Reference Dosimetry for Fast Neutron and Proton Therapy

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Abstract. Fast neutrons and protons undergo fundamentally different interactions in tissue. The former interact with nuclei, while the latter, as in the case of photons, interact mainly with atomic electrons. Protons do, however, also undergo some nuclear interactions, the probability of which increases with energy. For both modalities the practical instruments for determining the reference absorbed dose in a patient are ionization chambers. These provide indirect determination of absorbed dose because calibration factors measured in standard radiation fields, as well as conversion factors that require knowledge of various physical data, have to be applied. All dosimetry protocols recommend that reference absorbed dose measurements in the clinical situation be made with ionization chambers having $^{60}$Co calibration factors traceable to standards laboratories. Neutron doses determined with the current internationally accepted protocol (ICRU Report 45 [1989]) have a relative uncertainty of ±4.3% ($1\sigma$), while proton doses determined with the two protocols (ICRU Report 59 [1998] and IAEA Report TRS 398 [2000]) presently in use have relative uncertainties ($1\sigma$) of ±2.6% and ±2.0%, respectively.

INTRODUCTION

Tumor control and normal tissue-complication probabilities are steep functions of absorbed dose, the determination of which must therefore be accurate and reproducible. Dosimetry measurements at any facility must be consistent with those made at other facilities if clinical data are to be compared. A relative accuracy of ±3% is desirable, although ±5% is often accepted, while relative reproducibility of ±2% is required.

Comparisons of dose measurements between different centers are important for establishing uniform standards and for verifying the integrity of the dosimetry procedures. These are especially important for new facilities with exotic beams such as neutrons and protons, and it is recommended that all such facilities undertake dosimetry comparisons with existing similar facilities before commencing the clinical program.

The requirements for a dosimeter depend on the accuracy of the absorbed dose determination required, the sensitivity of the measuring system, the energy dependence of the dosimeter response, and the spatial resolution required. In principle, calorimeters give the smallest uncertainty in the determination of absorbed dose in any intense radiation field. These instruments give a direct determination of the energy imparted (dose) in a sensing element as indicated by a temperature rise. Assuming that all (or a known amount) of the deposited energy is converted to heat, absorbed dose may be absolutely determined.

However, calorimeters are cumbersome devices and not practical for routine clinical use. Ionization chambers are more practical but provide an indirect determination of absorbed dose since calibration factors determined in standard radiation fields, as well as correction factors that require knowledge of various physical data and constants, have to be applied.

Several dosimetry protocols for both neutron [1–6] and proton [6–11] therapy dosimetry have been published. These protocols all recommend that, in the absence of a calorimeter, reference absorbed dose measurements in the clinical situation be made with ionization chambers having $^{60}$Co calibration factors traceable to standards laboratories. The latter requirement is a result of the fact that there are no primary standards of neutron and proton therapy beams. The calibration factors can be given in terms of absorbed dose to water, air kerma, or exposure. The former is preferred because the uncertainties in the chamber-dependent factors used to convert the measurements to absorbed dose are less [12] and the formalism is simpler and easier to interpret.
NEUTRON AND PROTON DOSIMETRY

Fast neutrons and protons undergo fundamentally different interactions in tissue. The former interact with nuclei, while the latter, as in the case of photons, interact mainly with atomic electrons.

Neutron dosimetry requires the measurement of absorbed dose to standard ICRU muscle tissue because of the nuclear interactions that neutrons undergo. Tissue-equivalent (TE) dosimetry materials must be used and specific correction factors are required because the compositions differ from muscle tissue. The percentages by mass of C and O in ICRU muscle tissue, A150 plastic, and methane-based TE gas are 12.3 and 72.9, 77.7 and 5.2, and 45.6 and 40.7, respectively [1]. The fractions of C and O are about the same in all three materials. In addition, neutron beams are always accompanied by gamma rays, which should be taken into account for accurate dosimetry.

Table 1 shows the prescribed reference conditions under which neutron and proton therapy beam dose calibrations are performed.

<table>
<thead>
<tr>
<th>Neutrons (n)</th>
<th>Protons (p)</th>
</tr>
</thead>
<tbody>
<tr>
<td>DOSIMETER</td>
<td>Thimble ion chamber</td>
</tr>
<tr>
<td>Wall material</td>
<td>A150 plastic</td>
</tr>
<tr>
<td>Gas filling</td>
<td>Dry TE gas/methane</td>
</tr>
<tr>
<td>Co-60 cal. factor</td>
<td>Air kerma</td>
</tr>
<tr>
<td>DOSE</td>
<td>Tissue</td>
</tr>
<tr>
<td>SPECIFICATION</td>
<td></td>
</tr>
<tr>
<td>PHANTOM</td>
<td>Water</td>
</tr>
<tr>
<td>FIELD SIZE</td>
<td>10 cm x 10 cm</td>
</tr>
<tr>
<td>MEASUREMENT</td>
<td>5 cm depth</td>
</tr>
<tr>
<td>POINT</td>
<td></td>
</tr>
<tr>
<td>BEAM QUALITY</td>
<td>Average energy/LET</td>
</tr>
</tbody>
</table>

In general, the absorbed dose $D_g$ to the mass of gas $m_g$ in the cavity of an ionization chamber [6] is:

$$D_g = (Q / mg) \left( W_g / e \right).$$

If the ionization chamber satisfies the Bragg-Gray principle [small or homogeneous chamber, absorbed dose in the cavity is deposited entirely by the charged particles crossing it], then the dose-to-wall material $D_m$ is:

$$D_m = D_g s_{mg} = (Q / mg) \left( W_g / e \right) s_{mg},$$

where $Q$ is the charge produced in ionization chamber cavity gas, $W_g/e$ is the mean energy to form a ion pair in the gas, and $s_{mg}$ is the mean ratio of mass electronic stopping powers of the wall material to the gas.

Neutron Dosimetry

For neutron dosimetry with tissue-equivalent A150 plastic ionization chambers flushed with dry methane-based TE gas, the dose to the wall is [5,6]:

$$D_{A150} = \left( Q/m_{TE} \right) \left( W_{TE} / e \right) a \left( r_{A150,TE} \right) d_T \left[ 1/(1 + \delta) \right],$$

where $r_{A150,TE}$ is the A150 plastic to TE gas-absorbed dose conversion factor (it is a corrected value of $s_{A150,TE}$ and accounts for non Bragg-Gray compliance of the ionization chamber), $d_T$ is the displacement correction factor (difference in absorption and scattering when the chamber is replaced by phantom material), and $\delta$ is the correction factor to account for the difference in response of the chamber to neutrons and gamma rays in the beam.

The total absorbed dose to ICRU muscle tissue $D_T$ in the mixed field is the sum of the neutron $D_n$ and gamma $D_{\gamma}$ absorbed doses and is given by:

$$D_T = D_n + D_{\gamma} = D_{A150} \left( K_{n,A150} \right),$$

where $(K_{n,A150})$ is the ratio of kerma in ICRU muscle tissue to A150 plastic in the neutron beam.

It can be shown that [5,6]:

$$D_{\gamma} = M \left[ \prod N_i \left( 1 - g \right) A_{\text{wall}} \left( \mu_{\text{wall}} / \rho \right) c \right] \left( r_{A150,TE} \right) \left( W_{TE} / e \right) a \left( K_{A150} \right) d_T \frac{1}{k_T} \frac{1}{1 + \delta},$$

where $n$ and $c$ refer to the neutron and $^{60}$Co calibration beams; $M_{\text{wall}}$ is the chamber electrometer reading corrected for ion recombination, temperature, and pressure and other response modifying factors; $N_k$ is the air kerma calibration factor; $g$ is the fraction of secondary electron energy converted to bremsstrahlung in air (0.003 for $^{60}$Co); $A_{\text{wall}}$ is the wall correction factor in $^{60}$Co; $A_{\text{fail}}$ is the correction for ion recombination in $^{60}$Co; $\mu_{\text{wall}}/\rho$ is the mass energy absorption coefficient; $k_T$ is the sensitivity of the ionization chamber to neutrons relative to its sensitivity to $^{60}$Co; and $(L_P)$ is the mean restricted collision mass stopping power.

It can be shown that $1/(1 + \delta)$ is much greater than 0.99 and it is therefore assumed to be equal to 1.

The relative uncertainty in the determination of neutron-absorbed dose is estimated to be $\pm 4.3\%$ (1$\sigma$) [5], which is largely attributable to uncertainties in the C and O kerma coefficients (Fig. 1).
Proton Dosimetry

There are currently two protocols being used for proton therapy dosimetry, viz. ICRU Report 59 [10] and IAEA Report TRS 398 [11]. ICRU 59 is based on standards of air kerma, although the procedures for proton dosimetry based on absorbed dose to water standards are also given, while TRS 398 is exclusively based on standards of absorbed dose to water.

Proton Dosimetry using ICRU Report 59

Dose to water $D_{w,p}$ in the proton beam is given by:

$$D_{w,p} = M_{c,corr} N_{D, air} C_p,$$

where $M_{c,corr}$ is the chamber electrometer reading corrected for ion recombination, temperature and pressure, and other response modifying quantities; $N_{D, air}$ is the absorbed dose calibration factor; and $C_p$ is a chamber-specific factor.

$$N_{D, air} = \frac{N_k (1-g) A_{wall} A_{ion}}{s_{wall,air} ([\mu e V/\mu g])_{air,wall} K_{hum}},$$

where $N_k$ is the air kerma calibration factor; $g$ is the fraction of secondary electron energy converted to bremsstrahlung in air (0.003 for $^{60}$Co); $A_{wall}$ is the wall correction for the attenuation factor in $^{60}$Co; $A_{ion}$ is the correction for ion recombination in $^{60}$Co; $s_{wall,air}$ is the mean ratio of the restricted mass stopping powers of the wall material to the gas for secondary electrons for $^{60}$Co gamma rays; $([\mu e V/\mu g])_{air,wall}$ is the mass-energy absorption coefficient for the calibration $^{60}$Co gamma rays; $K_{hum}$ is the correction factor to account for the differences between ambient air and dry air [NB. The use of $K_{hum}(=0.997)$ is problematic because physical data are given for dry air—see below].

$$C_p = (s_{w,air})_p \frac{(W_{air})_p}{(W_{air})_c},$$

where $(s_{w,air})_p$ is the water-to-air mass electronic stopping power ratio in the proton beam; $(W_{air}/e)_p$ is the mean energy forming an ion pair in the ionization chamber air for protons; and $(W_{air}/e)_c$ is the mean energy forming an ion pair in the ionization chamber air in the $^{60}$Co calibration beam.

Proton Dosimetry using IAEA Report TRS 398

Dose to water $D_{w,Q_o}$ in the $^{60}$Co beam (quality $Q_o$):

$$D_{w,Q_o} = M_{Q_o} N_{D, w,Q_o};$$

dose to water $D_{w,Q}$ in the proton beam (quality $Q$):

$$D_{w,Q} = M_Q N_{D, w,Q};$$

where $M$ is the chamber electrometer reading corrected for ion recommendation, temperature and pressure, and other response modifying quantities; $N_{D, w,Q_o}$ is the calibration factor in terms of absorbed dose to water in $^{60}$Co (quality $Q_o$); and $N_{D, w,Q}$ is the calibration factor in terms of absorbed dose to water in the proton beam (quality $Q$).

Since no primary dose standards for proton beams are available, $D_{w,Q}$ has to be calculated:

$$D_{w,Q} = M_Q N_{D, w,Q_o} k_{Q,Q_o},$$

$$k_{Q,Q_o} = \frac{(s_{w,air})_Q (W_{air})_Q P_Q}{(s_{w,air})_{Q_o} (W_{air})_{Q_o} P_{Q_o}},$$

where $k_{Q,Q_o}$ is the chamber specific factor that corrects for differences between $^{60}$Co beam quality ($Q_o$) and proton beam quality ($Q$) [calculated]; $s_{w,air}$ is the mean water-to-air mass stopping power ratio; $(W_{air}/e)$ is the mean energy forming an ion pair in the ionization chamber air; and $P$ is the combined chamber perturbation factors.

Comparison of Proton Dosimetry Protocols

The main difference between the two protocols lies in the $W/e$ value (Fig. 2) recommended for protons. ICRU 59 recommends a value of $34.8 \pm 0.7$ (1σ), which is a compromise between direct measurements and indirect determinations (e.g., from comparisons of calorimeter and ionization chamber measurements). TRS 398 recommends a value of $34.23 \pm 0.13$ (1σ), based on a rigid statistical analysis using [14]. Both protocols use stopping powers given in ICRU Report 49 [15], but TRS 398 includes secondary electron transport and nuclear interactions, which yield $s_{w,air}$ values for protons that are about 0.6% higher than
the corresponding ICRU 59 values. TRS 398 provides a formula to calculate $W/e$. Chamber perturbation factors in proton beams are in both cases taken to be 1.00, but TRS 398 includes the factors explicitly and provides uncertainties in each case. ICRU 59 includes a humidity correction factor in calculating the chamber response, but this is problematical as the physical constants refer to values for dry air.

Overall relative uncertainties ($1\sigma$) in proton-absorbed dose determinations are $\pm 2.6\%$ (ICRU 59) and $\pm 2.0\%$ (TRS 398) for cylindrical ionization chambers. Differences of up to $\pm 2\%$ ($1\sigma$) between doses measured using ICRU 59 and TRS 398 are observed (Fig. 3), but this is not clinically significant.

It is recommended that TRS 398 be adopted as the standard dosimetry protocol. It is simple to use; it provides tabulated quality correction factors for a range of common ionization chambers; it provides a formula for calculating the proton beam quality parameter (residual range); it harmonizes with the protocols for standard radiotherapy beams (also given in TRS 398), which are being universally adopted; and more recent and accurate physical constants are used and the formalism is more robust and rigorous than that of ICRU 59.

REFERENCES