Beam hardening and attenuation of photon beams using Integral Quality Monitor in radiotherapy

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Purpose: The influence of the Integral Quality Monitor (IQM) transmission detector on photon beam properties was evaluated using data from nine participating centres: (i) the change of beam quality (beam hardening) and (ii) the attenuation of the IQM detector.
A newly developed transmission detector (a prototype was designed by Islam et al [1]), the Integral Quality Monitor (IQM, i-RT, Germany) overcomes the limitation of resolution by using an area integrating energy fluence monitoring sensor. The IQM system offers a new possibility to validate the accuracy of beam delivery during the treatment by real-time segment-by-segment signal readout. The sensitive area of 26.5 x 26.5 cm^2 covers the entire range of radiation fields offered by present linear accelerators, while high spatial sensitivity of the signal (0.5 %/mm) provides high geometrical and dosimetric resolution [2 - 4].

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 according to the Eq. (1)

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

where j denotes participating centre and i selected radiation field size. mean values for the beam hardening effect δ_Q^{IQM} for all n radiation fields and m participating centres were calculated using Eq. (2)

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

The transmission factor was calculated by means of measured absorbed dose at 10 cm depth for all available energies and field sizes using Eq. (3)

$$k_{Q,i}^{IQM} = 100 \cdot \frac{D_i(IQM)}{D_i(no\ IQM)} \qquad (3)$$

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. (4)

$$k_Q^{IQM} = \frac{1}{m \cdot n} \sum_j^m \sum_i^n k_{Q,i,j}^{IQM} \qquad (4)$$

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 5x5 cm^2.

Results: (i) A small (0.11%—0.53%) yet statistically significant beam hardening effect was observed, depending on photon beam energy (Fig 1 and Tab 1). (ii) For standard beams, transmission of the IQM showed a weak dependence on the field size; 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 2). 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), was found (Tab 2, Fig 3 and Fig 4).

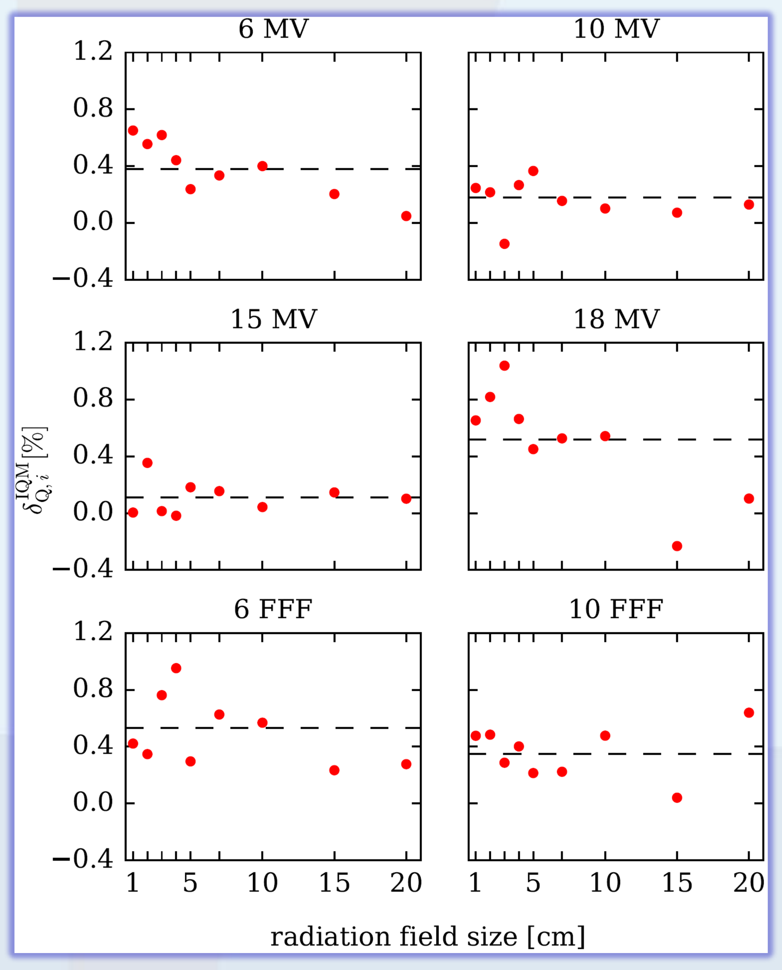

Figure 1. Changes in beam quality $\delta_{Q,i}^{IQM}$ versus radiation field size for investigated beam energies when IQM was mounted on the linear accelerator. For every beam energy and radiation field size, data represent average values of measurements from all participating institutions. Dashed lines represent mean differences δ_Q^{IQM} for a given energy.

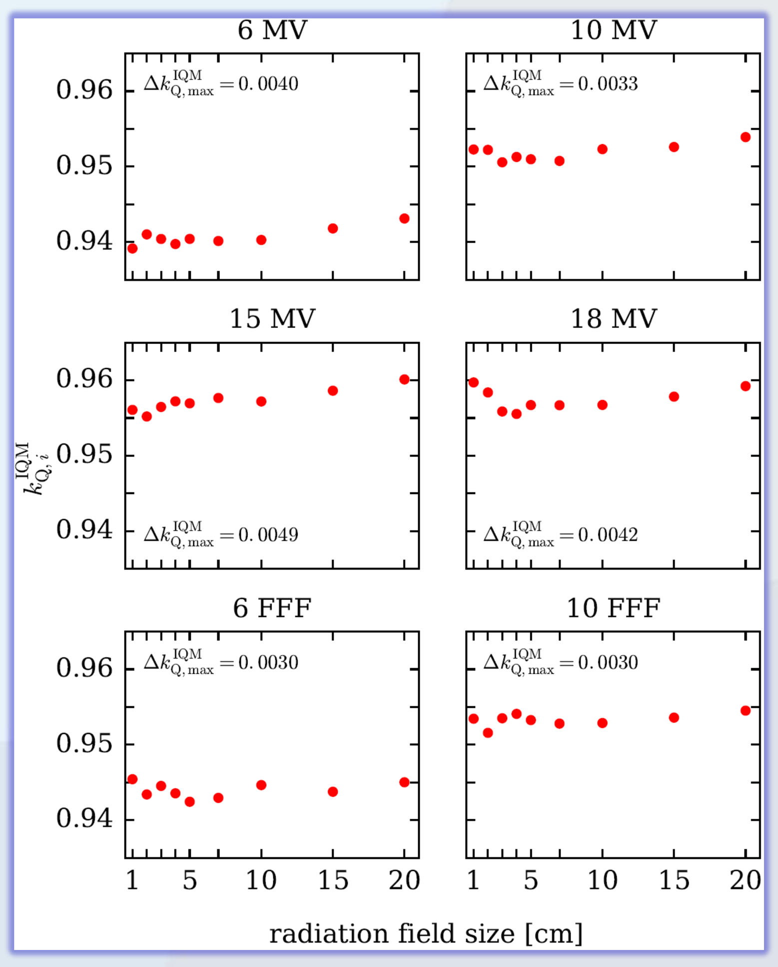

Figure 3. Transmission factors $k_{Q,i}^{IQM}$ of IQM versus radiation field size, for each nominal beam energy. Data represent average values of measurements from all participating institutions. $\Delta k_{Q,i}^{IQM}$ denotes maximal difference of $k_{Q,i}^{IQM}$ for a given nominal energy.

Table 1: 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 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	$8\cdot10^{-4}$	$7\cdot10^{-5}$

Table 2: 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.

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 [%]	0.0058	0.0056	0.0020	0.0057	0.0030	0.0011

A polynomial fit of second order is proposed in Eq. (5) 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 TPR20,10. Due to the high correlation between measured data and polynomial fit (R^2 = 0.996), extrapolation of $TPR_{20,10}$ ≈ 0.02 outside the investigated range of beam energies was considered as indicated in Fig. 3.

$$k_Q^{IQM}(TPR_{20,10}) = -0.8186 \cdot (TPR_{20,10})^2 + 1.3872 \cdot TPR_{20,10} + 0.3754 \qquad (5)$$

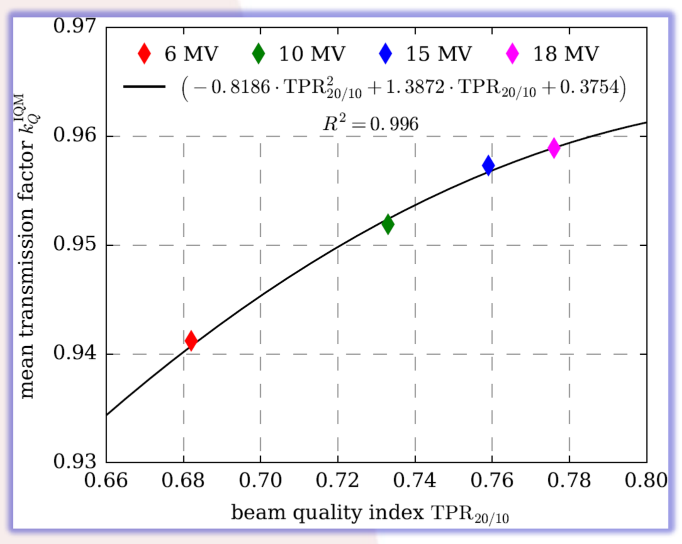

Figure 4. Mean transmission factors k_Q^{IQM} of IQM versus beam qualities $TPR_{20,10}$ for investigated set of standard flattened beams. For every investigated beam energy and radiation field size, data represent average values of measurements from all participating institutions.

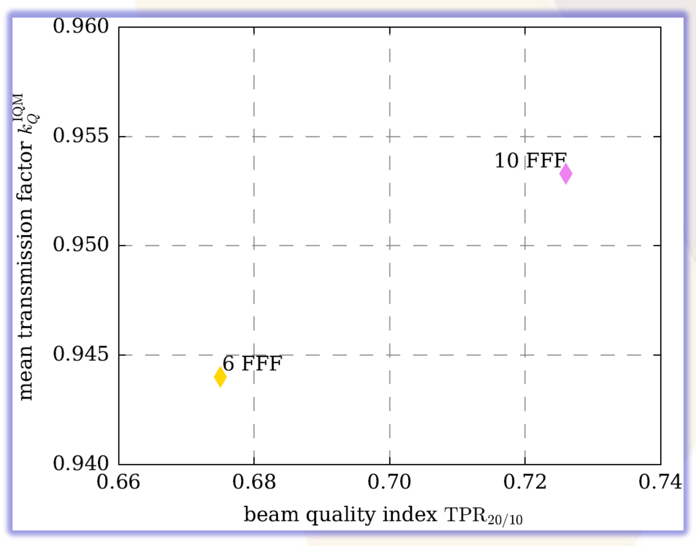

Figure 5. Mean transmission factor k_Q^{IQM} of IQM versus beam quality $TPR_{20,10}$, aggregated by nominal energies 6 MV FFF and 10 MV FFF photon beams.

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.

Acknowledgements: The authors would like to sincerely thank Denis Brojan for his patient and skilful preparation of figures. The authors would like to thank also to collegues for kindly providing us the data collected at their institutions: Marlies Pasler, Sonja Wegener, David Hoffman, Cinzia Talamonti, Jianguo Qian, Bruce Perrin, Martijn Kusters, Richard Canters, Stefania Pallotta and Yinkun Wang. Božidar Casar and Primož Peterlin acknowledge the financial support from the Slovenian Research Agency through research grant P1-0389.

References:

[1] Islam MK, Norrlinger BD, Smale JR, Heaton RK, Galbraith D, Fan C, Jaffray DA. An integral quality monitoring system for real-time verification of intensity modulated radiation therapy. Med Phys 2009;36(12): 5420–8.

[2] Jung J, Farrokhish M, Norrlinger B, Wang Y, Heaton R, Haffray D and Islam M. Efficient and Enhanced QA Testing of Linear Accelerators Using a Real-Time Beam Monitor. Med Phys 2015:42: 3415, 2SU-E-T-354.

[3] Hoffman D, E. Chung E, Hess CB, Stern RL, Benedict SH. Online Quality Assurance of External Beam Radiation Therapy With an Integrated Quality Monitoring System. Int J Radiat Oncol Biol Phys 2015: 93(3): E582.

[4] Qian J, Lin L, Gonzales R, Keck J, Armour EP, Wong JW. In Vivo Dosimetry of Stereotactic Radiation Therapy Using Integral Quality Monitor (IQM) System. Int J Radiat Oncol Biol Phys 2015; 93(3): E614.