Theoretical Aspects of Dosimetry for Intravascular Brachytherapy

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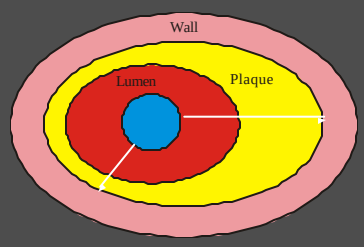
Outline

- Now that IVB is clinical, what good is theory?
- Theoretical dose calculations can help with
  - Clinical decisions
    - Margin
    - Individualized patient plans?
  - Clinical trials
  - New designs
- How are they done?
  - Strengths and weaknesses of each technique
  - Examples

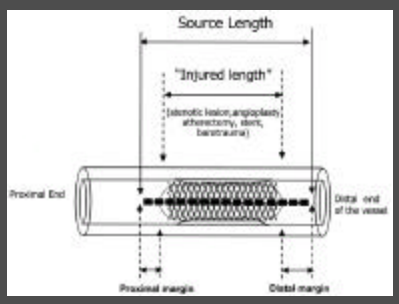
3-Dim Dose Maps for Variety of Clinical Situations

- Non-ideal geometry
  - Device is not centered in lumen.
    - Curved vessel
  - Lumen cross-section is eccentric.
  - Lumen is not centered in artery.
  - Heart motion
- Presence of high-Z materials
  - Plaque, contrast media, stents (catheter-based sources)

Eccentric Artery with Nonuniform Plaque



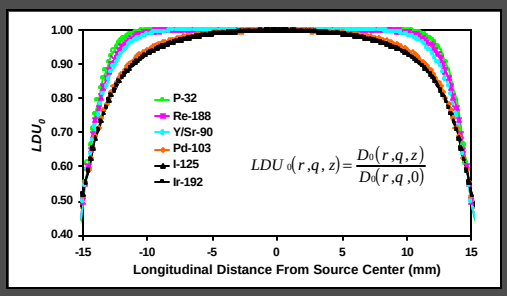
Must leave margin for positioning error, source movement, dose falloff (Giap et al. 2000).



Evaluation of Clinical Trials

- Comparison of different devices and techniques.
  - Example: Task Group 60 tables
- Possible explanations of failures and complications.
  - Example: Target coverage by radioactive stents and "candy wrapper" restenosis
  - Example: Possibly inadequate margins during some gamma emitter trials

Longitudinal Dose Uniformity at A Radial Distance of 2 mm for a Centered Source of 30 mm Length (Yue et al., 2001)



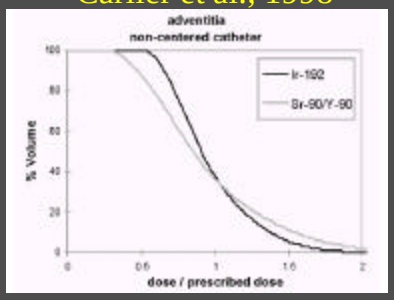
Evaluation of New Devices and Isotopes

- Novel source designs: Dumbbell-loaded stent, miniature x-ray tube
- Novel isotopes: W/Re-188 and Au-198 (mixed β/γ), Pd-103 (γ), Ga-68, V-48 and Cu-62 (positrons), and Ge-71 K-shell x-rays compared to P-32, Sr/Y-90, Ir-192

Planning for Individual Implants

- Based on intravascular ultrasound (IVUS)
  - Echogenic blood-vessel and media-adventitia interfaces
  - Dose-volume histograms
    - Cylindrical shell volumes in arterial wall
  - Plaque composition cannot be determined.
  - Examples:
    - Carlier et al., Kirisits et al.

Dose-Volume Histogram
Carlier et al., 1998



Dose Calculation Techniques
General description

- Monte Carlo simulation is the basis for all modern techniques.
- Techniques differ mainly in how far the simulation is carried.
  - Simulation of a point source followed by convolution with source distribution
  - Simulation of one piece of treatment device followed by superposition of dose from all pieces
  - Simulation of complete source and realistic artery or experimental setup

Point Source Convolution

- Equation for stent with activity on surface

$$D(r,t) = \frac{A_0}{S\,l} \times \left[\, 1 - \exp(-l\ t) \,\right] \times \int K(x)\, ds$$

where A_0 is the initial activity, λ is the decay constant of the radionuclide, S is the active stent area and *x* is the distance between a source point on the surface and the field point where the dose is calculated. *K(x)* is the dose-point-kernel (DPK).

Point Source Convolution

- Good points
  - Fast
  - Easy to change geometry
- Bad points
  - Hard to account for inhomogeneities
    - Layered geometry approximation by Janicki
    - Very hard to account for effects of high-Z materials in source

Examples of Point Source Convolution

- Prestwich et al.
  - P-32 stent as cylindrical surface
- Xu et al., Yang and Chan
  - P-32 wire source
- Duggan et al.
  - P-32 stent as cylindrical shell based on Berger geometric function

More Examples of Point Source Convolution

- Janicki et al.
  - Exact geometry of Palmaz-Schatz and BX stents
  - Beta kernel for layer geometry
  - Photon kernel for layer geometry
- Yue et al.
  - Line sources with various beta or gamma emitters

Janicki Beta DPK for Multilayer System

Starting with the beta DPK in ICRU Report 56, for infinite medium m

$$K^m(x) = \frac{S^m(E(x))}{4p\, r_m x^2}$$

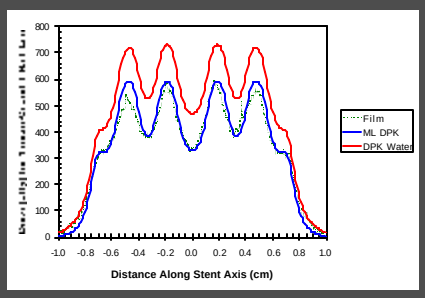
Janicki derived the approximate multilayer DPK

$$K^m(x) = h(x)\left(\frac{<hr>_m}{r_w}\right)^2 K^w\left(\frac{<hr>_m}{r_w}x\right)$$

where $<\eta\rho>$ is line average of *local* scaling factor $\eta(x)$ times *local* density $\rho_m(x)$ along rayline from source to calculation point.

P-32 Stent with 0.39 mm Teflon

Dose 0.5 mm from Stent



Extension of Photon Dose Point Kernel Approach

- Approximate photon dose point kernel for case in which source surrounded by layers of different material.
- Based on Sievert integral.
- Compared to MCNP simulation of stents (modeled as cylindrical shells) with Pd-103 and Cs-131 by Janicki and Duggan (Med. Phys., 28, 1397-405, 2001)

Janicki Photon DPK for Multilayer System

$$K^S(x) = \sum_i K_i(x) \times \exp\left[-\sum_j (m_i^j - m_i^w) t_j\right]$$

where $K_i(x)$ is the photon dose-point-kernel (DPK) as defined in MIRD Pamphlet No. 2 in units of (cGy / decay) at a distance *x* for spectral component *i* in water and μ_i^j, μ_i^w are the linear attenuation coefficients in the material *j* and in water respectively, t_j is the thickness of material j.

MC Simulation of One Piece Followed by Superposition

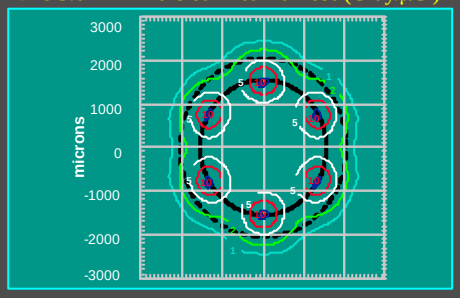
- Good points
  - Almost as fast as convolution
  - Accounts for some of effects of source materials
- Bad points
  - Hard to account for inhomogeneities
    - Surrounding inhomogeneities, even in layers
    - Shadowing of one part of source by another

Examples of MC Simulation of One Piece and Superposition

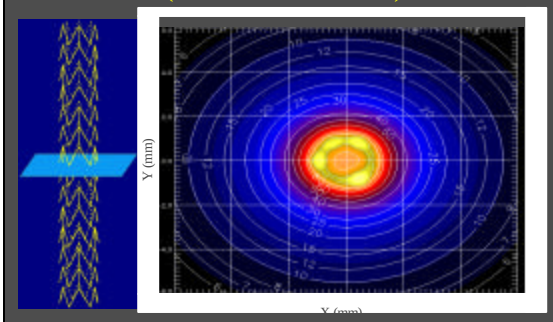
- Li and Whiting
  - Single stent strut with V-48 or P -32 throughout
  - Superposeds to make Palmaz-Schatz
- McLemore
  - Single stent strut with Pd-103 in thin surface layer
  - Superposed to make ACS Multilink

Simulate Strut and Superpose (Li and Whiting)

V48 3.0 mm Mid-slot Lifetime Dose (Gray/µCi)



Single stent strut with Pd-103 in thin surface layer (McLemore, AAPM 1999)



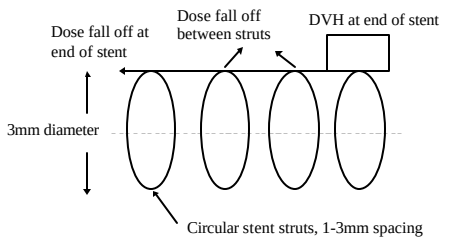
Monte Carlo Simulation of Entire Device

- Good points
  - All effects of geometry and materials in source and surrounding can be realistically simulated
- Bad points
  - Very slow
  - Hard to model complex source geometry

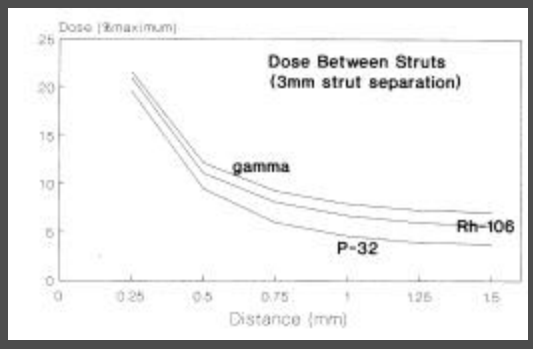
Examples of Monte Carlo Simulation of Entire Source

- Amols
  - Liquid-filled balloon inside stent, ring model of stent
- Amols, X. A. Li
  - Ring model of stent with various isotopes and ring spacings
- Reynaert et al.
  - Helicoid model of stent
- Stabin et al., X. A. Li
  - Square-hole or "mesh" stent

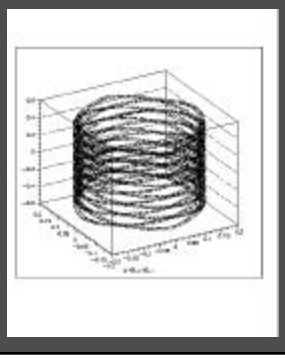
Monte Carlo Simulation of Ring Stent (Amols et al.)



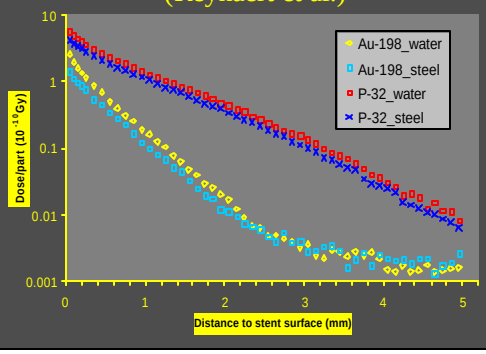
Monte Carlo Simulation of Ring Stent (Amols et al.)



Helicoid Model of Palmaz-Schatz Stent (Reynaert et al.)



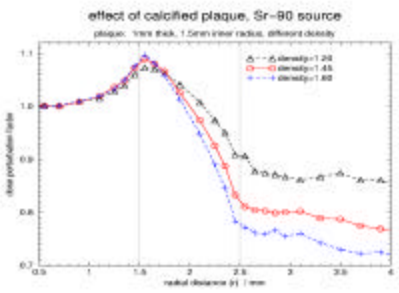
Self Absorption in Strut Material (Reynaert et al.)



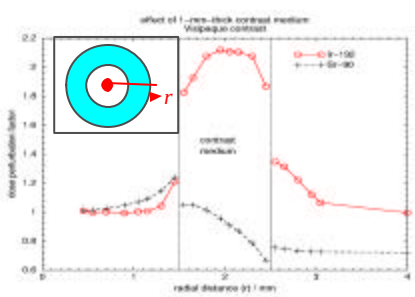
More Examples of Monte Carlo Simulation of Entire Source

- Soares et al.
  - BetaCath seed
- Ye et al.
  - Train of beta-emitting seeds inside stent
- Schumer, Wang et al.
  - Ir-192 sources

Effect of 1 mm Thick Plaque on Sr-90 Source (X. A.Li et al.)



Effect of Contrast on Ir-192 and Sr-90 Sources (X. A. Li et al.)



Summary

- Theoretical calculations:
  - Predict target coverage under variety of situations.
  - Enable comparison of clinical trials.
  - Predict the performance of novel devices.
- Monte Carlo simulation at heart of most modern methods.

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