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Joint ICTP/IAEA Advanced School on Dosimetry in Diagnostic Radiology and its Clinical Implementation

11 - 15 May 2009

Dosimetry Framework, Formalism including Uncertainties

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Dosimetry framework, formalism including uncertainties

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Miramare, Trieste, Italy

IAEA

International Atomic Energy Agency

Why do we need dosimetry in DG :

✓ Risk assessment

20% accuracy for stochastic effects (low doses, highly uncertain risk)

Deterministic effects : 7% accuracy

Comparative dose measurements : 7% accuracy

Paediatric examinations : 7% accuracy

Doses to embryo/foetus : 7% accuracy

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Dosimetry framework

Why do we need dosimetry in DG :

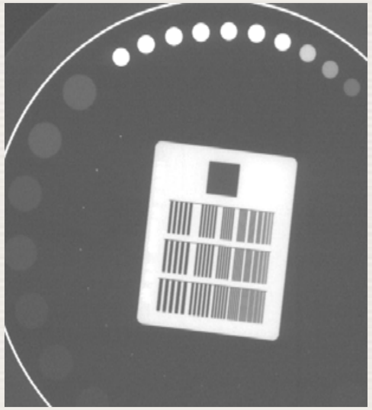
✓ Risk assessment

✓ Quality Assurance and equipment testing

provide confidence for optimum quality and minimum doses

- Baseline values
- QC & comparison with baselines

7% accuracy



Dosimetry framework

Why do we need dosimetry in DG :

✓ Risk assessment

✓ Quality Assurance and equipment testing

✓Radiation surveys

exposure levels & potential risks

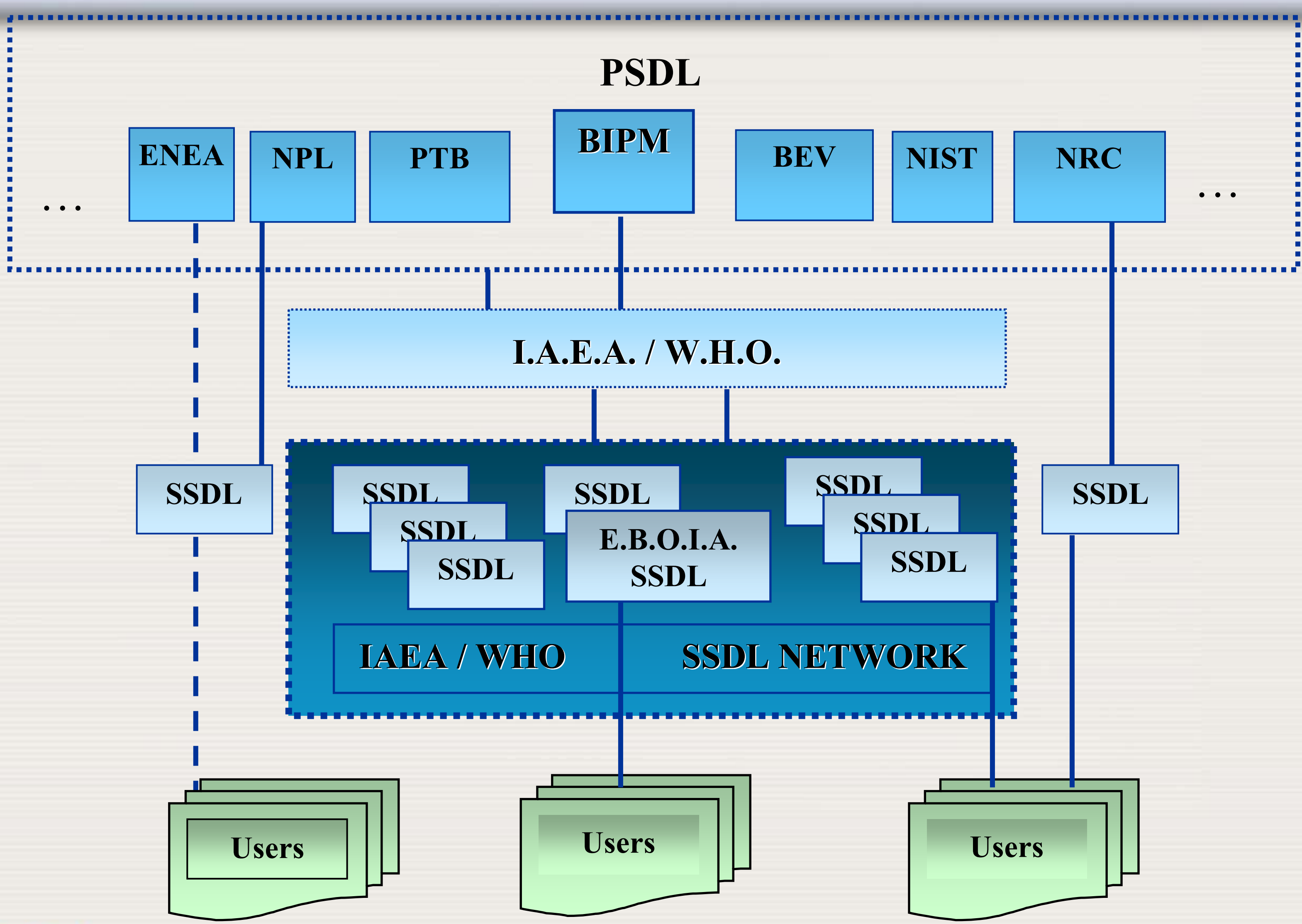
Accuracy 20% is sufficient

Contents

What we are going to discuss during this session :

- International Measurement System
  - PSDL, SSDL, user : traceability of standards & measurements
- Dosimetry formalism
  - Influence quantities, corrections factors, …
- Uncertainties
  - Type, evaluation, assumptions, expression, …

IMS : International Measurement System

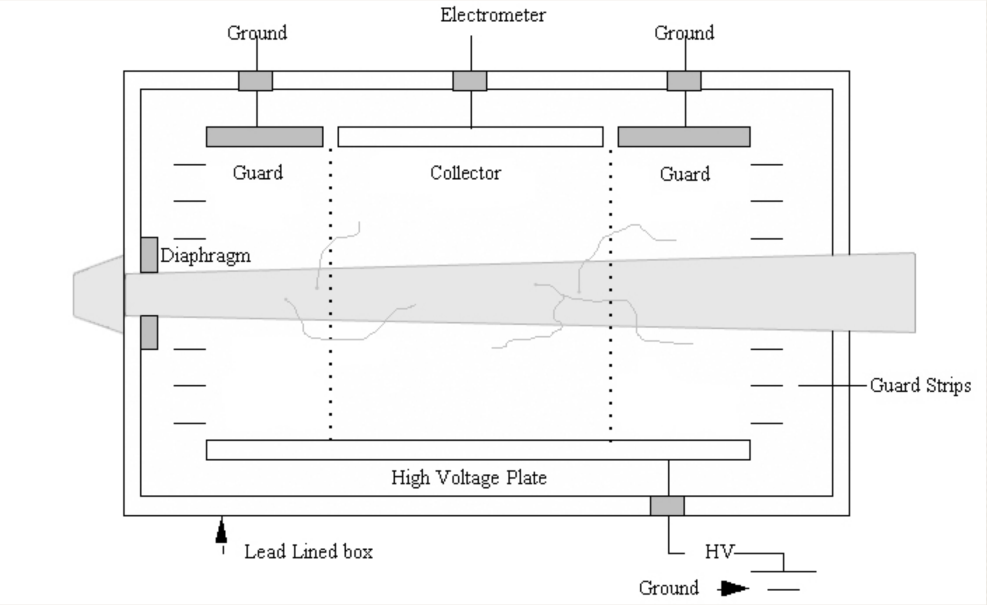


Dosimetry framework

Classification of instruments	Standards laboratories
Primary standard An instrument of the highest metrological quality that permits determination of the unit of a quantity from its definition, the accuracy of which has been verified by comparison with the comparable standards of other institutions at the same level.	Primary Standards Dosimetry Laboratory (PSDL) A national standardizing laboratory designated by the government for the purpose of developing, maintaining and improving primary standards in radiation dosimetry.
Secondary standard An instrument calibrated by comparison with a primary standard.	Secondary Standards Dosimetry Laboratory (SSDL) A dosimetry laboratory designated by the competent authorities to provide calibration services, and which is equipped with at least one secondary standard that has been calibrated against a primary standard.
National standard A standard recognized by an official national decision as the basis for fixing the value in a country of all other standards of the given quantity.	
Reference instrument An instrument of the highest metrological quality available at a given location, from which measurements at that location are derived.	
Field instrument A measuring instrument used for routine measurements whose calibration is related to the reference instrument.	

Primary Standard Dosimetry Laboratory

All PSDLs employ free-air chambers for the realization of the unit of air kerma in low and medium energy X ray beams.



Dosimetry framework

All PSDLs employ free-air chambers for the realization of the unit of air kerma in low and medium energy X ray beams.

$$K^{prim} = \frac{dQ}{dm} \cdot (W/e)_{air} \cdot k_{e-loss} \cdot k_{sc} \cdot k_{att} \cdot k_{apert} \cdot k_{wall} \cdot k_{rec} \cdot k_{TP} \cdot k_{field}$$

U_{Kair} : 0.20%, with W_{air}/e : 0.15%

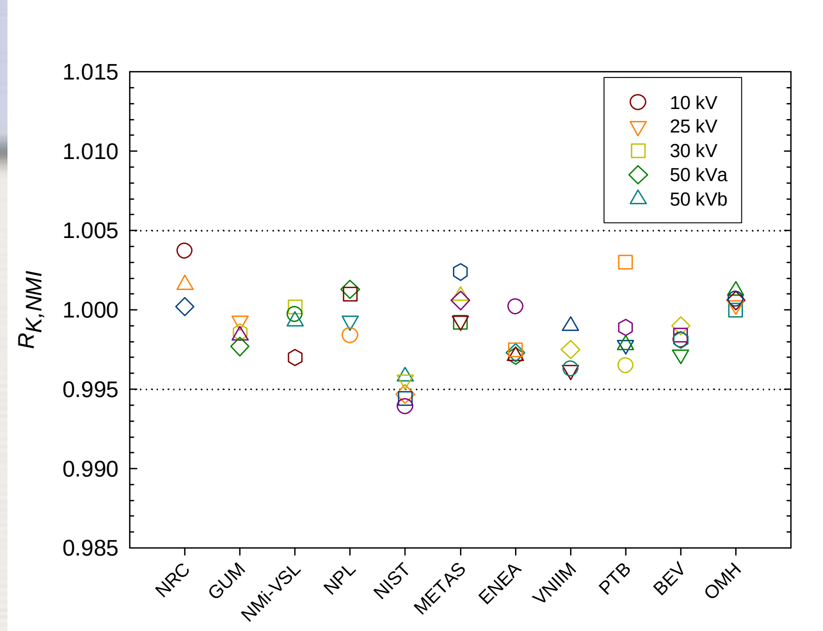
- LEE, J.-H., et al., The performance of the INER improved free-air ionization chamber in the comparison of air kerma calibration coefficients for medium-energy X-rays, Radiation Measurements 39 (2005) 1-10.
- BOUTILLON, M., ALLISY-ROBERTS, P.J., BURNS, D.T., Measuring conditions used for the calibration of ionization chambers at the BIPM, Rapport BIPM-01/04, Paris (2001).
- BOUTILLON, M., PERROCHE-ROUX, A.-M., Re-evaluation of the W value for electrons in dry air Phys. Med. Biol. 32 (1987) 213-219.

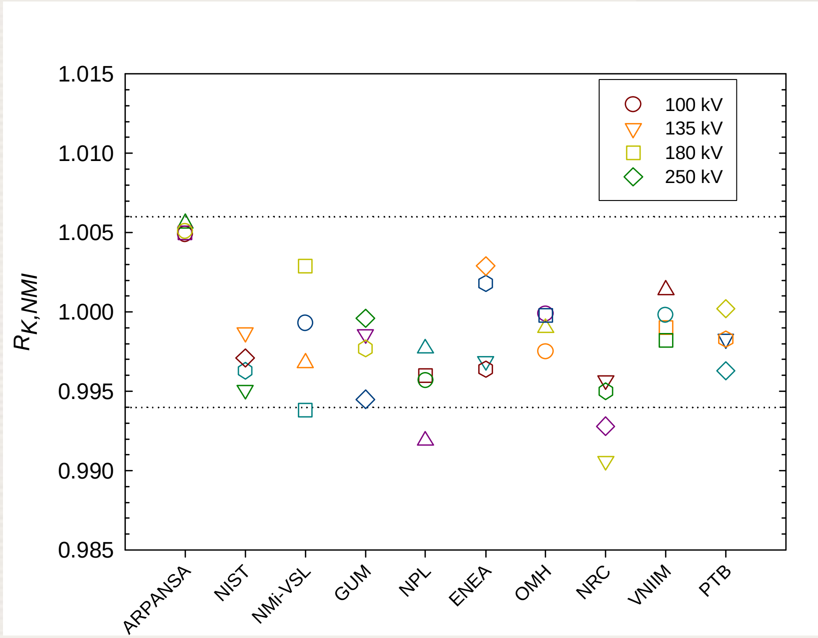
Dosimetry framework

How are the primary verified ?

- International comparisons of measurements, known as **key comparisons**;
- Supplementary international comparisons of measurements; and
- Quality systems and demonstrations of competence by the NMIs.

Mutual recognition arrangement (MRA)





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Secondary Standard Dosimetry Laboratory

- to bridge the gap between the Primary Standard Dosimetry Laboratory (PSDL) and the USER of Ionizing Radiation.
- to improve dosimetric accuracy and reliability of ionizing radiation measurements.
- to promote the compatibility of dosimetric methods in order to achieve homogenization and uniformity of dosimetry in all ionizing radiation laboratories.
- to advice, inform & guide the user of ionizing radiation on dosimetry issues as well as to exchange the experience and knowledge between users.

Dosimetry framework

Secondary Standard Dosimetry Laboratory

Traceability
Transfer instrument
Plane-parallel and cylindrical types of different designs are in use.

$$N^{SSDL}_{K,Q_0,P_0,T_0,cond_{PSDL}} = \frac{K^{PSDL}}{M^{SSDL}_{Q_0,P_0,T_0,cond_{PSDL}}}$$

N_K^{SSDL} : calibration coefficient of the transfer instrument

Q_0 : the X-ray beam quality (energy) at 70 kV – HVL = 2.58 mm Al

P_0 = 101.325 kPa, T_0= 293.15 ^oK (20^{o}C)

$cond_{PSDL}$: conditions at PSDL – influence quantities (humidity, distance, field size, scatter radiation, background, electromagnetic fields, etc)

at the SSDL

Then at SSDL irradiation conditions (beam, environment etc)
K is determined (local – reference value)

$$K^{SSDL} = M^{SSDL}_{cond_{SSDL}} \cdot N^{SSDL}_{K,Q_0}$$

In principal "conditions" at SSDL differ from those at PSDL

$$\left(N^{SSDL}_{K,Q_{0,}P_0,T_0,cond_{PSDL}} = \frac{K^{PSDL}}{M^{SSDL}_{Q_{0,}P_0,T_0,cond_{PSDL}}} \right)$$

Dosimetry framework

at the SSDL

Then at SSDL irradiation conditions (beam, environment etc)
K is determined (local – reference value)

In principal, "conditions" at SSDL differ from those at PSDL

$$K^{SSDL} = M^{SSDL}_{cond_{SSDL}} \cdot N^{SSDL}_{K,Q_0} \cdot \prod_i k_i^{PSDL->SSDL}$$

$$\left[N^{SSDL}_{K,Q_0,P_0,T_0,cond_{PSDL}} = \frac{K^{PSDL}}{M^{SSDL}_{Q_0,P_0,T_0,cond_{PSDL}}} \right]$$

$cond_{SSDL}$: conditions at SSDL (beam quality, P, T, humidity, distance, field size, scatter radiation, background, electromagnetic fields, etc)

k_i : corrections factors that corrects the effect of a influence quantity

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Dosimetry framework

as a USER

$$K = M_Q \, N_{K,Q_O} \prod_i k_i$$

- $N_{K,Qo}$: calibration coefficient from a SSDL (or PSDL) and refers to reference conditions, Q_0 T_0, P_0 etc.
- M_Q : the instrument reading under certain conditions, e.g. for *P, T, etc.* A measurement is usually performed at non-reference conditions
- k_i : corrections factors that corrects the effect of a influence quantity

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Influence quantities

are defined as quantities that are not the subject of the measurement, but yet may have an influence on the result of the measurement.

Examples : X-ray energy, P, T, field size, electrometer leakage current, etc

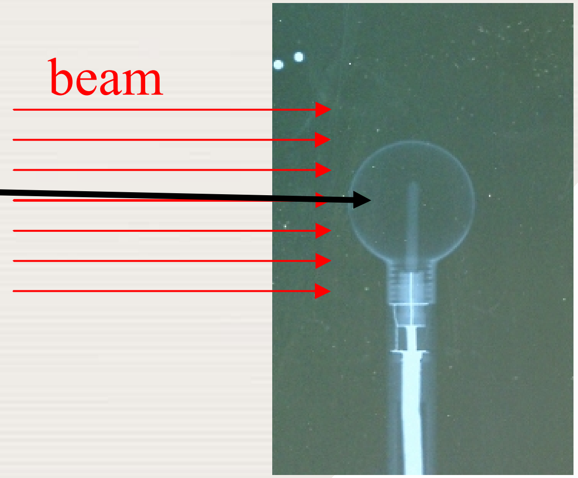
k_i : correct for the effect of the influence quantities, e.g. k_Q, k_{TP}, …

Reference conditions

Reference conditions represent a set of values (reference values) of influence quantities for which the calibration coefficient is valid without further corrections

Examples : P_0 = 101.3 kPa, θ_0 = 20°C, FCD=100cm, Q=RQR5 (70kV)

Correction for density of air, k_{TP}



$$K = \frac{\varepsilon}{m}$$

$$P \cdot V = \frac{m}{MW} \cdot R \cdot T$$

$$k_{TP} = \frac{P_0 \cdot T}{P \cdot T_0} = \frac{P_0 \cdot (273.2 + \theta)}{P \cdot (273.2 + \theta_0)}$$

$P_0 = 101.3$ kPa = 1 atm

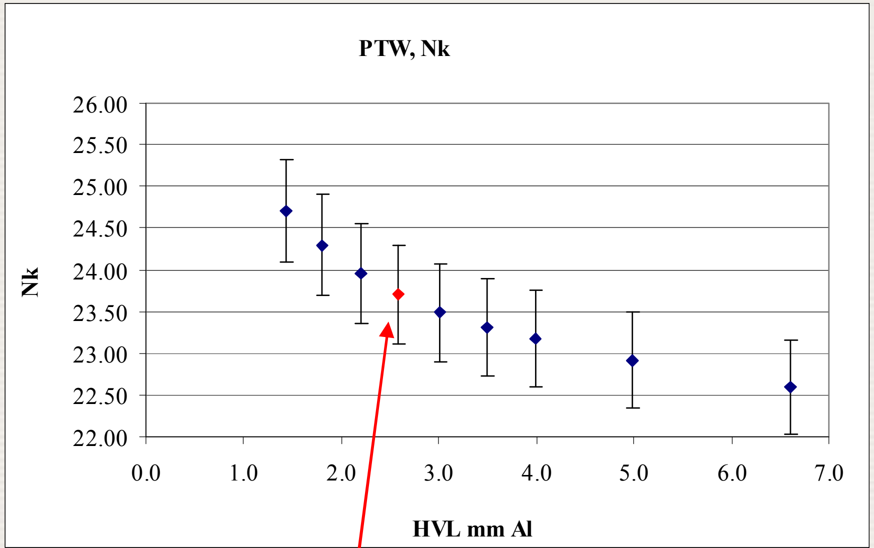
$\theta_0 = 20^{o}$C or 22^{o}C

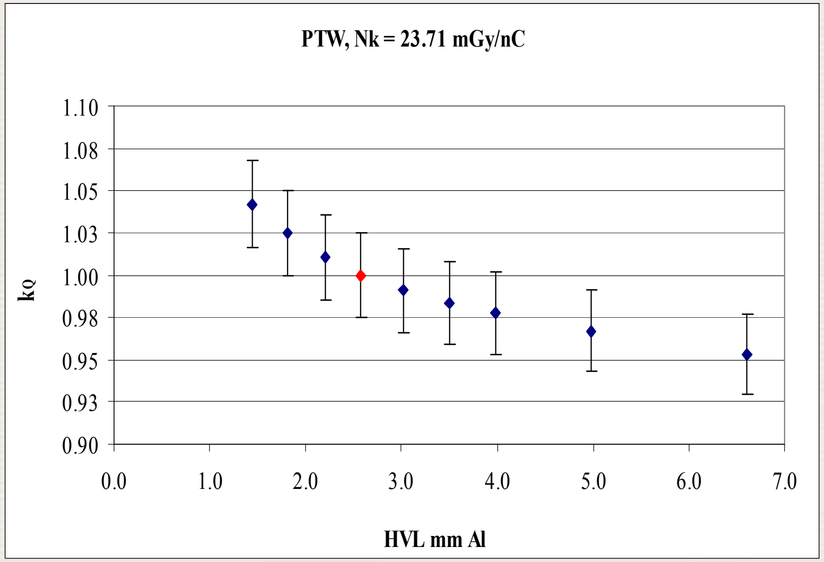
Solid state detectors : $k_{TP} = 1.000$

Sealed (?) chambers : $k_{TP} = 1.000$

Dosimetry formalism

Correction for radiation quality of the beam, k_Q





$$K_Q = M_Q \; N_{K,Q_o} \; k_{Q,Q_0}$$

$$k_{Q,Q_0} = \frac{N_{K,Q}}{N_{K,Q_0}} \left(= k_Q\right)$$

where the factor $k_{Q,Qo}$ corrects for the effects of the difference between the reference beam quality, *Qo*, and the actual quality, *Q*, during the measurement

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Dosimetry formalism

Other corrections for influence quantities

k_{dist} : for deviation of chamber position from the reference position

k_{lin} : for non-linearity of the measuring assembly sensitivity

k_{dir} : for incident radiation direction

k_{emc} : for the effect of electromagnetic compatibility

k_{fs} : for departure of field size/field homogeneity from reference condition

k_{lt} : for long time variations of response

k_{ms} : for the dependence of the instrument on supply voltage (mains or battery)

$$K = M_Q \cdot k_{TP} \cdot N_{K,Q_O} \cdot \prod_i k_i \qquad \prod_i k_i = k_Q \overbrace{\underbrace{k_{dist}\, k_{lin}\, k_{dir}\, k_{emc}\, k_{fh}\, k_{lt}\, k_{ms}}_{\text{contribution to uncertainties}}}^{\mathbf{1.000}}$$

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Cross calibration of dosimeters

Some users themselves calibrate their **field dosimeters** for various reasons

Cross-calibration of a field instrument refers to its direct comparison in a suitable user's beam of a quality, $\boldsymbol{Q_{cross}}$, against a reference instrument that had been calibrated at the SSDL.

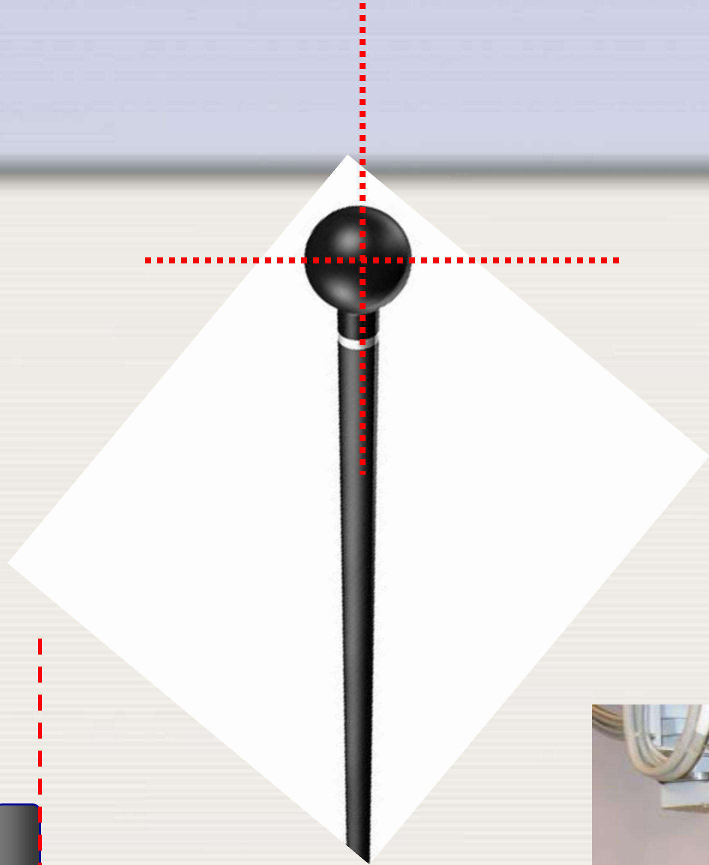
$$K_{Q_{cross}} = M_{Q_{cross}}^{ref} \cdot k_{TP}^{ref} \cdot N_{K,Q_0}^{ref} \cdot k_{Q_0,Q_{cross}}^{ref}$$

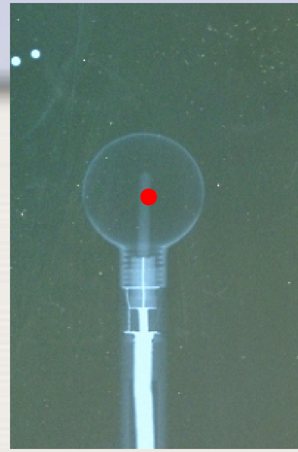
$$N_{K,Q_{cross}}^{field} = \frac{K_{Q_{cross}}}{M_{Q_{cross}}^{field} \cdot k_{TP}^{field}}$$

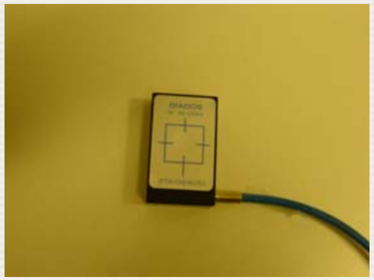
$$N_{K,Q_{cross}}^{field} = \frac{M_{Q_{cross}}^{ref} \cdot k_{TP}^{ref}}{M_{Q_{cross}}^{field} \cdot k_{TP}^{field}} N_{K,Q_0}^{ref} k_{Q_{cross}}^{ref}$$

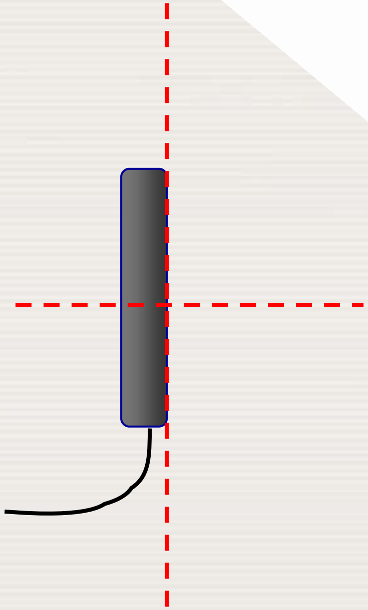
Dosimetry formalism

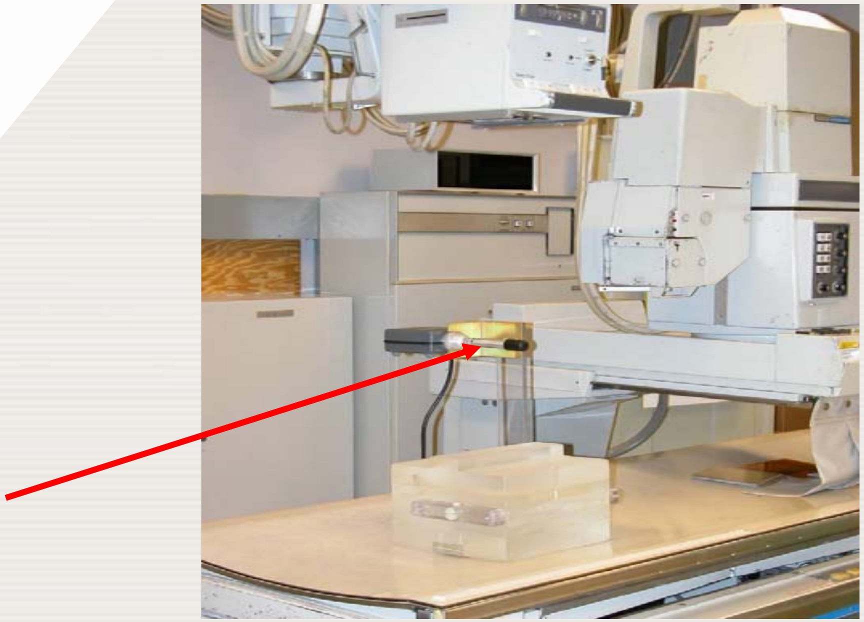
Reference point











Uncertainties (and errors)

Error : has both a numerical value and a sign

Example : L = 3.4 mm ± 0.2 mm

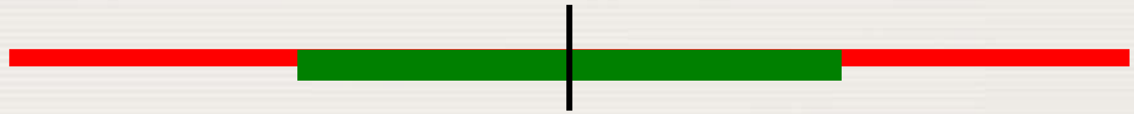
means that the “true” length could be anywhere between 3.2 and 3.6 mm.

Uncertainty : characterizes the dispersion of the values “that could reasonably be attributed to the measurand”.

U is associated with a confidence level (c.l.).

Example : Q = 100 nC with u=1.0% @ **67% c.l** (1sd)

means that we are sure by 67% that the “true” value lies within the range 99.0 nC and 101.0 nC



This is equivalent to u=2.0% @ **95% c.l** (2sd),

which means that we are sure by 95% that the “true” value lies within the range 98.0 nC and 102.0 nC (increased confidence BUT in a broader dispersion)

INTERNATIONAL ORGANIZATION FOR STANDARDIZATION, GUM, Guide to the Expression of Uncertainty of Measurement, ISO, Geneva (1995).

Uncertainties

Mean value of measurement

$$\bar{x} = \frac{1}{n}\sum_{i=1}^{n} x_i$$

The scatter of the measured values around their mean can be characterised, for an individual result xi, by the standard deviation, s_i :

$$s(x_i) = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n}(x_i - \bar{x})^2}$$

Variance of a single measurement

$$s^2(x_i)$$

The standard deviation of the mean value

$$s(\bar{x}) = \frac{1}{\sqrt{n}} s(x_i)$$

!!! Excel STDEV function corresponds to : $s(x_i)$

and NOT to the standard deviation of the mean

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Uncertainties

Type A standard uncertainty
(Statistical, since obtained by repetitive measurements)

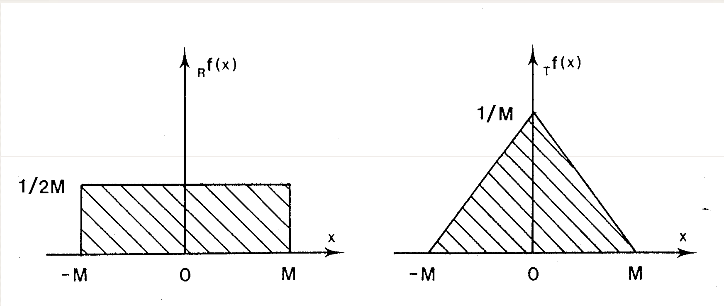
$$u_A = s(\bar{x})$$

Application examples : chamber long term stability, constancy of X-ary tube output, temperature stability, etc

Type B standard uncertainty
(non statistical, typical-observation-mechanical errors, etc)

Application examples : reading resolution (0.00**0 mGy**) , calibration coefficient uncertainty (e.g. 1.02 ± **0.04**°C), instrument accuracy (e.g. **5%**), distance errors, etc

$$u_B = \frac{M}{\sqrt{3}}$$



where -M and +M
are maximum limits of a quantity

$$\left\{ \text{for a triangular distribution} \quad u_B = \frac{M}{\sqrt{6}} \right\}$$

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Uncertainties

For the determination of the uncertainty of a measured quantity (e.g. the K)

- **step 1 : all influence quantities should be determined**

$$K = M_Q \cdot \mathrm{k}_{\mathrm{TP}} \cdot N_{K,Q_O} \cdot \prod_i k_i$$

Measurements of Kair by SSDL chamber
Nk from PTB
Nk stability
Electrometer accuracy
Scale reading / resolution
Current measurements
Uniformity of Xray beam
Difference in X ray spectra (HVL)
Positioning in same distance
Temperature & Pressure
Electrometer Built-In timer
Leakage current
Recombination loss

Uncertainties

- step 2 : for each influence quantity Type A and B uncertainties should be assigned

Measurements of Kair by SSDL chamber	Type A %	Type B %
Nk from PTB	-	+
Nk stability	+	-
Electrometer accuracy	-	+
Scale reading / resolution	-	+
Current measurements	+	+
Uniformity of Xray beam	+	+
Difference in X ray spectra (HVL)	-	+
Positioning in same distance	+	+
Temperature & Pressure	+	+
Electrometer Built-In timer	-	+
Leakage current	-	+
Recombination loss	-	+

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Uncertainties

• step 3 : for each influence quantity, a value (%) should be assigned to Type A and B :

• true or objective estimation

Measurements of Kair by SSDL chamber	Type A %	Type B %
Nk from PTB	NR	0.99
Nk stability	0.50	NR
Electrometer accuracy	NR	0.00
Scale reading / resolution	NR	0.00
Current measurements	0.01	0.02
Uniformity of Xray beam	0.02	0.58
Difference in X ray spectra (HVL)	NR	0.50
Positioning in same distance	0.02	0.12
Temperature & Pressure	0.07	0.08
Electrometer Built-In timer	*	*
Leakage current	NR	0.00
Recombination loss	NR	0.00

In general, but not as a strict rule …

1. U are expressed as percentages (%)

Example :

N_K = 23.2 ± 0.3 mGy/nC (with U at 95% c.l. - 2 sd)

u = 0.3/23.2 x 100% = 1.29 %

2. U are referred at 1 sd (confidence level)

Example : u= 1.29 /2 = 0.65% @ 67% c.l. - 1sd

3. For type B : uncertainty division √3.

Example : u= 1.29 / √3 = 0.74 %

4. U type A : standard deviation of the mean

Example : the N_K stability from all calibration data at PSDL

Uncertainties

Propagation of uncertainties

$\boldsymbol{y = f(x_1, x_2, x_3, \ldots)}$ *with* $x_1, x_2, x_3, \ldots$ are independent of each other

$$u(y) \cong \sqrt{\left(\frac{\partial f}{\partial x_1}\right)^2 u^2(x_1) + \left(\frac{\partial f}{\partial x_2}\right)^2 u^2(x_2) + \left(\frac{\partial f}{\partial x_3}\right)^2 u^2(x_3) + \ldots}$$

$\boldsymbol{y = c1\ x1 + c2\ x2 + c3\ x3 + \ldots}$

$$u(y) = \sqrt{c_1^2 u^2(x_1) + c_2^2 u^2(x_2) + c_3^2 u^2(x_3) + \ldots}$$

$$y = x_1^{\alpha} x_2^{\beta} x_3^{\chi}$$

$$r(y) = \sqrt{\{a^2 r^2(x_1) + \beta^2 r^2(x_1) + \chi^2 r^2(x_1)}$$

r $(x1) = u(x1)/|x1|$

Uncertainties

Combined uncertainties and expanded uncertainties

If uA and uB are the Type A and the Type B standard uncertainties of a quantity, the combined standard uncertainty of that quantity is :

$$u_C = \sqrt{\left(u_A^2 + u_B^2\right)}$$

Expanded uncertainty, U is the multiplication of the combined standard uncertainty with coverage factor, k

k = 2 corresponding to confidence limit of about 95%, k=3 to 99%.

$$\boldsymbol{U = k\,u_c}$$

$$\boldsymbol{U = 2\,u_c}$$

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Uncertainties

In practice …

Measurements of Kair by SSDL chamber	Type A	Type B
	%	%
Nk from PTB	NR	0.99
Nk stability	0.5	NR
Electrometer accuracy	NR	0
Scale reading / resolution	NR	0
Current measurements	0.01	0.02
Uniformity of Xray beam	0.02	0.58
Difference in X ray spectra (HVL)	NR	0.5
Positioning in same distance	0.02	0.12
Temperature & Pressure	0.07	0.08
Electrometer Built-In timer	*	*
Leakage current	NR	0
Recombination loss	NR	0
QUADRATIC SUM	0.50	1.26
COMBINED UNCERTAINTY	1.36	%
EXPANDED UNCERTAINTY	2.71	%

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Uncertainties in patient dosimetry in clinics

Scenario 1 : An instrument in compliance with IEC 61674 is used. No k_{TP} applies but normal pressure at sea level. K_i deduced from reading and calibration coefficient

Scenario 2 : A reference class dosimeter is used with a performance exceeding the requirements of IEC 61674. k_{TP} applies using the actual T & P values.

Scenario 3 : A reference class dosimeter is used. Conditions of exposure are tightly controlled, i.e. in terms of radiation quality, direction of radiation incidence, density of air etc. and where corrections for the relevant influence quantities are made.

Uncertainties in patient dosimetry in clinics

Influence quantity	IEC 61674	Uncertainty (k=1)/%		
	±*L* in %	Scenario 1	Scenario 2	Scenario 3
Intrinsic error, $N_{K,Q}$ or $N_{K,Q0}*k_Q$	5	2,89	1,6	1,6
Radiation quality, i.e. differences between SSDL and user	5	2,89	1,5	0,5
Kerma rate	2	1,15	0,5	0,5
Direction of radiation incidence	3	1,73	1,0	0,5
Air pressure	2	1,15	0,5	0,5
Temperature and humidity	3	1,73	0,5	0,5
Electromagnetic compatibility	5	2,89	1,5	1,0
Field size/field homogeneity	3	1,73	1,0	1,0
Operating voltage	2	1,15	1,2	1,0
Long term stability of user's instrument	2	1.15	1,0	0,5
Relative combined standard uncertainty (k=1)		**6,3**	**3,5**	**2,7**
Relative expanded uncertainty (k=2)		**12,6**	**7,0**	**5,4**

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Uncertainties in patient dosimetry in clinics

Source of uncertainty	Uncertainty (k=1)/ %		
	Scenario 1	Scenario 2	Scenario 3
Measurement scenario (see previous slide table)	6.3	3.5	2.7
Precision of reading	1.0[1)]	0. 6[2)]	0.6[2)]
Uncertainty in measurement position[3)]	1.2	1.2	1.2
Relative combined standard uncertainty (k=1)	6.5	3.7	3.0
Relative expanded uncertainty (k=2)	**13.0**	**7.4**	**6.0**

1) One single reading taken
2) Standard deviation of the mean of 3 readings
3) 2 mm in positioning of a detector at distance 200 mm from the X ray focus

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