NIST Traceability

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Ionizing Radiation Division
Physical Measurement Laboratory
National Institute of Standards and Technology (NIST)
Calibration Network

Secondary Calibration Facilities
Calibration Network

End Users
NIST Policy on Metrological Traceability

• “Property of a measurement result whereby the result can be related to a reference through a documented unbroken chain of calibrations, each contributing to the measurement uncertainty."

International Vocabulary of Metrology - Basic and General concepts and Associated Terms (VIM), definition 2.41
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• Establishes metrological traceability of the results of its own measurements and of results provided to customers in NIST calibration and measurement certificates, operating in accordance with the NIST Quality System for Measurement Services.
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• Establishes metrological traceability of the results of its own measurements and of results provided to customers in NIST calibration and measurement certificates, operating in accordance with the NIST Quality System for Measurement Services.

• Asserts that providing support for a claim of metrological traceability of the result of a measurement is the responsibility of the provider of that result, whether that provider is NIST or another organization; and that assessing the validity of such a claim is the responsibility of the user of that result.
Dosimetry Traceability Chain

Primary Standard Dosimetry Laboratory

Secondary Standard Dosimetry Laboratory

PSDL

SSDL

User

\[ D_w \]

\[ \left( \frac{D_w}{Q} \right)_{SSDL} \]

\[ D_w^{User} = Q^{User} \left( \frac{D_w}{Q} \right)_{SSDL} \]
$D_w = 14.28 \text{ mGy}$
\[ D_w = 14.28 \text{ mGy} \]

\[ D_w = (14.28 \pm 0.12) \text{ mGy} \]
\[ D_w = 14.28 \text{ mGy} \]

\[ D_w = (14.28 \pm 0.12) \text{ mGy} \]

<table>
<thead>
<tr>
<th>Uncertainty Component</th>
<th>Type A (%)</th>
<th>Type B (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heat defect</td>
<td>0.30</td>
<td></td>
</tr>
<tr>
<td>Reproducibility of measurement groups</td>
<td>0.15</td>
<td>0.30</td>
</tr>
<tr>
<td>Beam attenuation from glass wall</td>
<td></td>
<td>0.10</td>
</tr>
<tr>
<td>Beam attenuation from calorimeter lid</td>
<td>0.05</td>
<td></td>
</tr>
<tr>
<td>Field size</td>
<td></td>
<td>0.23</td>
</tr>
<tr>
<td>Vessel positioning</td>
<td>0.02</td>
<td></td>
</tr>
<tr>
<td>Thermistor calibration</td>
<td>0.01</td>
<td></td>
</tr>
<tr>
<td>Water density</td>
<td>0.02</td>
<td></td>
</tr>
<tr>
<td>Quadratic sum</td>
<td>0.16</td>
<td>0.39</td>
</tr>
<tr>
<td>Relative combined standard uncertainty</td>
<td>0.42 %</td>
<td></td>
</tr>
<tr>
<td>Relative expanded uncertainty ( (k = 2) )</td>
<td></td>
<td>0.84 %</td>
</tr>
</tbody>
</table>
Strategic Element

Develop dosimetric standards for x rays, gamma rays, and electrons based on the SI unit, the gray, for homeland security, medical, radiation processing, and radiation protection applications.
Strategic Element

Develop dosimetric standards for x rays, gamma rays, and electrons based on the SI unit, the gray, $1 \text{ Gy} \equiv 1 \text{ J/kg}$

<table>
<thead>
<tr>
<th>kV x rays</th>
<th>MV x rays</th>
<th>gamma rays</th>
<th>electrons</th>
</tr>
</thead>
<tbody>
<tr>
<td>x-ray tube</td>
<td>linac</td>
<td>irradiator</td>
<td>linac, Van de Graaff</td>
</tr>
<tr>
<td>radioactive source</td>
<td></td>
<td>$(^{60}\text{Co, }^{137}\text{Cs})$</td>
<td>radioactive source</td>
</tr>
</tbody>
</table>
Free-Air Ionization Chamber (< 300 keV)

20 keV to 100 keV

\[
K_{\text{air}} = \frac{Q_{\text{air}}}{\rho_{\text{air}}V} \left( \frac{W}{e} \right)
\]

\[
\frac{C}{\text{kg}} \times 33.97 \frac{\text{J}}{\text{C}}
\]
Air Kerma as Realized by Free-Air Chambers

\[ K_{\text{air}} = \frac{Q_{\text{air}}}{\rho_{\text{air}} V} \frac{W_{\text{air}}}{e} \frac{1}{1 - g_{\text{air}}} \prod_{i} k_{i} \]

\( K_{\text{air}} \) is the air kerma at a given distance in air.

\( Q_{\text{air}} / (\rho_{\text{air}} V) \) is the measured charge due to ionization divided by the mass of air in the measuring volume.

\( W_{\text{air}} \) is the mean energy expended by an electron of charge \( e \) to produce an ion pair in dry air. The value used at NIST is \( W_{\text{air}}/e = 33.97 \text{ J/C} \).

\( g_{\text{air}} \) is the fraction of the initial kinetic energy of secondary electrons dissipated in air through radiative processes, which is 0.0 (negligible) for x rays with energies less than 300 keV.

\( \prod k_{i} \) is the product of various correction factors.
Primary Standard for Mammography X Rays ($\leq 50$ kV)

Mo, Rh anode x-ray tubes

Electrometer

Attix free-air chamber

filters
Cavity Ionization Chamber (> 300 keV)

\[ K_{\text{air}} = \frac{Q_{\text{air}}}{\rho_{\text{air}} V} \left( \frac{W_{\text{air}}}{e} \right) \left( \frac{1}{1 - g} \right) \left[ \frac{\mu_{\text{en}}}{\rho_{\text{graphite}}} \right] \left[ \frac{\mu_{\text{en}}}{\rho_{\text{air}}} \right] \left[ \frac{(\mu_{\text{en}}/\rho)_{\text{air}}}{(\mu_{\text{en}}/\rho)_{\text{graphite}}} \right] \prod_{i} k_{i} \]
Water Calorimetry (MV photons, electrons)

\[ D_{\text{water}} = c\Delta T \]

Vessel with thermistors

Vessel with an ion chamber
Monte Carlo Simulations

- Photon and electron source modeling
- Detector response calculations
- Ionization chamber correction factors $k_{\text{wall}}$
- Stopping power ratios
- Mass-energy absorption coefficient ratios
Photon and Charged-Particle Data Center

\[ \frac{\mu}{\rho} = \frac{\sigma_{\text{pe}} + \sigma_{\text{coh}} + \sigma_{\text{incoh}} + \sigma_{\text{pair}} + \sigma_{\text{trip}} + \sigma_{\text{ph.n.}}}{uA} \]

\[ \frac{S}{\rho} = \frac{S_{\text{col}}}{\rho} + \frac{S_{\text{rad}}}{\rho} \]
Web-based Photon and Electron Databases

XCOM: Photon Cross Sections Database
http://www.nist.gov/pml/data/xcom/index.cfm

Photon Cross Sections
Bibliography
http://www.nist.gov/pml/data/photon_cs/index.cfm

ESTAR: Stopping-power and range tables for electrons
http://physics.nist.gov/PhysRefData/Star/Text/ESTAR.html
How do we know what to do?

- Council on Ionizing Radiation Measurements and Standards (CIRMS)
- Consultative Committee for Ionizing Radiation (CCRI)
- National Academy of Sciences review panel
- Membership in professional societies and committees
- Feedback from colleagues and calibration customers
How do we know that our standards are accurate?

Bureau International des Poids et Mesures (BIPM)

- “The task of the BIPM is to ensure world-wide uniformity of measurements and their traceability to the International System of Units (SI).”
  
  www.bipm.org

- Calibration and Measurements Capabilities (CMCs)

- Key comparisons between NIST and the BIPM
# Calibration and Measurement Capabilities (CMCs)

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Parameter</th>
<th>Reference Standard</th>
<th>Key Comparison</th>
<th>Calibration Service?</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Air Kerma</strong></td>
<td>x ray (10 to 50) kV</td>
<td>free-air chamber</td>
<td>K2</td>
<td>Yes</td>
</tr>
<tr>
<td></td>
<td>mammography</td>
<td></td>
<td>K7</td>
<td>Yes</td>
</tr>
<tr>
<td></td>
<td>x ray (50 to 300) kV</td>
<td></td>
<td>K3</td>
<td>Yes</td>
</tr>
<tr>
<td></td>
<td>Cs-137</td>
<td>graphite cavity chamber</td>
<td>K5</td>
<td>Yes</td>
</tr>
<tr>
<td></td>
<td>Co-60</td>
<td>graphite cavity chamber</td>
<td>K1</td>
<td>Yes</td>
</tr>
<tr>
<td><strong>Absorbed Dose</strong></td>
<td>Co-60</td>
<td>water calorimeter</td>
<td>K4</td>
<td>Yes</td>
</tr>
<tr>
<td></td>
<td>Co-60 (high dose)</td>
<td>water calorimeter</td>
<td>CCRI(I)-S2</td>
<td>Yes</td>
</tr>
<tr>
<td></td>
<td>MV x rays</td>
<td>water calorimeter</td>
<td>K6</td>
<td>No</td>
</tr>
<tr>
<td></td>
<td>Sr-90/Y-90</td>
<td>extrapolation chamber</td>
<td></td>
<td>Yes</td>
</tr>
<tr>
<td><strong>Air Kerma</strong></td>
<td>Cs-137 brachy</td>
<td>graphite cavity chamber</td>
<td></td>
<td>Yes</td>
</tr>
<tr>
<td></td>
<td>Ir-192 brachy</td>
<td>graphite cavity chamber</td>
<td></td>
<td>Yes</td>
</tr>
<tr>
<td></td>
<td>HDR Ir-192 brachy</td>
<td></td>
<td>K8</td>
<td>No</td>
</tr>
<tr>
<td></td>
<td>I-125 brachy</td>
<td>WAFAC</td>
<td></td>
<td>Yes</td>
</tr>
<tr>
<td></td>
<td>Pd-103 brachy</td>
<td>WAFAC</td>
<td></td>
<td>Yes</td>
</tr>
<tr>
<td></td>
<td>Cs-131 brachy</td>
<td>WAFAC</td>
<td></td>
<td>Yes</td>
</tr>
</tbody>
</table>
How do we disseminate our standards?

Calibration Services in Radiation Dosimetry at NIST

- **X-Ray and Gamma-Ray Measuring Instruments**
  - Air kerma - $^{60}\text{Co}$, $^{137}\text{Cs}$, x-ray beams
  - Irradiation of passive dosimeters
  - kV measuring devices
  - Absorbed dose to water - $^{60}\text{Co}$

- **Gamma-Ray and Beta-Particle Sources and Measuring Instruments**
  - Air kerma strength - photon brachytherapy sources: $^{125}\text{I}$, $^{103}\text{Pd}$, $^{131}\text{Cs}$, $^{192}\text{Ir}$, $^{137}\text{Cs}$
  - Absorbed dose to water - beta brachytherapy sources: $^{90}\text{Sr}/\text{Y}$, $^{106}\text{Ru}/\text{Rh}$
  - Surface dose rate – $^{90}\text{Sr}/\text{Y}$, $^{147}\text{Pm}$, $^{204}\text{Tl}$ sources and extrapolation chambers

- **High-Dose Dosimetry**
  - Irradiation of dosimeters in high-dose gamma ray fields ($^{60}\text{Co}$)
  - Alanine/EPR dose measurements
How do we disseminate our standards?

Secondary Standard Dosimetry Laboratory (SSDL)

- Accredited laboratory that provides NIST-traceable dosimetry calibrations to end users

- An example: Accredited Dosimetry Calibration Laboratories (ADCLs)
  
  - Accredited by the American Association of Physicists in Medicine (AAPM)
  
  - Calibrate clinical dosimetry instrumentation and radioactive sources used in medical diagnostic and therapeutic applications of ionizing radiation
  
  - Establishment and maintenance of NIST traceability of ADCL calibrations overseen by the Calibration Laboratory Accreditation (CLA) Subcommittee
The only type of laboratory accredited by the AAPM is a secondary standard laboratory with the capability of providing direct traceability to the National Institute of Standards and Technology (NIST). Such a laboratory is referred to as an Accredited Dosimetry Calibration Laboratory (ADCL).

A3.6.1.6 Calibration traceability to NIST dosimetry standards shall be maintained by participation in NIST measurement quality assurance tests and in ADCL intercomparisons at intervals prescribed by the Subcommittee.
Wide-Angle Free-Air Chamber (WAFAC)

160 mm Al Center Electrode

Al Filter

Rotating Source

W Aperture

Electrometer

$V = -1674\ V$

$V/2$
Wide-Angle Free-Air Chamber (WAFAC)

Rotating Source

Al Filter

43 mm Al Center Electrode

W Aperture

V/2

V = -450 V

Electrometer

Wide-Angle Free-Air Chamber (WAFAC)
Original and Automated WAFACs

- HPGe Spectrometer
- Automated WAFAC
- Original WAFAC
- Al filter wheel
- Seed
Air Kerma Strength \( (S_K) \) Standard for \(^{125}\text{I}\) seeds

\[
S_K = \hat{K}_{\text{air}}(Q)d^2 = \left(\frac{W}{e}\right)\left(\frac{d^2}{\rho_{\text{air}}V_{\text{eff}}}\right)K_{\text{dr}}(\hat{K})M_{\text{det}}(\hat{K},Q)\prod_i K_i \prod_j K_j(Q)
\]

<table>
<thead>
<tr>
<th></th>
<th>Value</th>
<th>Type A (%)</th>
<th>Type B (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Net current, ( M_{\text{det}}(\hat{K},Q) )</td>
<td>( s )</td>
<td>0.06</td>
<td></td>
</tr>
<tr>
<td>( \bar{W}/e )</td>
<td>33.97 J / C</td>
<td>-</td>
<td>0.15</td>
</tr>
<tr>
<td>Air density, ( \rho_{\text{air}} )</td>
<td>1.196 mg / cm(^3)</td>
<td>-</td>
<td>0.03</td>
</tr>
<tr>
<td>Aperture distance, ( d )</td>
<td>-</td>
<td>0.24</td>
<td></td>
</tr>
<tr>
<td>Effective chamber volume, ( V_{\text{eff}} )</td>
<td>0.11</td>
<td>0.01</td>
<td></td>
</tr>
<tr>
<td>Decay correction, ( K_1 )</td>
<td>( T_{1/2} = 59.43 \text{ d} )</td>
<td>-</td>
<td>0.02</td>
</tr>
<tr>
<td>Recombination, ( K_{\text{dr}}(\hat{K}) )</td>
<td>&lt; 1.004</td>
<td>-</td>
<td>0.05</td>
</tr>
<tr>
<td>Attenuation in filter, ( K_3(Q) )</td>
<td>1.0295</td>
<td>-</td>
<td>0.61</td>
</tr>
<tr>
<td>Air attenuation in WAFAC, ( K_4(Q) )</td>
<td>1.0042</td>
<td>-</td>
<td>0.08</td>
</tr>
<tr>
<td>Source-aperture attenuation, ( K_5(Q) )</td>
<td>1.0125</td>
<td>-</td>
<td>0.24</td>
</tr>
<tr>
<td>Inverse-square correction, ( K_6 )</td>
<td>1.0089</td>
<td>-</td>
<td>0.01</td>
</tr>
<tr>
<td>Humidity, ( K_7(Q) )</td>
<td>0.9982</td>
<td>-</td>
<td>0.07</td>
</tr>
<tr>
<td>In-chamber photon scatter, ( K_8(Q) )</td>
<td>0.9966</td>
<td>-</td>
<td>0.07</td>
</tr>
<tr>
<td>Source-holder scatter, ( K_9 )</td>
<td>0.9985</td>
<td>-</td>
<td>0.05</td>
</tr>
<tr>
<td>Electron loss, ( K_{10} )</td>
<td>1.0</td>
<td>-</td>
<td>0.05</td>
</tr>
<tr>
<td>Aperture penetration, ( K_{11}(Q) )</td>
<td>0.9999</td>
<td>-</td>
<td>0.02</td>
</tr>
<tr>
<td>External photon scatter, ( K_{12}(Q) )</td>
<td>1.0</td>
<td>-</td>
<td>0.17</td>
</tr>
</tbody>
</table>

Combined standard uncertainty, \( u_c \) \( (s^2 + 0.762^2)^{1/2} \)

Expanded uncertainty, \( V \) \( 2u_c \)
Measurement Traceability for Brachytherapy Sources

NIST

Sources

ADCL

Well-ionization chambers

Secondary standard

Manufacturer

Verification for treatment planning

Sources

Clinic

SK

SK

SKClinic
Recommendations of the Calibration Laboratory Accreditation SC:

New source

1. 5 sources are sent to NIST for $S_K$ calibration, well chamber measurements ($S_K / I$), and spectrum analysis

2. If ($S_K / I$) for each source is within ± 1.00 % of average, 3 sources are sent to the ADCLs, and 2 sources are returned to the manufacturer or sent to a dosimetry investigator for measurement of $\hat{D}(r, \theta)$

3. If ($S_K / I$) is out of tolerance for one or more sources, another set of 5 sources is sent by the manufacturer to NIST

Measurement Traceability for Brachytherapy Sources – New Source

\[ S_K \]

\[ u_c = 0.8 \% \]

ADCL

Manufacturer

Clinic
Measurement Traceability for Brachytherapy Sources – New Source

ADCL1 → ADCL2 → ADCL3

3 sources

secondary standard

$S_K$

$u_c = 0.9\%$

ADCL calibration date

$(S_K / I)_0$

$u_c = 0.9\%$

Manufacturer

$S_K / I$?

Clinic
Measurement Traceability for Brachytherapy Sources – New Source

\[ S_K \]
\[ u_c = 0.8 \% \]

ADCL \quad \text{well-ionization chambers}

\[ (S_K / I)_{ADCL} \]
\[ u_c = 1.2 \% \]

source

Manufacturer

Clinic
Measurement Traceability for Brachytherapy Sources – New Source

$S_K$

$u_c = 0.8 \%$

ADCL

Manufacturer

$S_K^{\text{Clinic}}$

$u_c = 1.3 \%$
Measurement Traceability for Brachytherapy Sources – New Source

$S_{KM}$

$uc = ?$

$S_{KClinic}$

$uc = 1.3\%$
Recommendations of the Calibration Laboratory Accreditation SC:

**QA for sources with established NIST $S_K$ standard**

1. 3 sources sent to NIST (preferably within 6 months but not exceeding 1 year) for $S_K$ calibration and ($S_K / I$) evaluation

2. If ($S_K / I$) for each source is within ± 2.00 % of established ($S_K / I$) at NIST or the ADCLs, no action needs to be taken

3. If ($S_K / I$) is out of tolerance, the cause should be investigated, and another set of 3 sources is sent by the manufacturer to NIST and the ADCLs

4. If ($S_K / I$) remains out of tolerance for the second set of source measurements, discrepancies among the ADCLs and NIST should be resolved quickly
Measurement Traceability for Brachytherapy Sources – Annual QA

NIST

3 sources

$S_K$

3 sources

ADCL1 ➔ ADCL2 ➔ ADCL3

Manufacturer

3 sources

Clinic

$(S_K / I)_t$

± 2.00 %

vs.

$(S_K / I)_0$
Clinical Brachytherapy Source Measurements

Well-ionization chambers, calibrated by an ADCL

\[ S_{K}^{Clinic} = I^{Clinic} \left( \frac{S_{K}}{I} \right)_{ADCL} \]
Control Chart, $I/S_K$, seed “E”
Control Chart, $I / S_K$, seed “E”

Manufacturer vs. NIST ($S_K^M / S_K^{NIST}$)
Fluorescence $K_\alpha$ / Decay $K_\alpha$, seed “E”

Manufacturer vs. NIST ($S_{K}^M / S_{K}^{NIST}$)
Control Chart, $I / S_K$, seed “E”

Manufacturer vs. NIST ($S_K^M / S_K^{NIST}$)
Control Chart, $I / S_K$, seed “E”

Manufacturer vs. NIST ($S_K^M / S_K^{NIST}$)
Source manufacturers have generally been successful in transferring the NIST $S_K$ standard to their facilities. However, there is much variation with respect to the magnitude and precision of reported uncertainties on calibration certificates, if uncertainties are reported at all.
Summary

• A measurement is “NIST traceable” if it is part of a documented and unbroken chain of measurements from the user to NIST, including uncertainties.

• Uncertainty analysis is not only a critical element of the science of metrology, but is required for a valid traceability chain.

• NIST provides traceability to users both directly and through accredited secondary calibration laboratories.

• Once established, traceability must be maintained through the use of intercomparisons and proficiency tests.
Radiation Interactions and Dosimetry Group Staff

Dr. Fred Bateman, Physicist
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