What shade is your gray?

The black and white solution for a better gray
- and improved becquerel

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BIPM
Shades of gray

- Introduction to the international framework
- Uncertainty of the primary realization
  - gray and becquerel
- Uncertainty of dissemination
- Uncertainty of use
- International comparisons
- Equivalence of national standards
- New developments at the BIPM
The Bureau International des Poids et Mesures (BIPM) set up under the Metre Convention in 1875 for the traceability of the SI.

Established an ionizing radiation laboratory in 1960 with the strong support of the NMIs and in particular the International Committee on Radiation Units and Measurements (ICRU).
International traceability for ionizing radiation standards

- Radiation dosimetry comparisons were started in the early 1960s and a continuing series of BIPM on-going comparisons enables every Member State to claim traceability to the SI.
- Traceability can be directly through the BIPM, through an NMI that holds primary standards or via the IAEA Dosimetry Laboratory programme for the SSDL Network.

- Activity comparisons for radionuclides were started in the late 1960s and continue to this day.
- Traceability is through an NMI that holds primary standards.
The International Committee for Weights and Measures (CIPM) established a Mutual Recognition Arrangement (MRA) in 1999. All signatory national metrology institutes (NMIs) can demonstrate the equivalence of their standards through participation in international key comparisons. Thus, the NMIs are able to claim equivalence for their calibration and measurement capabilities (CMCs). To date, 77 institutes from 48 Member States, 26 Associate States of the General Conference and 3 international organizations, including the IAEA, have signed the CIPM MRA.
Quantities and Units (Dosimetry)

- Air kerma and absorbed dose to water measured in terms of J/kg
- Dosimetry uses the special name of gray
  \[ 1 \text{ Gy} = 1 \text{ J/kg} \]
- All measurements must be traceable to the SI
  - a gray measured in one laboratory or hospital for a given quantity is then equivalent to the same measurement elsewhere of the same quantity
Quantities and Units (Activity)

- Similarly, for the measurement of activity
- The special name of becquerel is used
  \[ 1 \text{ Bq} = 1 \text{ s}^{-1} \]
- For radionuclide patient dosimetry in one hospital to match another, each needs to measure activity traceable to the SI becquerel and use approved protocols e.g. MIRD
International comparisons under the CIPM MRA

- Demonstration of the degrees of equivalence of the gray and becquerel held by the Member States and Associate States
- Through BIPM and other international comparisons run by the Regional Metrology Organizations (RMOs) into which the IAEA dosimetry capabilities are linked.
- The CIPM MRA key comparison database (KCDB) contains up-to-date details of all degrees of equivalence for national standards.
What uncertainties for the gray?

- Air kerma in a $^{60}$Co beam
- **Uncertainty is dependent on**
  - The measurement equation
  - The practical realization – ionization chamber
  - Repeatability and reproducibility
  - The dissemination chain
  - Use in practice
• The measurement equation

The air kerma rate is determined by

$$\dot{K} = \frac{l}{m} \frac{W}{e} \frac{1}{1 - \bar{g}} \left( \frac{\mu_{en}}{\rho} \right)_{a,c} \bar{s}_{c,a} \prod k_i$$

where

• \(l/m\) is the ionization current per unit mass of air measured by the standard,
• \(W\) is the average energy spent by an electron of charge \(e\) to produce an ion pair in dry air,

• \(\bar{g}\) is the fraction of electron energy lost by bremsstrahlung production in air,

• \(\left( \frac{\mu_{en}}{\rho} \right)_{a,c}\) is the ratio of the mean mass energy-absorption coefficients of air and graphite,

• \(\bar{s}_{c,a}\) is the ratio of the mean stopping powers of graphite and air,

• \(\prod k_i\) is the product of the correction factors to be applied to the standard.
What uncertainties for the gray?

<table>
<thead>
<tr>
<th>Physical Constants</th>
<th>BIPM values</th>
<th>uncertainty (1)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>100 $s_i$</td>
</tr>
<tr>
<td>$\rho_0$ dry air density (2) /kg m$^{-3}$</td>
<td>1.2930</td>
<td>–</td>
</tr>
<tr>
<td>$(\mu_{en} / \rho)_{a,c}$</td>
<td>0.9989</td>
<td>0.01</td>
</tr>
<tr>
<td>$s_{c,a}$</td>
<td>1.0010</td>
<td>–</td>
</tr>
<tr>
<td>$W / e$ J/C</td>
<td>33.97</td>
<td>–</td>
</tr>
<tr>
<td>$\bar{g}$ bremsstrahlung loss</td>
<td>0.0031</td>
<td>–</td>
</tr>
</tbody>
</table>

(1) Expressed as one standard deviation
   $s_i$ represents the relative standard uncertainty estimated by statistical methods, type A
   $u_i$ represents the relative standard uncertainty estimated by other means, type B

(2) At 101 325 Pa and 273.15 K

(3) Combined uncertainty for the product
What uncertainties for the gray?

**Uncertainties related to the construction of the ionization chamber**

<table>
<thead>
<tr>
<th></th>
<th>BIPM</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>values</td>
</tr>
<tr>
<td></td>
<td>100 $s_i$</td>
</tr>
<tr>
<td><strong>Correction factors:</strong></td>
<td></td>
</tr>
<tr>
<td>$k_g$</td>
<td>re-absorption</td>
</tr>
<tr>
<td>$k_h$</td>
<td>humidity</td>
</tr>
<tr>
<td>$k_s$</td>
<td>recombination losses</td>
</tr>
<tr>
<td>$k_{st}$</td>
<td>stem scattering</td>
</tr>
<tr>
<td>$k_{wall}$</td>
<td>wall attenuation and scattering</td>
</tr>
<tr>
<td>$k_{an}$</td>
<td>axial non-uniformity</td>
</tr>
<tr>
<td>$k_{rn}$</td>
<td>radial non-uniformity</td>
</tr>
<tr>
<td>$V$</td>
<td>chamber volume /cm$^3$</td>
</tr>
<tr>
<td>$I$</td>
<td>ionization current / pA</td>
</tr>
</tbody>
</table>

(4) Standard CH6.1
(5) The uncertainties for $k_{wall}$ and $k_{an}$ are included in the determination of the effective volume
What uncertainties for the gray?

**Combined standard uncertainty for air kerma in $^{60}\text{Co}$**

<table>
<thead>
<tr>
<th></th>
<th>BIPM</th>
</tr>
</thead>
<tbody>
<tr>
<td>uncertainty (1)</td>
<td></td>
</tr>
<tr>
<td>$100 s_i$</td>
<td>$100 u_i$</td>
</tr>
<tr>
<td>Relative standard uncertainty</td>
<td></td>
</tr>
<tr>
<td>quadratic summation</td>
<td>0.02</td>
</tr>
<tr>
<td>combined uncertainty</td>
<td>0.15</td>
</tr>
</tbody>
</table>

For a comparison of national standards for the measurement of air kerma, the correlated uncertainties are removed.
How do we compare national standards?

- The national metrology institute (NMI) brings its national standard to the BIPM.
- The NMI and the BIPM standards measure the air kerma in the same photon beam.
- The NMI and the BIPM compare the results and the related uncertainty budgets.
- The comparison result is expressed as the ratio:

\[ R_K = K_{\text{NMI}} / K_{\text{BIPM}} \]

- Or, when transfer standards are used, as:

\[ R_K = N_{K,\text{NMI}} / N_{K,\text{BIPM}} \]

- The uncertainty budgets are combined appropriately.
Equivalence of National Standards, $K / \text{Gy in } ^{60}\text{Co}$

A snapshot of degrees of equivalence for $^{60}\text{Co}$ air kerma measured by BIPM Member States, the IAEA and some Associate States that have taken part in BIPM or RMO comparisons.

The NMI acronyms are given in the key comparison database of the CIPM MRA.
What uncertainties for comparison of the gray?

**Uncorrelated uncertainty for comparison of air kerma in $^{60}$Co**

<table>
<thead>
<tr>
<th>Component</th>
<th>BIPM uncertainty $^{(1)}$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$100 , s_i$</td>
</tr>
<tr>
<td>Correction factors</td>
<td>0.02</td>
</tr>
<tr>
<td>Long term stability</td>
<td>0.04</td>
</tr>
<tr>
<td><strong>combined standard uncertainty</strong></td>
<td><strong>0.10</strong></td>
</tr>
</tbody>
</table>
The key comparison reference value (KCRV) is the BIPM value – our best estimate of the gray the uncorrelated uncertainty component at $k = 2$ (expanded uncertainty) is 2 parts in $10^3$. 

N.B. Black squares indicate results that are more than 10 years old.
Dissemination of air kerma in $^{60}$Co

Relative standard uncertainty of $N_{K,\text{lab}}$

<table>
<thead>
<tr>
<th>Relative standard uncertainty</th>
<th>BIPM</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$100 , s_i$</td>
</tr>
<tr>
<td>Air kerma</td>
<td>0.02</td>
</tr>
<tr>
<td>Ionization current of the transfer chamber including $(P,T)$</td>
<td>0.01</td>
</tr>
<tr>
<td>Distance and orientation</td>
<td>0.01</td>
</tr>
<tr>
<td>quadratic summation</td>
<td>0.02</td>
</tr>
<tr>
<td>combined standard uncertainty</td>
<td></td>
</tr>
</tbody>
</table>
Equivalence of National Standards, \( K / \text{Gy} \) in \(^{60}\text{Co}\)

The IAEA traceability to the SI is through the characterizations of their standards at the BIPM. Only uncorrelated uncertainties are included here \((k = 2)\).
Absorbed dose - what uncertainties?

• The measurement equation
  Defined as the energy *absorbed* in matter

\[ D = \frac{E}{m} \]

• The practical realization
  (ionometry and calorimetry)
• Repeatability and reproducibility
• Dissemination
• Use in practice
### Uncertainties for primary standards

<table>
<thead>
<tr>
<th>Standard</th>
<th>Uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>BIPM standard uncertainties</strong></td>
<td></td>
</tr>
<tr>
<td>ionometric standard</td>
<td>$2.9 \times 10^{-3}$</td>
</tr>
<tr>
<td>calorimetric standard</td>
<td>$3.4 \times 10^{-3}$</td>
</tr>
<tr>
<td><strong>NMI standard uncertainties</strong></td>
<td></td>
</tr>
<tr>
<td>calorimetric standards (water and graphite)</td>
<td>$2.1 \times 10^{-3}$ to $5.0 \times 10^{-3}$</td>
</tr>
<tr>
<td><strong>Comparison standard uncertainties</strong></td>
<td></td>
</tr>
<tr>
<td></td>
<td>$3.0 \times 10^{-3}$ to $5.4 \times 10^{-3}$</td>
</tr>
</tbody>
</table>
Equivalence of National Standards, $D_w / \text{Gy in }^{60}\text{Co}$

A snapshot of degrees of equivalence for $^{60}\text{Co}$ absorbed dose to water measured by BIPM Member States, the IAEA and some Associate States that have taken part in BIPM or RMO comparisons.

The NMI acronyms are given in the key comparison database of the CIPM MRA.
Absorbed dose to water - what uncertainties?

Dissemination of absorbed dose to water

Standard uncertainties for the direct calibration of ionization chambers in $^{60}$Co:

$3.0 \times 10^{-3}$ to $6.0 \times 10^{-3}$

Standard uncertainties for the direct calibration of ionization chambers in linac beams:

$4.1 \times 10^{-3}$ to $7.0 \times 10^{-3}$
Absorbed dose to water - what uncertainties?

Hospital measurements of absorbed dose to water

Standard uncertainties for $^{60}$Co beam calibrations:

$7.0 \times 10^{-3}$ to $9.0 \times 10^{-3}$

Standard uncertainties for linac beam calibrations:

$10.5 \times 10^{-3}$ to $15.0 \times 10^{-3}$

**Conclusion**: reference beam calibrations in hospitals should be better than 3 % (expanded uncertainty)

Ref: TRS 398 guidelines
• Activity measurements also need to be traceable to the SI
• Key comparisons are held for the determination of the becquerel, for a large number of different radionuclides
• The BIPM operates the Système International de Référence (SIR) for gamma-emitting radionuclides.

Measurements since 1975

Based on two well-type ionization chambers
The SIR enables any NMI to submit an ampoule of a radioactive solution or gas to the SIR at any time. A normalized value of equivalent activity results and is compared against all other such measurements for the same radionuclide. Comparisons of radionuclide activity within the regions are linked to the SI via the SIR comparisons. Other international comparisons are also run by issuing aliquots of the same material to each participant.
Standard uncertainties range from 0.2 % to 2.5 %
- e.g. for $^{60}\text{Co}$, from 0.2 % using $4\pi (\beta, \gamma)$ coincidence to 1 % using a high-efficiency NaI $4\pi$ detector
- Method dependent
- Radionuclide dependent

A measurement methods matrix has been developed to reduce the number of comparisons needed to support calibrations.
A snapshot of degrees of equivalence for $^{60}$Co activity measurements made by BIPM Member States and the IRMM that have taken part in the BIPM SIR comparisons.

The NMI acronyms are given in the key comparison database of the CIPM MRA.
Other ionizing radiation dosimetry quantities also require traceability
  - e.g. ambient or personal dose equivalent
Mixtures of radionuclides, in complex matrices also require traceability
  - e.g. in food, soil samples etc

Compared through supplementary comparisons
Uncertainties are generally larger than for key comparisons – sufficient for the purpose
Air kerma comparisons in $^{137}\text{Cs}$ beams

Also used for traceability for ambient dose equivalent
Developments at the BIPM

- The CCRI meets every 2 years
- Advises on the programme at the BIPM
- Has proposed the BIPM develop appropriate standards for dosimetry comparisons in the fields of
  - mammography
  - brachytherapy
  - clinical accelerator beams
- Has proposed the BIPM develop appropriate standards for activity comparisons for
  - short-lived radionuclides (Tc-99m, F-18 etc)
  - pure beta emitters
  - pure alpha emitters
- The BIPM undertakes what it can within its limited budget
Need for comparisons in clinical accelerator beams

- To provide a more direct route using clinical beams
- To ensure traceability to the SI
- For confidence in measurements
- To support CMC declarations
- To satisfy legislation
BIPM accelerator dosimetry comparison facility

Primary standard graphite calorimeter

Setting up in an NMI accelerator beam

\[ BIPM \ u_i = 3.4 \times 10^{-3} \]
First comparison results for accelerator dosimetry

Absorbed dose to water comparison BIPM.RI(I)-K6 with the NRC, Canada

Results given as ratios with a combined standard uncertainty

Other participations to date PTB (Germany), NIST (USA)

Future participations METAS (Switzerland in spring 2011); NPL (UK in autumn 2011)
Need for comparisons in mammography dosimetry

- To provide a more direct route using clinical-type beams
- To ensure traceability to the SI
- For confidence in measurements
- To support CMC declarations
- To satisfy legislation
BIPM mammography comparison facility

Mo/Mo tube  BIPM free air chamber (FAC L-02)

\[ u_i = 2 \times 10^{-3} \]
Air kerma comparison with the NMIJ, Japan

Other participations to date, NIST (USA), PTB (Germany)

NIM (China) for characterization of their national standard
Need for comparisons in brachytherapy

- To provide a more direct route for clinical sources
- To ensure traceability to the SI
- For confidence in measurements
- To support CMC declarations
- To satisfy legislation
BIPM brachytherapy comparison facility

Well-type ionization chamber  thimble chamber

\[ u_i = 2 \times 10^{-2} \]

\[ u_i = 2 \times 10^{-4} \]
Developments for activity measurements

- Travelling transfer instrument for short-lived radionuclides

- Extension of the SIR for pure beta emitters using liquid scintillation counting methods.

\[ \text{Degrees of equivalence for equivalent activity of } ^{99m}\text{Tc} \]

\[ D_i = \frac{x_i - x_R}{(\text{MBq})} \]

\[ \left[ \frac{D_i}{x_R} \right] / (\text{kBq}/\text{MBq}) \]

63Ni trial comparison 2011
What shade is your gray?

✓ You know its traceability
✓ Your standard’s calibration is in-date
✓ You check your standards regularly
✓ You handle your standards with care
✓ You take part in dosimetry or activity audits with satisfactory results

✓ Then your gray is in a rosy state of health

Thank-you for listening!
Acknowledgements

- All my colleagues in the Ionizing Radiation Department at the BIPM for their contributions in comparisons and the characterizations of national standards
- All our ionizing radiation colleagues in our partner NMIs for their collaborations in terms of the realizations of the quantities used in ionizing radiation metrology
- All our colleagues in the Nuclear Applications Division of Human Health at the IAEA for their contributions in comparisons and particularly for the dissemination of ionizing radiation standards
- Google internet images


IAEA, 1999, SSDL Network Charter IAEA, Vienna, 1999

IAEA/WHO/SSDL/99

BIPM, the Key Comparison database of the CIPM MRA, [http://kcdb.bipm.org](http://kcdb.bipm.org)


IAEA, Absorbed dose determination in external beam radiotherapy, 2000, TRS 398