# AAPM TG-43 Update for 2004 and Beyond

**Mark J. Rivard, Ph.D.**

on behalf of the Working Group authors:

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## Full Disclosure

Dr. Rivard has received research funds from the following brachytherapy source manufacturers:

Implant Sciences Corporation
IsoRay Medical, Inc.
Mentor Corporation
North American Scientific
Nucletron Corporation
Theragenics Corporation
Xoft, Inc.

other Working Group members may also serve as manufacturer consultants - see AAPM COI website

## Purpose

**Present summary of:**

- **AAPM TG-43U1 brachytherapy dosimetry protocol,**
- **future supplements, and**
- **possible future projects.**

## 2004 AAPM TG-43U1 Report

- high level perspective of brachytherapy in U.S.
- dosimetry formalism and clinical datasets
- revised dosimetry formalism
  - 2-D,1-D, and air kerma strength definition
- consensus data formulation
- clinical implementation recommendations
- clarify interpolation / extrapolation methods
- recommendations to dosimetry investigators
  - experimental measurements & Monte Carlo calculations
- formalism errata and published comments

## Brachytherapy Background

1898: Marie Curie discovered radioactivity ($^{210}$Po), and later $^{226}$Ra

1903: awarded Nobel Prize, same year that Alexander Graham Bell proposed brachytherapy

$^{226}$Ra brachytherapy dominated for next 60 years

post-1950s reactor development produced man-made radionuclides: $^{60}$Co, $^{137}$Cs, $^{192}$Ir, $^{198}$Au, etc.

currently wide variety of source manufacturers, radionuclides, and brachytherapy source types

## Permanent LDR Brachytherapy

CT and radiograph of clinical LDR $^{125}$I implant

## AAPM Committee Structure 101

AAPM BoD

Science Council

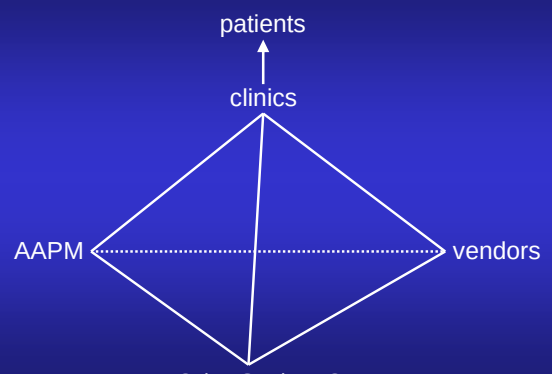
Imaging | Therapy

Radiation Safety
Therapy Research
Calibrations
Quality Assurance
Therapy Imaging
Treatment Planning
Treatment Delivery
Brachytherapy

LIBC (Butler) | LEBD (Rivard) | HEBD (Li) | EBM (Thomadsen) | BSR (Ibbott)

ASTRO, ABS, ESTRO, NRC, FDA, etc

## Brachytherapy Data Coordination



## Purpose of the Revised Protocol

The goals of the revised protocol (TG-43U1) were:

(a) provide a revised definition of air-kerma strength;

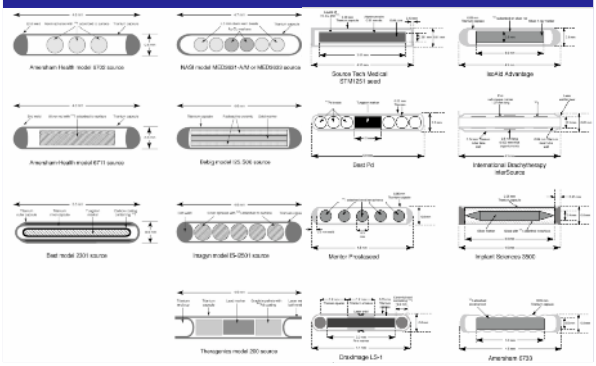
(b) eliminate *apparent activity* for specification of source strength;

(c) eliminate the anisotropy constant in favor of the distance dependent 1-D anisotropy function;

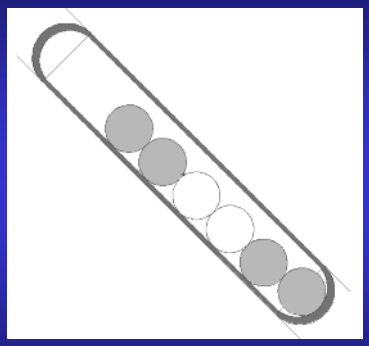
(d) provide guidance on extrapolating tabulated TG-43 parameters to longer and shorter distances; and

(e) eliminate minor inconsistencies and omissions in the original protocol and its implementation.

## Brachytherapy Seeds



## NASI LDR $^{125}$I Source



**realistic modeling of internal components**

## $S_K$ Measurement Requirements

accidental manufacture of sources with zero activity or twice the activity

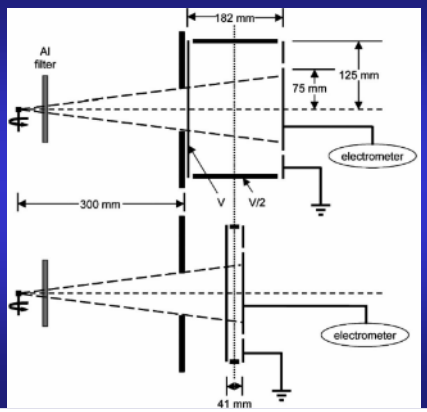
may not trust 3rd party (nuclear pharmacy) assay

measure all sources preceding clinical use

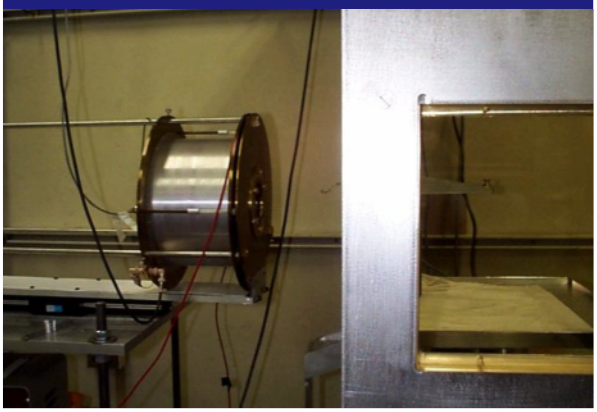
also use film for autoradiograph

required by AAPM TG-40 and TG-56 reports

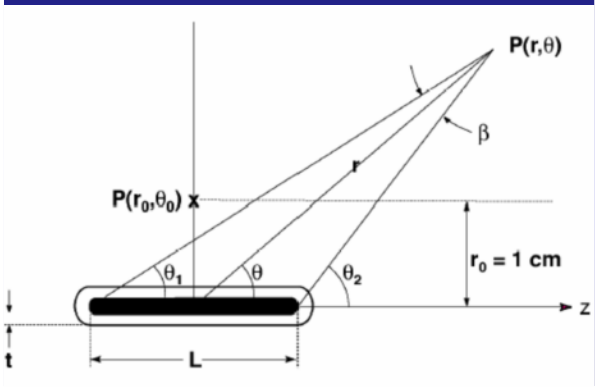
## NIST WAFAC




## NIST WAFAC



## Brachytherapy Calculation Geometry




## Revised AAPM TG-43 Brachytherapy Dosimetry Formalism (2-D)

$$\dot{D}(r,\theta) = S_K \cdot \Lambda \cdot \frac{G_L(r,\theta)}{G_L(r_0,\theta_0)} \cdot g_L(r) \cdot F(r,\theta)$$

| | |
|---|---|
| $\dot{D}(r,\theta)$ | dose rate to water at point P(r,θ) |
| $S_K$ | air kerma strength |
| $\Lambda$ | dose rate constant |
| $g_L(r)$ | radial dose function |
| $G_L(r,\theta)$ | geometry function (line source approximation) |
| $F(r,\theta)$ | 2-D anisotropy function |

## Revised AAPM TG-43 Brachytherapy Dosimetry Formalism (1-D)

$$\dot{D}(r) = S_K \cdot \Lambda \cdot \frac{G_L(r,\theta_0)}{G_L(r_0,\theta_0)} \cdot g_L(\mathrm{r}) \cdot \phi_{an}(r)$$

| | |
|---|---|
| $\dot{D}(r)$ | dose rate to water at point P(r) |
| $S_K$ | air kerma strength |
| $\Lambda$ | dose rate constant |
| $g_L(r)$ | radial dose function |
| $G_L(r,\theta)$ | geometry function (line source approximation) |
| $\phi_{an}(r)$ | 1-D anisotropy function |

## Revised Air Kerma Strength Definition

$$S_K \equiv \dot{K}_\delta(d)\ d^2$$

$S_K$ air kerma strength

$\dot{K}_\delta(d)$ air kerma rate *in vacuo* at specification point d with energy cutoff $\delta$, typically 5 keV

- low-energy photon cutoff now included, and
- measurement conditions are now specified

| Manufacturer and source type | | $_{CONSENSUS}\Lambda$ [cGy h$^{-1}$ U$^{-1}$] | % difference in $\Lambda$ from 1999 value |
|---|---|---|---|
| Amersham 6702 | $^{125}$I | 1.036 | N/A |
| Amersham 6711 | $^{125}$I | 0.965 | N/A |
| Best Industries 2301 | $^{125}$I | 1.018 | +3.3% |
| NASI MED3631-A/M | $^{125}$I | 1.036 | +1.0% |
| Bebig/Theragenics 125.SO6 | $^{125}$I | 1.012 | +2.2% |
| Imagyn IS-12501 | $^{125}$I | 0.940 | +3.5% |
| Theragenics 200 | $^{103}$Pd | 0.686 | +4.0% |
| NASI MED3633 | $^{103}$Pd | 0.693 | +4.3% |

## Comparison of 1-D Formalisms

BAD $$\dot{D}(r) = S_K \cdot \Lambda \cdot \frac{G_L(r,\theta_0)}{G_L(r_0,\theta_0)} \cdot g_P(\mathrm{r}) \cdot \phi_{an}(r)$$

BAD $$\dot{D}(r) = S_K \cdot \Lambda \cdot \left(\frac{r_0}{r}\right)^2 \cdot g_L(r) \cdot \phi_{an}(r)$$

GOOD $$\dot{D}(r) = S_K \cdot \Lambda \cdot \left(\frac{r_0}{r}\right)^2 \cdot g_P(r) \cdot \phi_{an}(r)$$

BEST $$\dot{D}(r) = S_K \cdot \Lambda \cdot \frac{G_L(r,\theta_0)}{G_L(r_0,\theta_0)} \cdot g_L(\mathrm{r}) \cdot \phi_{an}(r)$$

## Consensus Dataset Formulation Methodology

- comparisons of all candidate datasets
- average $_{MC}\Lambda$ and average $_{EXP}\Lambda$ from literature

$$_{CON}\Lambda = \frac{(_{MC}\Lambda + {}_{EXP}\Lambda)}{2}$$

- g(r) and F(r,θ) candidate datasets transformed using common L, possibly with $L_{eff} = \Delta S \times N$
- g(r) and F(r,θ) typically taken from Monte Carlo
- $\phi_{an}(r)$ calculated from consensus F(r,θ) dataset
- final results tabulated with common mesh

## Consensus Dataset Formulation Methodology

- Literature review of experimental methods & Monte Carlo dosimetry characterization of 8 brachytherapy seeds (2004 AAPM TG-43U1)
  - Amersham / Oncura model 6733 $^{125}$I
  - DraxImage model LS-1 $^{125}$I
  - Implant Science model 3500 $^{125}$I
  - IBt 1251L $^{125}$I
  - IsoAid model IAI-125 $^{125}$I
  - Mentor model SL-125/SH-125.SO6 $^{125}$I
  - SourceTech Medical STM1251 $^{125}$I
  - Best Medical model 2335 $^{103}$Pd

## Consensus Dataset Formulation Methodology

- Literature review of experimental methods & Monte Carlo dosimetry results for 8 brachytherapy seeds:
  - Amersham Health models 6702 and 6711 $^{125}$I
  - Bebig/Theragenics Corporation model I25.SO6 $^{125}$I
  - Best Industries model 2301 $^{125}$I
  - Imagyn Medical Technologies model IS-12501 $^{125}$I
  - North American Scientific model MED3631-A/M $^{125}$I
  - Theragenics Corporation model 200 $^{103}$Pd
  - North American Scientific model MED3633 $^{103}$Pd

## Clinical Implementation Recommendations

- know your Bx TxP algorithm, deal with limitations
- acceptance testing and commissioning
  - follow AAPM TG-40, TG-53, & TG-56 recommendations
  - compare/validate with Eq.(10) reference dose rates

| r (cm) | Amersham 6702 | Amersham 6711 | Best 2301 | NASI MED3631-A/M | Bebig I25.SO6 | Imagyn IS-12501 | Theragenics 200 | NASI MED3633 |
|---|---|---|---|---|---|---|---|---|
| 0.5 | 4.119 | 3.937 | 3.978 | 4.112 | 3.922 | 3.426 | 3.014 | 3.184 |
| 1.0 | 0.995 | 0.911 | 1.004 | 0.986 | 0.950 | 0.815 | 0.587 | 0.626 |
| 1.5 | 0.413 | 0.368 | 0.419 | 0.420 | 0.398 | 0.334 | 0.199 | 0.215 |
| 2.0 | 0.213 | 0.186 | 0.217 | 0.207 | 0.205 | 0.169 | 0.0837 | 0.0914 |
| 3.0 | 0.0768 | 0.0643 | 0.0783 | 0.0746 | 0.0733 | 0.0582 | 0.0206 | 0.0227 |
| 4.0 | 0.0344 | 0.0284 | 0.0347 | 0.0325 | 0.0323 | 0.0246 | 0.00634 | 0.00697 |
| 5.0 | 0.0169 | 0.0134 | 0.0171 | 0.0157 | 0.0157 | 0.0118 | 0.00221 | 0.00247 |
| 6.0 | 0.00890 | 0.00688 | 0.00908 | 0.00811 | 0.00840 | 0.00592 | 0.000846 | 0.000933 |
| 7.0 | 0.00490 | 0.00373 | 0.00506 | 0.00429 | 0.00459 | 0.00328 | 0.000342 | 0.000364 |

- well chamber ADCL calibrations, NIST traceability

## Correction of Errors and Inconsistencies

- g(r) presented for dimensionless units, consistency with investigator g(r), and 5$^{th}$ order polynomial
- explicit *contraindication* for erroneous 1-D equation

$$\dot{D}(r) = S_K \ \Lambda \ \cdot \frac{G_P(r,\theta_0)}{G_P(r_0,\theta_0)} \cdot \mathrm{g_L}(\mathrm{r}) \cdot \phi_{an}(r)$$

- goodbye $A_{app}$ and anisotropy constant
- methodology to extrapolate dose calculations for large and small distances

## Removal of Previously Defined Terms

- apparent activity: $A_{app}$
  - choice of $(\Gamma_\delta)_x$ may lead to dosimetric errors
  - AAPM solely specifies $S_K$ for calibration standard
- anisotropy constant: $\overline{\phi}_{an}$
  - not able to accurately reproduce dosimetry data r < 1 cm
  - changes may be made to minimize error, but can lead to significant errors under specific circumstances

## Reference Data

- NIST-specified source spectra, half-lives, ρ and atomic composition for both air and water

TABLE XIII. Recommended nuclear data for $^{125}$I and $^{103}$Pd for brachytherapy dosimetry.

| $^{125}$I (half-life = 59.40 ± 0.01 days) | | $^{103}$Pd (half-life = 16.991 ± 0.019 days) | |
|---|---|---|---|
| Photon energy (keV) | Photons per disintegration | Photon energy (keV) | Photons per disintegration |
| 27.202 | 0.406 | 20.074 | 0.224 |
| 27.472 | 0.757 | 20.216 | 0.423 |
| 30.98 | 0.202 | 22.72 | 0.104 |
| 31.71 | 0.0439 | 23.18 | 0.0194 |
| 35.492 | 0.0668 | 39.75 | 0.00068 |
| | | 294.98 | 0.00003 |
| | | 357.5 | 0.00022 |
| | | 497.1 | 0.00004 |
| Weighted mean energy = 28.37 keV | Total = 1.476 | Weighted mean energy = 20.74 keV | Total = 0.7714 |
| $^{125}$I $\Gamma_{\delta\,\mathrm{keV}}$ = 0.0355 $\mu$Gy·m$^2$·h$^{-1}$·MBq$^{-1}$ | | $^{103}$Pd $\Gamma_{\delta\,\mathrm{keV}}$ = 0.0361 $\mu$Gy·m$^2$·h$^{-1}$·MBq$^{-1}$ | |

TABLE XIV. Composition (percent mass) of air as a function of relative humidity at a pressure of 101.325 kPa.

| Relative humidity (%) | Hydrogen | Carbon | Nitrogen | Oxygen | Argon |
|---|---|---|---|---|---|
| 0 | 0.0000 | 0.0124 | 75.5268 | 23.1781 | 1.2827 |
| 10 | 0.0181 | 0.0124 | 75.4048 | 23.2841 | 1.2806 |
| 40 | 0.0732 | 0.0123 | 75.0325 | 23.6077 | 1.2743 |
| 60 | 0.1101 | 0.0123 | 74.7837 | 23.8238 | 1.2701 |
| 100 | 0.1842 | 0.0122 | 74.2835 | 24.2585 | 1.2616 |

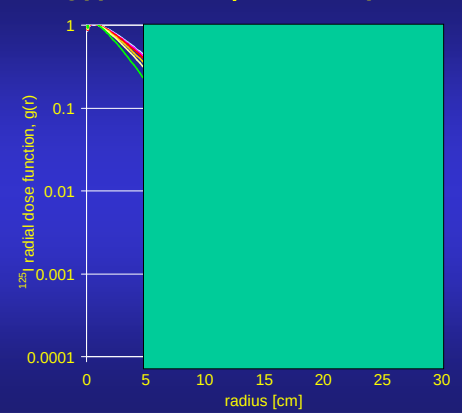
## Need for Uncertainty Analyses

TABLE XII. Generic uncertainty assessment for experimental measurements using TLDs, and Monte Carlo methods for radiation transport calculations. Type A and B uncertainties correspond to statistical and systematic uncertainties, respectively. All values provided are for 1 $\sigma$.

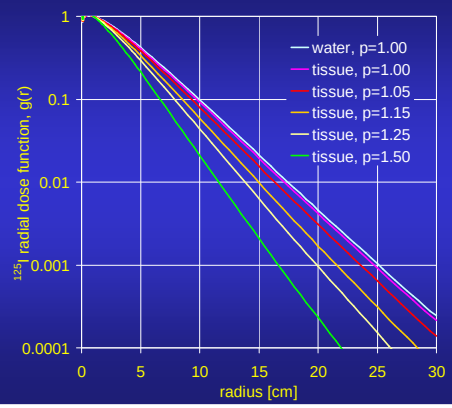
| TLD uncertainties | | |
|---|---|---|
| Component | Type A | Type B |
| Repetitive measurements | 4.5% | |
| TLD dose calibration (including linac calibration) | | 2.0% |
| LiF energy correction | | 5.0% |
| Measurement medium correction factor | | 3.0% |
| Seed/TLD positioning | | 4.0% |
| Quadrature sum | 4.5% | 7.3% |
| Total uncertainty | 8.6% | |
| ADCL $S_K$ uncertainty | 1.5% | |
| Total combined uncertainty in A | 8.7% | |

| Monte Carlo uncertainties | | |
|---|---|---|
| Component | $r$ = 1 cm | $r$ = 5 cm |
| Statistics | 0.3% | 1.0% |
| Photoionization[a] | 1.5% | 4.5% |
| Cross-sections (2.3%) | | |
| Seed geometry | 2.0% | 2.0% |
| Source energy spectrum[a] | 0.1% | 0.3% |
| Quadrature sum | 2.5% | 5.0% |

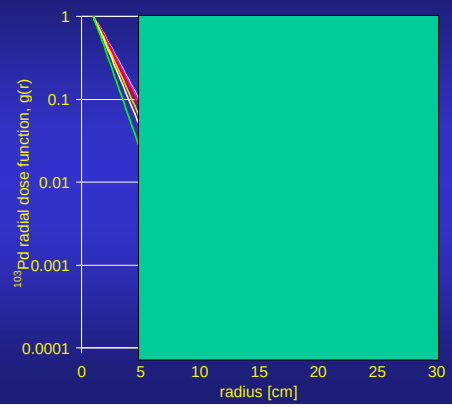
## I-125 g(r), Variable ρ and Composition



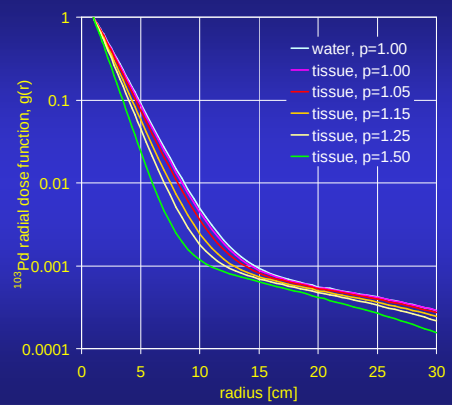
## Need for Extrapolation Methodology




## Pd-103 g(r), Variable ρ and Composition




## Need Extrapolation Methodology




## Recommendations to Dosimetry Investigators

- experimental measurement descriptors
  - description of internal and external source geometry
  - source irradiation geometry, orientation, irradiation timeline
  - detector calib. technique & energy response function, *E(r)*
  - radiation detector and readout system
  - measurement phantom
  - phantom dimensions and use of backscatter
  - estimation volume averaging effect at all detector positions
  - # of repeated readings with standard deviation, # of sources
  - NIST $S_K$ value and uncertainty for measured source
  - uncertainty analysis section (statistical and systematic)

## Recommendations to Dosimetry Investigators

- Monte Carlo recommended good practices
  - primary calculations in 30 cm diameter liquid water phantom, with at least 5 cm of backscatter material
  - use sufficient histories to limit statistical uncertainty
    - $1\sigma \leq 2$ % for $r \leq 5$ cm in water; $1\sigma \leq 1$ % for $s_K$ calculations
  - modern cross-section libraries should be used
  - verify manufacturer's source dimensions
  - Volume averaging effects should be limited to < 1 %
  - model *k(d)* as a function of polar angle for $s_K$ simulation
  - point source modeling is unacceptable
  - mechanical mobility of internal source structures

## Recommendations to Dosimetry Investigators

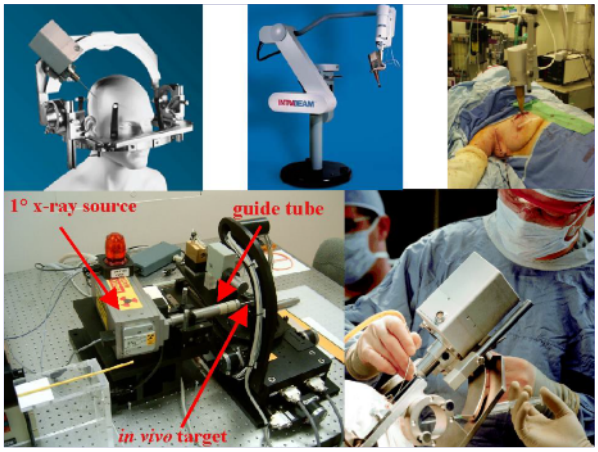
- Monte Carlo calculation descriptors
  - radiation transport code, version, and major options
  - cross-section library name, version, and customizations
  - radiation spectrum of source
  - manner in which dose-to-water and air-kerma strength are calculated (*i.e.*, tally used)
  - source geometry, phantom geometry, and sampling space
  - composition and mass density of materials in the source
  - composition and mass density of materials in the phantom
  - physical distribution of radioisotope within the source
  - uncertainty analysis section (statistical and systematic)

## Publication of Dosimetry Results

- unofficial *Medical Physics* Seed Policy (2001) limiting publication of basic dosimetry parameters to a Technical Note
- focus more on new science versus mundane data
- other scientific journals are receptive to publish
- do not reiterate TG-43U1 formalism, established methods, and citeable literature towards KISS
- TG-43U1 Independence Policy
  - authors should minimize conflict-of-interest with vendors
  - measurements & calculations should be gathered independently and not be dependent upon each other

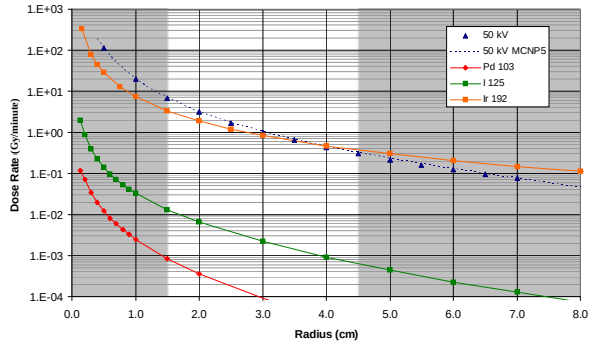
## Errata and Literature Comments

- *Medical Physics* (August 2002) letter-to-the-editor (Jerry Meli) and AAPM response to justify retention of line-source geometry functions
- erratum in *Medical Physics* (December 2004) primarily to address typos
- *Medical Physics* (June 2005) letter-to-the-editor (Ali Meigooni *et al*.) and AAPM response to clarify the geometry function and Eq.(5) $L_{eff} = \Delta S \times N$
- $U = \mu Gy.m^2.h^{-1}$ or $cGy.cm^2.h^{-1}$

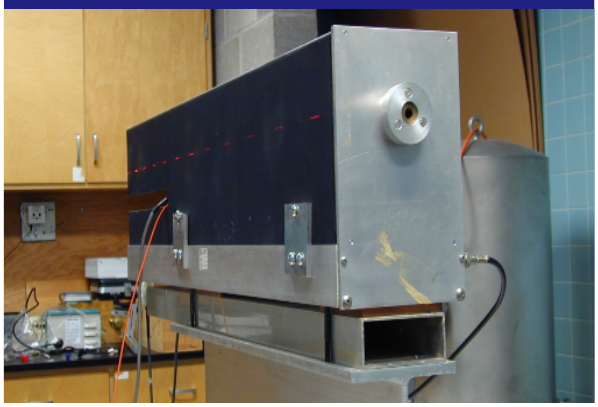



## Depth Dose Characteristics

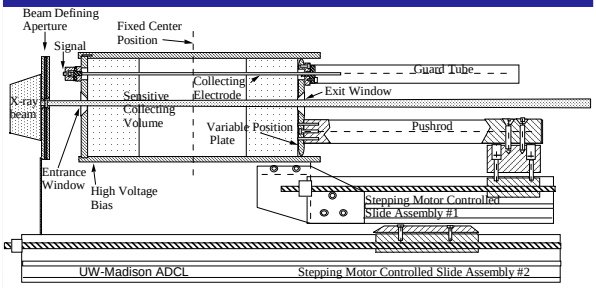
similar dose rates to 10 Ci HDR $^{192}$Ir over region of interest



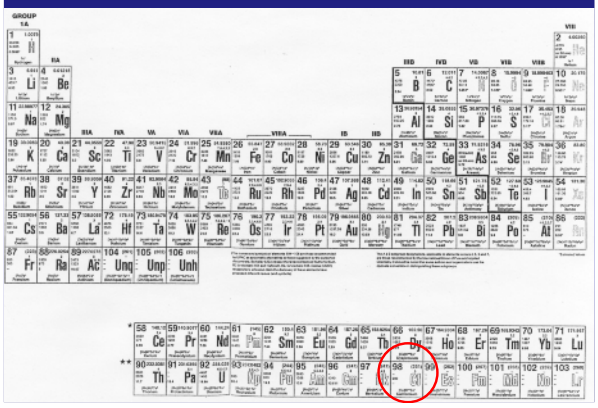

## Free Air Attix Ionization Chamber



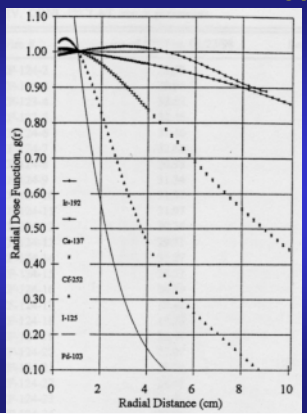
## Free Air Attix Chamber Schematic



## $^{252}$Cf Brachytherapy ?



## Radial Dose Functions, g(r)




## Conclusion

- need to supplement consensus data from the AAPM TG-43U1 (2004) report
- consensus datasets for 8+8 brachytherapy sources are provided for consistent clinical use
- guidance provided to physicists and RTP software vendors for interpolation / extrapolation methods
- draft report is under review at AAPM, results to be published in *Medical Physics*
- forthcoming supplement for additional sources
- need to advance the field through better algorithms