IQM Detector Characteristics:
Signal Linearity and Dose Rate (In-) Dependence

The Integral Quality Monitor (IQM) System is a real-time beam verification system that monitors the accuracy of radiation delivery throughout each patient treatment without any user interaction. IQM continuously monitors every single beam segment in real-time during every treatment fraction. The IQM Detector is capable of measuring deviations related to dose (incorrect photon energy or MU's), beam direction (both collimator and gantry angles are monitored), individual beam size, beam segment shape and intensity maps.

Characteristics of the IQM detector such as signal reproducibility, linearity, sensitivity and dose rate independence are fundamental for the successful application of the IQM principle of operation.

IQM has been thoroughly evaluated at some of the world's leading Radiation Therapy Centers. 21 clinical centers equipped with state-of-the-art treatment planning and delivery systems have performed a variety of tests to ensure and improve the clinical usefulness of the IQM System. Measurements to verify signal reproducibility (short-term and long-term), signal linearity, dose rate dependency and sensitivity were performed as part of the installation routine at each clinical center. Additional measurements have been carried out as part of the pre-clinical evaluation of the IQM System. The results outlined in this publication are based on measurements performed on the following types of Linear Accelerators (the number of Linac's of each type are shown in brackets.)

Elekta Versa HD (1)
Elekta Infinity (1)
Elekta Synergy with Agility Collimator (7)
Elekta Synergy with MLCi2 Collimator (6)
Varian TrueBeam (4)
Varian TrueBeam STX (2)
Varian C-Series (1)

Each Linear Accelerator was fully commissioned and verified for clinical use at the time of the measurements.

Signal linearity

The signal linearity test verifies that the signal detected by IQM is directly proportional to the dose output. If all other variables remain constant, the signal should double if the dose output is doubled.

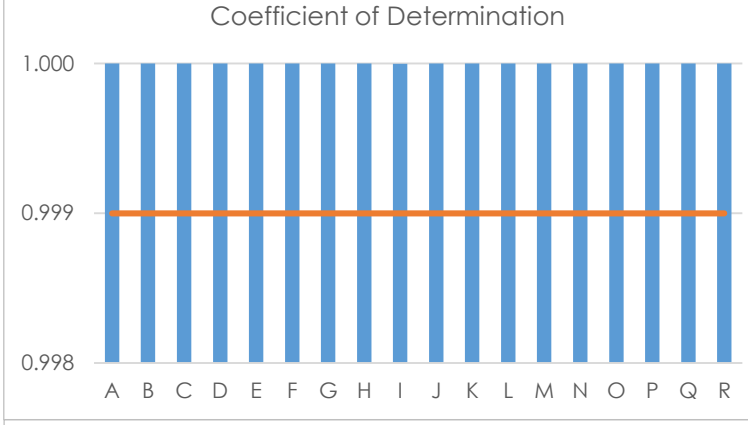

Figure 1: The calculated coefficient of determination with the pass criteria of 0.999 (red line).

The signal linearity test uses the reference field size of 10cm x 10cm (defined by MLC and Jaws) for a 6MV photon beam. The dose output is increased through 8 measurements in the following steps:

- 2 MU
- 5 MU
- 10 MU
- 20 MU
- 50 MU
- 100 MU
- 200 MU
- 500 MU

The coefficient of determination R^2 indicates the variation of observed data from the line of best fit.

R^2 is defined as:

$$R^2 = 1 - \frac{\sum_{i=1}^{n}\left(Y_i - \hat{Y}_i\right)^2}{\sum_{i=1}^{n}(Y_i - \bar{Y}_i)^2} = 1 - \frac{Sum\ of\ squared\ residual}{Total\ sum\ of\ squares}$$

n: Number of observed data
Y: Observed data
$\bar{Y}$: Mean of observed data
$\hat{Y}$: Predicted (or modeled) value

The signal linearity test passes if the R^2 value is 0.999 or better for a linear fit equation (IQM signal vs. delivered MU).

The measured IQM Signal for all doses and the calculated coefficient of determination is listed in Table 1 and diagrammed in Figure 1 with the pass criteria. Rounded to three decimals places, the coefficient of determination is 1.000 for all sites, so all passed the criteria of having R^2 at or better than 0.999.

Conclusion:
As shown, every installed IQM passed the criteria for linearity (the coefficient of determination R^2 being 0.999 or better.) This result confirms that IQM Signal changes linearly with applied dose output.

Table 1: IQM Signal for all doses delivered at each site.

Site		Doses in MU								R^2
		2	5	10	20	50	100	200	500	
Elekta	A	4939.64	12168.99	24177.91	48478.92	121047.46	242003.59	482230.81	1208040.74	1.000
	B	n/a	11195.78	22410.52	44700.15	111865.34	223714.09	447691.28	1119490.10	1.000
	C	6097.89	14841.91	29537.90	58911.38	147079.08	294104.73	588330.72	1470732.25	1.000
	D	5326.65	13317.16	26479.47	52910.80	132509.28	264916.02	529828.91	1325190.10	1.000
	E	6031.30	14974.39	29869.76	59705.08	149170.50	298481.83	597123.74	1493850.87	1.000
	F	6849.43	17034.39	34108.29	68035.02	169905.97	339892.04	680125.86	1701794.97	1.000
	G	4863.39	12105.83	24215.76	48348.74	120785.49	241689.52	483297.29	1208749.08	1.000
	H	4574.46	11441.31	22859.88	45689.76	114098.78	228357.83	456852.15	1142941.04	1.000
	I	4471.00	11074.00	21988.00	43935.00	109811.00	219390.00	439421.00	1095362.00	1.000
	J	4868.03	12012.11	24158.05	48156.11	120354.55	241101.52	482161.79	1204304.18	1.000
	K	4939.13	12233.82	24404.78	48765.88	121726.65	243426.67	487016.34	1218354.27	1.000
	L	n/a	15354.96	30551.59	61011.52	152543.39	304858.66	609988.16	1524521.45	1.000
Varian	M	n/a	n/a	n/a	38557.39	96433.54	192698.60	385256.47	962675.32	1.000
	N	4050.00	10160.00	20100.00	40210.00	100684.00	201408.00	402976.00	1007928.00	1.000
	O	n/a	10614.74	21403.27	42699.60	106784.99	213920.66	427741.56	1068749.74	1.000
	P	4569.44	11355.31	22867.42	45579.06	114200.55	228354.57	456665.64	1143885.43	1.000
	Q	4579.70	11517.08	23215.76	46410.65	116315.73	232889.26	465727.37	1163396.33	1.000
	R	n/a	n/a	n/a	44159.30	110127.88	220538.18	440618.05	1102184.36	1.000

Dose rate (in-) dependence test

Linear Accelerators can be set to deliver fields at different dose rates (MU/min). The higher the dose rate the faster the total dose is delivered.

The dose rate dependence test verifies that the IQM system measures the same signal for the same dose independent of the dose rate at which the dose is delivered.

The dose rate dependence test uses the reference field size of 10cm x 10cm (defined by MLC and Jaws) for a 6MV photon beam and a constant dose output of 100 MU. The test was performed for a number of dose rates available at the specific Linear Accelerator, typically for the following dose rates:

- 20 MU/min
- 50 MU/min
- 100 MU/min
- 200 MU/min
- 400 MU/min
- 600 MU/min
- (for FFF beams the highest dose rate is also measured).

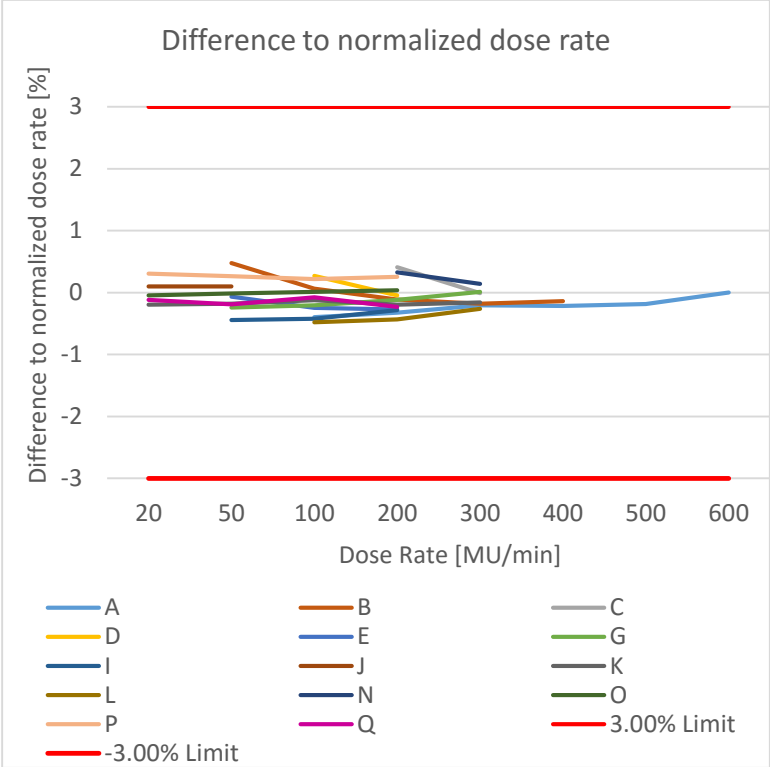

Figure 2: Difference in percent of IQM Signal for different measured dose rates normalized to highest measured dose rate with the pass criteria of +/- 0.50% deviation.

The pass criteria for the dose dependency test is that the variation between the signal at the highest dose rate and the signal measured at the other dose rates must be less than 0.5%.

Results of the dose rate dependence test are listed in Table 2 and diagrammed in Figure 2.

Thirteen (13) of our 21 sites participated in the dose rate dependence test. Because many Linac's are limited to deliver only certain, pre-defined dose rates, certain sites have measured at only a few dose rates. Results at each site were normalized to the signal detected at the highest dose rate measured at that site.

The smallest variation with dose rate seen in our results is 0.00%, measured at Site A at 600 MU/min and the largest variation seen was 0.48%, measured at Site B at 50 MU/min. The mean variation over all sites at all dose rates was 0.19%.

Table 2: Difference (in percent) of IQM Signal for different measured dose rates normalized to highest measured dose rate, with Mean and Standard Deviation (SD) for each site and global averages.

Site		Dose Rates [MU/min]									Mean	SD
		20	50	100	200	300	400	500	600	800		
Elekta	A	n/a	n/a	-0.40	-0.32	-0.21	-0.22	-0.19	0.00	ref.	-0.27	0.09
	B	n/a	0.48	0.06	-0.11	-0.18	-0.14	n/a	ref.	n/a	0.02	0.27
	C	n/a	n/a	n/a	0.41	-0.01	ref.	n/a	n/a	n/a	0.20	0.30
	D	n/a	n/a	0.27	-0.05	n/a	ref.	n/a	n/a	n/a	0.11	0.22
	E	n/a	-0.06	-0.25	-0.27	n/a	-0.03	n/a	ref.	n/a	-0.15	0.13
	G	n/a	-0.24	-0.21	-0.12	0.01	n/a	n/a	ref.	n/a	-0.14	0.11
	I	n/a	-0.44	-0.42	-0.28	n/a	ref.	n/a	n/a	n/a	-0.38	0.09
	J	0.10	0.10	n/a	0.40	n/a	0.10	n/a	ref.	n/a	0.18	0.15
	K	-0.19	-0.18	-0.12	-0.20	-0.16	n/a	n/a	ref.	n/a	-0.17	0.03
	L	n/a	n/a	-0.48	-0.43	-0.26	n/a	n/a	ref.	n/a	-0.39	0.11
Varian	N	n/a	n/a	n/a	0.32	0.14	ref.	n/a	n/a	n/a	0.23	0.13
	O	-0.05	-0.01	0.01	0.04	n/a	0.02	n/a	ref.	n/a	0.00	0.03
	P	0.31	0.27	0.22	0.25	n/a	0.04	n/a	ref.	n/a	0.22	0.11
	Q	-0.12	-0.19	-0.08	-0.23	n/a	-0.12	n/a	ref.	n/a	-0.15	0.06
Average		**0.05**	**0.14**	**0.18**	**0.25**	**0.07**	**0.05**	**0.01**	**0.00**	**n/a**	**0.19**	**0.13**

Conclusion:
The IQM system measures dose independently from the dose rate at which the dose is delivered. The variation in the IQM Signal measured for a given dose delivered at different dose rates are well within our acceptance criteria of +/- 0.5%.

Overall conclusion

The signal linearity test, performed at all 21 research partner Linear Accelerators, assesses the influence of dose output variation on the measured by IQM. All tests confirmed that the IQM signal varies linearly with the applied dose. Any change in the dose output changes the IQM signal in the same proportion.

The dose rate dependence test, performed at 13 research partner Linear Accelerators, confirmed that the IQM signal measured for a given dose does not depend on the dose rate at which that dose is delivered. IQM signal is virtually independent of dose rate.