Optimization in permanent prostate implant treatment planning using the adjoint dose calculation and the source influence fields

*Sua Yoo, +Douglass L. Henderson, and ++Bruce R. Thomadsen

University of Wisconsin-Madison

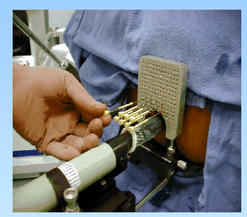
*Dept. Of Medical Physics, +Dept. Of Engineering Physics,

++Dept. Of Medical Physics and Human Oncology

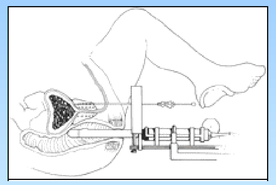
Introduction

- Prostate permanent implantation is a radiation treatment in which radioactive seeds are directly implanted into the prostate and left forever.
- Adjoint field of a region-of-interest ROI (Φ^{+}_{ROI}) and source influence fields (Φ_s) are used to find out a seed configuration which delivers optimal dose distribution for the prostate permanent implantation treatment plan.

Prostate Implantation

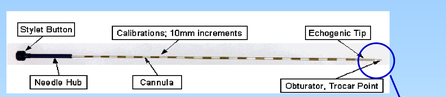


(courtesy of Mick radio-nuclear instruments, inc)

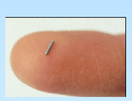


(Courtesy of Seattle-Prostate-institution http://seattleprostateinstitute.com/)

Implantation Seeds and Needles

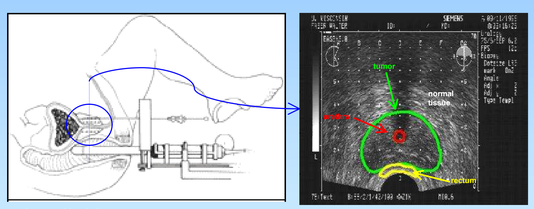


Needle
1.3-1.5mm diameter, 20cm long tube



Seed
0.8mm diameter,4.5-5.0mm long

Transrectal Ultrasound image



(Courtesy of Seattle-Prostate-institution http://seattleprostateinstitute.com/)

Discrete ordinate transport code: TWODANT

- DANTSYS (A Diffusion Accelerated Neutral Particle Transport Code System)
  - Boltzmann transport equation for multigroup particles.
- Three group photon cross section library
  - The lowest three energy groups of the FENDL-2-42 group cross section library
  - 1st 20-30keV, 2nd 10-20keV, 3rd 1-10keV
  - Common Implantation brachytherapy seeds: ^{125}I and ^{103}Pd $\in$ 1st group [20-30keV]

Optimization

- Optimization goal is to find a seed configuration achieving optimal dose distribution which delivers high enough dose to the target while sparing sensitive structures.
- Optimization system GAMS (GAMS development corporation)
  - General algebraic modeling system.
- Mixed-integer-programming (MIP).
  - CPLEX solver.
  - Branch-and-bound method.
  - Binary variable $\delta_j \in \{1, 0\}$.

Optimization based on dose to each pixel data

minimize $\sum_{\forall i} \sum_{\forall j} x_i \cdot \delta_j$

subject to

$$\begin{cases} \dot{D}_i + x_i \geq L_{tu}, & \text{if } \dot{D}_i \leq L_{tu} \ \&\ i \in \text{tumor}, \\ \dot{D}_i - x_i \leq U_{ROI}, & \text{if } \dot{D}_i \geq U_{ROI} \ \&\ i \notin \text{tumor}, \\ x_i = 0, & \text{otherwise.} \end{cases}$$

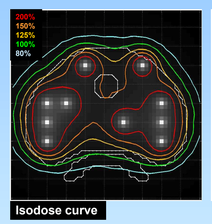
ROI $\in$ {tumor, urethra, normal tissue, rectum}

$U_{ROI} \in \{U_{ur}, U_{no}, U_{re}\}$

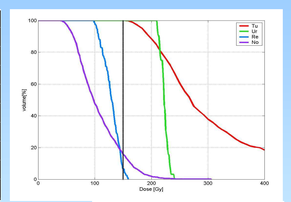
- L_{tu} lower dose boundary for tumor
- U_{ur} upper dose boundary for urethra
- U_{no} upper dose boundary for normal tissue
- U_{re} upper dose boundary for rectum

$\delta_j \in \{1, 0\}$

Isodose Curves & DVHs



Isodose curve

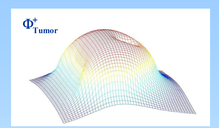


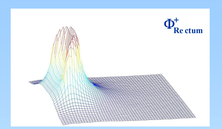
DVH – Dose volume histogram

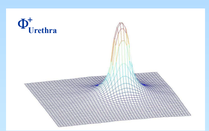
- 0.3mCi strength seed & 150Gy prescribed dose
- Dose constraints

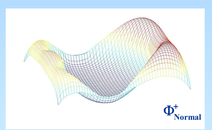
L_{tu} = 180%, U_{ur} = 150%, U_{no} = 125%, U_{re} = 80% of D_p

Adjoint fields (Φ^{+}_{ROI}) of ROIs





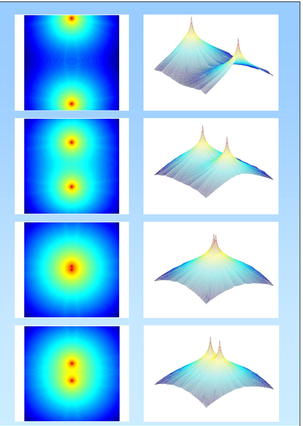




$$\dot{\bar{D}}_{ROI} = \sum_{\forall j} \left(\Phi^{+}_{ROI}(j) \times S \times V_j / V_{ROI} \right)$$

Source influence fields (Φ_j)

An influence field analogous to a repulsive electric field pushes the sources away from each other resulting in a more uniform seed configuration as well as a more uniform dose distribution.



Optimization based on dose to each ROI and source influence fields

minimize $\sum_{\forall ROI} \sum_{\forall j} x_{ROI} \cdot \delta_j + \sum_{\forall j} \Delta\Phi_j \cdot \delta_j$

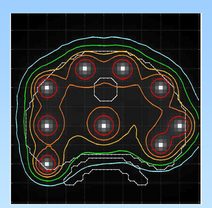
subject to

$$\begin{cases} \dot{\bar{D}}_{ROI} + x_{ROI} \geq L_{tu}, & \text{if } \dot{\bar{D}}_{ROI} \leq L_{tu} \ \&\ ROI = \text{tumor}, \\ \dot{\bar{D}}_{ROI} - x_{ROI} \leq U_{ROI}, & \text{if } \dot{\bar{D}}_{ROI} \geq U_{ROI} \ \&\ ROI \neq \text{tumor}, \\ x_{ROI} = 0, & \text{otherwise.} \end{cases}$$

$$\begin{cases} \sum_{\forall j'} \Phi_j(j') - \Delta\Phi_j \leq U_\Phi, & \text{if } \sum_{\forall j'} \Phi_j(j') \geq U_\Phi \\ \Delta\Phi_j = 0, & \text{otherwise.} \end{cases}$$

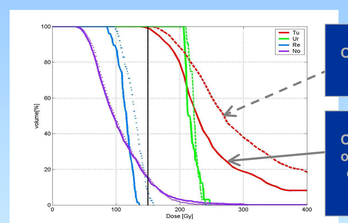
Isodose comparison

Optimization based on dose data for each pixel



Optimization based on dose data for an entire ROI and on source influence fields

DVH comparison



Dotted line Optimization based on dose data for each pixel

Solid line Optimization based on dose data for an entire ROI and on source influence fields

Dose constraints

L_{tu} = 180%, U_{ur} = 150%, U_{no} = 125%, U_{re} = 80% of D_p U_Φ= 245

Conclusion

- A new optimization model for the prostate implantation treatment plan was investigated using the adjoint flux distributions of ROIs and the source influence fields.
  - The adjoint fields of ROIs allow calculation of dose to ROIs providing data reduction and faster optimization.
  - The source influence field is an analogous concept of repulsive electric field thus the seeds tend to spread out delivering move uniform dose to the target.

Future Work

- Implementing the adjoint fields in the optimization process needs further investigation
- Finer group library (G-210) should be used to simulate actual implantation seeds for accurate dose calculation in 3-D treatment plan optimization.