Brachytherapy Sources, Dosimetry and Quality Assurance

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General References and Fundamentals


A good overview of brachytherapy calibration/source strength standardization practices


References 3 and 4 are recently-written and fairly comprehensive reviews of model- and table-based dose-calculation algorithms. Reference 5 reviews in detail Monte Carlo and experimental dosimetry techniques from speaker’s perspective. Reference 6 provides guidance to early adopters of Monte Carlo based dose-calculation, discrete ordinates calculation, and other model-based algorithms that go beyond TG-43 algorithms in which single-source dosimetry, seed-to-seed attenuation, applicator shielding, and tissue inhomogeneities are incorporated into a single unified process.
Low Energy Sources: Dosimetry and Calibration Issues


   Definitive presentation of NIST WAFAC primary $S_{K,N99}$ standard for low energy brachytherapy sources.


   Reference 3 is a major new update of the 1995 TG-43 report. It contains a revised dose-calculation formalism, a modified definition of air-kerma strength, a concise history of source-strength standards, a formal procedure for merging datasets, and consensus datasets for 8 I-125/Pd-103 source models. Essential reading for all medical physicists.


   Classic 1995 paper outlining the TG-43 dose calculation formalism, although much of its content is superceded by the new 2004 TG-43 report. Excellent review of low-energy dosimetry history and relationship between classical and TG-43 dose-calculation formalisms.


   Important document, now accepted as a de facto industry standard, describing AAPM’s standards for dosimetric characterization and calibration of low-energy brachytherapy seeds for routine clinical use.


These two short reports outline AAPM recommendations on operational aspects of maintaining NIST traceability of brachytherapy vendor calibrations. Reference 6 describes minimum standards for vendor-NIST-ADCLS K intercomparisons while 7 discusses the problems encountered by hospital physicists in verifying calibrations of prepackaged seeds previously calibrated by third party calibration services. See reference NN in low energy seed section.

The dosimetry fundamentals and source strength specification practices for intravascular brachytherapy, especially beta-emitting sources, differ significantly from those of photon-emitting sources.


How to adapt prescribed doses for I-125 implants to accommodate change from classical to TG-43 dose calculations and how to correct for transition from NIST 1985 to 1999 standards.


References 12 and 13 provide current guidance on adapting prescribed doses for Pd-103 implants to accommodate transition from old vendor activity standard to NIST 1999 standard as well as revised TG-43 dose-calculation parameters.

High Energy Brachytherapy Sources

Classic paper describing interim secondary standard for HDR Ir-192 sources used in absence of national primary standard.


AAPM dosimetric recommendations, similar in scope to TG-43 reports for low energy seeds, but for Cs-137, Ir-192, and other sources emitting mean photon energies greater than 50 keV. Reference 3, often referred to as the HEBD report, is a major milestone, outlining in detail dosimetric recommendations for high energy sources and presenting consensus datasets in TG-43 format for approximately 20 source models.


More Low Energy Brachytherapy Dosimetry References


Good discussion of LDR sources, including low energy seeds.

Quality Assurance Readings and AAPM Reports


Reference 3 provides the most detailed and comprehensive set of brachytherapy QA guidelines published date. The document mainly addresses device QA; process-oriented QA for LDR non-image-based brachytherapy and treatment planning; and dosimetry practice. The QA recommendations for re-entrant ionization chambers, table-based brachytherapy dose-calculation algorithms, and treatment delivery systems, including remote afterloaders, are still valid today as are interim guidelines for source-strength standardization of HDR Ir-192 sources. Only limited discussion of patient- and procedure-specific QA for image-guided permanent seed implants and HDR brachytherapy is included. See TG-59 for a good discussion of the latter. Reference 2 is synthesizes in one document AAPM and ACR guidance circa 2000 into a single document that is much shorter than AAPM TGs but more detailed than ACR standards. References 1 and 4 are useful and highly detailed QA references. US NRC regulations are required periodic reading to maintain currency of regulatory knowledge. While most states are not regulated directly by USNRC, the Suggested State Regulations and most agreement state regulations adhere closely to NRC regulations.


References 8 - 12 represent the available non-dosimetric QA for permanent seed prostate implants. No advisory entity has published guidance on procedure-specific QA and medical error mitigation for or any other example of image-based or -guided brachytherapy.


TG-59, which addresses design of non-image-based HDR brachytherapy procedures, is the only AAPM document which focuses almost exclusively on design of clinical process and integrating QA/QC tests into the execution of each clinical procedure.


Strictly speaking, references 14 and 15 are clinical practice guidelines rather than QA guidance documents. They outline modification of ICRU target volume nomenclature appropriate for definitive radiation therapy of cervical cancer.


This group of references contains a critical assessment of available brachytherapy QA guidance, most of which was formulated in the 2D brachytherapy planning era and is device centered. Reference 16 is one the first publications to illustrate application of industrial engineering approaches to radiation oncology (brachytherapy specifically) in the form of process tree development, fault tree analysis, and taxonomic-based root cause analysis of reported misadministrations. Reference 19 is a detailed application of TG-100 prospective risk-assessment methodologies to quality management program formulation for breast brachytherapy.


Major new AAPM task group report demonstrating that total propagated uncertainty for a coverage factor, k= 1.0, is about 4%-5% at 1 cm distance for both high and low energy sources. The analysis includes uncertainties associated with primary S_K standards, source strength transfers into the clinic, TG-43 parameters, and RTP dose-algorithm interpolation errors.
21. Study Questions and Problems

1) Which of the following statements best describes the TG-43 dose-calculation formalism?
   a) An accurate analytical model for estimating doses in brachytherapy
   b) A protocol for tabulating measured or calculated dose rates around single brachytherapy sources
   c) Applicable only to sources emitting photons less than 50 keV
   d) Uses nonlinear interpolation to estimate dose rates between tabulated data points
   e) Requires independent TLD measurements or Monte Carlo simulations as input
   f) b) and e) only
   g) b), d) and e) only
   h) all [a) through e)] of the above

Answer: (g), because the 2004 formalism is applicable to all photon emitting sources.

2) Using the general 2D formula and data tables from the updated TG-43 report (2004), calculate the dose rate at a distance of 1.3 cm and polar angle of 16 degrees from a model 6711 seed that has an apparent activity of 0.6 mCi.

Answer

From Table III: \( g_L (1) = 1.0 \) and \( g_L (1.5) = 0.908 \Rightarrow g_L (1.5) = 0.945 \)

\[
\begin{align*}
g_L (r, \theta) &= \begin{cases} 
0.537 & \text{if } (r, \theta) = (1, 10^\circ) \\
0.705 & \text{if } (r, \theta) = (1, 120^\circ) \\
0.580 & \text{if } (r, \theta) = (2, 10^\circ) \\
0.727 & \text{if } (r, \theta) = (1, 20^\circ) 
\end{cases}
\end{align*}
\]

From Table V: \( F(r, \theta) = \)

\[
\begin{align*}
F(1, 16^\circ) &= 0.638 \\
F(2, 16^\circ) &= 0.688 \\
F(1.16^\circ) &= 0.653 \\
0.5989 & \text{ if } (r, \theta) = (1.20^\circ)
\end{align*}
\]

\[
x = 1.3 \sin 16^\circ = 0.3583, \quad L = 0.3 \\
y = 1.3 \cos 16^\circ = 1.2496
\]

\[
G(1.3, 16^\circ) = \frac{\Delta \beta}{Lx} = \left[ \tan^{-1} \left( \frac{1.2496 + 0.3/2}{0.3583} \right) - \tan^{-1} \left( \frac{1.2496 - 0.3/2}{0.3583} \right) \right] \frac{1}{0.3583 \times 0.3} \\
= \left[ 1.3202 - 1.2588 \right] / 0.1975 = 0.5989
\]

\[
G(1.0, 90^\circ) = \frac{2}{Lx} \tan^{-1} \left( \frac{L/2}{x} \right) = 0.9926
\]

\( \Lambda = 0.965 \)

\[
S_k = A_{\text{app}} \frac{W}{e} = 0.6 \times 1.45 \times 0.876 = 0.762 \text{ mGy} \cdot \text{m}^2 / \text{h}
\]

\[
D(r, \theta) = S_k \cdot \Lambda \cdot \frac{G_L (r, \theta)}{G_L (r_0, \theta_0)} \cdot F(r, \theta) = 0.762 \times 0.965 \times 0.5989 \times 0.9926 \times 0.945 \times 0.653 = 0.274 \text{ cGy/h}
\]

3. Assume that you are asked to establish a low-energy seed prostate brachytherapy in a clinic that has not previously performed this procedure.

   a. Describe the process, including equipment selection, you will use to provide a secondarily traceable measurement of air-kerma strength to verify the vendor’s calibration assay. Describe the commissioning procedures that TG-56 requires.
b. Describe how you will implement dose-calculation around the selected I-125 or Pd-103 seed and how you will verify the accuracy of the calculated doses before treating patients. (Hint: review the “clinical implementation” section of the 2004 TG-43 report.)

4. Define the concepts of direct and secondary traceability.

5. Explain why the dose-rate constant for the Model 6711 seed published in the 1995 TG-43 report differs by 15% from the value derived from the classical (1983) dose-calculation model. Explain why the 2004 TG-43 report has changed the dose-rate constant from 0.88 to 0.965.

6. Nuclear medicine dose calibrators are often used as calibration transfer instruments in the clinic to verify air-kerma strength calibrations. They come equipped with radionuclide push buttons, e.g., “Cs-137”, “I-125”, etc., that provide direct readout in mCi for the selected radionuclide. Explain why you can not calibrate an I-125 seed by pressing the “I-125” button and converting the mCi readout to air-kerma strength.

   **Answer:** The dose calibrator pushbuttons are designed to approximately (within 10%) realize the NIST radioactivity standards assuming that the sample being measured is in aqueous solution in a standard NIST glass ampoule. Hence the pushbuttons are irrelevant to brachytherapy because they provide inadequately accurate traceability to the wrong standard and assume a source geometry far different from that of an encapsulated seed. This is one of my favorite oral board exam questions.

7. Convert the following to air-kerma strength
   
   (a) 4.0 mCi $^{125}$I seed
   (b) 22 mgRaEq $^{137}$Cs source
   (c) 1.5 mg $^{226}$Ra needle
   (d) 15 mg $^{226}$Ra intracavitary tube

8. Your treatment planning computer is down and an HDR patient is waiting on the treatment table for a post-op endometrial cancer treatment using small (2 cm diameter) Fletcher colpostats.

Manually calculate the dwell time/position needed to deliver 600 cGy to the vaginal apex at depth of 5 mm. Assume
that the colpostat centers are separated by 2.5 cm and that the source strength, \( S_K = 2.50 \) cGy m\(^2\)h\(^{-1}\) at the time of treatment. Further assume that dwell positions 1, 2 and 3 are activated uniformly and that the spacing is 5 mm.

**Solution:**

1. **Find dose-rate per second at 1 cm from single dwell position**

\[
\Lambda = S_K \cdot \left( \frac{10^4 \text{ cm}^2/\text{m}^2}{3600 \text{ s/h}} \right) \cdot (\mu_{en}/\rho_{air})_{\text{wat}}
\]

\[
= 2.5 \text{ cGy/cm}^2/\text{h} \cdot \left( \frac{10^4 \text{ cm}^2/\text{m}^2}{3600 \text{ s/h}} \right) \cdot 1.11 = 7.71 \text{ cGy/cm}^2/\text{s}
\]

2. **Adapt line source model to problem**

\[
L = N \cdot \Delta S
\]

is equivalent to

\[
r = \sqrt{(1.5)^2 + (2.5/2)^2} = 1.95 \text{ cm}
\]

3. **Write equation relating, t, dwell time/position to Dose**

\[
\text{Dose} = 2 \text{ ovoids} \times 3 \text{ dwell positions/ovoid} \times t \cdot \Lambda \cdot \frac{\Delta \theta}{L \cdot r}
\]

\[
= 6 \cdot t \cdot \Lambda \cdot \frac{2 \cdot \tan^{-1}(L/2r)}{L \cdot r}
\]

4. **Substitute values into equation**

\[
\text{Dose} = 2 \cdot 3 \cdot t \cdot \Lambda \cdot \frac{\Delta \theta}{L \cdot r}
\]

\[
600 \text{ cGy} = 6 \cdot t \cdot 7.71 \cdot \frac{2 \cdot \tan^{-1}(0.75/1.95)}{1.5 \cdot 1.95}
\]

\[
= t \cdot 46.3 \cdot \frac{2 \cdot 0.3672}{2.925} = 11.62 \cdot t
\]

\[\Rightarrow t = 51.6 \text{ seconds/position}\]