1
T and p	Recorded	Recorded
	Point measurements	
	Small fields	Large fields
Scanning system	1D or 3D automatic water phantom	1D or 3D automatic water phantom
Detectors	IBA CC01, PTW Pinpoint, IBA SFD, PTW diamond, Exradin A14	IBA CC13, PTW Semiflex, Exradin A1
Eff. point of detector	As defined by manufacturer	At the centre of the ionization chamber
Fields [cm^2]	1 × 1, 2 × 2, 3 × 3, 4 × 4, 5 × 5, 7 × 7	4 × 4, 5 × 5, 7 × 7, 10 × 10, 15 × 15, 20 × 20
SSD [cm]	90	90
T and p	Recorded	Recorded

Table 1 Study protocol for the execution of measurements which was followed by the participating institutions. PDD measurements were used for the analysis of beam hardening effect and influence of the IQM system on surface doses (only for large fields), while point measurements were used for the determination of the IQM transmission factors. Measurements were performed for 6 MV, 10 MV, 15 MV and 18 MV flattened beams as well as for 6 MV FFF and 10 MV FFF beams without flattening filter.

where j denotes participating centre and i selected radiation field size. $\delta_{Q,i,j}^{IQM}$ were aggregated for all radiation fields for particular beam energy and the measurements from all participating centres were taken into account. Finally, mean values for the beam hardening effect δ_Q^{IQM} for all n radiation fields and m participating centres were calculated using Eq. (2)

$$\delta_Q^{IQM} = \frac{1}{m \cdot n} \sum_j^m \sum_i^n \delta_{Q,i,j}^{IQM} \tag{2}$$

2.2 Analysis of surface doses

The influence of the IQM on the surface dose (at depth = 0 cm) was assessed for field sizes ranging from 4 × 4 cm^2 to 20 × 20 cm^2 for all available photon energies through the comparison of measured signals. Detectors used for the evaluation of the effect on surface dose were cylindrical ionization chambers which are commonly used for relative dosimetry measurements during the commissioning of linear accelerators for photon beams (IBA CC13, PTW Semiflex and Exradin A1). Relative changes of surface dose $\delta_{S,i,j}^{IQM}$ for selected radiation field size x_i and participating centre j, with/without the IQM attached to the linac, were obtained according to Eq. (3)

$$\delta_{S,i,j}^{IQM} = 100 \times \frac{PDD_{S,i,j}(\text{IQM}) - PDD_{S,i,j}(\text{no IQM})}{PDD_{S,i,j}(\text{no IQM})} \tag{3}$$

where $PDD_{S,i,j}$ is the reported measured absorbed dose at the surface from centre j for radiation field size x_i at certain beam energy normalized to the maximum dose.

The calculated relative differences $\delta_{S,i,j}^{IQM}$ from m participating institutions were aggregated and averaged over the selected beam energy to obtain mean values of investigated differences of surface doses $\delta_{S,i,j}^{IQM}$ for particular radiation field size x_i (Eq. (4)).

$$\delta_{S,i}^{IQM} = \frac{1}{m}\sum_{j=1}^{m}\delta_{S,i,j}^{IQM} \quad (4)$$

Correlations between $\delta_{S,i}^{IQM}$ and radiation field size x_i for all investigated beam energies were determined using the Pearson product-moment correlation coefficient ρ.

2.3 Transmission factor measurements

The attenuation of photon beams in the presence of IQM was assessed as a function of radiation field size and beam energy defined as beam quality $TPR_{20,10}$. $TPR_{20,10}$ were measured or alternatively calculated from $PDD_{20,10}$ curves collected at SSD = 100 cm and field size 10 × 10 cm^2 using Eq. (5) introduced by Followill et al. [26] and adopted in IAEA TRS 398 dosimetry protocol [27]

$$TPR_{20,10} = 1.2661 \cdot PDD_{20,10} - 0.0595 \quad (5)$$

As the stopping power ratios air/water are different for flattened and unflattened beams, for later only measured data for $TPR_{20,10}$ were used. Analysis was performed separately for 4 standard photon beams with flattening filter and for 2 FFF photon beams. For a selected square radiation field x_i, transmission factors $k_{Q,i}^{IQM}$ were calculated using Eq. (6)

$$k_{Q,i}^{IQM} = 100 \times \frac{D_i \;\; \text{(IQM)}}{D_i \;\; \text{(no IQM)}} \quad (6)$$

where D_i (IQM) is the reported measured absorbed dose at 10 cm depth for field x_i with IQM in place and D_i (no IQM) in the absence of IQM. As the differences in $TPR_{20,10}$ for the same nominal energy were negligible among participating centres, mean transmission factors k_{Q}^{IQM} for particular beam energy was calculated using Eq. (7)

$$k_{Q}^{IQM} = \frac{1}{m \cdot n}\sum_{j}^{m}\sum_{i}^{n}k_{Q,i,j}^{IQM} \quad (7)$$

where n is the number of analysed radiation field sizes and m is the number of participating centres. Before the final analysis, collected data from each of the participating centres were normalized: all data collected with small detectors were normalized to the values collected with ionization chambers at 5 × 5 cm^2.

3 Results

3.1 Analysis of beam quality changes – beam hardening effect

The analysis of 4 standard and 2 FFF photon beams demonstrated that the presence of IQM causes measurable changes in beam quality $\delta_{Q,i}^{IQM}$ for all investigated beams and radiation field sizes averaging data from m participating centres with absolute differences ranging from −0.23% to 1.04% (Fig. 2). Comparison of $PDD_{20,10}$ derived from measured PDD curves with and without IQM in place revealed small dispersions within the data for a given beam energy, with standard deviations ranging from 0.18% to 0.70% of $\delta_{Q,i}^{IQM}$. No significant correlation between $\delta_{Q,i}^{IQM}$ and the radiation field size was found. Averaging of the results for all beam sizes was therefore justified. When all data were aggregated, mean relative differences (beam hardening, δ_{Q}^{IQM}) from 0.11% to 0.53% were found, depending on photon beam energy. The beam hardening effect was statistically significant (p < 0.01) for all photon energies with the exception of 15 MV beam where p = 0.078 (Table 2).

3.2 Analysis of surface doses

Pearson's product–moment correlation coefficient ρ indicates a positive linear correlation between $\delta_{S,i}^{IQM}$ and the radiation field size x_i for all studied

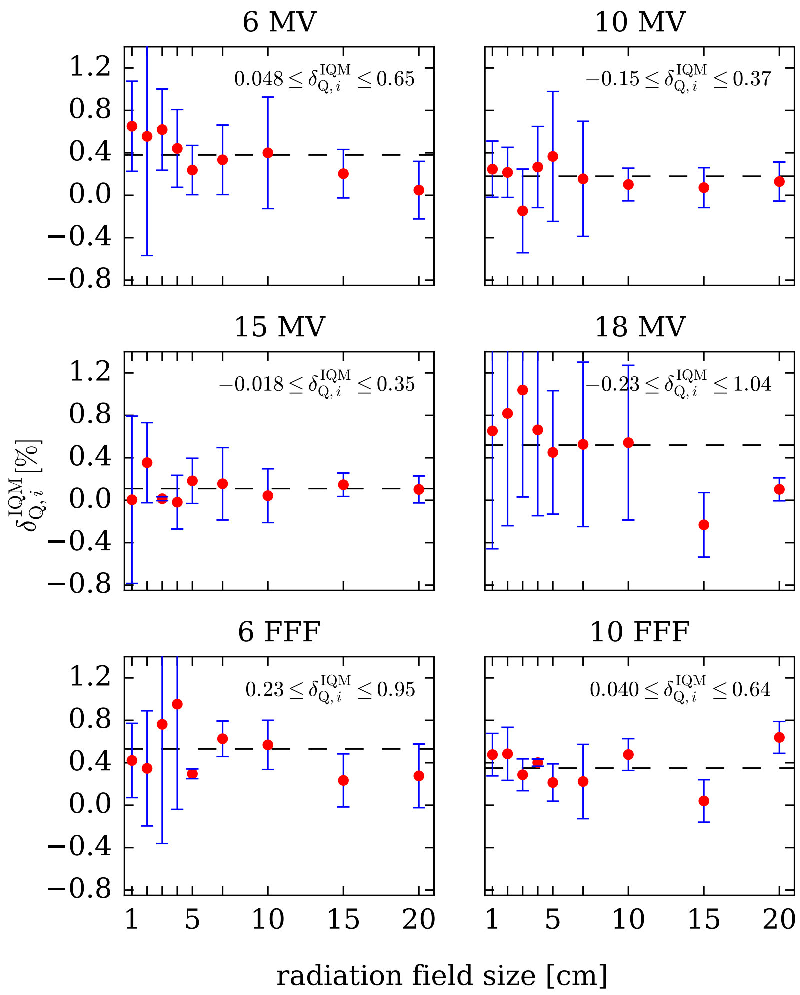

Figure 2. Changes in beam quality $\delta^{IQM}_{Q,i}$ versus radiation field size for investigated beam energies when IQM was mounted on the linear accelerator. For every beam energy and radiation field size, data represent average values of measurements from all participating institutions. Dashed lines represent mean differences δ^{IQM}_{Q} for a given energy. Error bars represent standard deviations of collected measured data.

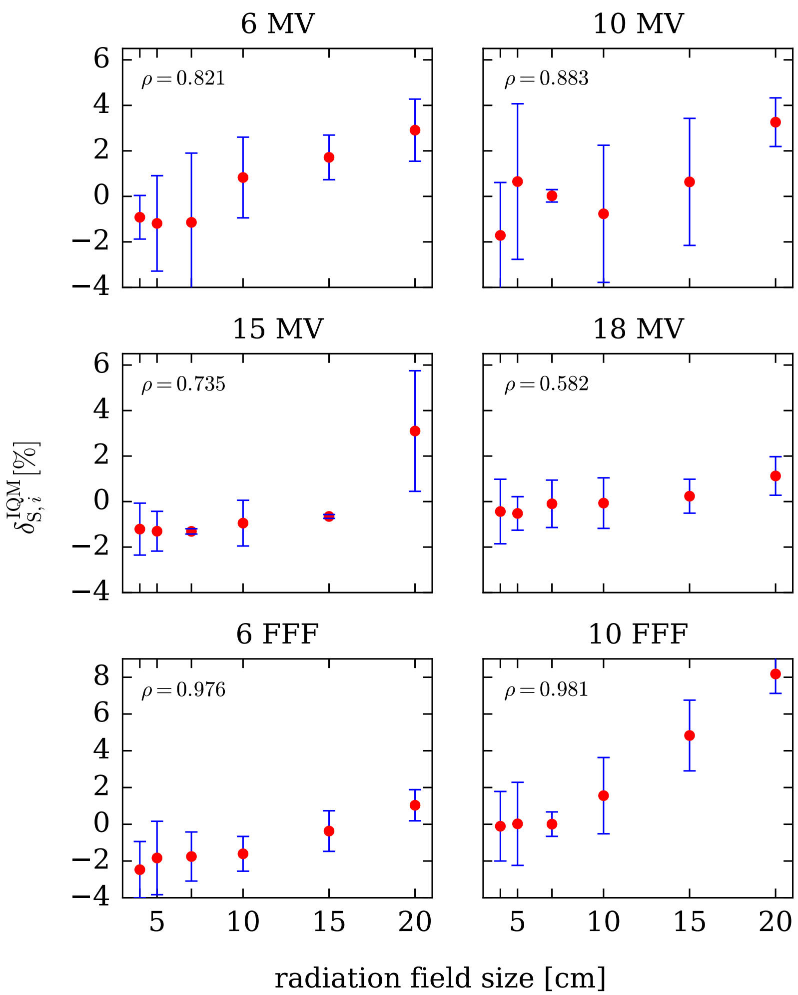

Figure 3. Relative changes of surface dose $\delta^{IQM}_{S,i}$ versus radiation field size with IQM in the beam path. For every investigated beam energy and radiation field size, data represent average values of measurements from all participating institutions. Degree of linear correlation was determined using Pearson's product–moment correlation coefficient ρ. Error bars represent standard deviations of collected measured data.

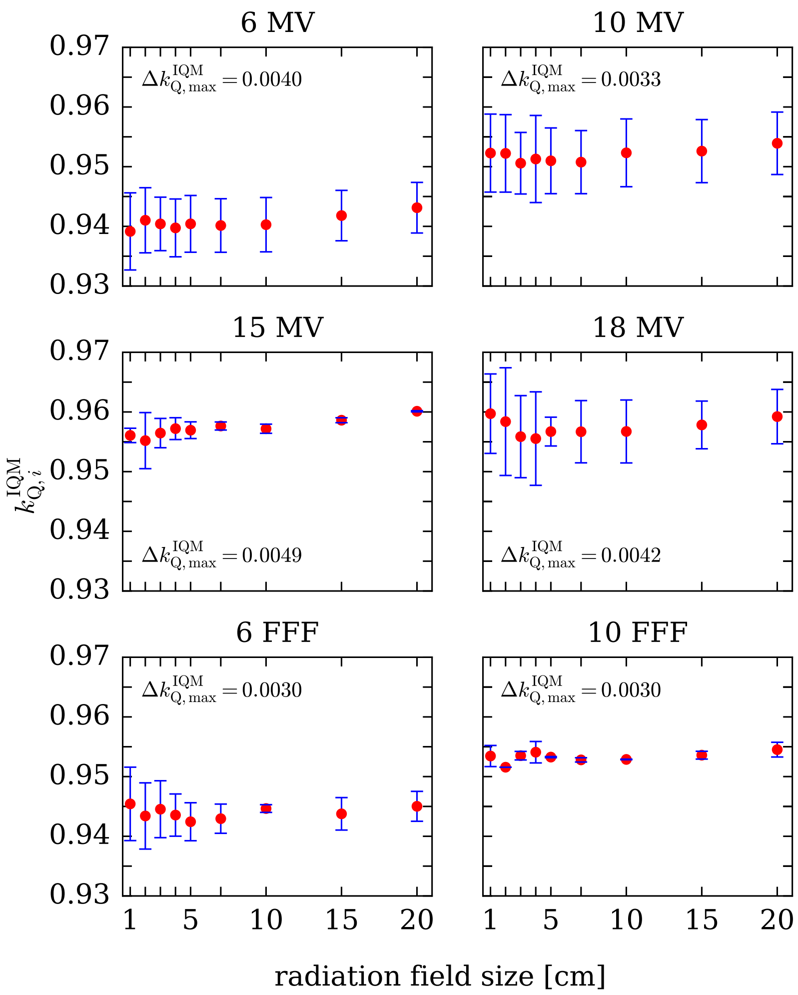

Figure 4. Transmission factors $k_{Q,i}^{IQM}$ of IQM versus radiation field size, for each nominal beam energy. Data represent average values of measurements from all participating institutions. $\Delta k_{Q,i}^{IQM}$ denotes maximal difference of $k_{Q,i}^{IQM}$ for a given nominal energy. Error bars represent standard deviations of collected measured data.

flattened and unflattened beams as shown in Fig. 3. For all beam energies, correlation coefficient ρ was in the range $0.5 < \rho < 1$. A statistically significant positive correlation was found ($p < 0.01$) for all beam energies with the exception of 18 MV standard beam where $p = 0.047$. The highest value of $\delta_{S,20}^{IQM} = 8.1\%$ was found for the largest investigated radiation field 20 × 20 cm^2 for 10 MV FFF beam. $\delta_{S,i}^{IQM}$ did not exceed 3.3% in any other case. Uncertainties of $\delta_{S,i}^{IQM}$ in terms of standard deviations ranged from 0.1% to 3.0% as indicated in Fig. 3.

3.3 Transmission of IQM

3.3.1 Standard photon beams

Transmission factors show evident energy dependence: from 0.9412 for lowest standard beam energy to 0.9589 for highest standard beam energy. On the other hand, the influ-ence of the IQM on transmission showed a weak dependence on the radiation field size for all beam energies from 6 MV to 18 MV. The maximum dispersion of the transmission factors $k_{Q,i}^{IQM}$ versus radiation field size x_i for all beam energies was found to be within 0.55% (Fig. 4). Thus, it was justified to use Eq. (7) for the calculation of mean transmission factors k_{Q}^{IQM} for IQM, summing the measurements for one particular beam energy from all participating centres and for all radiation fields (Table 3). In Fig. 5, mean transmission factors k_{Q}^{IQM} versus beam qualities are presented for a set of standard beam ener-gies. Following the measured and analysed data, a polynomial fit of second order is proposed in Eq. (8) for the determination of generic values of k_{Q}^{IQM} for the entire range of investigated standard photon beam energies characterized through beam quality values $TPR_{20,10}$. Due to the high correlation between measured data and polynomial fit ($R^2 = 0.996$), extrapolation of $TPR_{20,10} \approx 0.02$ outside the investigated range of beam energies was considered as indicated in Fig. 5.

$$k_{Q}^{IQM}(TPR_{20,10}) = -0.8186 \cdot (TPR_{20,10})^2 + 1.3872 \cdot TPR_{20,10} + 0.3754 \qquad (8)$$

Mean beam hardening effect δ_Q^{IQM} versus beam quality $TPR_{20,10}$						
$TPR_{20,10}$	0.682	0.733	0.759	0.776	0.675 FFF	0.726 FFF
E	6 MV (9)	10 MV (8)	15 MV (2)	18 MV (2)	6 MV FFF (2)	10 MV FFF (2)
δ_Q^{IQM} [%]	0.38	0.18	0.11	0.52	0.53	0.35
σ [%]	0.48	0.41	0.28	0.70	0.40	0.18
p	9×10^{-13}	2×10^{-4}	0.0781	0.0011	8×10^{-4}	7×10^{-5}

Table 2 Mean differences (beam hardening) δ_Q^{IQM} (Eq. (2)) and associated standard deviations σ, aggregated by nominal energy and all radiation field sizes of photon beams with and without IQM in place for all investigated beam energies. $TPR_{20,10}$ values stand for average beam qualities reported from participating centres for each nominal photon beam energy E without IQM in place. Number of studied beams is reported in brackets. Significance ***p*** of mean differences was determined according to one-sample two tailed Student's *t*-test.

Mean transmission factors k_Q^{IQM} for various beam energies						
$TPR_{20,10}$	0.682	0.733	0.759	0.776	0.675	0.726
E	6 MV (9)	10 MV (8)	15 MV (2)	18 MV (2)	6 MV FFF (2)	10 MV FFF (2)
k_Q^{IQM}	0.9412	0.9519	0.9573	0.9589	0.9440	0.9533
σ [%]	0.58	0.56	0.20	0.57	0.30	0.11

Table 3 Mean transmission factors k_Q^{IQM} (Eq. (7)) of IQM and associated standard deviations σ for all investigated beam energies. $TPR_{20,10}$ values stand for average beam qualities reported from participating centres for each nominal photon beam energy without IQM in place. The number of studied beams is reported in brackets.

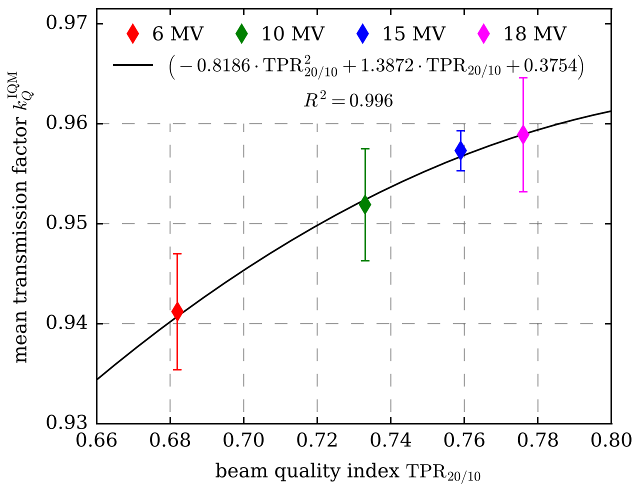

Figure 5. Mean transmission factors k_Q^{IQM} of IQM versus beam qualities $\mathrm{TPR}_{20,10}$ for investigated set of standard flattened beams. For every investigated beam energy and radiation field size, data represent average values of measurements from all participating institutions. A polynomial fit of second order is proposed for the determination of generic values of k_Q^{IQM} for the complete range of investigated beam energies characterized through beam quality values $\mathrm{TPR}_{20,10}$. Error bars represent standard deviations of collected measured data.

Reported $\mathrm{TPR}_{20,10}$ values for photon beams were averaged in our analysis. The highest standard deviation among the reported $\mathrm{TPR}_{20,10}$ values for specific nominal beam energy was found to be 0.33% which, applying Eq. (8), reflects in the additional uncertainty of 0.06% for the determination of k_Q^{IQM} factor. This additional uncertainty was included in the overall uncertainty budget of k_Q^{IQM}, although its contribution is negligible.

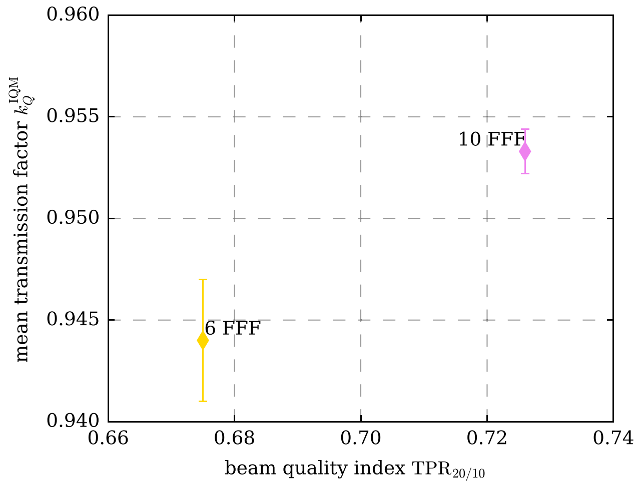

Figure 6. Mean transmission factor k_Q^{IQM} of IQM versus beam quality $\mathrm{TPR}_{20,10}$ aggregated by nominal energies 6 MV FFF and 10 MV FFF photon beams. Error bars represent standard deviations of collected measured data.

3.3.2 FFF photon beams

For 2 investigated FFF photon beams, 6 MV FFF and 10 MV FFF, dispersions of transmission coefficients $k_{Q,i}^{IQM}$ versus radiation field size x_i for a particular beam energy E, was found to be within 0.3%. Standard deviations of the collected measured data were ~0.001 for both FFF beam energies. The use of Eq. (7) is hence justified also for FFF beams; mean transmission factors k_Q^{IQM} were 0.9440 and 0.9533 for 6 MV FFF and 10 MV FFF beams, respectively (Table 3). These values are proposed as generic values for k_Q^{IQM} for the studied beam energies. Strictly speaking, k_Q^{IQM} for FFF beams are valid only for Elekta Versa HD linear accelerator, for which the measurements were performed. No fit was proposed although it can be considered that a linear fit around the values stated for FFF beams in Table 3 is acceptable. Transmission factors versus beam qualities for 2 investigated FFF beams are presented in Fig. 6.

4 Discussion

The aim of this multi-centre study was to investigate the influence of the IQM system for three important beam properties: change of beam quality (beam hardening effect), change of surface dose and determination of attenuation of IQM for flattened and un-flattened photon beams from linear accelerators. Within the collaboration of nine centres, all measurements were performed following a predefined experimental study protocol.

The presence of IQM caused a small but measurable and statistically significant beam hardening effect δ_Q^{IQM}. Beam hardening was most pronounced for the 6 MV FFF beam where δ_Q^{IQM} increased to 0.53%. Statistical significance of the beam hardening effect was demonstrated ($p < 0.01$) for all investigated beams except for 15 MV where no statistically significant difference was found. As beam quality changes were always lower than 0.53%, our conclusion is that this effect has no considerable clinical relevance.

The correlation between the relative differences of surface dose $\delta_{S,i}^{IQM}$ and radiation field x_i was found to be quasi linear (Fig. 3) for all beams, with positive Pearson's product-moment correlation coefficient ρ in the range $0.5 < \rho < 1$. $\delta_{S,i}^{IQM}$ was always below 3.3% except for field size 20 × 20 cm^2 at 10 MV FFF beam. For the 6 MV flattened beam a similar increase of 3.3% in the surface dose for the 30 × 30 cm^2 field was reported also for the Dolphin detector [19]. Another transmission detector – "magic plate" – exhibits an increase in the surface dose for 6 MV standard beam by 7.3% for 20 × 20 cm^2 field [20]. A modest increase of surface dose when IQM is in the beam path can be considered acceptable and not a limiting factor for its clinical use.

Mean transmission factors k_Q^{IQM} of IQM showed statistically significant energy dependence for all investigated flattened and FFF beams. $k_{Q,i}^{IQM}$ ranged from 0.9412 to 0.9589 for standard beams 6 MV to 18 MV, while for 6 MV FFF and 10 MV FFF beams, produced by Elekta Versa HD linear accelerators, k_Q^{IQM} was 0.9440 and 0.9533, respectively. Limited data for transmission factors is available for other transmission detectors. The reported transmission factors for the Dolphin detector for 6 MV flattened beam showed a field size dependency: they vary from 0.897 to 0.916 for field sizes 5 × 5 cm^2 to 20 × 20 cm^2 [19]. An average transmission factor of 0.990 for field sizes 10 × 10 cm^2, 20 × 20 cm^2 and 30 × 30 cm^2 was reported for the "magic plate" detector without field size dependency [20]. While it might be argued that transmission factors close to 1 are preferable, we emphasize that every transmission factor has to be adequately incorporated into the TPS. On the other hand, variations in the range of 2% or more of the transmission factors versus field size can be considered as a shortcoming for the straightforward use within TPS. In that case no single value can be recommended and a new beam model needs to be introduced to the TPS.

Within our study the maximal dispersion of k_Q^{IQM} of aggregated measurements from all participating centres and for all field sizes from 1 × 1 cm^2 to 20 × 20 cm^2 was less than 0.49%, with a maximal cumulative uncertainty of 0.58% (Table 3).

The use of a single value of k_Q^{IQM} for particular beam energy is thus justified, and a polynomial expression in Eq. (8) is provided as a generic formula for the calculation of transmission factors for IQM or as a verification tool of individually determined transmission factors.

5 Conclusions

When the IQM is placed in the path of a high energy photon beam, a small but statistically significant beam hardening effect is introduced. The influence of the detector on the surface dose was found to be clinically acceptable.

A second order polynomial expression is provided as a tool for the calculations of generic values for mean transmission factors k_Q^{IQM} for standard photon beams, while for 6 MV FFF and 10 MV FFF beams, k_Q^{IQM} were found to be 0.9440 and 0.9533, respectively.

This study demonstrates clinically negligible changes in beam quality and surface dose for all investigated beams. Therefore, the time needed to implement the IQM system can be shortened since no additional commissioning is needed regarding these two beam properties. Reported values for mean transmission factors k_Q^{IQM} of IQM can be used either as tray factors within TPS for a particular energy or alternatively as modified outputs for specific beam energy of linear accelerators.

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