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
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 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
  \[ D(r,t) = \frac{A_0}{S\lambda} \times \left[ 1 - \exp(-\lambda t) \right] \times \int K(x) \, ds \]
  
  where \( A_0 \) is the initial activity, \( \lambda \) 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

\[ K_m(x) = \frac{S_m(E(x))}{4\pi \rho_m x^2} \]

Janicki derived the approximate multilayer DPK

\[ K_m(x) = \eta(x) \frac{<\eta \rho>}{\rho} \left( \frac{<\eta \rho>}{\rho} \right) \]

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

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

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 \( \mu_i^j, \mu_i^w \) 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
  - Superposed to make Palmaz-Schatz
- **McLemore**
  - Single stent strut with Pd-103 in thin surface layer
  - Superposed to make ACS Multilink
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.)

- Dose fall off at end of stent
- Dose fall off between struts
- DVH at end of stent
- 3mm diameter
- Circular stent struts, 1-3mm spacing

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

- Dose Between Struts (3mm strut separation)
- Distance (mm)
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
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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