Practical Course in Reference Dosimetry

Electron Beam Dosimetry and Codes of Practice
The IPEM code of practice for electron beam dosimetry for radiotherapy beams of initial energy 4 to 25 MeV based on an absorbed dose to water calibration.

IPEM 2003 Code of Practice
Overview

• Based on the NPL absorbed dose calibration service, which gives direct factors for electron chambers in terms of absorbed dose to water

• Very simple procedure to follow in the clinic, together with a significantly reduced uncertainty compared to IPEMB 1996 Code based on air kerma

• Electron dosimetry now on the same footing as MV photons
Outline of Code

Section 1 - Introduction
Section 2 – Code of Practice
Appendices:
- A – Corrections
- B – Chambers
- C – Formalism
- D – Data
- E – Uncertainties

Everything you need to measure absorbed dose to water in electron beams is in this document.

Contents

1. Introduction
   1.1. Brief review of previous UK recommendations for electron dosimetry
   1.2. Development of the NPL absorbed dose calibration service for electron beams
   1.3. Current code of practice
   1.4. List of symbols

2. Code of practice
   2.1. Instrumentation
   2.2. Measurements in an electron beam
      2.2.1. General points
      2.2.2. Beam quality specification
      2.2.3. Calibration reference depth
      2.2.4. Determination of central-axis depth–dose curves
      2.2.5. Determination of absorbed dose at the reference point
      2.2.6. Transfer of dose from calibration reference point to the depth of dose maximum
      2.2.7. Determination of relative output factors
      2.2.8. Use of non-water phantoms
      2.2.9. Use of other chambers as field instruments
      2.2.10. Extension to beam qualities outside the range available at the standards laboratory

Appendix A. Corrections to the instrument reading
   A.1. Introduction
   A.2. Temperature, pressure and humidity
   A.3. Polarity
   A.4. Ion recombination
   A.5. Electrometer correction factor
   A.6. Summary of correction factors

Appendix B. Chamber characteristics
   B.1. Desirable properties of parallel-plate chambers
   B.2. Characteristics of the designated chamber types
   B.3. Desirable properties of measuring assemblies

Appendix C. Formalism
   C.1. Absorbed dose calibration of ion chambers
   C.2. Determination of absorbed dose to water in an electron beam

Appendix D. Data
   D.1. Calibration data for ion chambers
   D.2. Stopping power ratios
   D.3. Choice of reference depth
   D.4. Non-water phantoms
   D.5. Determination of energy parameters of electron beams
   D.6. Indirectly required parameters

Appendix E. Estimated uncertainties

References
(1) define reference depth in water for beams at NPL

\[ z_{ref,w} = 0.6 \, R_{50,w} - 0.1 \, \text{cm} \]

(2) use range scaling to get depth in graphite

\[ z_{ref,g} = z_{ref,w} \frac{R_{50,g}}{R_{50,w}} \]

(3) calibrate chamber against the calorimeter at NPL, in graphite, at

\[ N_{D,ref,g} = \frac{D_g}{M_{ref,g}} \]
(4) theoretical conversion from graphite to water

\[ N_{D,\text{ref},w} = N_{D,\text{ref},g} \frac{P_{\text{ref},w}}{P_{\text{ref},g}} \frac{S_{\text{w/air}}}{S_{\text{g/air}}} \]

(5) compare user and reference chambers at NPL, at \( z_{\text{ref},w} \) in water

\[ N_{D,\text{user},w} = N_{D,\text{ref},w} \frac{M_{\text{ref},w}}{M_{\text{user},w}} \]

The formalism is described in detail in Appendix C.
Trial calibrations carried out in 1996, 1997 and 1999

- 17 UK radiotherapy centres, supplied 46 chambers
  NACP, Markus, Farmer and Roos types, electrometers also supplied
- Calibrated at 7 energies in the range 3 to 17 MeV
- Comparison in clinic with IPEMB 1996 CoP

“The change in stated dose was no more than 2% for individual chambers of Farmer, NACP and Roos designs and generally less than 1%…”

“Based on this work, the Markus design is not recommended as a designated chamber for absolute dosimetry (see section 2.1.2 and appendix B)”. 
Validation

![Graph showing Dose (NPL) / Dose (IPEMB) vs. R_{50,D} (cm)]

- Dose (NPL) / Dose (IPEMB) values range from 0.98 to 1.05.
- The graph plots R_{50,D} (cm) on the x-axis and Dose (NPL) / Dose (IPEMB) on the y-axis.
- Different markers and line styles represent various data points and trends.
2. Code of practice

2.1. Instrumentation

2.2. Measurements in an electron beam

2.2.1. General points

2.2.2. Beam quality specification

2.2.3. Calibration reference depth

2.2.4. Determination of central-axis depth–dose curves

2.2.5. Determination of absorbed dose at the reference point

2.2.6. Transfer of dose from calibration reference point to the depth of dose maximum

2.2.7. Determination of relative output factors

2.2.8. Use of non-water phantoms

2.2.9. Use of other chambers as field instruments

2.2.10. Extension to beam qualities outside the range available at the standards laboratory
2.1.1 Equipment required

- Chamber & electrometer
- Temperature & Pressure sensors
- Scanning tank

2.1.2 Designated chambers

- Farmer: NE2571, PTW30004, PTW30012
- Parallel plate: Scanditronix NACP-02, PTW Roos 34001

Note: Manufacturers specified – not copies!

2.1.3 Effective point of measurement
Order of preference:
1. Water
2. Epoxy resin materials
3. PMMA, polystyrene

Reference material

- Calibration in a water phantom recommended
- Solid phantoms allowed, especially for low energy beams (see 2.2.8)

N.B. Uncertainties increase

Section 2 in more detail
2.2.1
Section 2 in more detail

2.2.2

**Beam quality specification**

Electron energy as a specifier can be confusing – what does it refer to?

- Mean energy emerging from linac?
- Mean energy at phantom surface?

Choose $R_{50,D}$ as the specifier:

- Defines reference depth
- Calibration factors on the NPL certificate given as a function of $R_{50,D}$

depth in water, $z$/cm
Section 2 in more detail

2.2.3

**Calibration reference depth**

\[ z_{\text{ref}} = 0.6 \ R_{50,D} - 0.1 \]

What’s wrong with the peak?
Depth-dose curves for NPL Clinical Linac

- 4 MeV
- 6 MeV
- 8 MeV
- 10 MeV
- 12 MeV
- 15 MeV
- 18 MeV
- 20 MeV
- 22 MeV
The graph shows a linear fit equation for the relationship between $R_{50}$ in water and $R_{100}$ in water. The equation is:

$$R_{50} = 3.5 \text{ cm} \quad R_{100} = 0.60 \quad R_{50} = 0.10$$

The data points represent measurements from different sources, including NPL, Royal London SL18, Edinburgh WG LA20, Mount Vernon SL20, Rogers SL75/20, 2100C, Therac 20, NKI SL75/20, and NRC.
Measurement of depth dose curves

Ion chamber or diode

Need to convert ionisation to dose:

a) Equation 2.1 $R_{50,I}$ to $R_{50,D}$ (Ding et al, 1995)
   - $R_{50,D} = 1.029R_{50,I} - 0.063$ cm
   - Based on evaluations of measurements and matched Monte Carlo calculations

b) Equation D.2 (the “Burns equation”)
   - Based on evaluations by Burns et al 1996, of the work by Ding et al, 1995

c) Table 1 (p2940)
   - Based on the Burns equation

d) Could also use stopping power ratios as calculated directly using Monte Carlo codes such as SPRRZ
### Table 1. Spencer-Attix restricted mass collision stopping power ratios ($\Delta = 10$ keV), water to air ($s_{w/air}$) for electron beams as a function of beam quality $R_{50,D}$ and depth in water; the values are calculated from equation (D.2) (Burns et al 1996, IAEA 2000).

<table>
<thead>
<tr>
<th>Depth in water (cm)</th>
<th>$R_{50,D}$ (cm)</th>
<th>Beam quality</th>
<th>$s_{w/air}$ ($s_{nfr}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1.102</td>
<td>1.088</td>
<td>1.078</td>
</tr>
<tr>
<td>0</td>
<td>1.075</td>
<td>1.055</td>
<td>1.041</td>
</tr>
<tr>
<td>0.1</td>
<td>1.080</td>
<td>1.059</td>
<td>1.044</td>
</tr>
<tr>
<td>0.2</td>
<td>1.085</td>
<td>1.063</td>
<td>1.047</td>
</tr>
<tr>
<td>0.3</td>
<td>1.091</td>
<td>1.067</td>
<td>1.050</td>
</tr>
<tr>
<td>0.4</td>
<td>1.096</td>
<td>1.071</td>
<td>1.053</td>
</tr>
<tr>
<td>0.5</td>
<td>1.102</td>
<td>1.075</td>
<td>1.057</td>
</tr>
<tr>
<td>0.6</td>
<td>1.108</td>
<td>1.079</td>
<td>1.060</td>
</tr>
<tr>
<td>0.8</td>
<td>1.120</td>
<td>1.088</td>
<td>1.067</td>
</tr>
<tr>
<td>1</td>
<td>1.132</td>
<td>1.097</td>
<td>1.074</td>
</tr>
<tr>
<td>1.2</td>
<td>1.146</td>
<td>1.107</td>
<td>1.082</td>
</tr>
<tr>
<td>1.4</td>
<td>1.171</td>
<td>1.109</td>
<td>1.070</td>
</tr>
<tr>
<td>1.6</td>
<td>1.127</td>
<td>1.098</td>
<td>1.071</td>
</tr>
<tr>
<td>1.8</td>
<td>1.138</td>
<td>1.106</td>
<td>1.084</td>
</tr>
<tr>
<td>2</td>
<td>1.115</td>
<td>1.091</td>
<td>1.073</td>
</tr>
<tr>
<td>2.5</td>
<td>1.139</td>
<td>1.111</td>
<td>1.089</td>
</tr>
<tr>
<td>3</td>
<td>1.132</td>
<td>1.107</td>
<td>1.088</td>
</tr>
<tr>
<td>3.5</td>
<td>1.126</td>
<td>1.104</td>
<td>1.086</td>
</tr>
<tr>
<td>4</td>
<td>1.147</td>
<td>1.122</td>
<td>1.101</td>
</tr>
<tr>
<td>4.5</td>
<td>1.141</td>
<td>1.118</td>
<td>1.099</td>
</tr>
<tr>
<td>5</td>
<td>1.136</td>
<td>1.115</td>
<td>1.097</td>
</tr>
<tr>
<td>5.5</td>
<td>1.132</td>
<td>1.112</td>
<td>1.080</td>
</tr>
<tr>
<td>6</td>
<td>1.127</td>
<td>1.092</td>
<td>1.065</td>
</tr>
<tr>
<td>7</td>
<td>1.120</td>
<td>1.088</td>
<td>1.063</td>
</tr>
<tr>
<td>8</td>
<td>1.152</td>
<td>1.113</td>
<td>1.083</td>
</tr>
<tr>
<td>9</td>
<td>1.142</td>
<td>1.106</td>
<td>1.079</td>
</tr>
<tr>
<td>10</td>
<td>1.132</td>
<td>1.100</td>
<td>1.074</td>
</tr>
<tr>
<td>11</td>
<td>1.149</td>
<td>1.115</td>
<td>1.087</td>
</tr>
<tr>
<td>12</td>
<td>1.128</td>
<td>1.075</td>
<td>1.038</td>
</tr>
<tr>
<td>13</td>
<td>1.108</td>
<td>1.063</td>
<td>1.017</td>
</tr>
<tr>
<td>14</td>
<td>1.091</td>
<td>1.036</td>
<td>1.011</td>
</tr>
<tr>
<td>15</td>
<td>1.057</td>
<td>1.028</td>
<td>1.022</td>
</tr>
<tr>
<td>16</td>
<td>1.081</td>
<td>1.046</td>
<td>1.066</td>
</tr>
<tr>
<td>17</td>
<td>1.091</td>
<td>1.036</td>
<td>1.011</td>
</tr>
<tr>
<td>18</td>
<td>1.057</td>
<td>1.028</td>
<td>1.022</td>
</tr>
<tr>
<td>19</td>
<td>1.081</td>
<td>1.046</td>
<td>1.066</td>
</tr>
</tbody>
</table>
Determination of absorbed dose at the reference point

For user chamber with NPL calibration factor $N_{D,\text{user,}w}$ (given as a function of $R_{50,D}$):

1. Measure $R_{50,D}$ for nominal 1 m SSD
2. Position chamber at $z_{\text{ref}} = 0.6 \times R_{50,D} - 0.1$ (cm)
3. Interpolate certificate data to derive $N_{D,w,\text{user}}(R_{50,D})$
4. At $z_{\text{ref}}$: $D_w = M_w \times N_{D,w,\text{user}}$
### Scanditronix, type NACP-02, serial number DFA000-12305

<table>
<thead>
<tr>
<th>$E_{\text{nom}}$ MeV</th>
<th>$R_{50,D}$ cm</th>
<th>$z_{\text{ref}}$ cm</th>
<th>$N_{D,w}$ Gy/C</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>1.70</td>
<td>0.92</td>
<td>$15.25 \times 10^7$</td>
</tr>
<tr>
<td>6</td>
<td>2.42</td>
<td>1.35</td>
<td>$15.17 \times 10^7$</td>
</tr>
<tr>
<td>10</td>
<td>3.99</td>
<td>2.29</td>
<td>$14.94 \times 10^7$</td>
</tr>
<tr>
<td>15</td>
<td>6.03</td>
<td>3.52</td>
<td>$14.65 \times 10^7$</td>
</tr>
<tr>
<td>20</td>
<td>8.06</td>
<td>4.74</td>
<td>$14.43 \times 10^7$</td>
</tr>
<tr>
<td>22</td>
<td>9.01</td>
<td>5.31</td>
<td>$14.35 \times 10^7$</td>
</tr>
</tbody>
</table>
Section 2 in more detail

2.2.8

Non-water phantoms

- Solid phantoms offer significant advantages:
  - Robust
  - Dry!
  - Mechanically stable
  - Easy to set up

- but we need absorbed dose to *water*
Section 2 in more detail
2.2.8

**Non-water phantoms**

- $h_m = \text{ratio of fluences in the water and non-water phantoms at the same water equivalent depth}$

\[
D_w(z_{w,\text{eff}}) = M_{ch,\text{non-w}} h_m N_{D,w}
\]

- Also need range scaling factor $C_{pl}$ to get the depth in solid where the electron spectrum is (approximately) the same:

\[
z_{w,\text{eff}} = z_{\text{non-w}} C_{pl}
\]

Data given in CoP for $h_m$ and $C_{pl}$ (Tables 2 & 3, p2945)
Section 2 in more detail

2.2.8  

**Non-water phantoms**

<table>
<thead>
<tr>
<th>Phantom material</th>
<th>Quoted standard density (g cm(^{-3}))</th>
<th>Typical range of densities (g cm(^{-3}))</th>
<th>Scaling factor (C_{pl})</th>
</tr>
</thead>
<tbody>
<tr>
<td>Epoxy resin</td>
<td>1.02 (photon formulation)</td>
<td>0.99—1.04</td>
<td>0.98 (photon formulations)(^a)</td>
</tr>
<tr>
<td>water substitutes</td>
<td>1.04 (electron formulation)</td>
<td></td>
<td>1.00 (electron formulations)(^b)</td>
</tr>
<tr>
<td>Clear polystyrene</td>
<td>1.045</td>
<td>1.03—1.06</td>
<td>0.98</td>
</tr>
<tr>
<td>White polystyrene</td>
<td>1.055</td>
<td>1.04—1.07</td>
<td>0.995</td>
</tr>
<tr>
<td>PMMA</td>
<td>1.185</td>
<td>1.17—1.120</td>
<td>1.13</td>
</tr>
</tbody>
</table>

\(^a\) e.g. WT1 (St Bartholomews Hospital), ‘solid water’ RMI 451 (Gammex-RMI) (see the text and D.4.2).

\(^b\) e.g. WTe (St Bartholomews Hospital), ‘solid water’ RMI 457 (Gammex-RMI), ‘plastic water’ (Nuclear Associates) (see the text and D.4.2).

<table>
<thead>
<tr>
<th>Phantom material</th>
<th>(h_{m})</th>
</tr>
</thead>
<tbody>
<tr>
<td>Epoxy resin materials:</td>
<td></td>
</tr>
<tr>
<td>WT1, RMI 451, RMI 457</td>
<td>1.011</td>
</tr>
<tr>
<td>Epoxy resin materials:</td>
<td></td>
</tr>
<tr>
<td>WTe, ‘plastic water’</td>
<td>1.000</td>
</tr>
<tr>
<td>Clear polystyrene</td>
<td>1.025</td>
</tr>
<tr>
<td>White polystyrene</td>
<td>1.018</td>
</tr>
<tr>
<td>PMMA</td>
<td>1.008</td>
</tr>
</tbody>
</table>

Table 2. Depth scaling factors, \(C_{pl}\), for non-water phantoms (see appendix D.4.4).
\[
D_w(z_{ref}) = M(z_{ref}) N_{D,w}(R_{50})
\]

\[
M(z_{ref}) = M_{raw} f_{TP} f_{pol} f_{ion} f_{elec}
\]
Recombination correction:

- It is important that a chamber is operated in the linear region:

![Graph showing recombination correction](image-url)
D.2. Stopping power ratios

D.4. Non-water phantoms

D.5. Determination of energy parameters of electron beams
Note that the uncertainties in the certificate are slightly different (and larger) than those in tables E.1 and E.2 of the CoP:

### Appendix E: Uncertainties

#### Uncertainties in the calibration of an ionisation chamber in terms of absorbed dose to water

<table>
<thead>
<tr>
<th>Source of uncertainty</th>
<th>Type A</th>
<th>Type B</th>
</tr>
</thead>
<tbody>
<tr>
<td>Graphite calibration factor for NPL chambers</td>
<td>0.25</td>
<td>0.25</td>
</tr>
<tr>
<td>Ratio of chamber measurements</td>
<td>0.1</td>
<td></td>
</tr>
<tr>
<td>Ratio of stopping powers</td>
<td></td>
<td>0.5</td>
</tr>
<tr>
<td>Ratio of perturbation factors</td>
<td></td>
<td>0.7</td>
</tr>
<tr>
<td>Recombination correct ion</td>
<td></td>
<td>0.17</td>
</tr>
<tr>
<td>Polarity correction</td>
<td></td>
<td>0.1</td>
</tr>
<tr>
<td>Electrometer calibration</td>
<td></td>
<td>0.05</td>
</tr>
<tr>
<td>Quadratic sum</td>
<td>0.34</td>
<td>0.90</td>
</tr>
<tr>
<td>Combined uncertainty</td>
<td>0.96</td>
<td></td>
</tr>
</tbody>
</table>

#### Uncertainties in the determination of absorbed dose to water

<table>
<thead>
<tr>
<th>Source of uncertainty</th>
<th>Type A</th>
<th>Type B</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water calibration factor for user chambers</td>
<td>0.34</td>
<td>0.90</td>
</tr>
<tr>
<td>Matching of NPL and clinical beam qualities</td>
<td></td>
<td>0.3</td>
</tr>
<tr>
<td>Practical set and chamber measurement per MU (^{[a]})</td>
<td>0.50</td>
<td></td>
</tr>
<tr>
<td>Influence factors</td>
<td>0.25</td>
<td></td>
</tr>
<tr>
<td>Measuring chamber stability</td>
<td>0.25</td>
<td></td>
</tr>
<tr>
<td>Electrometer calibration</td>
<td>0.05</td>
<td></td>
</tr>
<tr>
<td>Quadratic sum</td>
<td>0.7</td>
<td>0.95</td>
</tr>
<tr>
<td>Combined uncertainty</td>
<td>1.2</td>
<td></td>
</tr>
</tbody>
</table>
Summary

• It’s all there!
• It is prescriptive but requires some interpretation
• You will need to read the entire CoP to implement it
Electron practical session

The practical session will focus on the IPEM 2003 Code of Practice through a combination of paper exercises and measurements.

Paper exercises: Determination of range parameters, $N_{D,w}$ factors and other data

Measurements: Output factors, recombination and polarity
The End
### Polarity corrections

**Farmer chambers**

<table>
<thead>
<tr>
<th>$E$ (MeV)</th>
<th>PTW</th>
<th>NE2505/3</th>
<th>NE2571</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>1.0008</td>
<td>0.9881</td>
<td>0.9961</td>
</tr>
<tr>
<td>12</td>
<td></td>
<td>0.9926</td>
<td>0.9982</td>
</tr>
<tr>
<td>16</td>
<td>1.0013</td>
<td>0.9951</td>
<td>0.9990</td>
</tr>
<tr>
<td>19</td>
<td>1.0011</td>
<td>0.9948</td>
<td>0.9981</td>
</tr>
</tbody>
</table>

- Beware - all graphite-walled Farmer chambers are **not** the same!
- Significant differences of up to 0.5%
- Difference between NE2505/3 and NE2571 is due to different guarding arrangements