X-ray fluence spectra of diagnostic and interventional radiology X-ray imaging equipment measured with a compact cadmium telluride spectrometer

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The goal

Experimental determination of the shape of energy spectra of primary X-ray photons generated by clinical X-ray devices.

Introduction

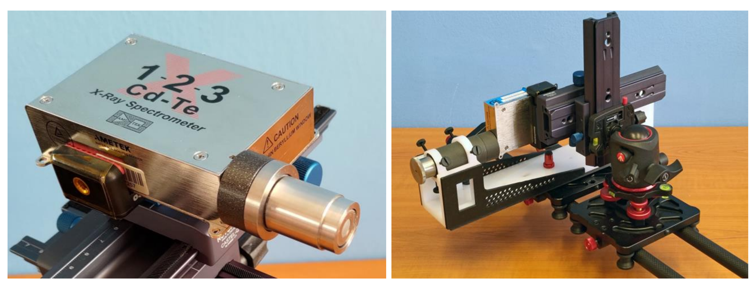
The knowledge of energy distribution of photon fluence is essential for various purposes, e.g., quality assurance and improved detector calibrations. Among others the European joint research project **TraMeXI** (*Traceability in Medical X-Ray Imaging Dosimetry,* https://tramexi.com/) will compile a catalogue of clinical X-ray spectra to be used to find a **new representative set of reference radiation qualities** for **calibrations** and **type testing of dosimeters** and **X-ray multimeters** aiming to decrease uncertainties in dosimetry measurements of medical physicists and technical services. Measurements of X-ray spectra under clinical conditions are difficult and were only reported sporadically by several groups. Now, for the first time, improved equipment and setup made it possible to determine a wider range of these spectra. More than 100 different spectra generated by a range of X-ray devices from general radiography, fluoroscopy, interventions, and dental applications were measured with CdTe spectrometers.

X-Ray Spectrometry

- A method to determine energy distribution of photons in X-ray beams;
- Photons originated directly in anode are measured, scattered photons are suppressed;
- Characterization of the detector is necessary: energy calibration, Monte Carlo simulations, etc.
- Measured detector spectrum + response matrix of detector + unfolding procedure = fluence spectrum of primary photons.

X-Ray Spectrometer

- Compact detector *X-123CdTe* with cadmium—telluride sensor (3x3x1 mm³);
- Integrated electric cooling down to 215 K;
- Easy handling and transportation.



Measurement Setup

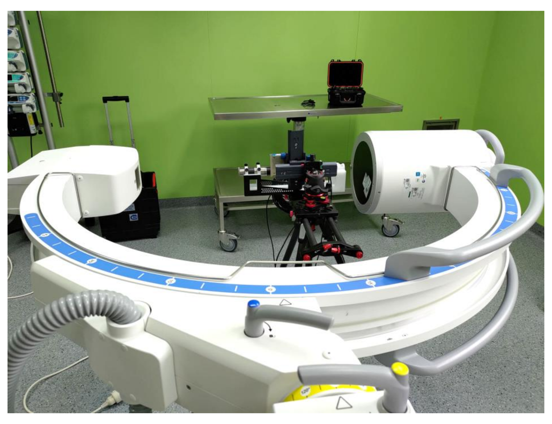
- Detector positioned on a tripod with sliding platforms;
- Alignment of the detector axis towards the anode focus point (source of photons) is crucial – realized using tools imaging two distant points into one projection;
- Strong shielding and collimation is needed to reduce the number of photons reaching the detector: diameter of collimation hole down to 50 µm;
- Setup assembly and alignment: 1 hour. Disassembly: 10 min.
- Spectrum acquisition: typically 15 min, depending on the X-ray device.

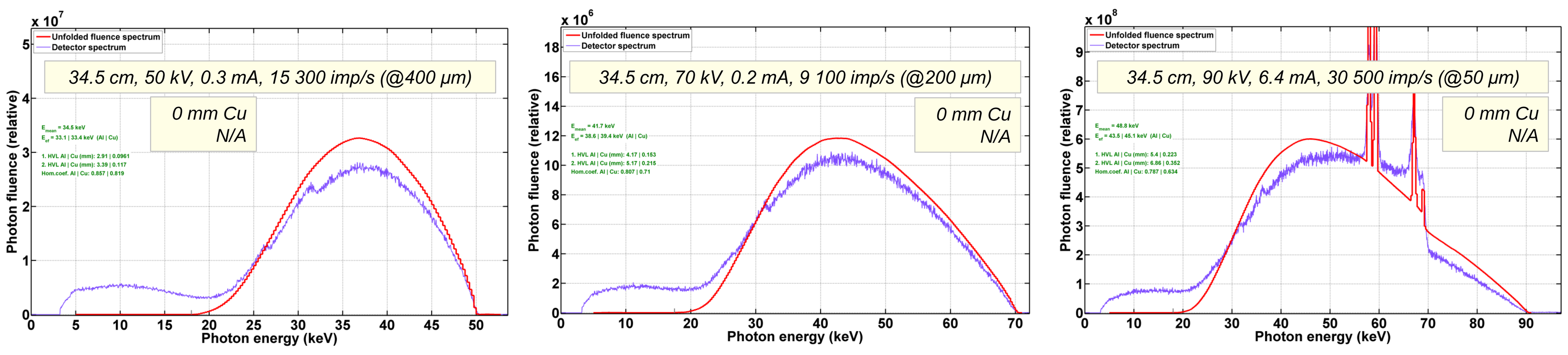
Measured Clinical X-Ray Spectra

Raw detector amplitude spectrum
All other curves Final X-ray fluence spectrum

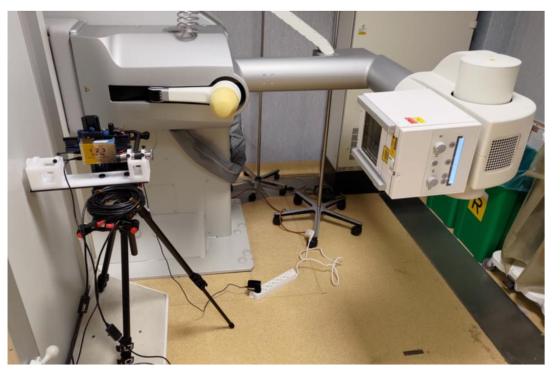
Information provided in plots: Detector to X-ray device exit window distance (cm), additional filtration (mm Cu), X-ray generator pulse width time (s), nominal tube voltage (kV), nominal tube current (mA or mAs), detector total count rate (imp/s), diameter of hole in collimator (µm)

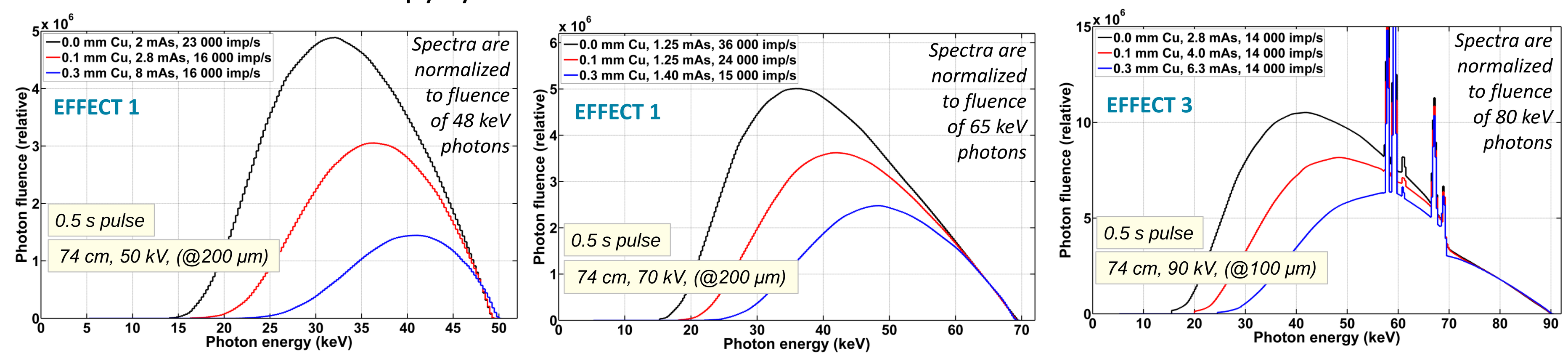
Siemens Cios Connect: mobile C-arm



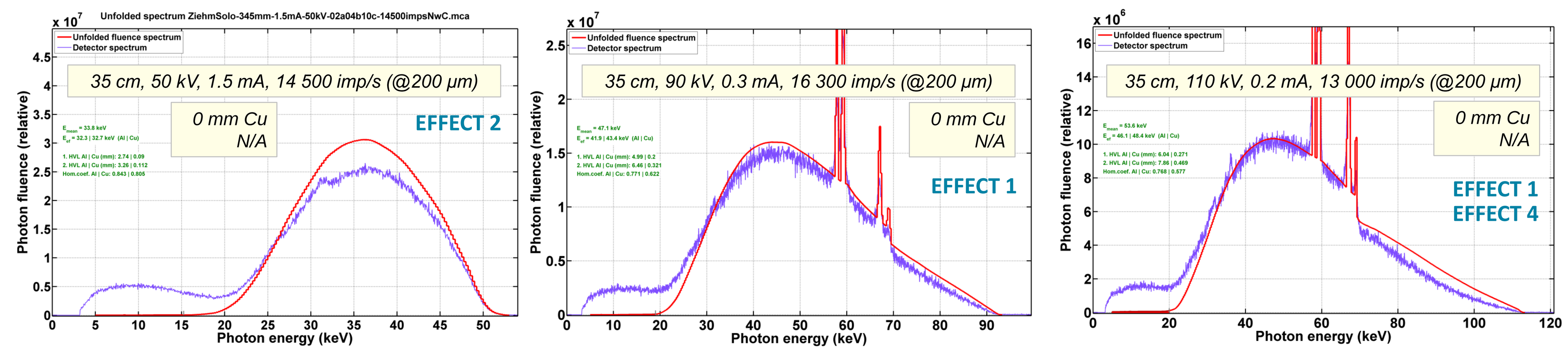


Siemens Luminos dRF Max: remote-controlled fluoroscopy system

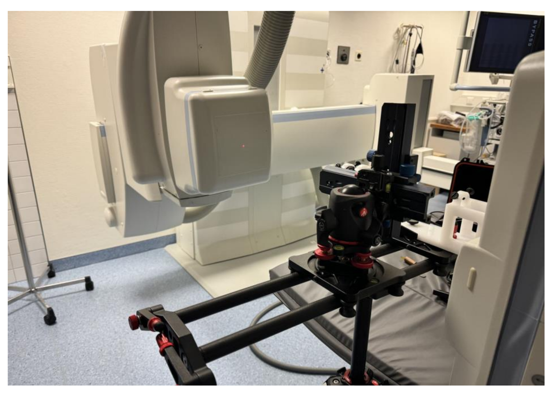


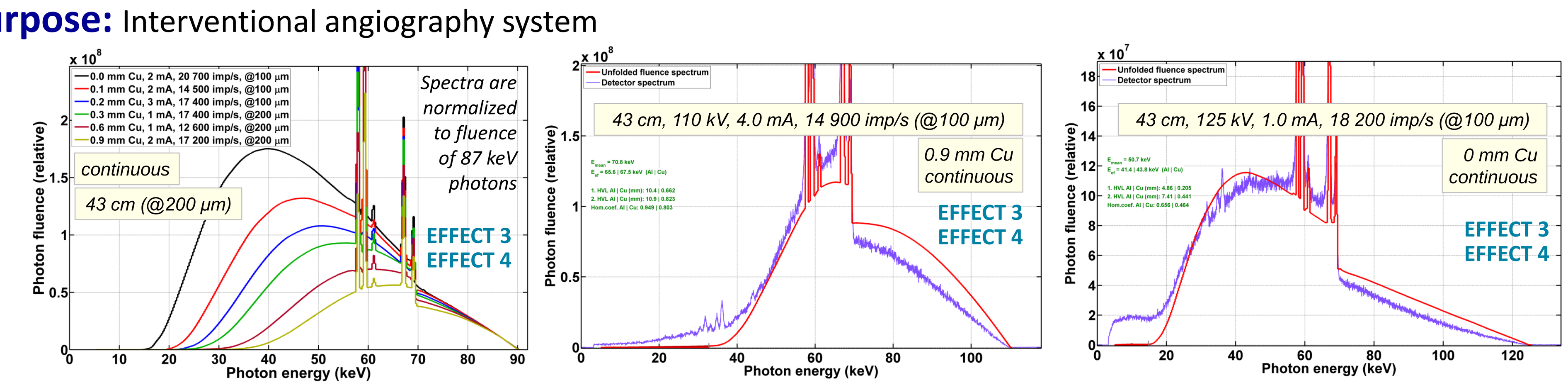


Ziehm Solo: mobile C-arm



Siemens Artis zee multi-purpose: Interventional angiography system



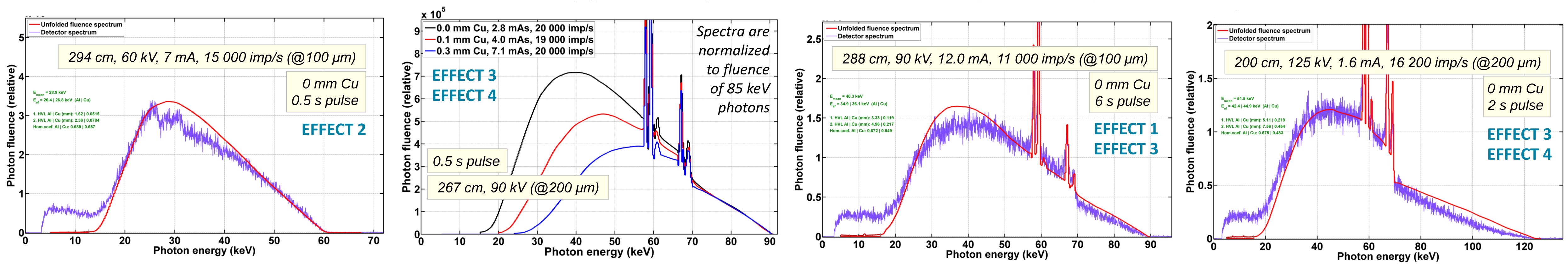


Dentsply Sirona Heliodent Plus: dental intraoral

Siemens Multix Fusion: stationary general X-ray

Philips Medio 65CP-H: stationary general X-ray

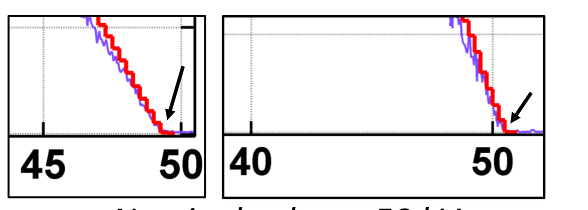
Philips Optimus: stationary general X-ray



Example of observed effects

Different maximum energy

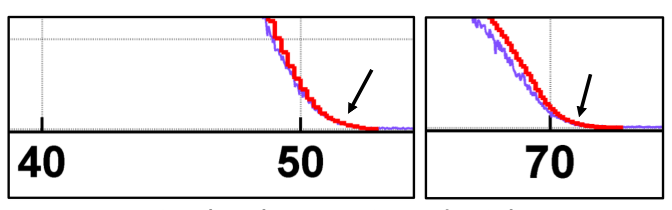
EFFECT 1: The maximum energy of the spectrum differs from the preset nominal tube voltage.



Nominal voltage 50 kV.

Voltage ripple

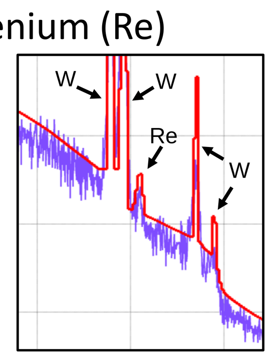
EFFECT 2: Tube voltage variations during irradiation. Spectrum end-point is blurred.



Nominal voltage 50 and 70 kV.

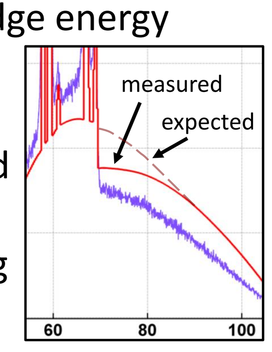
Rhenium characteristic peaks

EFFECT 3: Characteristic photons emitted from rhenium (Re) element present in the tungsten (W) alloy, which anode is made of.



Anode aging

EFFECT 4: Change of spectrum shape behind tungsten K-edge energy because of roughening the anode surface caused by burning off by electron beam during X-ray device usage.



Applicability of Spectrometry

To deliver reliable shape of spectra (distinguished peaks, no pile-ups, etc.), the detector count-rate has to be controlled;
This can be expressed as a restriction on **air kerma rate, K_{air} (Figure 1)**.

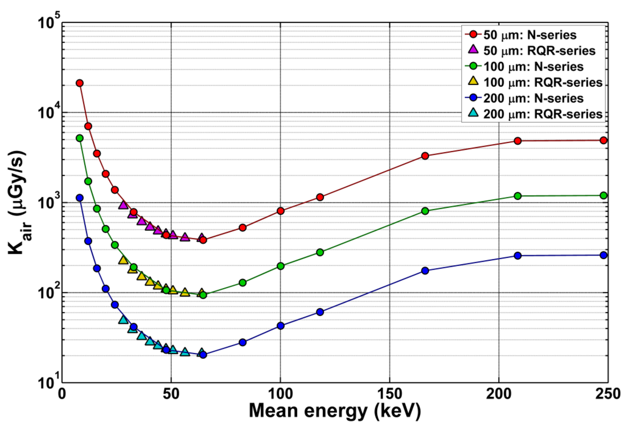


***Figure 1**: Maximum recommended K_{air} for X-ray spectra measurement as a function of the spectrum mean energy and diameter of hole in a collimator. Valid for a target count-rate of 13 000 imp/s in continuous regime of X-ray device (proportionally lower in pulsed regime). Determined from reference narrow (N) and RQR-series qualities.*

Comparison of Half-Value Layers

Half-value layer (HVL): thickness of material that decreases air kerma to 50 %. Can be calculated from X-ray spectrum;
HVL in aluminum from measured spectrum compared to HVL measured by another method.

Inherent filtration is usually unknown; therefore, additional filtration stated by the manufacturer is presented only.

***Table 1**: Comparison for reference RQR X-ray qualities realized at CMI.*

X-ray quality	U(1) (kV)	Ad. filt.(2) Al	E_{mean}(3) (keV)	Ref.(6) 1st HVL	Spec.(4) 1st HVL	RD to spec.(5)
RQR2	40	2.45	28.1	1.43	**1.38**	**3.4%**
RQR3	50	2.45	32.3	1.78	**1.76**	**1.3%**
RQR4	60	2.68	36.5	2.18	**2.19**	**-0.8%**
RQR5	70	2.83	40.3	2.58	**2.61**	**-1.1%**
RQR6	80	2.90	44.0	2.98	**3.01**	**-0.8%**
RQR7	90	3.23	47.7	3.51	**3.55**	**-1.3%**
RQR8	100	3.40	50.8	4.07	**4.04**	**0.9%**
RQR9	120	3.73	56.3	5.05	**5.04**	**0.3%**
RQR10	150	4.43	64.0	6.55	**6.59**	**-0.6%**

(1) Nominal X-ray tube voltage;
(2) Additional filtration (mm);
(3) Mean energy of spectrum over fluence;
(4) HVL from spectrometry (mm Al);
(5) Relative difference of HVL;
(6) HVL from air kerma (mm Al);
(7) HVL* from Raysafe X2 (mm Al);
(8) HVL* from RadCal AGMS-D (mm Al);
(9) HVL from manufacturer data (mm Al).

** HVL uncertainty is 10 % or 0.2 mm (from manual)*

*Siemens **Artis zee multi-purpose** (**Table 2**, left) and **Ysio** (**Table 3**, right).*

U(1) (kV)	Ad.filt.(2) Cu	E_{mean}(3) (keV)	XMM(7) 1st HVL	Spec.(4) 1st HVL	RD to spec.(5)
50	0	33.4	2.03	**1.93**	**4.8%**
50	0.1	36.6	3.02	**2.90**	**4.0%**
50	0.2	38.4	3.59	**3.47**	**3.5%**
50	0.3	39.7	4.02	**3.89**	**3.3%**
50	0.6	41.9	4.76	**4.60**	**3.5%**
50	0.9	43.3	5.23	**5.04**	**3.7%**
70	0	41.2	2.93	**2.73**	**7.2%**
70	0.1	45.4	4.36	**4.18**	**4.3%**
70	0.2	47.7	5.22	**5.03**	**3.6%**
70	0.3	49.5	5.91	**5.68**	**4.0%**
70	0.6	52.8	7.09	**6.82**	**4.0%**
70	0.9	55.0	7.83	**7.54**	**3.9%**
90	0	47.9	3.78	**3.55**	**6.5%**
90	0.1	52.4	5.53	**5.33**	**3.8%**
90	0.2	55.0	6.55	**6.35**	**3.1%**
90	0.3	57.0	7.35	**7.11**	**3.5%**
90	0.6	60.7	8.66	**8.40**	**3.1%**
90	0.9	63.4	9.57	**9.19**	**4.1%**
110	0	53.2	4.55	**4.31**	**5.6%**
110	0.1	57.9	6.43	**6.30**	**2.2%**
110	0.2	60.7	7.53	**7.40**	**1.7%**
110	0.3	62.9	8.32	**8.20**	**1.5%**
110	0.6	67.2	9.75	**9.55**	**2.0%**
110	0.9	70.3	10.77	**10.38**	**3.7%**
125	0	56.8	5.08	**4.86**	**4.7%**
125	0.1	61.5	6.99	**6.93**	**0.8%**
125	0.2	64.4	8.11	**8.04**	**0.8%**
125	0.3	67.1	8.94	**8.89**	**0.6%**
125	0.6	71.6	10.40	**10.26**	**1.4%**
125	0.9	75.6	11.47	**11.18**	**2.6%**

U(1) (kV)	Ad.filt.(2) Cu	E_{mean}(3) (keV)	XM2(8) 1st HVL	Spec.(4) 1st HVL	RD to spec.(5)
50	0	34.1	2.30	**2.26**	**2.0%**
50	0.1	36.3	3.09	**2.96**	**4.4%**
50	0.3	39.8	3.96	**3.95**	**0.2%**
70	0	42.5	3.27	**3.29**	**-0.7%**
70	0.1	45.9	4.48	**4.44**	**1.0%**
70	0.3	49.8	5.96	**5.80**	**2.8%**
90	0	49.5	4.46	**4.22**	**5.8%**
90	0.1	53.1	5.90	**5.62**	**5.1%**
90	0.3	57.4	7.58	**7.26**	**4.5%**
121	0.3	66.4	-	**8.92**	-
150	0.3	75.9	-	**10.51**	-

***Table 4: Ziehm Vision**. No Ad.filt.(2).*

U(1) (kV)	E_{mean}(3) (keV)	Manu(9) 1st HVL	XMM(7) 1st HVL	Spec.(4) 1st HVL	RD to spec.(5)
50	37.1	3.02	3.22	**3.11**	**3.4%**
70	45.8	4.37	4.69	**4.39**	**6.8%**
90	53.2	5.68	5.79	**5.66**	**2.3%**
110	59.2	6.75	6.43	**6.81**	**-5.6%**

***Table 5: Siemens Multix Fusion**.*

U(1) (kV)	Ad.filt.(2) Cu	E_{mean}(3) (keV)	XMM(7) 1st HVL	Spec.(4) 1st HVL	RD to spec.(5)
50	0.0	33.6	2.07	**2.02**	**2.6%**
50	0.1	36.6	2.98	**2.89**	**3.1%**
50	0.3	39.8	3.98	**3.89**	**2.2%**
70	0.3	49.5	5.80	**5.67**	**2.2%**
90	0.3	57.2	7.24	**7.12**	**1.7%**
109	0.0	53.2	4.49	**4.33**	**3.6%**

Conclusions

- Large number of X-ray spectra generated by various diagnostic and interventional radiology X-ray imaging equipment were reliably measured with cadmium-telluride spectrometers;
- HVL obtained from spectrometry were compared to another methods; for reference RQR qualities agreement typically within ±1.3 % was achieved; for clinical spectra HVL obtained with X-ray multimeters was typically higher by about 3 % in average; source of the difference will be further studied within Tramexi project but it is well below XMM uncertainty of 10 % stated by manufacturers;
- The ability to measure clinical X-ray spectra boosts up the aim of the TraMeXI project to recommend new reference radiation qualities for calibration laboratories allowing to decrease uncertainties in dosimetry measurements of medical physicists and technical services.

(1) CMI: Czech Metrology Institute, Czech Republic
(2) SKBS: Städtisches Klinikum Braunschweig gGmbH, Germany
(3) OPBG: Bambino Gesù Children's Hospital, Italy
(4) ENEA-INMRI: National Institute of Ionizing Radiation Metrology, Italy
(5) VINS: Vinca Institute of Nuclear Sciences, Serbia
(6) STUK: Radiation and Nuclear Safety Authority, Finland

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