TraMeXI

Workshop
for radiation metrologists on calibration of dosimeters used for X-ray imaging
Greek Atomic Energy Commission (EEAE),
Athens, Greece, September 1st – 3rd, 2025

EUROPEAN PARTNERSHIP
Co-funded by the European Union
METROLOGY PARTNERSHIP
EURAMET

Definition of XMM measurement quantities

Quantities and parameters beyond air kerma

(based on the presentation given in TraMeXI workshop with Markus Borowski, in 2024)

Milos Zivanovic, Vinca Institute of Nuclear Sciences
University of Belgrade

stuk RADIATION AND NUCLEAR SAFETY AUTHORITY
CZECH METROLOGY INSTITUTE
INMRI ISTITUTO NAZIONALE DI METROLOGIA DELLE RADIAZIONI IONIZZANTI ENEA
TÉCNICO LISBOA
IMBIH STÄDTISCHES KLINIKUM BRAUNSCHWEIG
PTB Physikalisch-Technische Bundesanstalt National Metrology Institute
HUS Helsinki University Hospital
TENMAK NÜKEN
Bambino Gesù OSPEDALE PEDIATRICO
VSL National Metrology Institute
EEAE ΕΛΛΗΝΙΚΗ ΕΠΙΤΡΟΠΗ ΑΤΟΜΙΚΗΣ ΕΝΕΡΓΕΙΑΣ GREEK ATOMIC ENERGY COMMISSION
Institutul Național de Metrologie
skbs

X-ray multimeters (XMM)

- In order to measure multiple quantities, previously you would need to use ionisation chamber, electrometer, voltage divider, aluminum filters…
- Now you can use a single XMM – a device based on several solid-state detectors
- Easy to operate, quick to set-up, relatively cheap
- Usually able to calculate multiple parameters in one exposure, including air kerma, half-value layer (HVL), total filtration (TF), one or more tube voltage related quantities, irradiation time

- Some of these quantities can be measured both invasivelly and non-invasively, by dosimetric means
- The quantities that can be measured by dosimetric means using an XMM are here called XMM measurement quantities: this is the focus of the presentation

X-ray multimeters (XMM)

- We can get indications of multiple XMM quantities in several seconds using one easy-to-use device
- However there are multiple problems:
  - How to estimate the measurement uncertainty?
  - What are the standard requirements for XMMs for measuring different quantities?
  - What are the limits of deviation of the response for different influence quantities?
  - How is the calibration performed, and is it possible to establish traceability?
  - What are the definitions of the quantities that are measured?
- Everything is well defined for air kerma
- For all other XMM quantities, there are smaller or larger gaps in the metrological background and standardization
- TraMeXI project is trying to answer all these questions!

Which quantities are used in clinical practice? General radiology / fluoroscopy

Parameter	Frequency / %
Exposure time	92
HVL	90
Tube voltage	88
Dose per pulse	75
Total filtration	70
Frame rate	70
ppV	19
Tube current time product	18

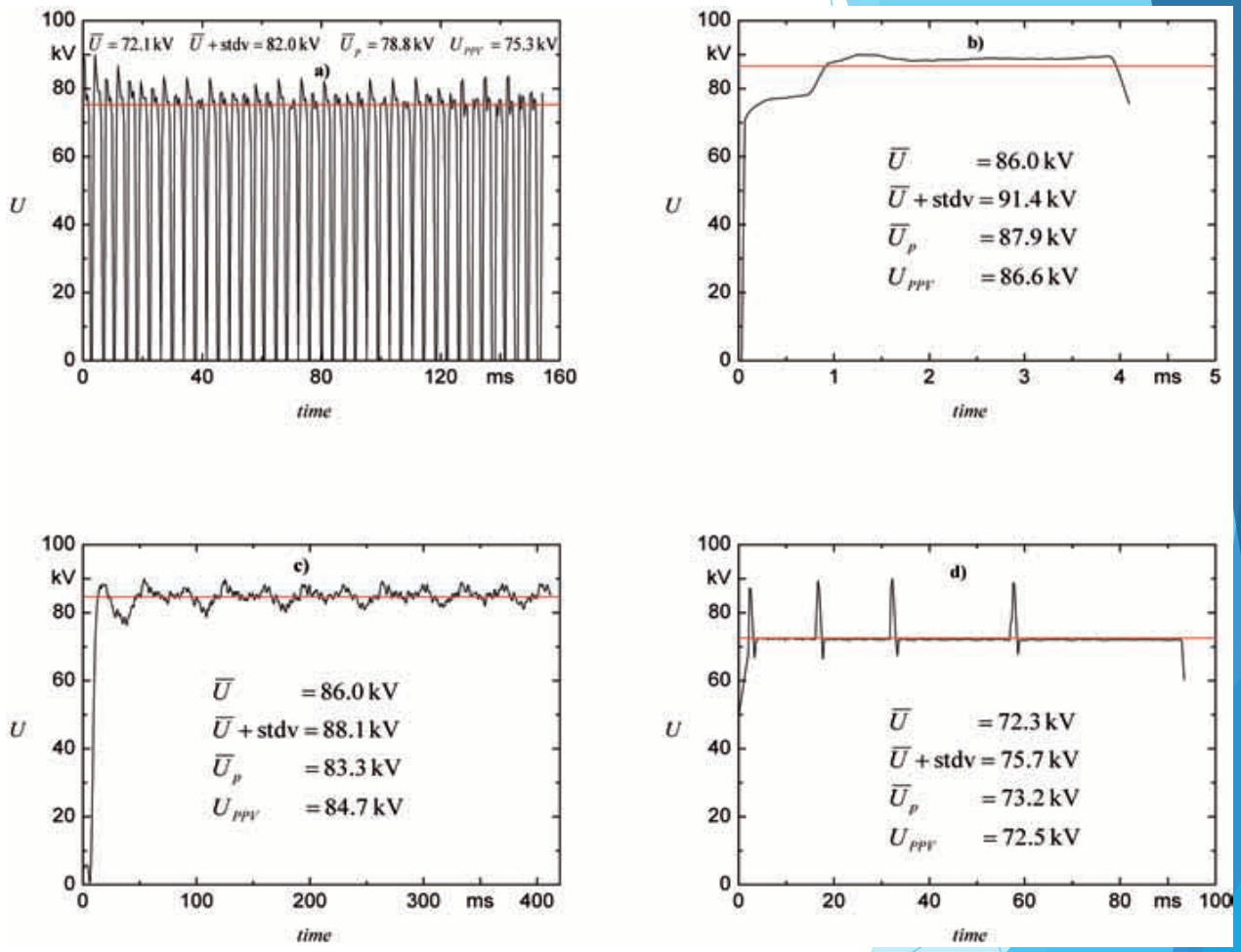
Medical physicist survey results

Which quantities are used? mammography

Parameter	Frequency / %
Exposure time	79
HVL	75
Tube voltage	75
Total filtration	44
Dose per pulse	25
ppV	15

Medical physicist survey results

Tube voltage related quantities



IAEA TRS 457, pp. 257

Tube voltage

- X-RAY TUBE VOLTAGE (60601-1-3) potential difference applied to an X-RAY TUBE between the anode and the cathode
- Primary standards are available: high voltage dividers and spectrometers
- Traceability is available for different tube voltage values and also for different filtrations for non-invasive measurements
- There is a clear idea about measurement uncertainty
- There is a standard for one of the tube voltage quantities

- There are multiple quantities that are used by the end users, often without understanding their specifics and differences
- Definitions of some quantities are ambiguous
- There are no standards for all but one quantity

- Silver lining: for constant potential X-ray generators, all tube voltage related quantities are equal

Tube voltage (ppV)

- Standardized definition and requirements for non-invasive measurement devices in IEC 61676
- There is a clearly defined voltage cut-off (20 kV)
- Definition / formula / idea-> Based on the contrast produced by 1 mm thick aluminum on 10 cm PMMA phantom irradiated by “reference” X-ray tube
- PPV is the value of the high voltage of constant potential X-ray tube that would produce the same contrast as the tube under consideration
- Suitable to compare image quality between different machines
- ppV requires constant current

To be considered:

- Only displayed by XMMs from some vendors
- Waveform is necessary to calculate PPV

$$\hat{U} = \frac{\sum_{i=1}^{n} p(U_i) w(U_i) U_i}{\sum_{i=1}^{n} p(U_i) w(U_i)}$$

Tube voltage (kVp_{max})

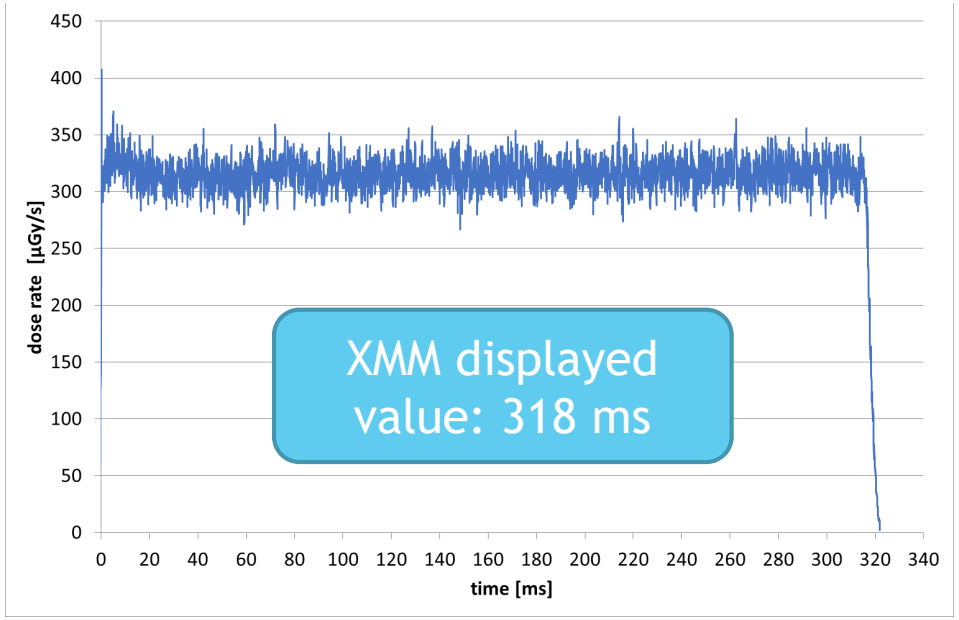
- Definition -> Maximum value of the X-ray tube voltage during a specified time interval (corresponds to the maximum photon energy)
- How it is determined -> High voltage waveform is obtained, and the maximum peak voltage is taken as the kVp value (or by spectrometry)
- What to do with rush current effects?
- How to define “specified time”
- There are no standard requirements for non-invasive measurement devices

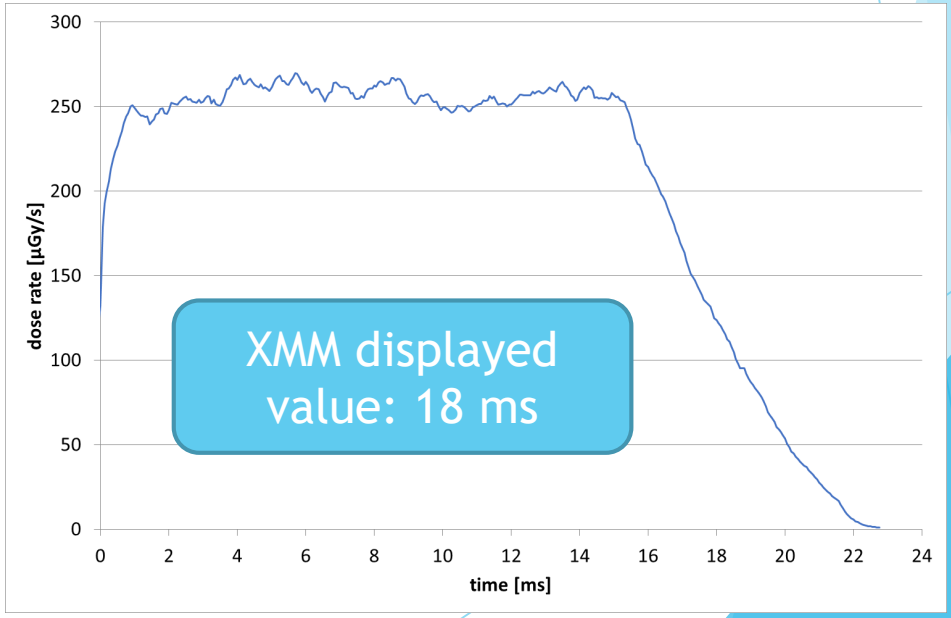
To be considered for XMM measurements:

- Only displayed above minimum dose and dose rate, e.g. 50 µGy and 10 µGy/s (peak)
- Displayed in specified voltage range only, e.g. 40 – 150 kVp
- Tube aging may influence the measurements

Irradiation time

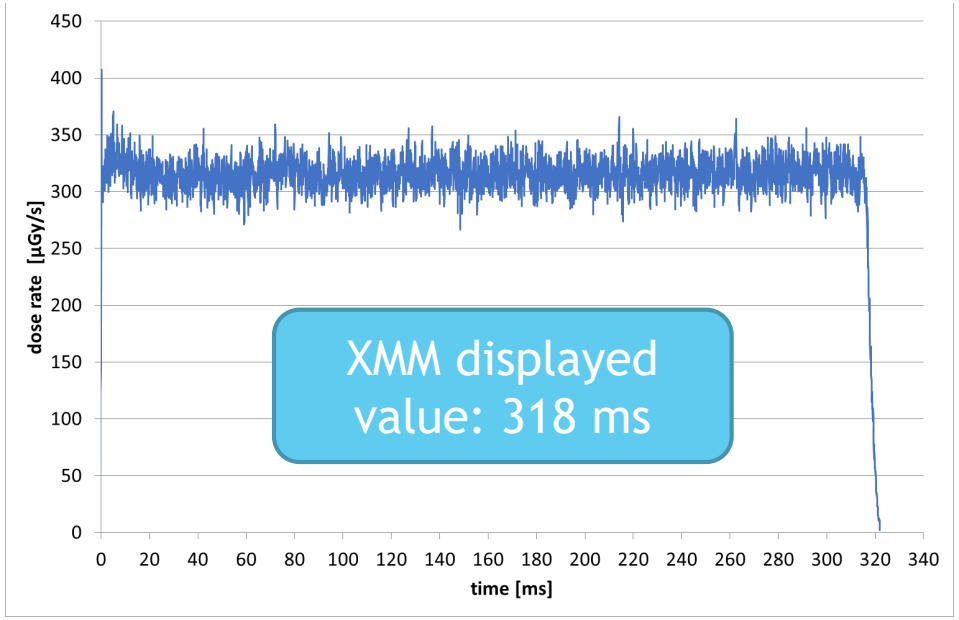
- Definition -> the time between the first and the last transitions through the 50 % level of the maximum air kerma rate (IEC 60601-2-54:2022)
- Can be defined for different values (e.g. 75% of the peak value) and in relation to different quantities, e.g. for certain percentage of tube voltage
- Harmonized definition is necessary to be able to compare the measurements
- Time resolved data is necessary to measure irradiation time

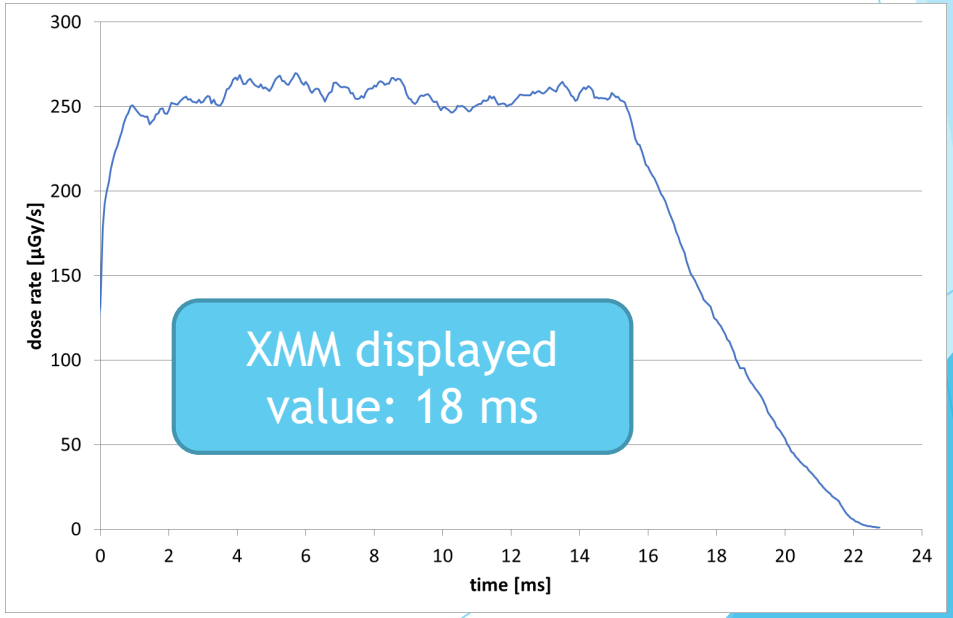




Irradiation time

- IEC 61267, IEC 61674 and IEC 61676 do not give a definition of the irradiation time
- There is no separate standard or specific requirements for XMMs measuring irradiation time
- Determination of measurement uncertainty is complicated
- In calibration laboratories, irradiation may be controlled by a shutter
- Some laboratories provide calibrations in terms of irradiation time (but majority does not do it)





Half value layer (HVL)

- How it is determined technically -> In ideal case, HVL is determined in narrow beam geometry, using an ionization chamber with low energy dependence and aluminum sheets with different thicknesses. Multi-detector XMMs can determine HVL based on the ratio of signals on different detectors

Caution:

- With ionisation chambers use data from multiple exposures with Al-sheets of different thickness
- With XMMs, using this method is a problem
  - For HVL determination correct dose measurements are essential
  - For correct dose measurements radiation quality must be known by the XMM
  - When radiation quality is known HVL can be indicated from XMM directly

Half value layer (HVL)

- IEC 61674 and IEC 61676 do not give a definition of HVL, and IEC 61267 defines HVL as the thickness of a specified material which reduces the air kerma rate to half the value without this material – the material is usually aluminum in diagnostic radiology
- Should we use the whole exposure for HVL measurement? (Yes)
- HVL measurement procedure is given e.g. in ISO 4037, IAEA TRS 457
- There is no standard for XMMs measuring HVL and no standard requirements for accuracy or limits of variation
- There is no published harmonized calibration procedure and measurement uncertainty is almost never estimated by calibration laboratories
- There is no primary standard for HVL and no consensus on how to establish traceability

Total filtration

- There is no primary standard, no clear consensus about the traceability
- There are no standard documents for total filtration measurements by XMMs, no limits of variation or accuracy requirements
- There are no published comparisons for total filtration measurements
- Total filtration is comprised of different thicknesses of different materials, but there is a need to express it as a single number --> quality equivalent filtration (total filtration expressed in terms of a certain material (e.g. Aluminum) is a function of radiation quality)
- IEC standards for medical X-ray devices and international protocols set minimum values for total filtration

Total filtration

- Definition -> Total effect of the combined inherent (permanent) and added filtration (e.g. in IEC 60601-1-3)
- Inherent (permanent) filtration -> The filtration provided by permanent materials through which the radiation beam must pass before emerging from the X ray tube.
- Total filtration is usually expressed in mm Al – so the inherent filtration must also be expressed in the same way, i.e. as equivalent aluminum
- Aluminum equivalent thickness is a function of energy, different for different materials – so it depends on tube voltage
- Tube voltage is in general case not constant – does the total filtration change during the exposure?
- Total filtration, like HVL, is defined for the full exposure only

Total filtration

- For a given tube voltage, HVL is a function of total filtration – this can be used to measure total filtration, e.g. by multi-detector XMMs (this can also be done by using look-up tables)
- IEC 60522-1:2020 gives a method for determination of the permanent filtration of X-ray tube assemblies and quality equivalent filtration
- ISO 4037-1:2019 gives a method for measuring of the inherent filtration based on HVL measurement, but there is a lookup table only for 60 kV
- If the total filtration (quality equivalent filtration) is defined by tube voltage and HVL, is there a point in measuring it separately?

Can XMMs be used to measure XMM quantities?

- Early results show that modern XMMs behave well in many different scenarios for most quantities
- Harmonized definitions and test conditions and traceability and uncertainty calculations are needed before final conclusions can be made
- There is a need for standard requirements and limits of variations, against which XMMs can be benchmarked (for all quantities that are measured)
- More data and publications are coming soon, you can find up to date information or send your feedback at TraMeXI website:

https://tramexi.com/