Treatment Planning for Brachytherapy

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Introduction

Despite large dose gradients:

Inaccurate dose calculation for an excellent implant procedure

May be as bad as

Accurate dose calculation for a terrible implant procedure

Introduction (continued)

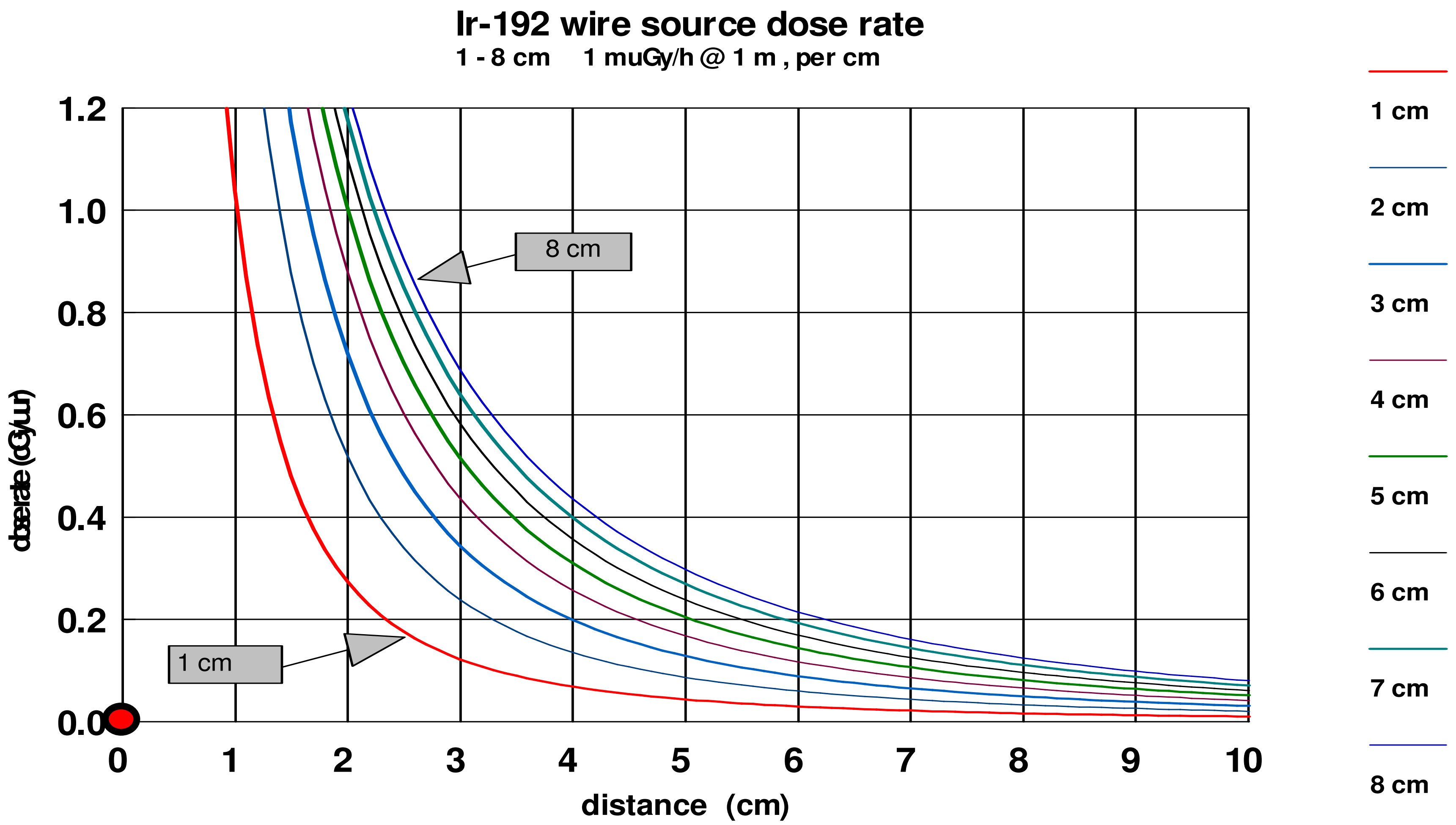
We need to improve our dose calculation technique as we are developing the implant procedures.

Recommended BT accuracy:

- Physics global accuracy 5-10%
- Input data and algorithm TPS numerical accuracy of at least ±2%

AAPM TG56, 1997

“depth dose”, dose as a function of distance for linear Ir-192 sources with the same *linear source* strength



Current most commonly algorithm:

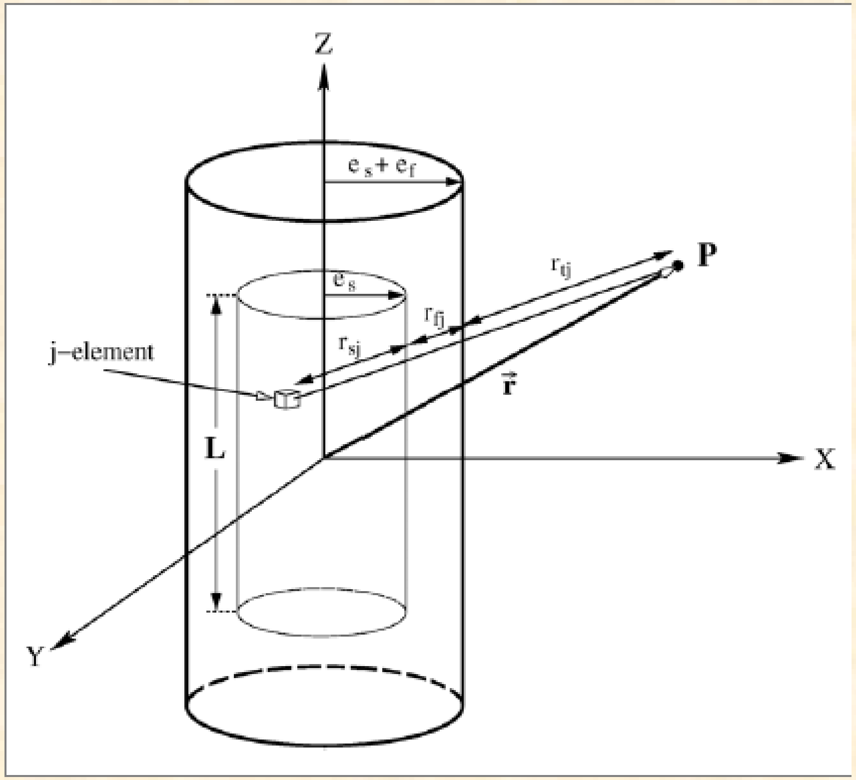
TG-43

AAPM Task Group 43: Brachytherapy Dose Calculation Formalism

- Nath et al., Med.Phys. 1995
- Update1: Rivard et al., Med.Phys. 2004
- U1Supplement1: Rivard et al, Med.Phys. 2007

Previously: Sievert Integral

$$\dot{D}(\mathbf{r}) = \left[\dot{K}_R \overline{\left(\frac{\mu_{en}}{\rho}\right)}_{\text{air}}^{\text{water}} \right] e^{(\mu_s e_s + \mu_f e_f)} \frac{1}{N} \sum_{j=1}^{N} e^{(-\mu_s r_{sj} - \mu_f r_{fj})} \frac{\varphi(r_{tj})}{r_j^2}$$

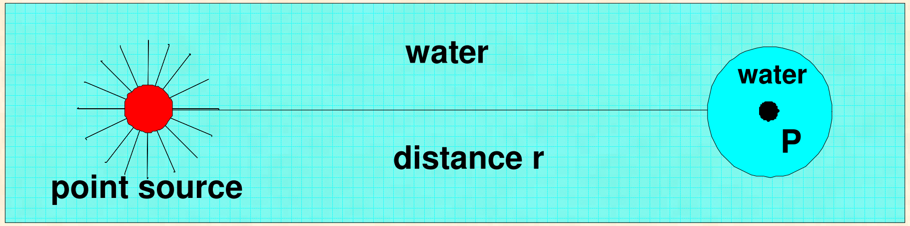


Sievert 1921

Cassell 1982

Williamson 1988

Simplified to point source



$$\dot{D}_{water} = \dot{K}_{\text{ref}} \cdot \left[\frac{\bar{\mu}_{en}}{\rho}\right]_{air}^{water} \cdot \left(\frac{r_0}{r}\right)^2 \cdot \varphi(r)$$

$$\left[\frac{\bar{\mu}_{en}}{\rho}\right]_{\text{air}}^{\text{water}}$$

Ratio of mean mass energy absorption coefficients water to air

(almost independent of energy, and therefore almost always equal to ratio of mean mass energy transfer coefficients, except for low energy)

$$\left(\frac{r_0}{r}\right)^2$$

Inverse square law term, relative to the distance at which the reference air kerma is defined (e.g., at 1 cm, or at 100 cm)

$\phi(r)$ **Correction factor for scatter and attenuation at distance r from the source, when compared to the same point in *vacuo***

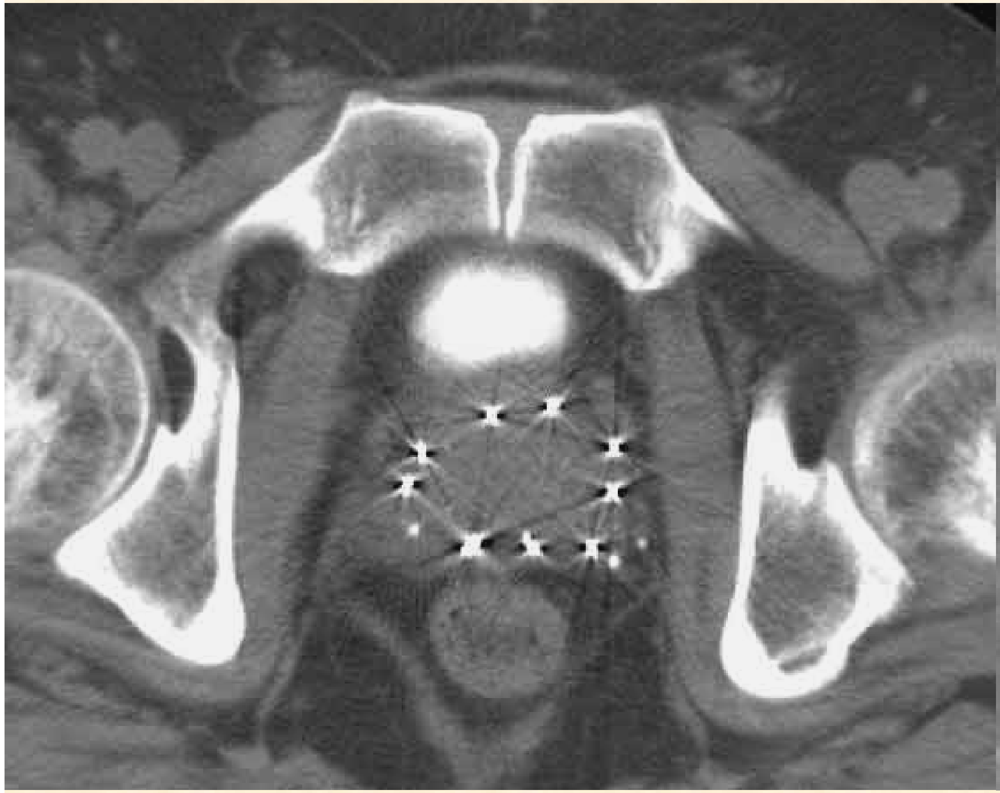
Generally based on Meisberger (1968) data

Sievert limitations

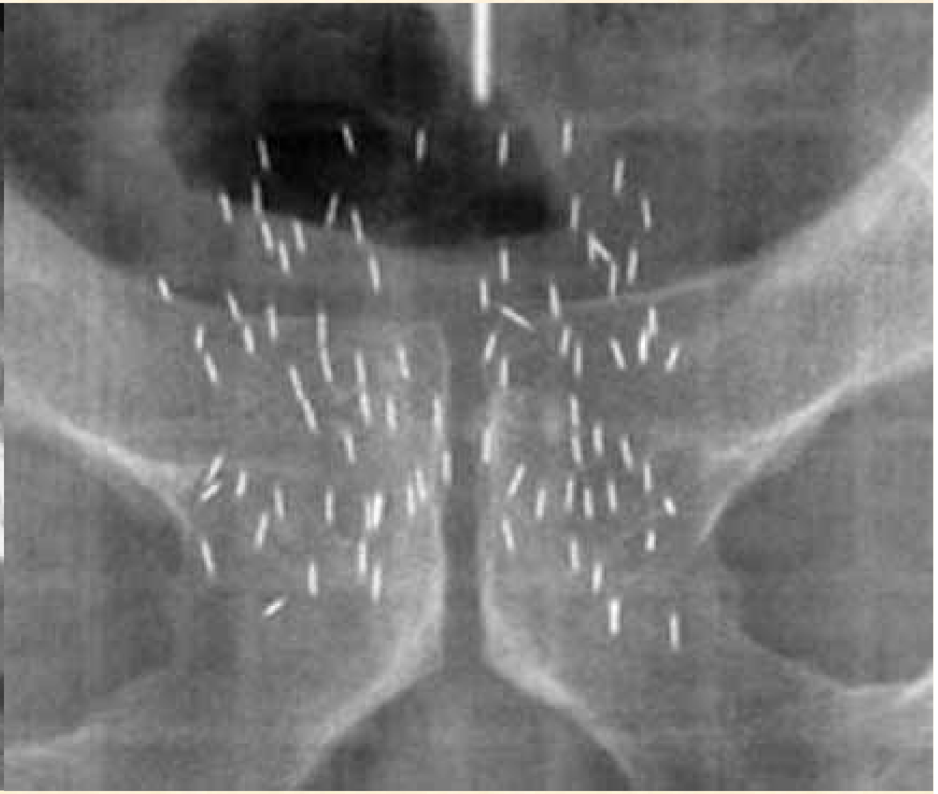
- Does not take into account real scatter behaviour
- μ_s, μ_f: mathematical best fit, not physical quantities

=> Acceptable results for ^{137}Cs and ^{192}Ir, but errors up to 25% for ^{125}I (AAPM 1995)

How to Calculate Seed Implant Dosimetry?



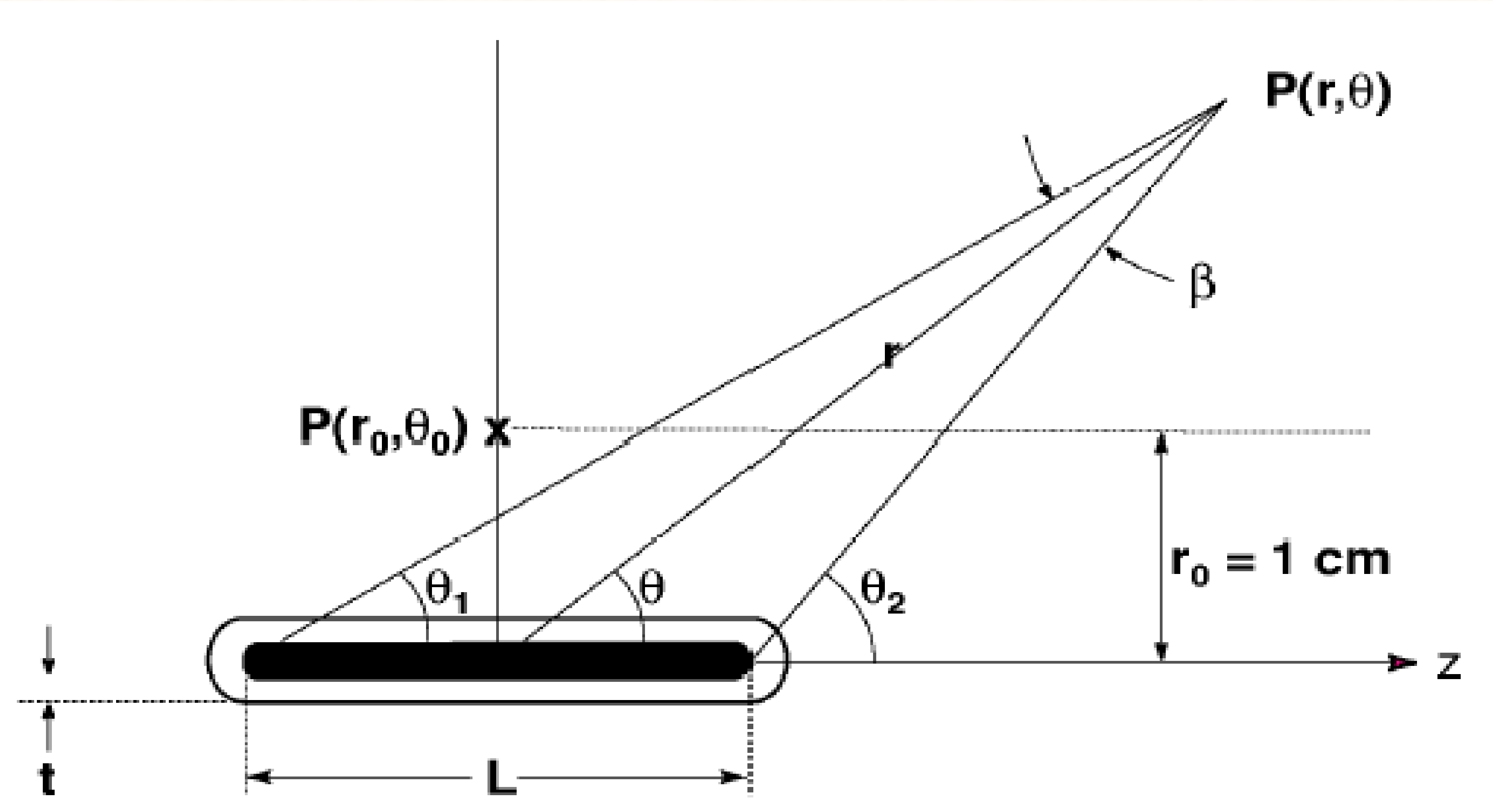
CT



radiograph

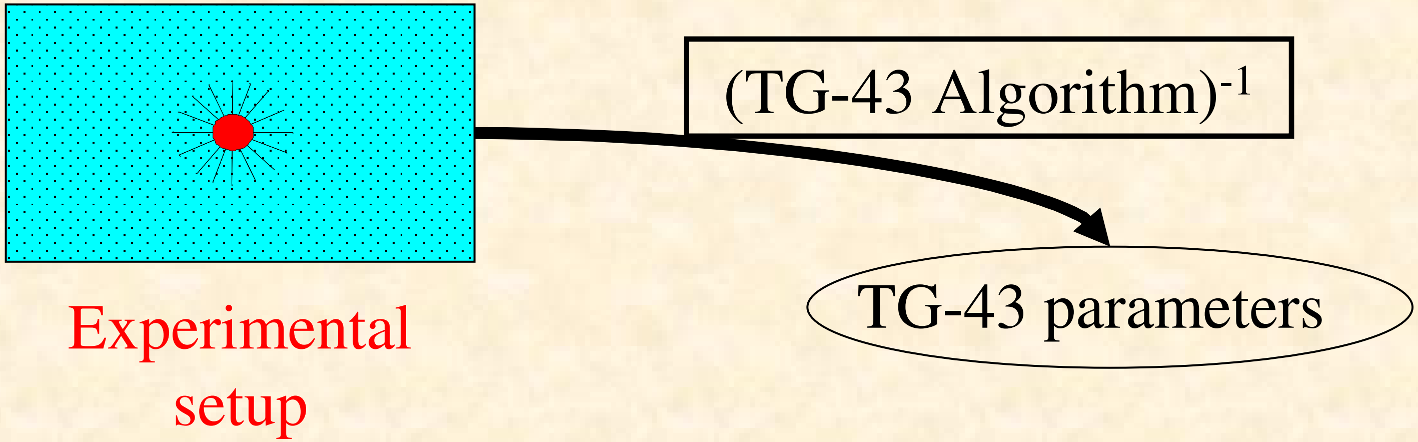
BT Dose Calculation: TG-43

$$\dot{D}(r,\theta) = S_k \bullet \Lambda \bullet \frac{G(r,\theta)}{G(r_0,\theta_0)} \bullet g(r) \bullet F(r,\theta)$$



TG-43 Concept

- Calculate (Monte-Carlo) and measure the dose distribution around a source => ***GUIDELINES***
- Parameterize TG-43 parameters to fit to the measurements => ***CONSENSUS DATASETS***



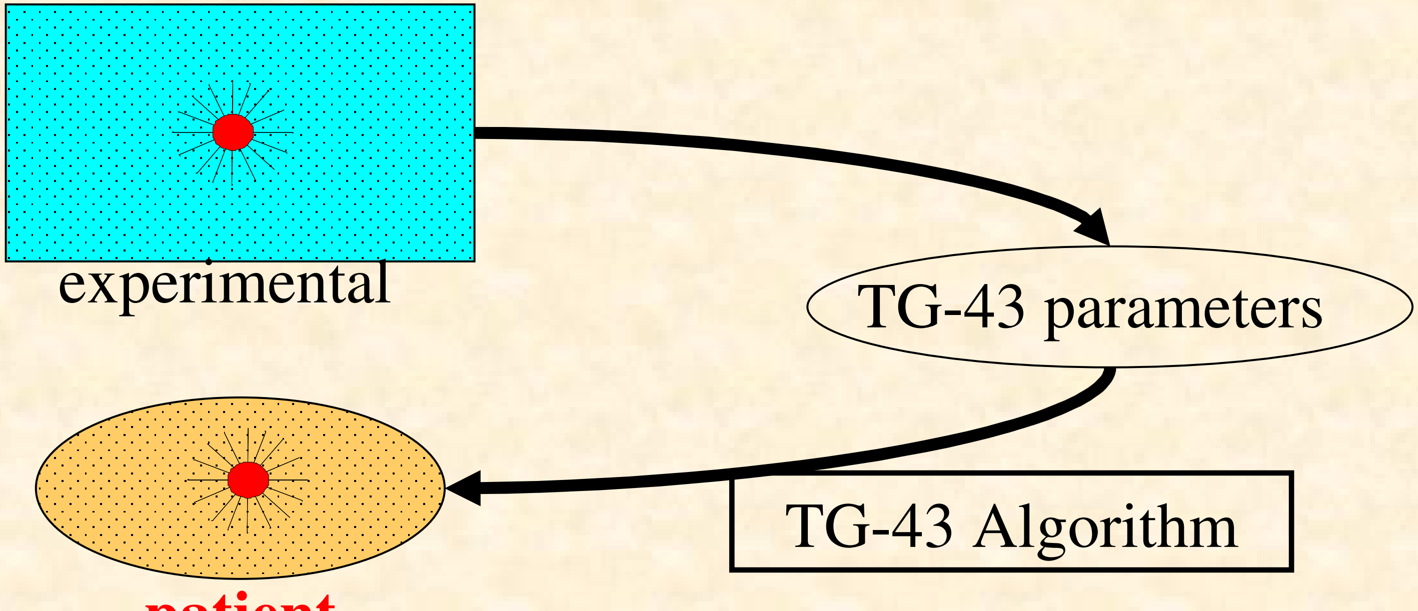
(TG-43 Algorithm)$^{-1}$

Experimental setup

TG-43 parameters

TG-43 Concept

- Calculate (Monte-Carlo) and measure the dose distribution around a source => ***GUIDELINES***
- Parameterize TG-43 parameters to fit to the measurements => ***CONSENSUS DATASETS***



experimental

TG-43 parameters

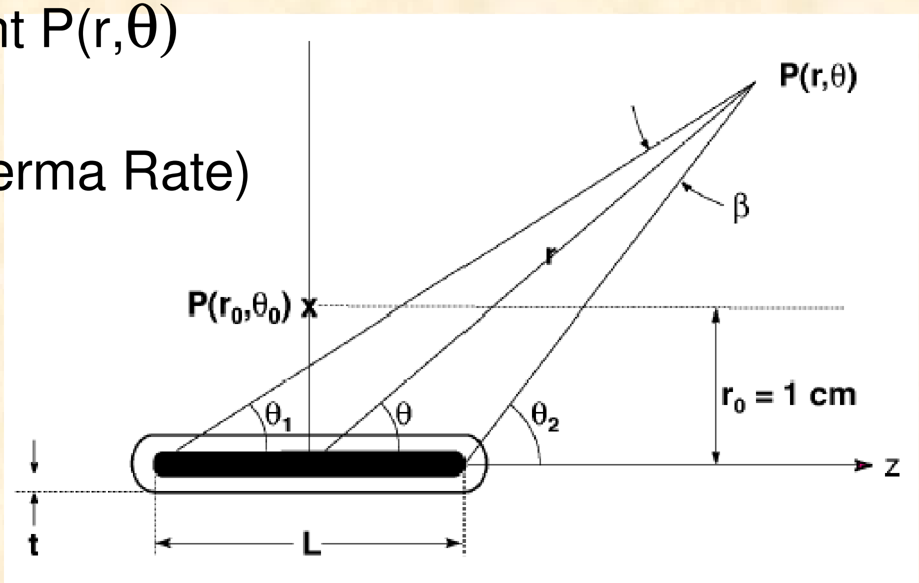
TG-43 Algorithm

patient

TG-43 general Brachytherapy Dosimetry Formalism

$$\dot{D}(r,\theta) = S_k \bullet \Lambda \bullet \frac{G_x(r,\theta)}{G_x(r_0,\theta_0)} \bullet g_x(r) \bullet F(r,\theta)$$

$\dot{D}(r,\theta)$	dose rate to water at point P(r,θ)
S_K	Source Strength,
	(numerically = Ref. Air Kerma Rate)
Λ	dose rate constant
$g_x(r)$	radial dose function
$G_x(r,\theta)$	geometry function
$F(r,\theta)$	2-D anisotropy function



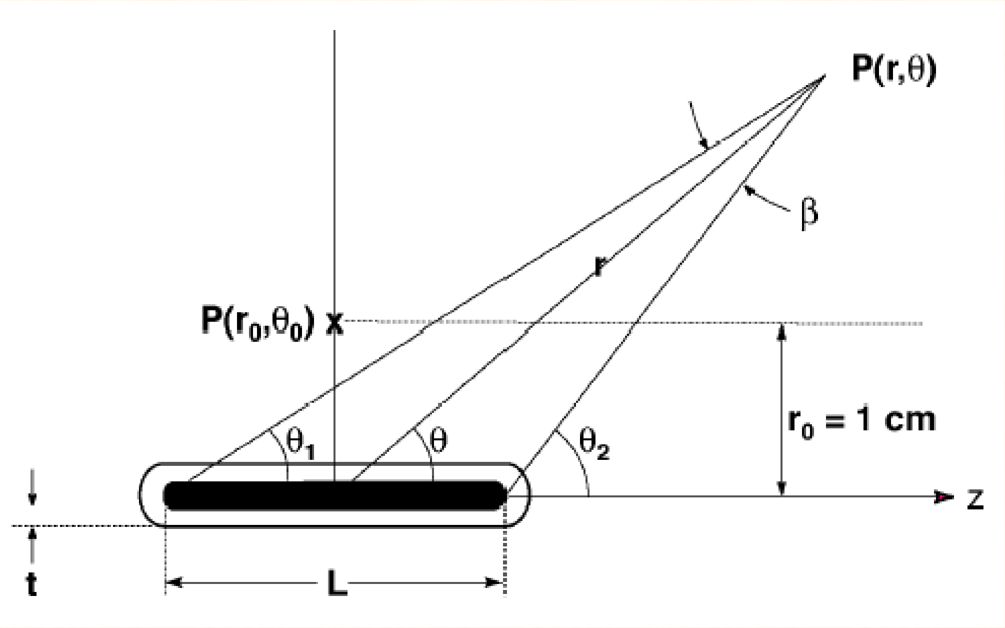
Subscript x : L for line source, P for point source approximation

Dose rate constant

$$\Lambda = \frac{\dot{D}(r_0, \theta_0)}{S_k}$$

Ratio of the dose at the reference position over the source strength

=> Converts Air Kerma to dose at the reference point



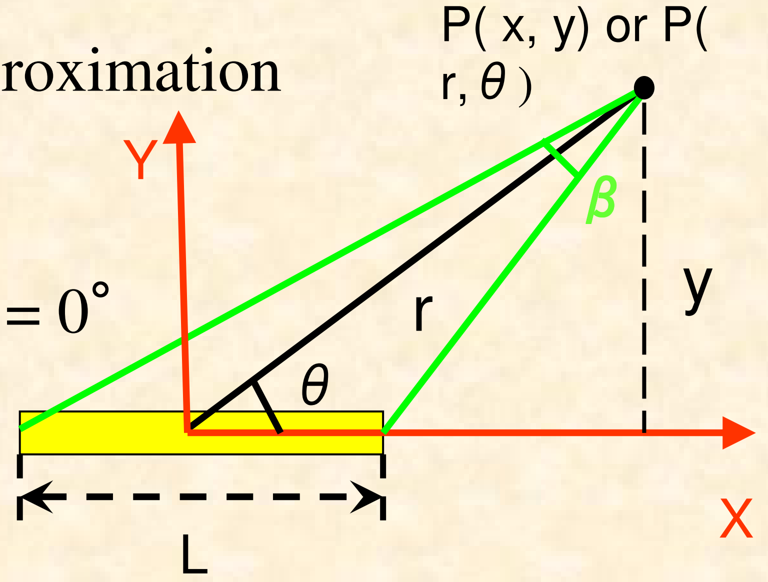
Geometry function

Deals with inverse square law, eliminating largest variation in other parameters

$$G_{P(r,\theta)} = \frac{1}{r^2}$$ Point source approximation

$$G_{L(r,\theta)} = \frac{\beta}{L \bullet r \bullet \sin\theta}$$ Line source approximation

$$G_{L(r,\theta)} = \frac{1}{r^2 - L^2/4}$$ Line source, $\theta = 0°$

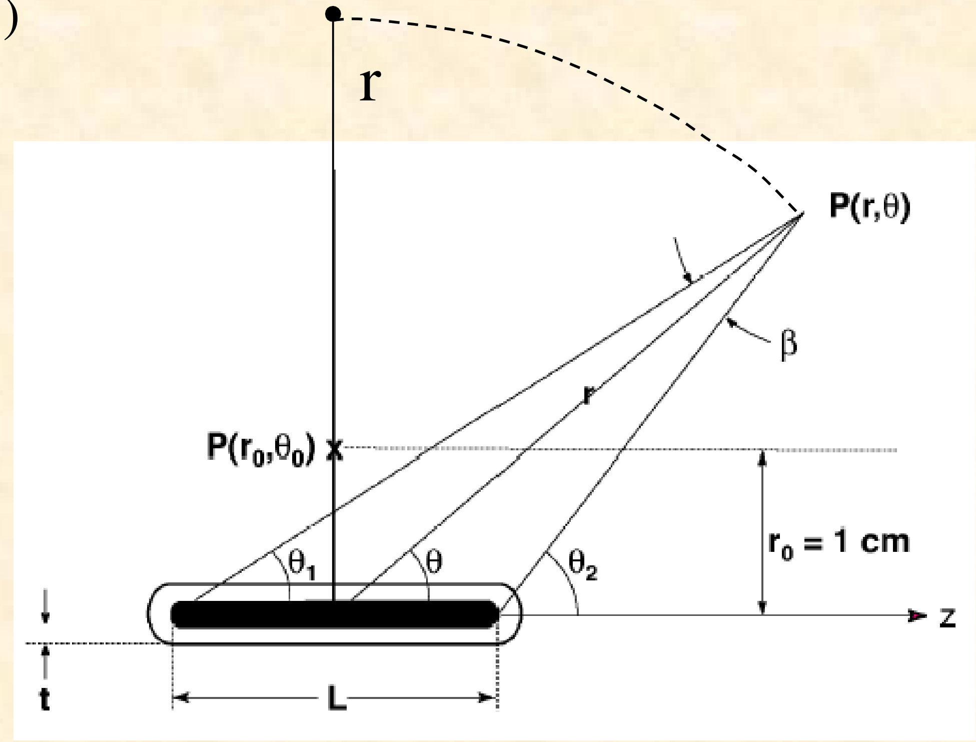


Radial Dose function

Dose fall-off along the transverse axis of the source (absorption and scatter effects in water)

$$\dot{D}(r,\theta) = S_k \bullet \Lambda \bullet \frac{G_x(r,\theta)}{G_x(r_0,\theta_0)} \bullet g_x(r) \bullet F(r,\theta)$$

$$g_x(r) = \frac{\dot{D}(r,\theta_0) \bullet G_x(r_0,\theta_0)}{\dot{D}(r_0,\theta_0) \bullet G_x(r,\theta_0)}$$

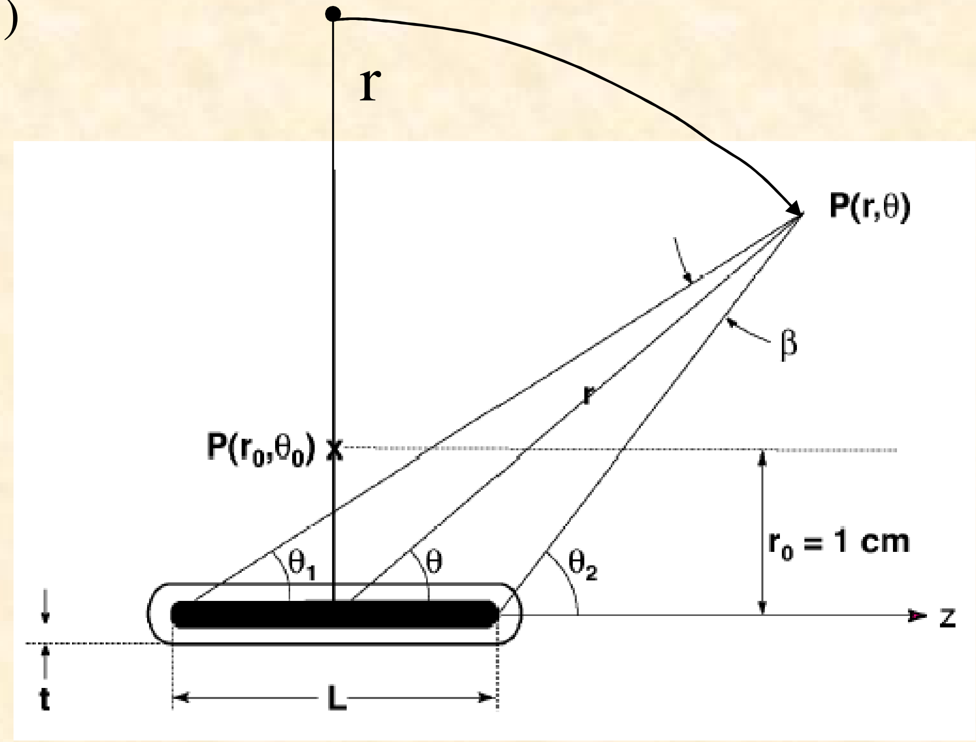


Anisotropy function

Accounts for anisotropy of the dose distribution around the source, including absorption and scatter in source and water

$$\dot{D}(r,\theta) = S_k \bullet \Lambda \bullet \frac{G_x(r,\theta)}{G_x(r_0,\theta_0)} \bullet g_x(r) \bullet F(r,\theta)$$

$$F(r,\theta) = \frac{\dot{D}(r,\theta) \bullet G_L(r,\theta_0)}{\dot{D}(r,\theta_0) \bullet G_L(r,\theta)}$$



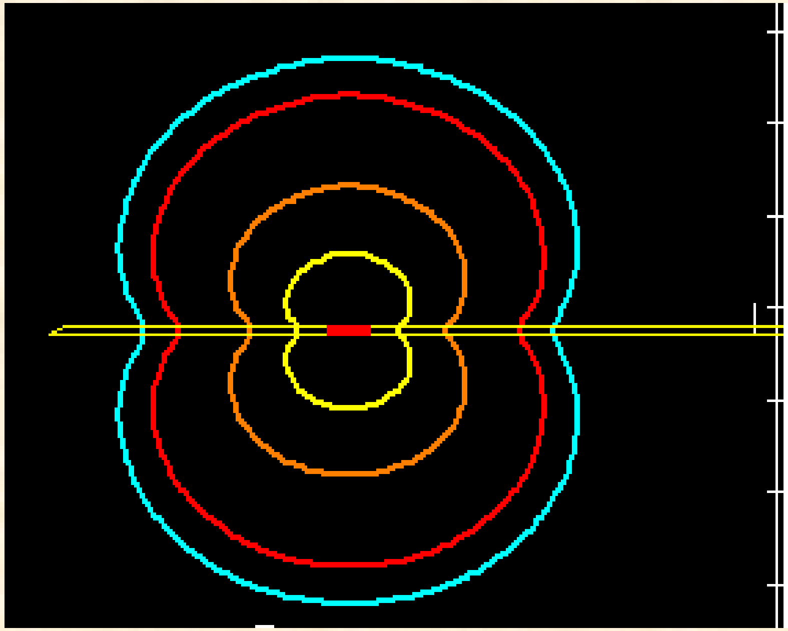
Anisotropy function

$F(r, \theta)$ 2D-Anisotropy function

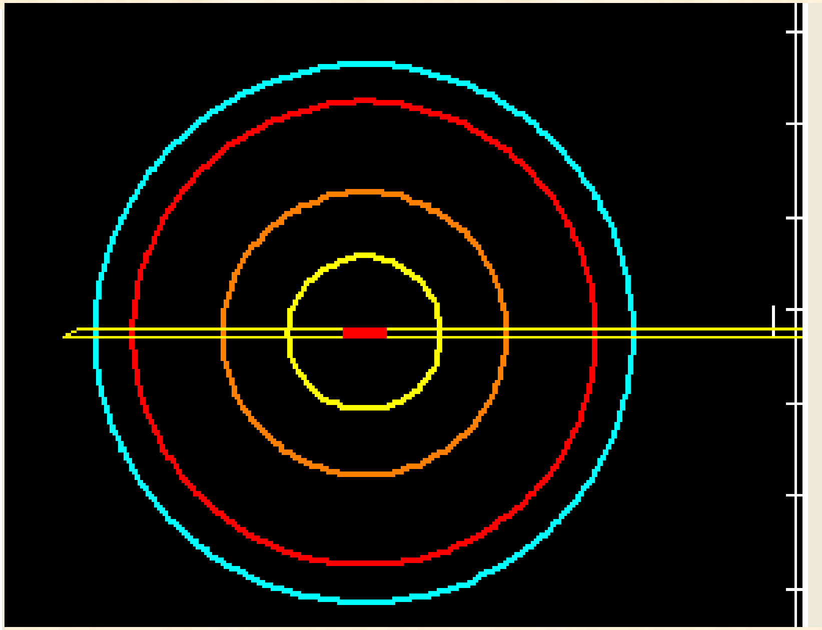
$\Phi_{an}(r)$ 1D-Anisotropy function
(source orientation unknown)
Anisotropy factor

$\xcancel{\bar{\phi}_{an}}$ Anisotropy constant:
Use no longer recommended!

2D-Anisotropy function



1D-Anisotropy function

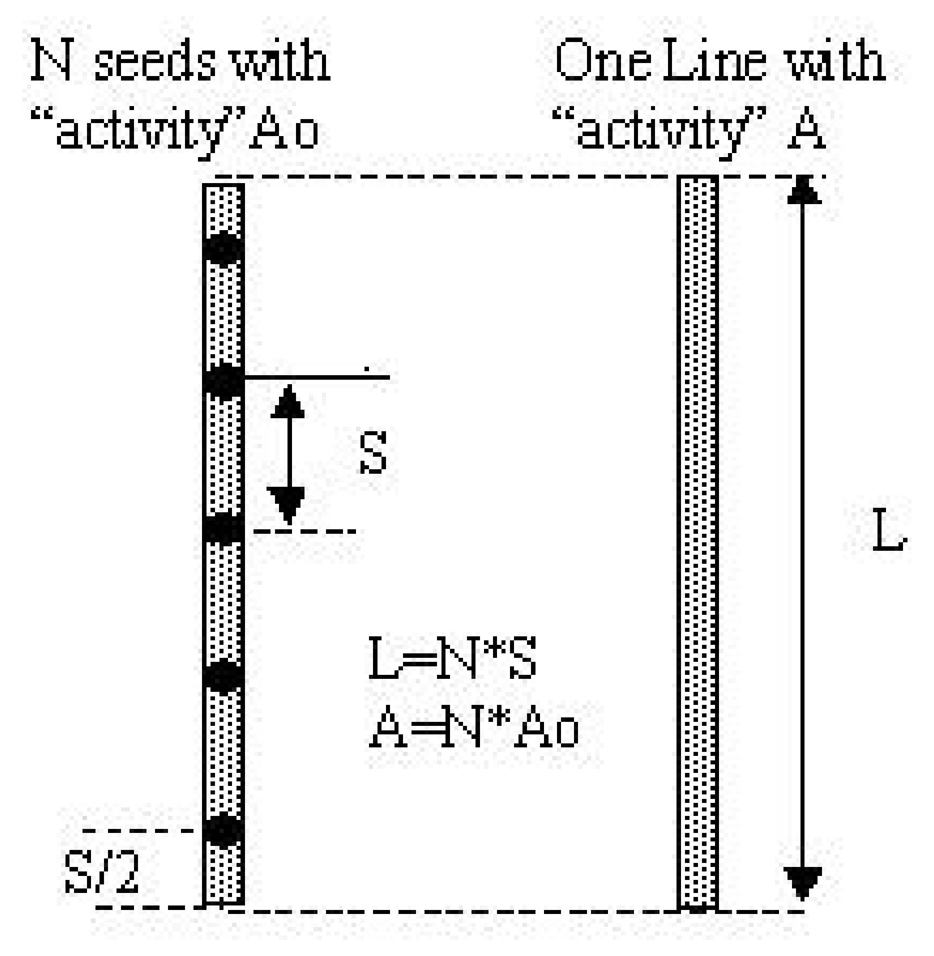


2004: Revised AAPM TG-43
BT Dosimetry Formalism (2-D)

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

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

Length L


N seeds with
"activity" Ao
One Line with
"activity" A
S
L
S/2
L=N*S
A=N*Ao

Revised AAPM TG-43 BT Dosimetry Formalism (1-D) BEST:

$$\dot{D}_{(r,\theta)} = S_k \bullet \Lambda \bullet \frac{G_{L(r,\theta)}}{G_{L(r_0,\theta_0)}} \bullet g_{L(r)} \bullet \Phi_{an(r)}$$

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

Comparison of 1D formalisms

BAD

$$\dot{D}_{(r,\theta)} = S_k \bullet \Lambda \bullet \frac{{r_0}^2}{r^2} \bullet \boxed{g_{L(r)}} \bullet \Phi_{an(r)}$$

BAD

$$\dot{D}_{(r,\theta)} = S_k \bullet \Lambda \bullet \frac{G_{L(r,\theta)}}{G_{L(r_0,\theta_0)}} \bullet \boxed{g_{p(r)}} \bullet \Phi_{an(r)}$$

GOOD

$$\dot{D}_{(r,\theta)} = S_k \bullet \Lambda \bullet \frac{{r_0}^2}{r^2} \bullet g_{p(r)} \bullet \Phi_{an(r)}$$

BEST

$$\dot{D}_{(r,\theta)} = S_k \bullet \Lambda \bullet \frac{G_{L(r,\theta)}}{G_{L(r_0,\theta_0)}} \bullet g_{L(r)} \bullet \Phi_{an(r)}$$

Data entry in the TPS

TG43 data can be entered either :

- As lookup tables (using linear interpolation)
- As mathematical model fit: polynomial, other

Often data supplied by the TPS manufacturer

In some systems accessible to the user, in others closed

Data entry in the TPS

Possible problems linked to this:

- Extrapolation beyond published data (to 0, larger distances)

- Polynomial fitting might not always give the best result, attention for behaviour outside the range used for fitting

Where to find data?

Preferentially use “consensus” data sets

- Low photon energy sources:
  - AAPM TG43U and Supplement
  - RPC registry (rpc.mdanderson.org)
  - ESTRO website
- High energy sources:
  - ESTRO website (+ www.uv.es/braphyqs)
  - RPC registry (rpc.mdanderson.org)
- Literature

Where to find data?

Attention not to mix up data:

As geometry factor interferes in calculated g(r) and F(r, θ), same geometry function should be used in TPS

Check final result against the published dose rate tables

Source specification

$$\dot{K}_R$$

Reference Air Kerma Rate: to be used in

-Calibration certificate

-Dose rate table

-TPS

-Prescription

-Reporting

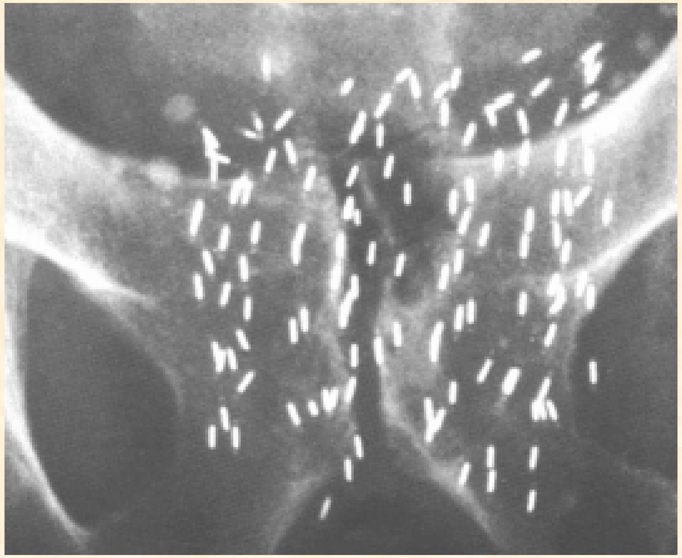
Source decay

- In TPS often: Dose = dose rate x time (mathematically: integration over time)

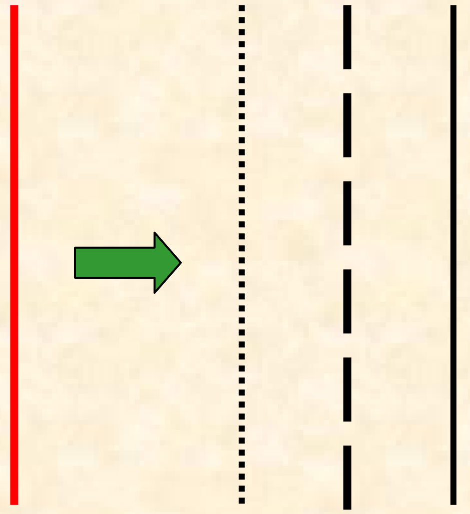
- For short time implantations (HDR), or long lived isotopes: dose rate can be considered constant
- In case of afterloaders: decay handling either by TPS or by Afterloader (or both)
- For manual-LDR (Ir) implants: compensate for decay during treatment (TPS-manually)
- Permanent implants: integration over time

Point source ⇔ Line source

- For small sources, with no anisotropy
  => Point source
- Seeds, but orientation not known
  => Line (Point) source, 1D anisotropy
- Short distances from a linear source
  => Line source, but even then dose on the source encapsulation ????



Line source approximation

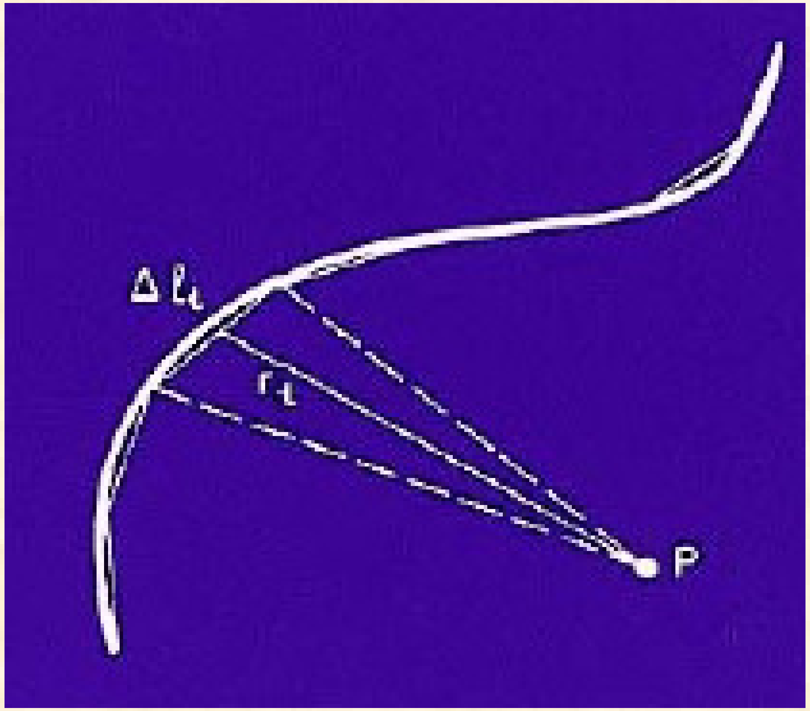


- Number of point sources
- Number of elementary line sources
- Line source model of correct length

=> Only last method can correctly model the anisotropy at close distance or along the source axis, but even then dose at surface of source not correctly calculated

Line source approximation

- Curved sources have to be decomposed in linear segments



Limitations of TG43 algorithm

- Line source ⇔ cylindrical source
- Homogeneous “water” patient
- Full scatter patient
- Transit dose (for afterloaders)
- Intersource effect
- Applicators
- Shielding

Cylindrical source

- Geometry function should be source (design) dependant

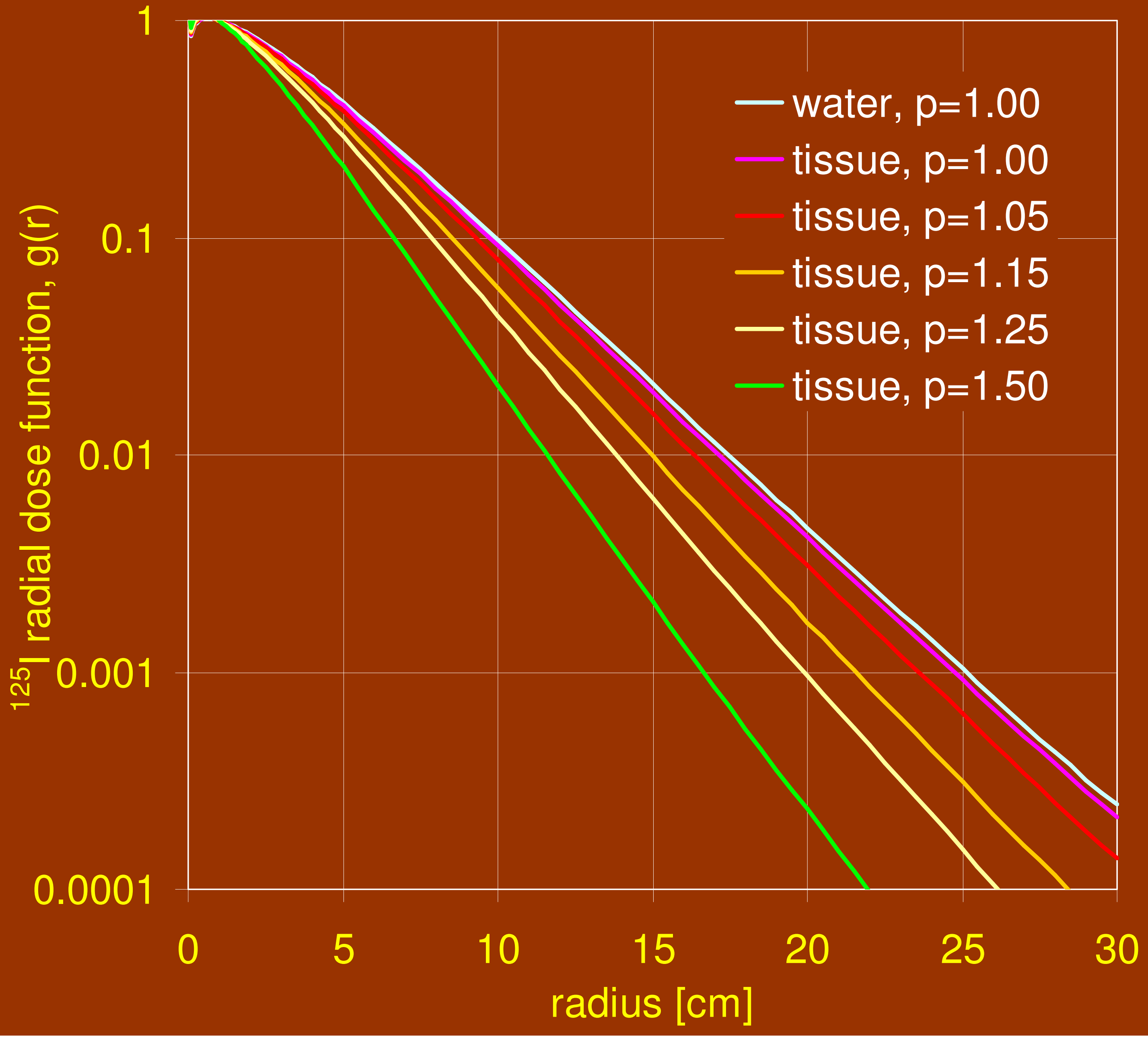
  => Change of TPS structure

- Does not effect accuracy as corrected for in $g(r)$ and $F(r, \theta)$

Lack of heterogeneity corrections

- High energy sources: nearly the same behaviour in tissues involved as in water
- Low energy sources: importance of photo-electric effect increases as energy decreases

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



Lack of heterogeneity corrections

- Historically: no density data available for BT planning, distance factor considered as predominant
- With the increased use of CT data: increasing interest to incorporate heterogeneity corrections

  => new algorithms (MC)

Lack of heterogeneity corrections

For HDR-PDR: at first glance problem could be biggest in bronchial implants

But: Prescription done at a fixed distance from the applicator (1 cm), dose effect correlated with this prescription system, dose gradient over distance far more important (palliative treatment).

Prasad 1985: ^{125}I implant in lung: difference of 9 to 20% with dose to water

Lack of full scatter

- Most TPS assume infinite and full scatter conditions
- Not true for some interstitial implants, close to the skin: breast implants, skin, lip,…
- Mangold et al.(2001): skin dose in breast implants up to 14% overestimated by TPS (TLD)
- Bernard et al. (2005): skin dose in breast implants up to 20% overestimated by TPS (MC)
- Also shielding creates lack of scatter: 2 to 15% dose reduction when using shielded vaginal applicator

Transit dose

- Source entry, interdwell movements, exit

Effect depends on:

- Interdwell velocity
- Source Intensity
- Implant geometry
- Prescribed dose

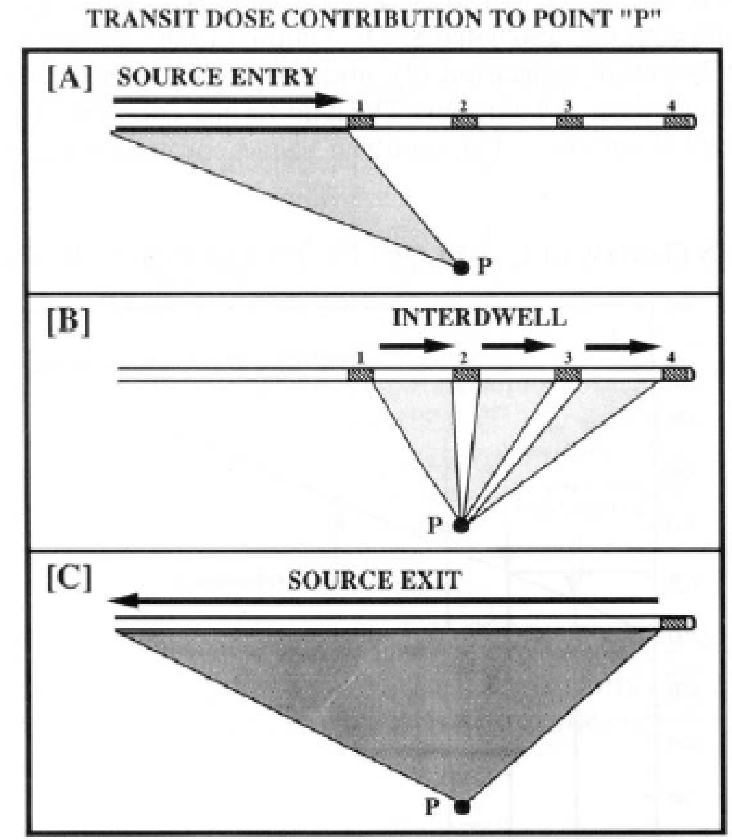


Fig. 4. The three different dynamic dose components produced during each treatment cycle result from source entry, interdwell, and exit movements.

Intersource effect

- Depending on number of sources, composition, geometry

- AAPM 1997: typical prostate implant with large number of ^{125}I seeds: peripheral dose reduction up to 6%
- Perez 2003: Tip of tandem of ^{137}Cs Selectron: reduction more than 20%

Applicators

- Still often metallic applicators, surrounding the source cylindrically
- E.g. interstitial needles (breast implant), ^{192}Ir: up to 1% absorption,

  Fletcher type applicator, ^{137}Cs: about 6%
- Could be taken into account during calibration (if always same kind of applicators is being used), but needs thorough experimental verification

Shielding

- Often used in vaginal applicators to protect rectum, urethra and/or bladder
- Reduction of bladder-rectum dose of 6% to 50%, depending on material and dimension of shield and isotope
- Some TPS do not allow corrections, some implemented 1D correction, others a 2D correction table (for a 3D problem)
- Warning for OR-dose reporting

Message

- Be aware off/take into account limitations of your system/corrections needed

- Whenever changes (improvements) in calculation algorithms are implemented

=> Discuss the influence of these changes with the radiation oncologist

Conclusions:
Shortcomings of current algorithm

Tissue heterogeneity corrections generally not available, nor lack of full scatter correction

Shielding effects not accurately taken into account

Linear Source calculations

TG43 formulation was originally intended for short brachytherapy sources, few mm in length

Elongated source extensions to TG43 needed (AAPM task group)

Shortcomings of current algorithms (2)

Point Source calculations

Point source based distribution calculations are common, particularly where only the source center location is known but not the 3D orientation and where orientations are assumed to be randomly distributed.

1D "anisotropy" corrections simply scale the transverse radial dose distribution in isotropic (spherical) geometry.

Linear source models provide more accurate anisotropy in single source dose distributions and for ensembles of implanted sources.

Fixed geometry implants, including ribbons and plaques, lend to linear source (TG43 "2D" formula) models

New algorithms

- Monte Carlo –…
- Varian: BrachyVision Acuros
- Nucletron/Elekta : Collapsed Cone

- AAPM TG-186: “Model-based Dose Calculation in BT: status and clinical requirements for implementation beyond TG-43”

References

- ESTRO Booklet n° 8: a practical guide to quality control of brachytherapy equipment (www.estro.org ; http://www.estro-education.org/publications/Pages/ESTROPhysicsBooklets.aspx)
- Nath R., Anderson L., Meli J., Olch A.,Stit J., Williamson J ," Code of practice for brachytherapy physics: Report of the AAPM Radiation Therapy Commitee Task Group 56" Med.Phys. 24, 1557-1598 (1997)
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