Stopping-power ratios and beam quality factors for carbon ion beams – impact of new ICRU90 key data

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Nothing to disclose.
Reference dosimetry for carbon ions relies on:
- Use of calibrated ionization chambers
- Absorbed dose-to-water

Heavy-Ion Beams (ch. 11)

\[ D_{w,Q} = M_Q \cdot N_{D,w,Q_0} \cdot k_{Q,Q_0} \]

- \( M_Q \): Corrected chamber reading
- \( N_{D,w,Q_0} \): Chamber calibration coefficient (for beam quality \( Q_0 \), mostly \( Q_0 = ^{60}\text{Co} \))
- \( k_{Q,Q_0} \): Beam quality correction factor
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- \( N_{D,w,Q_0} \): Chamber calibration coefficient (for beam quality \( Q_0 \), mostly \( Q_0 = ^{60}\text{Co} \))
- \( k_{Q,Q_0} \): Beam quality correction factor

No primary standard for carbon ions → obtained from calculations
Computation of beam correction factors

\[ k_{Q,Q_0} = \frac{(s_{w,\text{air}})_Q}{(s_{w,\text{air}})_{Q_0}} \cdot \frac{(p_{ch})_Q}{(p_{ch})_{Q_0}} \cdot \frac{(W/e)_Q}{(W/e)_{Q_0}} \]
ICRU Report no. 90 (2014)

New key data for dosimetry

\[ k_{Q,Q_0} = \frac{(s_{w,air})_Q}{(s_{w,air})_{Q_0}} \cdot \frac{(p_{ch})_Q}{(p_{ch})_{Q_0}} \cdot \frac{(W/e)_Q}{(W/e)_{Q_0}} \]
# Changes in ICRU 90

## Protons

<table>
<thead>
<tr>
<th>Quantity</th>
<th>TRS-398</th>
<th>ICRU73</th>
<th>DIN6801-1</th>
<th>ICRU90</th>
</tr>
</thead>
<tbody>
<tr>
<td>(s_{w,\text{air}})</td>
<td>1.133±0.5%±0.2%</td>
<td>—</td>
<td>1.133</td>
<td>(1.127)(^b) ±1.2% (NE-2571) chamber</td>
</tr>
<tr>
<td>(p)</td>
<td>—</td>
<td>—</td>
<td>Partly updated(^b)</td>
<td>—</td>
</tr>
<tr>
<td>(W_{\text{air}}/e)</td>
<td>33.97 eV±0.2%</td>
<td>—</td>
<td>33.97 eV</td>
<td>33.97 eV±0.12 eV (0.35%)</td>
</tr>
</tbody>
</table>

## Light ions (He-Ar)

<table>
<thead>
<tr>
<th>Quantity</th>
<th>TRS-398</th>
<th>ICRU73</th>
<th>DIN6801-1</th>
<th>ICRU90</th>
</tr>
</thead>
<tbody>
<tr>
<td>(s_{w,\text{air}})</td>
<td>Fixed value, 1.130</td>
<td>—</td>
<td>Analytical expression(^d)</td>
<td>—</td>
</tr>
<tr>
<td>(p)</td>
<td>1.0</td>
<td>—</td>
<td>1.0</td>
<td>—</td>
</tr>
<tr>
<td>(W_{\text{air}}/e)</td>
<td>34.50 eV(^a)</td>
<td>—</td>
<td>34.50 eV(^a)</td>
<td>34.71 eV±0.52 eV (1.5%)(^e,f)</td>
</tr>
<tr>
<td>(I_{\text{water}})</td>
<td>75.0±2.0 eV(^z,j)</td>
<td>67.2 (corr. 78) eV (Z &gt; 2)(^h)</td>
<td>75.0 eV (Z = 2)</td>
<td>78.0 eV±2.0 eV</td>
</tr>
<tr>
<td>(I_{\text{air}})</td>
<td>85.7±1.7 eV(^z,j)</td>
<td>82.8 eV (Z &gt; 2)(^h)</td>
<td>85.7 eV (Z = 2)</td>
<td>85.7 eV±1.2 eV</td>
</tr>
</tbody>
</table>

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\(^a\) Not explicitly stated (but \(s_{w,\text{air}} - p\)) isolated value given in [10].

\(^b\) From Muir and Rogers [21] - otherwise taken from TRS398.

\(^c\) \(u = h/R_{\text{air}}\), with \(a = 1.137, b = -2.3 \times 10^{-3}\), and \(c = 1.841 \times 10^{-3}\).

\(^d\) Same as \(^c\), with \(a = 1.130, b = -9.0 \times 10^{-3}\), and \(c = 8.889 \times 10^{-4}\) for alpha particles and \(a = 1.1203, a = -3.598 \times 10^{-3}\), and \(c = 1.942 \times 10^{-4}\) for \(Z > 2\).

\(^e\) Independent of particle energy / type.

\(^f\) For carbon ions.

\(^g\) Not explicitly stated; same data as ICRU48 (1993) - originally from ICRU47 (1984) - for protons and alpha particles.

\(^h\) Not explicitly stated; some composition and elemental data used as ICRU48 (1993) but applied Bragg's additivity rule for mixture.
**Changes in ICRU 90**

Table 7.2. Estimated relative changes in the reference dosimetry of high-energy radiotherapy beams and related quantities following the implementation of the new key data. The estimates are applicable to graphite-walled ionization chambers calibrated in terms of absorbed dose to water ($N_{D,w,\infty Co}$).

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Relative change, %</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>$D_{wa}$ for photons</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$N_{D,\infty Co}$</td>
<td>0</td>
<td>See Eqs. (7.2) and (7.3)</td>
</tr>
<tr>
<td>$(s_{wa,\infty Pch})_Q$</td>
<td>0.5</td>
<td>For lower-energy beam qualities</td>
</tr>
<tr>
<td>$(s_{wa,\infty Pbch})_\infty Co$</td>
<td>0.2</td>
<td>For higher-energy beam qualities</td>
</tr>
<tr>
<td>Total change in $D_{wa}$ for photons</td>
<td>-0.2</td>
<td>For lower-energy beam qualities</td>
</tr>
<tr>
<td>$D_{we}$ for electrons</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$N_{D,\infty Co}$</td>
<td>0</td>
<td>See Eqs. (7.2) and (7.3)</td>
</tr>
<tr>
<td>$(s_{we,\infty Pch})_Q$</td>
<td>0.3</td>
<td></td>
</tr>
<tr>
<td>$(s_{we,\infty Pbch})_\infty Co$</td>
<td>0.7</td>
<td></td>
</tr>
<tr>
<td>Total change in $D_{we}$ for electrons</td>
<td>-0.4</td>
<td></td>
</tr>
<tr>
<td>$W_{air}$ for protons and carbon ions</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$N_{D,\infty Co}-N_K$</td>
<td>-0.2</td>
<td>See text following Eq. (7.6)</td>
</tr>
<tr>
<td>$(s_{wo,\infty Pch})_Q$</td>
<td>-0.4</td>
<td>Protons and carbon ions</td>
</tr>
<tr>
<td>Total change in $(W_{air})_Q$</td>
<td>0.6</td>
<td>Based on the assumption $p_{ch,Q} \approx 1$</td>
</tr>
<tr>
<td>$D_{we}$ for protons and carbon ions</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$N_{D,\infty Co}$</td>
<td>0</td>
<td>See Eqs. (7.2) and (7.3)</td>
</tr>
<tr>
<td>$(s_{we,\infty Pch})_Q$</td>
<td>-0.4</td>
<td></td>
</tr>
<tr>
<td>$(s_{we,\infty Pbch})_\infty Co$</td>
<td>0.7</td>
<td></td>
</tr>
<tr>
<td>$(W_{air})_Q$</td>
<td>0.6</td>
<td></td>
</tr>
<tr>
<td>Total change in $D_{we}$ for protons and carbon ions</td>
<td>-0.5</td>
<td></td>
</tr>
</tbody>
</table>

Graphite-walled (NE-2571) chamber in 250 MeV carbon beam
Task: recalculate SPR with updated stopping power data from ICRU90

\[ k_{Q,Q_0} = \frac{(s_{w,\text{air}})_Q}{(s_{w,\text{air}})_{Q_0}} \cdot \frac{(p_{ch})_Q}{(p_{ch})_{Q_0}} \cdot \frac{(W/e)_Q}{(W/e)_{Q_0}} \]
Changes in $I_w$, $I_{\text{air}}$ and calculation method
Tabulated data for p, He and C (tables A.7 – A.15)

Figure A.2. Electronic stopping power for C ions in liquid water, comparing the results adopted here with those from the ICRU Report 73 Errata (Sigmund et al., 2009), from SRIM, and from the classical-trajectory Monte Carlo (CTMC) calculations of Liamsuwan and Nikjoo (2013). (a) Semi-log plot. (b) Log-log plot.

Figure A.3. Electronic stopping power for C ions in dry air, comparing the results adopted here with those from ICRU Report 73 (2005), from SRIM, and from the experiments of Fastrup et al. (1968) and of Hvelplund (1971). (a) Semi-log plot. (b) Log-log plot.
Implementing ICRU 90 stopping power data

No data for other ions in ICRU 90!

Tables for Li, Be, B and up to Ar) computed using same procedure as in ICRU90:

- MSTAR \((T \leq T_1)\)
- BEST \((T \geq T_2)\)
- Spline interpolation \((\beta \cdot S/\rho, \; T_1 < T < T_2)\)
Calculation procedure of SPR

Monte Carlo codes:
Geant4 → allowing implementing the ICRU 90 stopping power tables.

Computational approach:
\[ s_{w,\text{air}} = \frac{\sum_i \int_0^\infty \Phi_{E,i} \cdot \left( \frac{S_i(E)}{\rho} \right)_w dE}{\sum_i \int_0^\infty \Phi_{E,i} \cdot \left( \frac{S_i(E)}{\rho} \right)_{\text{air}} dE} \]

References conditions:
- Entrance region (1 g/cm² depth)
- Middle of physical SOBP
- Middle of RBE-weighted SOBP
Range concept

Residual range:
\[ R_{res} = R_p - z \]

Range:
\[ R_p \]

- Depth at which dose drops to 10 % of maximum value
- If fragmentation tail larger: tangent at steepest point
- SOBP: Bragg peak of highest energy
Pristine Bragg peaks

Almost independent of initial beam energy when using residual range as beam quality specifier.

SPR changes with residual range: ~0.1%
Spread-out Bragg peaks

**Physical SOBP**

- shallow SOBPs
- mid-depth SOBPs
- deep SOBPs

**Biological SOBP**

**Depth in water / cm**

**Physical dose / Gy**

**SPR**

**Residual range in water / cm**

- SPR largely independent of SOBP width and depth
- SPR change with residual range: ~0.2%
- Small change between physical and biological SOBP (+0.1%)
**Parametrization**

### Graphical Representation

The graph illustrates the residual range in water for SOBP beams, showing:
- **RBE-weighted SOBP**
- **Physical SOBP**
- **Monoenergetic**

### Mathematical Formulation

\[
s_{w,\text{air}}(R_{\text{res}}) = a + b \cdot R_{\text{res}} + \frac{c}{R_{\text{res}}}
\]

\[c = -b \cdot (R_{\text{res}}^{\text{rep}})^2\]

### Table: Constants

<table>
<thead>
<tr>
<th>Class</th>
<th>Simulation</th>
<th>Position</th>
<th>(R_{\text{res}}^{\text{rep}})</th>
<th>(a)</th>
<th>(b)</th>
<th>(c)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pristine Bragg peak</td>
<td>Ion transport</td>
<td>1 g cm(^{-2}) depth 10 cm</td>
<td>1.1247</td>
<td>-3.444 \times 10(^{-5})</td>
<td>3.444 \times 10(^{-3})</td>
<td></td>
</tr>
<tr>
<td>Physical SOBPs</td>
<td>Ion transport</td>
<td>Mid-SOBP</td>
<td>3.5 cm</td>
<td>1.1274</td>
<td>-2.418 \times 10(^{-4})</td>
<td>2.962 \times 10(^{-3})</td>
</tr>
<tr>
<td>Biological SOBPs</td>
<td>Ion transport</td>
<td>Mid-SOBP</td>
<td>3.5 cm</td>
<td>1.1282</td>
<td>-2.418 \times 10(^{-4})</td>
<td>2.962 \times 10(^{-3})</td>
</tr>
</tbody>
</table>

**Constant value 1.126 recommended**

TRS398 (2000, 2006): 1.130 → -0.4%
Recalculated SPR with updated stopping power data from ICRU90

\[ k_{Q,Q_0} = \frac{\left( s_{w,\text{air}} \right)_Q}{\left( s_{w,\text{air}} \right)_{Q_0}} \cdot \frac{\left( p_{ch} \right)_Q}{\left( p_{ch} \right)_{Q_0}} \cdot \frac{\left( W/e \right)_Q}{\left( W/e \right)_{Q_0}} \]
Experimental determination of $k_Q$

### Ionization chamber

<table>
<thead>
<tr>
<th>Ionization chamber</th>
<th>Experimental method</th>
<th>$k_Q^{exp}$</th>
<th>TRS-398</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Cylindrical</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TM30010</td>
<td>cross calibration</td>
<td>1.033</td>
<td></td>
</tr>
<tr>
<td>TM30011</td>
<td>cross calibration</td>
<td>1.032</td>
<td></td>
</tr>
<tr>
<td>TM30012</td>
<td>cross calibration</td>
<td>1.039</td>
<td></td>
</tr>
<tr>
<td>NE2571</td>
<td>cross calibration</td>
<td>1.035</td>
<td></td>
</tr>
<tr>
<td>FC65-P</td>
<td>cross calibration</td>
<td>1.032</td>
<td></td>
</tr>
<tr>
<td>FC23-C</td>
<td>cross calibration</td>
<td>1.034</td>
<td></td>
</tr>
<tr>
<td>CC25</td>
<td>cross calibration</td>
<td>1.031</td>
<td></td>
</tr>
<tr>
<td>CC13</td>
<td>cross calibration</td>
<td>1.029</td>
<td></td>
</tr>
<tr>
<td>TM30013</td>
<td>water calorimeter(^a)</td>
<td>1.036</td>
<td></td>
</tr>
<tr>
<td>FC65-G</td>
<td>water calorimeter(^a)</td>
<td>1.030</td>
<td></td>
</tr>
<tr>
<td><strong>Plane-parallel</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TM34001</td>
<td>cross-calibration</td>
<td>0.999</td>
<td></td>
</tr>
<tr>
<td>PPC-40</td>
<td>cross-calibration</td>
<td>0.988</td>
<td></td>
</tr>
<tr>
<td>PPC-05</td>
<td>cross-calibration</td>
<td>0.987</td>
<td></td>
</tr>
</tbody>
</table>

\(^a\): Osinga-Blättermann et al 2017

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Osinga-Blättermann and Krauss, PMB 64, 2018

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**PTB**

Physikalisch Technische Bundesanstalt
Braunschweig und Berlin

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**dkfz**

Research for a Life without Cancer

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**HIT**

Hamburg Institute for Thrombosis Research
Changes in ICRU 90

Recalculated SPR with updated stopping power data from ICRU90

\[ k_{Q,Q_0} = \frac{(s_{w,air})_Q}{(s_{w,air})_{Q_0}} \cdot \frac{(p_{ch})_Q}{(p_{ch})_{Q_0}} \cdot \frac{(W/e)_Q}{(W/e)_{Q_0}} \]
Changes in ICRU 90

ICRU90: 34.71 eV
(TRS-398, 2006: 34.50 eV)

\[ k_{Q, Q_0} = \frac{\left( s_{w, \text{air}} \right)_Q}{\left( s_{w, \text{air}} \right)_{Q_0}} \cdot \frac{\left( p_{ch} \right)_Q}{\left( p_{ch} \right)_{Q_0}} \cdot \frac{(W/e)_Q}{(W/e)_{Q_0}} \]
Changes in ICRU 90

\[ k_{Q, Q_0} = \frac{(s_{w, \text{air}})_Q}{(s_{w, \text{air}})_{Q_0}} \cdot \frac{(p_{ch})_Q}{(p_{ch})_{Q_0}} \cdot \frac{(W/e)_Q}{(W/e)_{Q_0}} \]
Changes in ICRU 90

\[ k_{Q,Q_0} = \frac{(s_{w,\text{air}})_Q}{(s_{w,\text{air}})_{Q_0}} \cdot \frac{(p_{\text{ch}})_Q}{(p_{\text{ch}})_{Q_0}} \cdot \frac{(W/e)_Q}{(W/e)_{Q_0}} \]
Experimental data

\[ k_{Q, Q_0} = \frac{(s_{\text{w,air}})_Q \cdot (p_{ch})_Q}{(s_{\text{w,air}} \cdot p_{ch})_{Q_0}} \frac{(W/e)_Q}{(W/e)_{Q_0}} = \frac{(s_{\text{w,air}})_Q \cdot (p_{ch})_Q}{f_{Q_0}} \frac{(W/e)_Q}{(W/e)_{Q_0}} \]

Combined effect from Monte-Carlo simulation
Perturbation factors: changes in Co-60

TRS-398, 2006: 54+7 = 61
Here: 22+9 = 31

Cylindrical: +0.19 %
(min. -0.5 %, max. +1.10 %)

Parallel-plate: +0.35 %

Data courtesy of P. Andreo, pers. comm.
Changes in $k_Q$

- Capintec PR-06C/G Farmer
- Extradin A1 mini Shonka
- Extradin A12 Farmer
- Extradin A12S Farmer
- Extradin A18
- Extradin A19 Classic Farmer
- Extradin A28
- IBA CC13
- IBA CC25
- IBA FC23-C Short Farmer
- IBA FC65-P Farmer
- IBA FC65-G Farmer
- NE 2571 (Farmer)
- NE 2561 / 2611 Sec Std
- PTW TM30001/30010 (Farmer)
- PTW TM30002/30011 (Farmer)
- PTW TM30004/30012 (Farmer)
- PTW TM30006/30013 (Farmer)
- PTW 31010 Semiflex
- PTW31013 Semiflex
- PTW 31016 PinPoint
- PTW 31021 Semiflex 3D
- Extradin A10
- Extradin A11
- Extradin A11TW
- IBA NACP-02
- IBA PPC-05
- IBA PPC-40
- PTW TM34045 Adv. Markus
- PTW TM23343 Markus
- PTW TM34001 (Roos)
Changes in $k_Q$

Relative change to TRS398/
Difference to experimental

Cylindrical:
+0.07 % (0.47 % / 0.52 %)
TRS398 / This

Parallel-plate:
+0.48 % (0.40 % / 1.77 %)
TRS398 / This
Summary

- Stopping power tables from ICRU 90 report extended (up to Ar).
- Stopping-power ratio \( s_{w,\text{air}} \) calculated for C for reference conditions.
- Parametrizations for \( s_{w,\text{air}} \) obtained as a function of residual range in water.
- New recommendation \( s_{w,\text{air}} = 1.126 \) (i.e. -0.4% to TRS-398, 2006).
- Updated \( k_Q \) data includes new \( s_{w,\text{air}} \) for C and \( f = (s_{w,\text{air}} \cdot p_{\text{ch}}) \) for Co-60.
- \( k_Q \) for C: small change and within 0.5% to experiments for cyl. chambers, larger (n.s.!) discrepancy but fewer data points for pp chambers.
- Uncertainty for \( k_Q \) smaller (2.4 % vs. 2.8 %/3.2 % TRS398), future potential using \( f_{\text{ch}} \) and more experimental data.

Results available at arXiv:1812.07877