Reference dosimetry of scanned proton beams - state of the art

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Overview

Calibration in terms of $n$ or DAP

Gradient corrections - SOBP ripples

Experimental and Monte Carlo $k_Q$ data

Ion recombination

Dosimetric end-to-end test and audit
Calibrations in terms of $n$ or DAP

TPS calculate number of protons per spot  
(comparable to fluence-based dose calculations in IMRT)

Requires, in principle, MU calibration in terms of $n$

$$K(E_i) = \frac{n(E_i)}{\text{MU}} \quad \rightarrow \quad K(E) = \frac{n(E)}{\text{MU}}$$

Determination of $n$ via $DAP_w$ of a single spot

$$n(E_i) = \frac{DAP_{w,Q_{\text{spot}}}(E_i)}{(S/\rho)_w(z_{\text{ref}})} = \frac{DAP_{w,Q_{\text{spot}}}(E_i)}{\frac{1}{\Phi_{p(0)}} \int (S/\rho)_w \Phi_{E'} dE'}$$
Method 1 for DAP (Hartmann et al 1999)

- Single-energy layer
- Shallow depth
- Assumptions:
  - Constant counts/spot
  - Constant $\Delta X, \Delta Y$ (2 mm)
  - Constant spot profile
  - OF “saturated”
Method 1 for DAP - cross calibrated plane-parallel ionization chamber

Formalism (Palmans and Vatnitsky 2016, Med Phys 43:5835)

\[
N_{D,w,Q_{cross}}^{PP} = \frac{M_{Q_{cross}}^{REF}}{M_{Q_{cross}}^{PP}} N_{D,w,Q_{0}}^{REF} k_{Q_{cross},Q_{0}}^{REF}
\]

\[
DAP_{w,Q_{spot}}^{\infty} = M_{Q_{spot-scan}}^{PP} N_{D,w,Q_{cross}}^{PP} k_{Q_{spot-scan},Q_{cross}}^{PP} \Delta x \Delta y
\]

\[
k_{Q_{spot-scan},Q_{cross}}^{PP} \approx 1
\]
Method 2 for DAP - cross calibrated large-area ionization chamber

Formalism (Palmans and Vatnitsky 2016, Med Phys 43:5835)

\[ N_{DAP,w,Q_{cross}}^{LAIC} = \frac{M_{Q_{cross}}^{REF}}{M_{Q_{cross}}^{LAIC}} N_{D,w,Q_0}^{REF} k_{Q_{cross},Q_0}^{REF} \iint_{A(LAIC)} OARdx\,dy \]

\[ DAP_{w,Q_{spot}}^{\infty} = \gamma DAP_{w,Q_{spot-stat}}^{A(LAIC)} = \gamma M_{Q_{spot-stat}}^{LAIC} N_{DAP,w,Q_{cross}}^{LAIC} k_{Q_{spot-stat},Q_{cross}}^{LAIC} \]

\[ k_{Q_{spot-stat},Q_{cross}}^{LAIC} \approx 1 \]
Method 1 and 2 for DAP

Experimental experience

at MedAustron

presented by Jhonnatan Osorio
Gradient corrections
Gradient corrections

\[ P_{\text{dis}} - 1 \text{ (Farmer)} \]

\[ 10.0\% \]

\[ 1.0\% \]

\[ 0.1\% \]

\[ 0 \]

\[ 10 \]

\[ 20 \]

\[ 30 \]

\[ 40 \]

\[ \text{residual range in water / cm} \]

\[ \text{z} = 1 \text{ cm} \]

\[ 2 \text{ cm} \]

\[ 3 \text{ cm} \]

\[ 4 \text{ cm} \]

\[ 5 \text{ cm} \]

\[ \rightarrow \text{Farmer chambers not recommended for } R_{\text{res}} < 15 \text{ cm} \]

\[ \text{without } p_{\text{dis}} \text{ or } P_{\text{eff}} \]
Ripples in SOBP

$\frac{ld_{w, SSD}(z_w) or ld_{g, SSD}(z_{w-eq})}{0.0 0.5 1.0 1.5 2.0 2.5 3.0 3.5}
\frac{z_w or z_{w-eq} / g cm^{-2}}{1.15 1.13 1.11 1.09 1.07 1.05 0.0 0.2 0.4 0.6 0.8 1.0 1.2}$
Calorimetry

Water calorimetry measurement published by

- Gagnebin et al. 2010, Nucl Instrum Meth B 268:524
- Sarfehnia et al. 2010, Med Phys 37:3541

Graphite calorimetry:
presentations Russell Thomas and Francesco Romano
Experimental $k_Q$ data compared with TRS-398 data
Experimental $k_Q$ data compared with TRS-398 revised data (Andreo/provisional)
Monte Carlo calculated $k_Q$ data

Goma et al. 2016
Phys. Med. Biol. 61:2389
Fano tests

Sterpin et al. 2014
Med. Phys. 41:011706
PENH

Lourenço et al. 2019
Med. Phys. 46:885
FLUKA

GEANT4

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Fig. 3. Ratio between the dose scored in water-property materials with different mass densities: water with graphite density (1.7 g.cm\(^{-3}\)), and water with air density (0.00120484 g.cm\(^{-3}\)), when all generated charged particles were transported.
Influence nuclear interactions


**Fig. 6.** Ionization chamber perturbation factors calculated using the $I$-values from previous ICRU Reports [31], $I_w = 75$ eV and $I_g = 78$ eV (dashed lines), and the new recommended values, $I_w = 78$ eV and $I_g = 81$ eV (straight lines), reported in ICRU Report 90.23
Ion recombination

Cyclotron and synchrotron beams: generally behave as continuous beams (Palmans et al 2006, Rossomme et al 2017)

Synchrocyclotron beams: generally behave as pulsed beams (Rossomme et al 2017) and recombination can be very high

Niatel method can be applied to separate initial and volume recombination

Use of PP chamber with small electrode spacing and high voltage, beware of charge multiplication
Face-to-face method
Recombination Roos pulsed beam

\[
k_S = \frac{M_{sat}}{M_{V_0}}
\]
Recombination PPC05 pulsed beam

\[ k_s = \frac{M_{sat}}{M_{V_0}} \]
Dosimetric end-to-end test

See presentations

Antonio Carlino

Marta Bolsa Ferruz
Conclusions

Formal treatment of MU calibration in terms of $n$

Gradient corrections - SOBP ripples

Experimental and Monte Carlo $k_Q$ data

Ion recombination