Dose Calculation and Optimization Algorithms: A Clinical Perspective

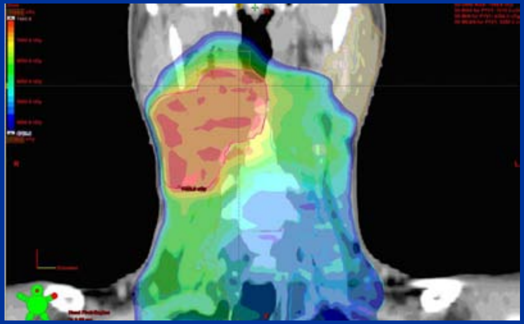
Daryl P. Nazareth, PhD
Roswell Park Cancer Institute, Buffalo, NY
T. Rock Mackie, PhD
University of Wisconsin-Madison
David Shepard, PhD
Swedish Cancer Institute, Seattle, WA

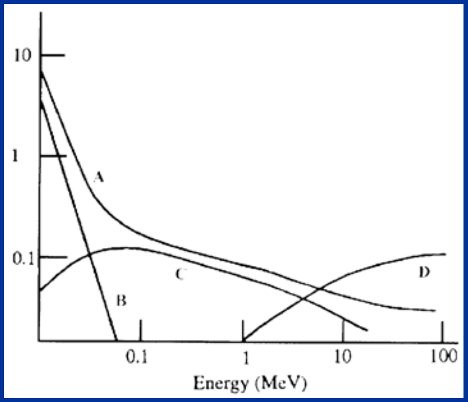
Outline

- Introduction to dose/optimization algorithms
- Focus on external-beam treatment
- History and overview
- Dose calculation by T. Rock Mackie
- Optimization by David Shepard

Dose Algorithm

- Calculates dose distribution in tissue/phantoms
- Relies on physics of photon/electron interactions (e.g. compton)
- Range in complexity from hand calc to monte carlo



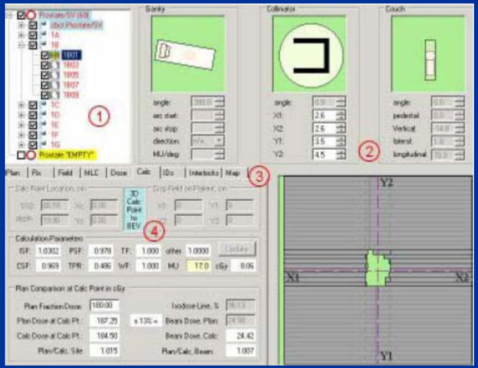


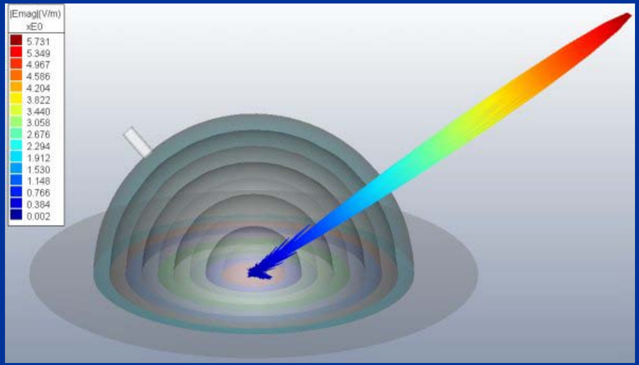
$$\mathrm{TMR}_{\mathrm{PB}}(c,d) = \left(\frac{\mathrm{SSD}+d}{\mathrm{SSD}+d_{\mathrm{cal}}} \right)^2 \times \mathrm{PDD}(c,d),$$

ROSWELL PARK CANCER INSTITUTE

Dose Algorithm

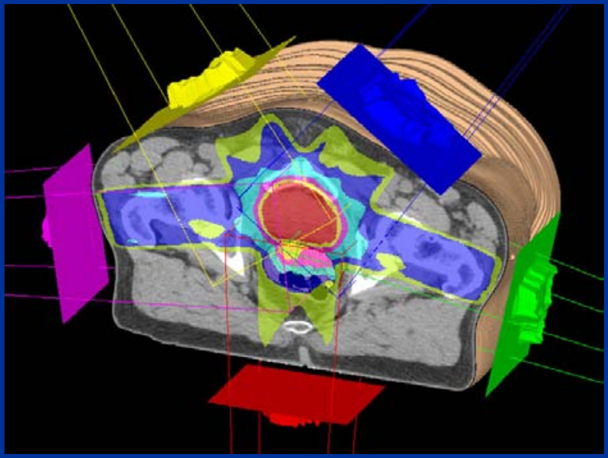
- Purpose: approximate actual deliverable dose with sufficient accuracy
- Required accuracy depends on purpose:
  - 3D treatment planning
  - secondary MU check
  - pencil beam as part of IMRT

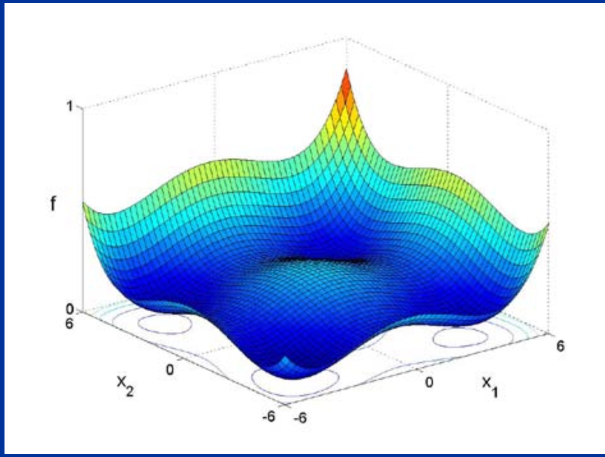


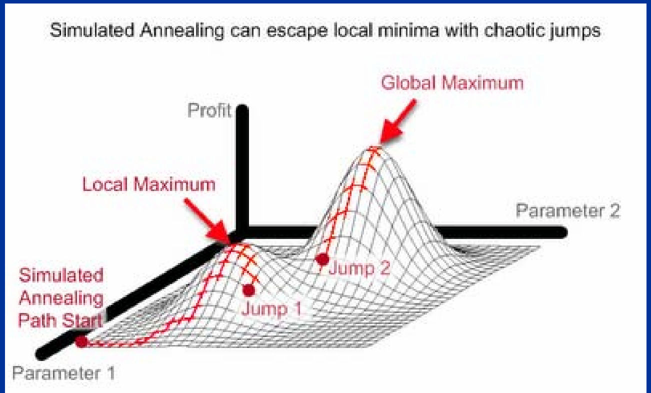


Optimization Algorithm

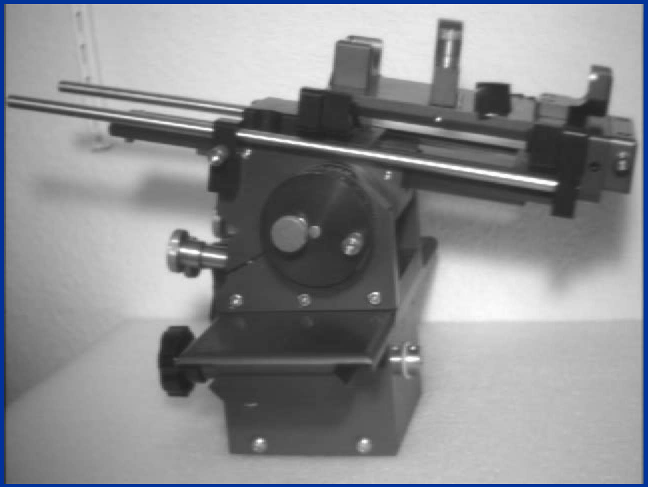
- Determines best parameters for particular treatment
- Requires objective function and (usually) constraints reflecting treatment goal
- Method for minimizing objective function

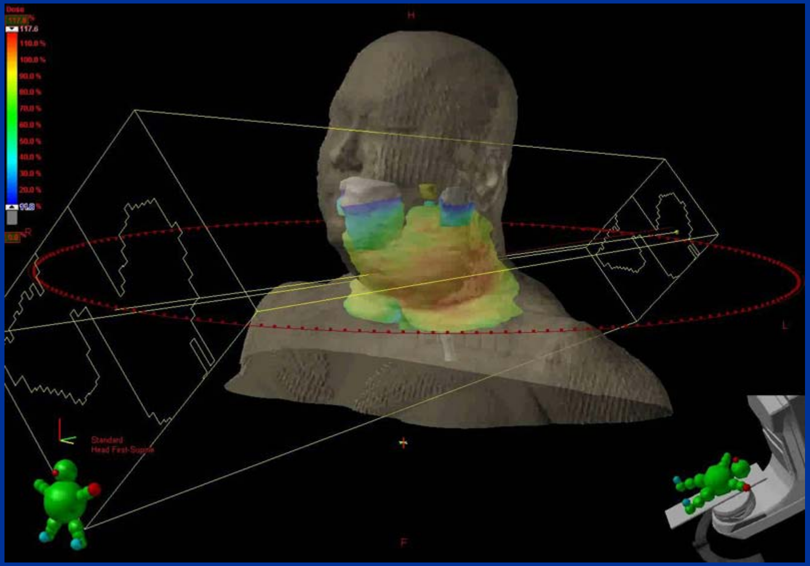






History

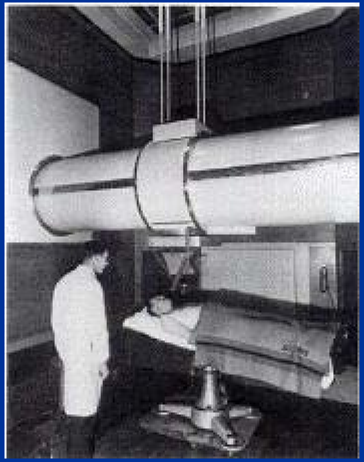




ROSWELL PARK CANCER INSTITUTE

Pre 1920's

- Physician selected x-ray unit and "dose" for patient
- "Physicist" calculated exposure time
- No universally-accepted concept of dose
- No medical physics profession



ROSWELL PARK CANCER INSTITUTE

1920's

- X-ray units had sufficient energy to treat at depth
- Unit of "x-ray intensity" defined
- Physicists made developments:
  - Created depth-dose tables
  - Measured isodose curves
  - Devised opposing-beam techniques to spare superficial tissue

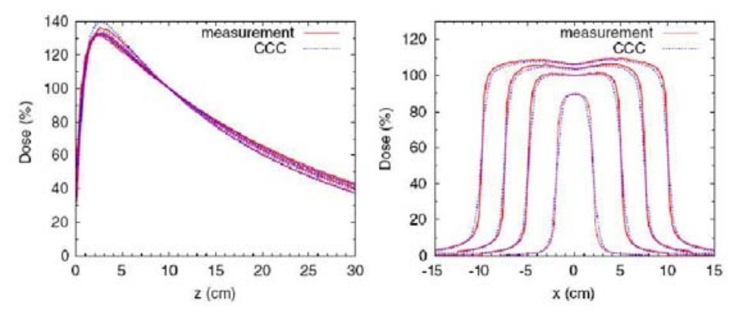


Figure 2. 15 MV percentage depth dose curves (left) and profiles at $z = 10$ cm (right) for field sizes of 4×4, 10×10, 15×15 and 20×20 cm^2. Depth dose curves are normalized to 100% at $z = 10$ cm and profiles to the corresponding output factors.

ROSWELL PARK CANCER INSTITUTE

1920 – 1950

- Idea of “treatment planning” developed:
- Combine isodose curves to produce high-dose region
- Only done in 2D with limited imaging technology
- Calculations performed manually

$$\mathrm{TMR}_{\mathrm{PB}}(c,d) = \left(\frac{\mathrm{SSD}+d}{\mathrm{SSD}+d_{\mathrm{cal}}}\right)^2 \times \mathrm{PDD}(c,d),$$

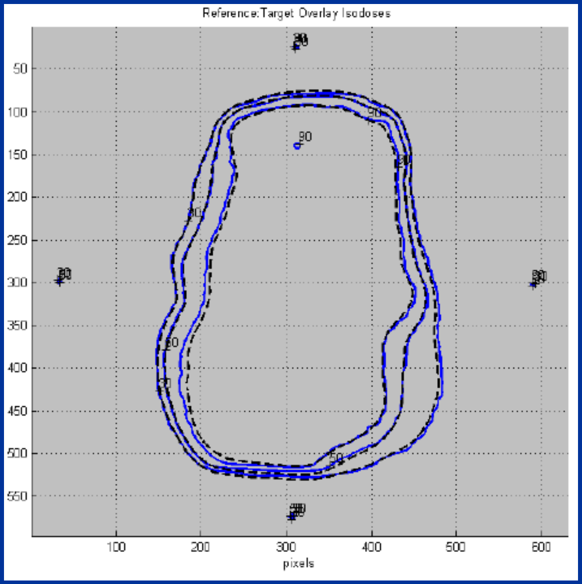
50’s & 60’s

- Computers first used to compute dose distributions
- Calculations performed for multiple planes
- Dose calculations correlated with internal anatomy

ROSWELL PARK CANCER INSTITUTE

IAEA

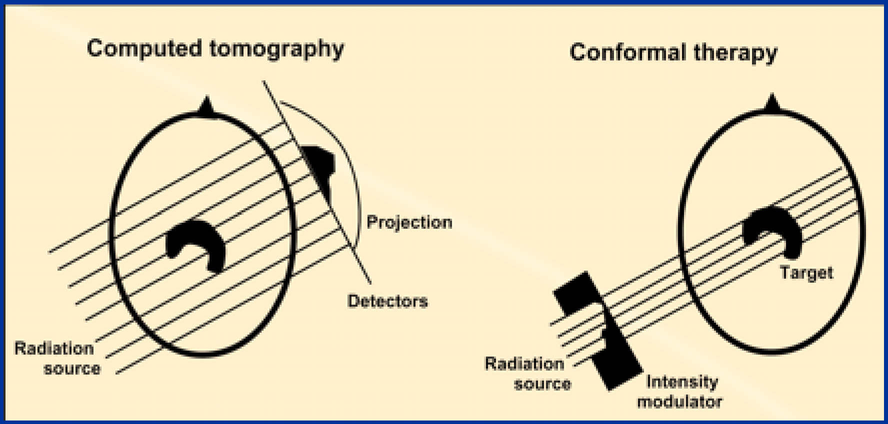
- Published series of atlases of isodose distributions
- First was for single-beam distribution in 1965
- Next for multiple fields, and then moving fields

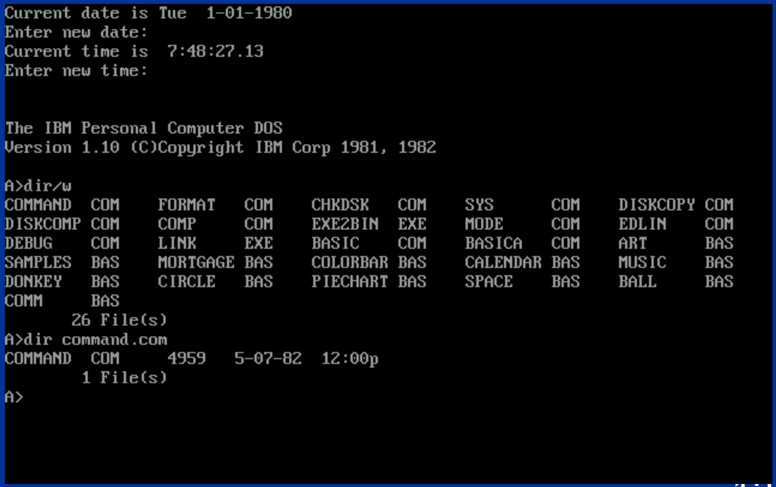


ROSWELL PARK CANCER INSTITUTE

1970's

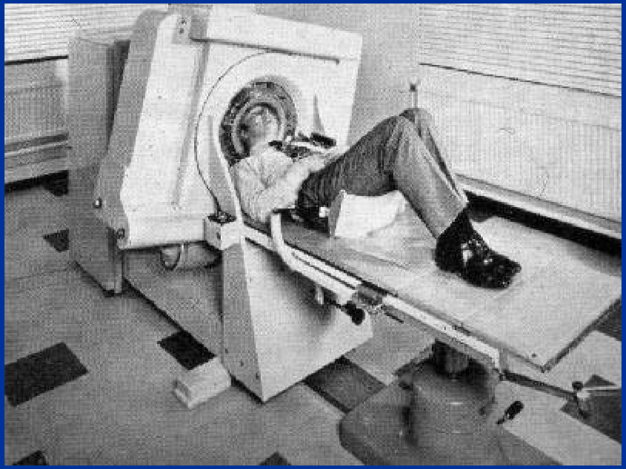
- CT units became prevalent
- 3D dose calculation/treatment planning software developed
- EXTDOS and GRATIS freely available to physicists by van de Geijn, Sherouse

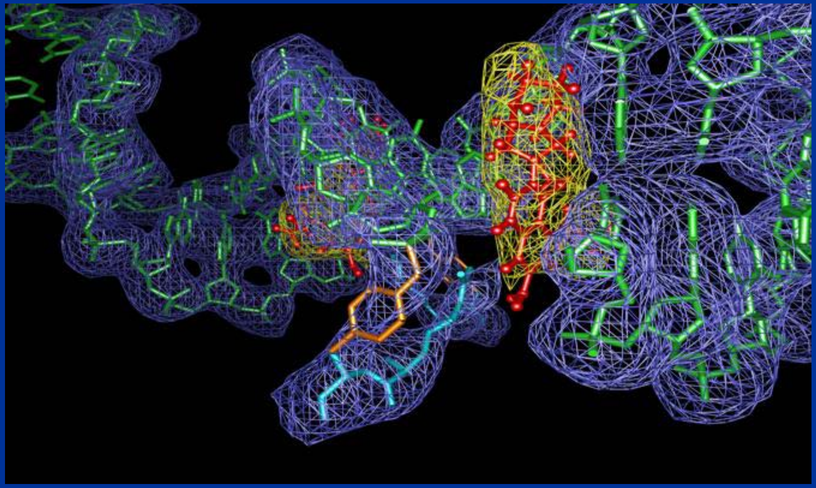




CT

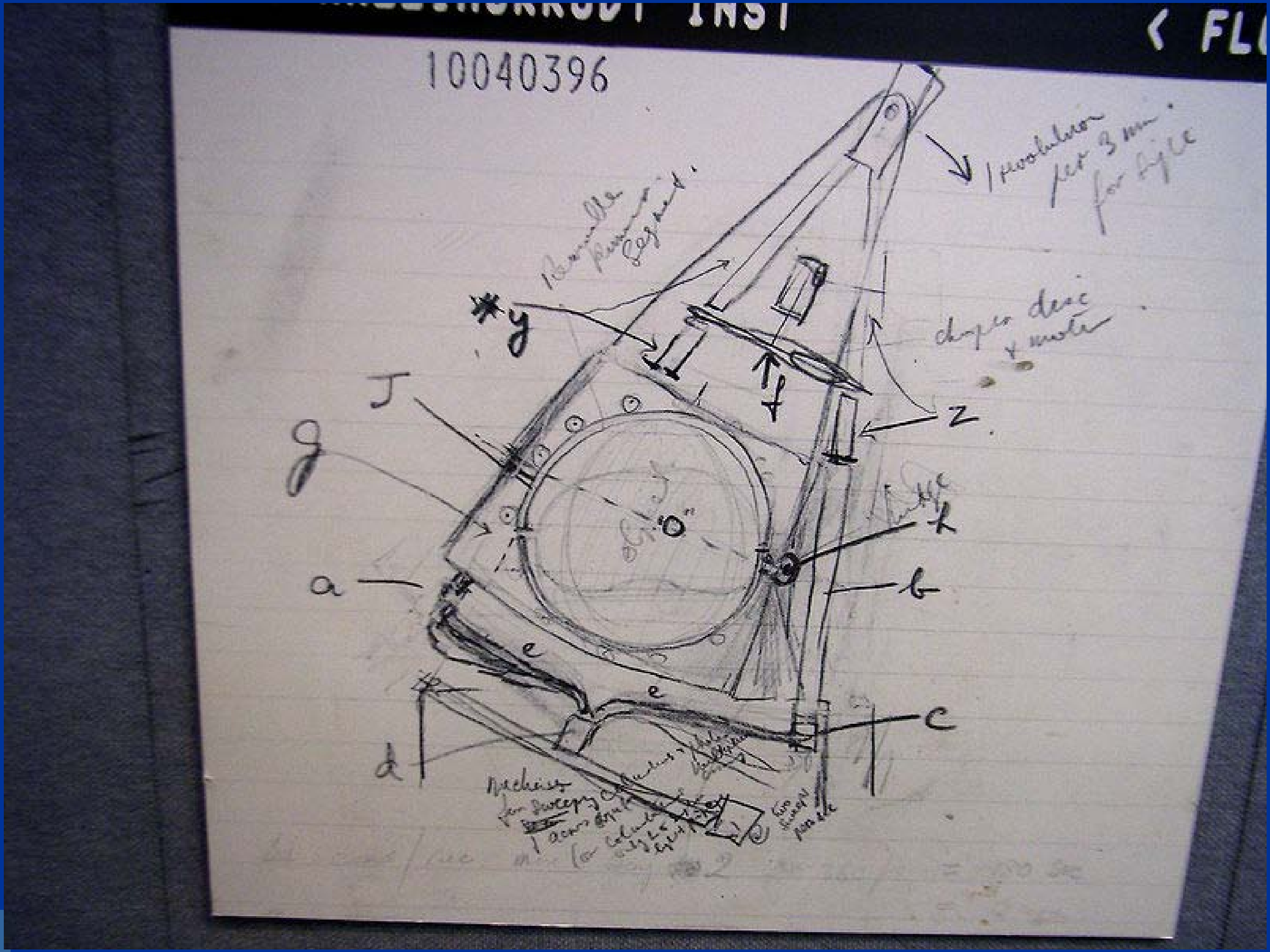
- Early CT scans used for photon/electron treatment, including Co-60
- One motivation for CT was to image and quantify electron density
- This enabled more accurate radiation dose calculations





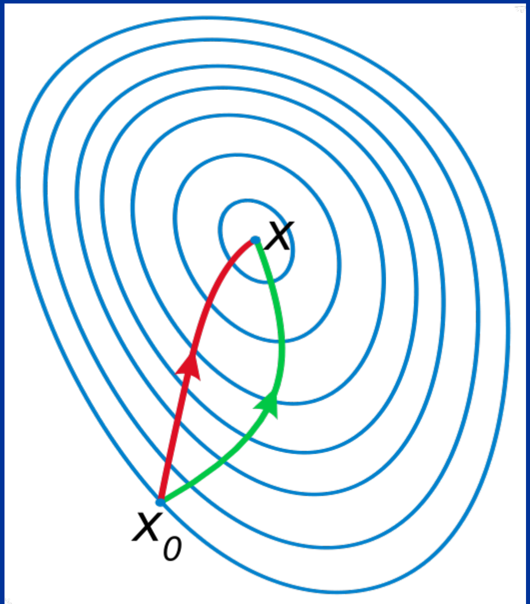
ROSWELL PARK CANCER INSTITUTE

CT



Pre-IMRT Era

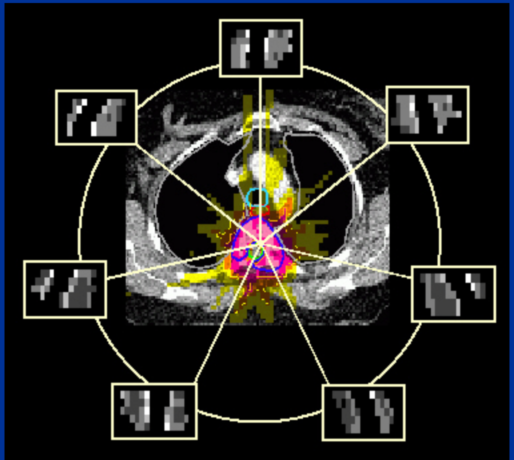
- Early optimization introduced in 1960's
- Not used much in clinical 2D or 3D treatment planning
- From 1974-1990, only 13 articles in *Medical Physics* involved optimization

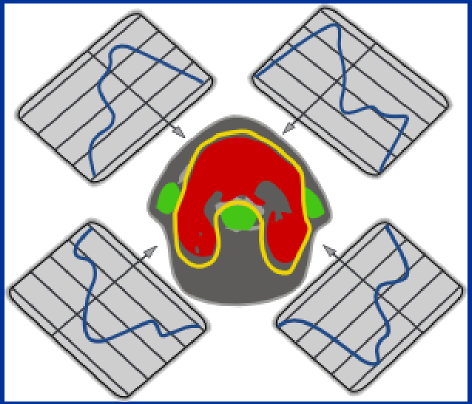


ROSWELL PARK CANCER INSTITUTE

IMRT Era

- In contrast, from 1991-2007, *Med Phys* published 479 such articles
- Why does IMRT depend heavily on optimization?
  - Many degrees of freedom:
  - ~1000 beamlet intensity variables
  - High degree of flexibility in dose distribution

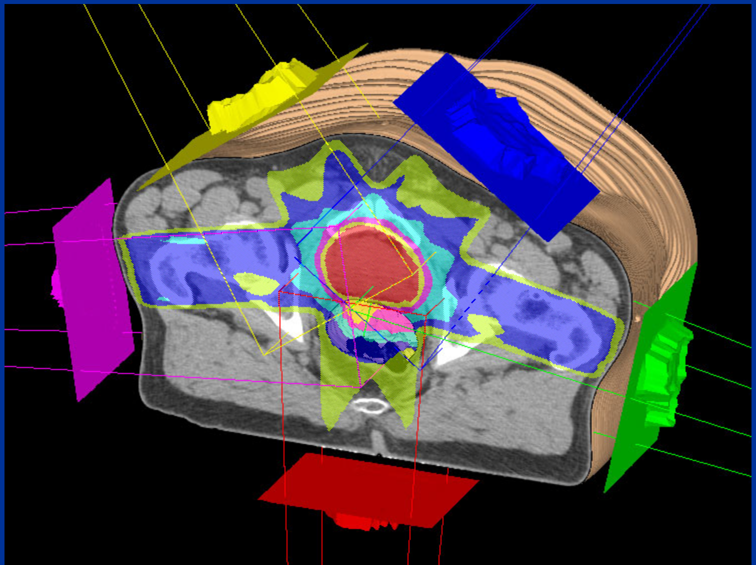


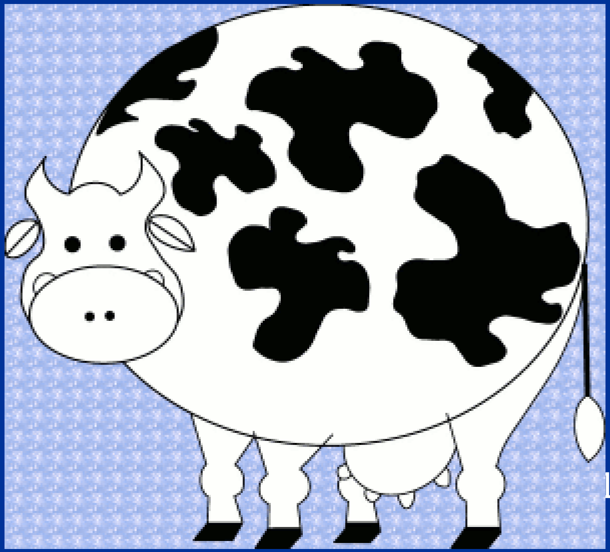


ROSWELL PARK CANCER INSTITUTE

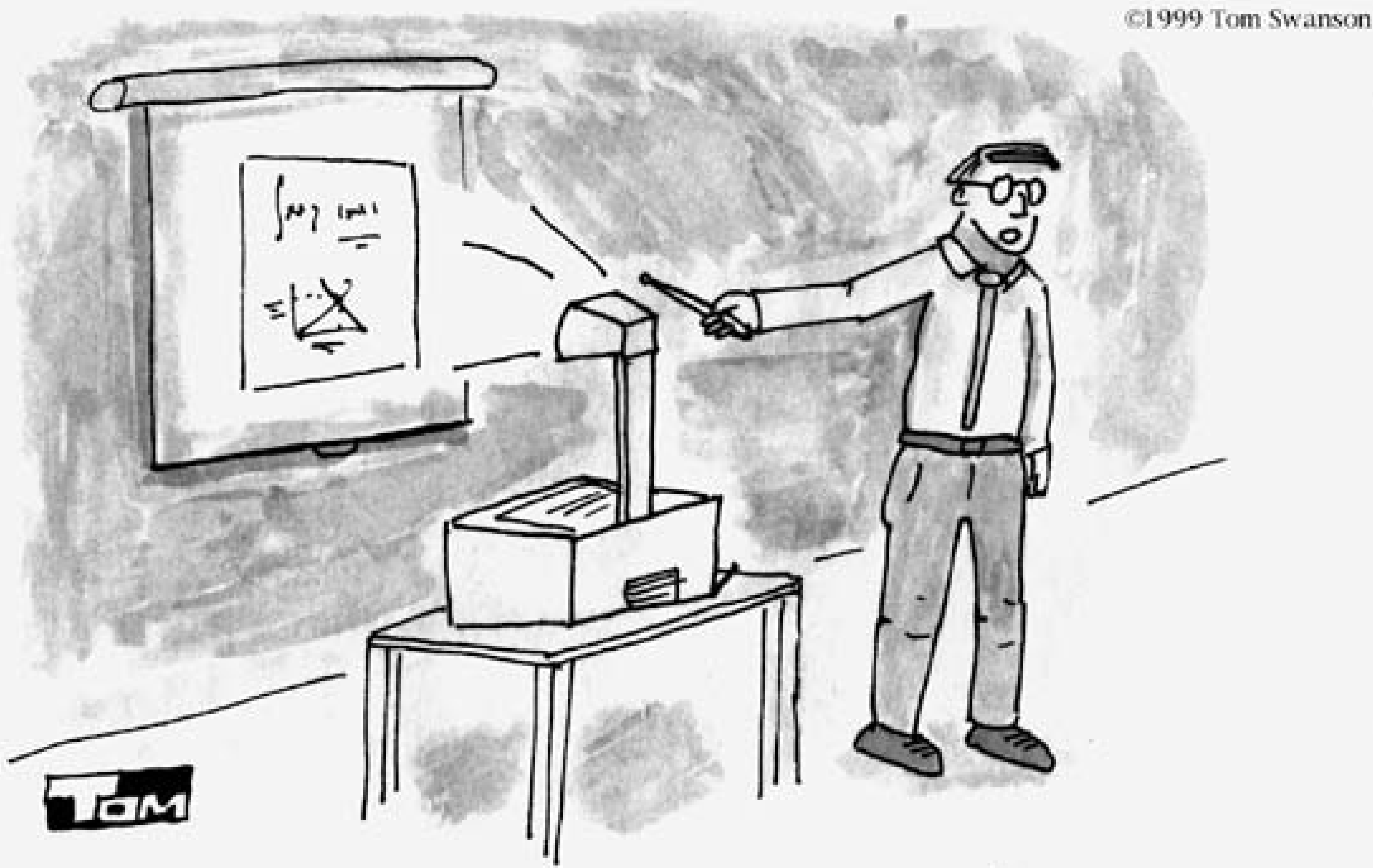
IMRT Problem

- Calculation of beamlet intensities which generate desired distribution
- Known as *inverse problem*
- Analytical methods first attempted in 1980's
- Could only be applied to geometrically-simple cases





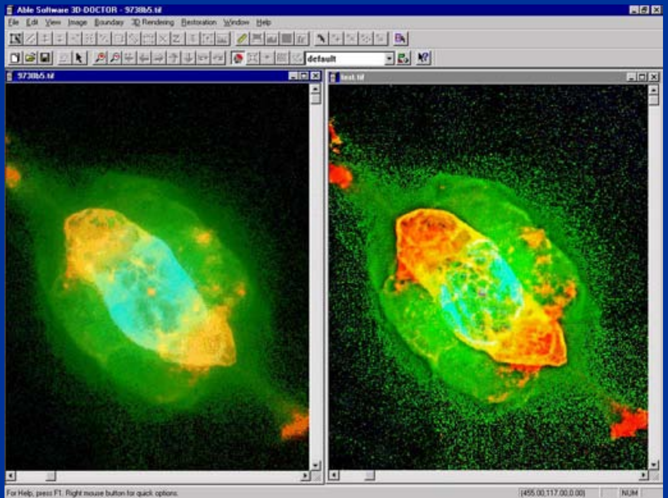
ROSWELL PARK CANCER INSTITUTE

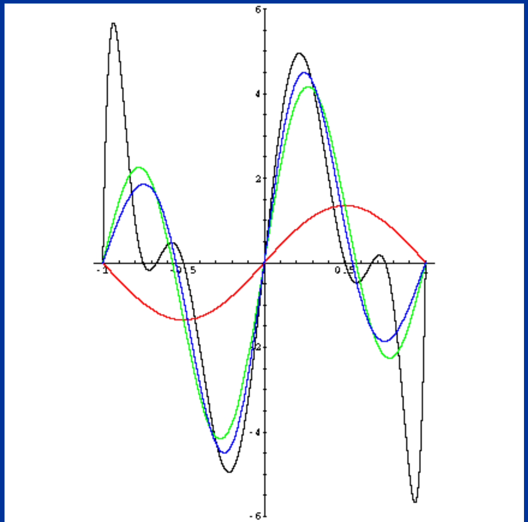


ACTUALLY, THAT ASSUMPTION ISN'T REALLY NECESSARY. WE CAN SEE HERE THAT THE POINT-COW APPROXIMATION WORKS EQUALLY WELL.

Numerical Techniques

- In early 90's, analytical techniques were abandoned in favor of numerical methods
- Primary approach: deconvolution
  - Deconvolve rotational dose kernel from desired dose distribution
  - Accomplished using Fourier analysis, iterative techniques

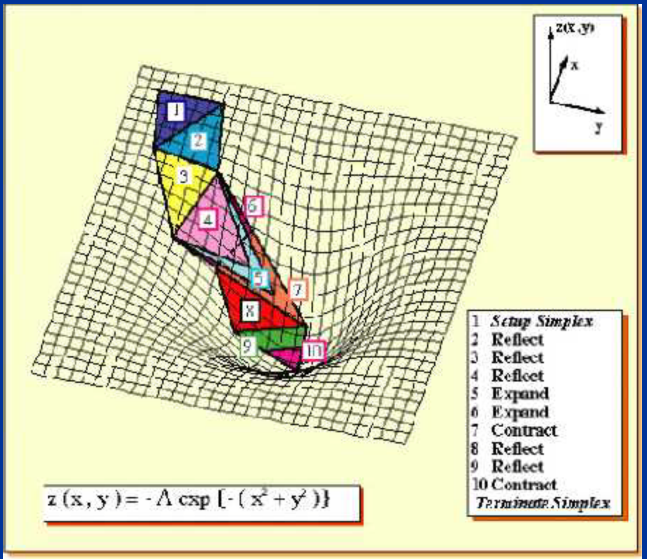


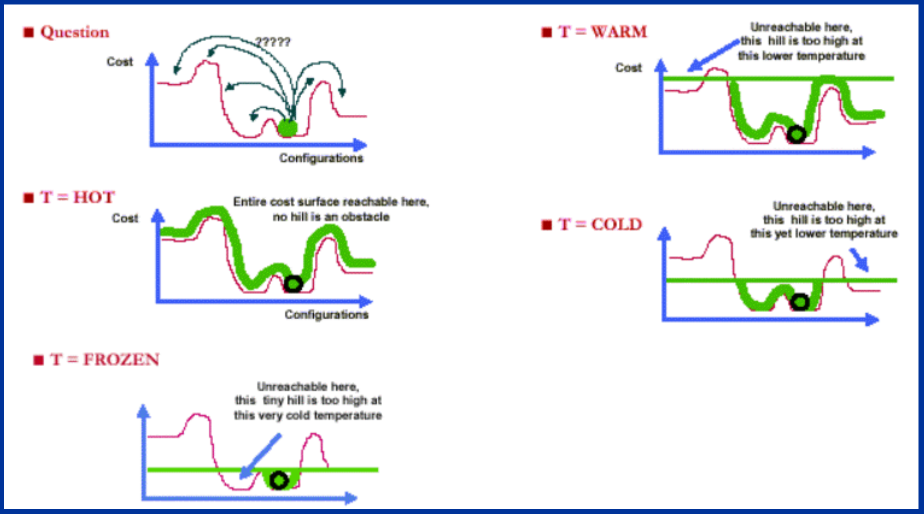


ROSWELL PARK CANCER INSTITUTE

Optimization Algorithms

- No exact solution to inverse problem
- Therefore, develop objective function and employ optimization methods
- Most algorithms based on two techniques:
  - Gradient descent
  - Simulated annealing

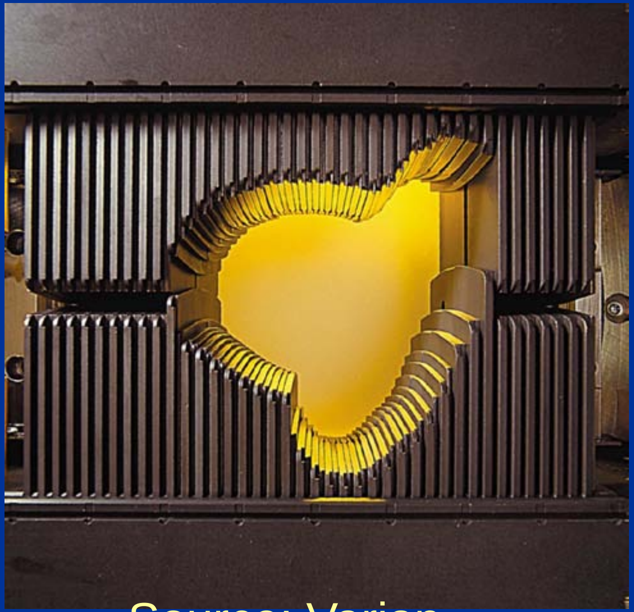




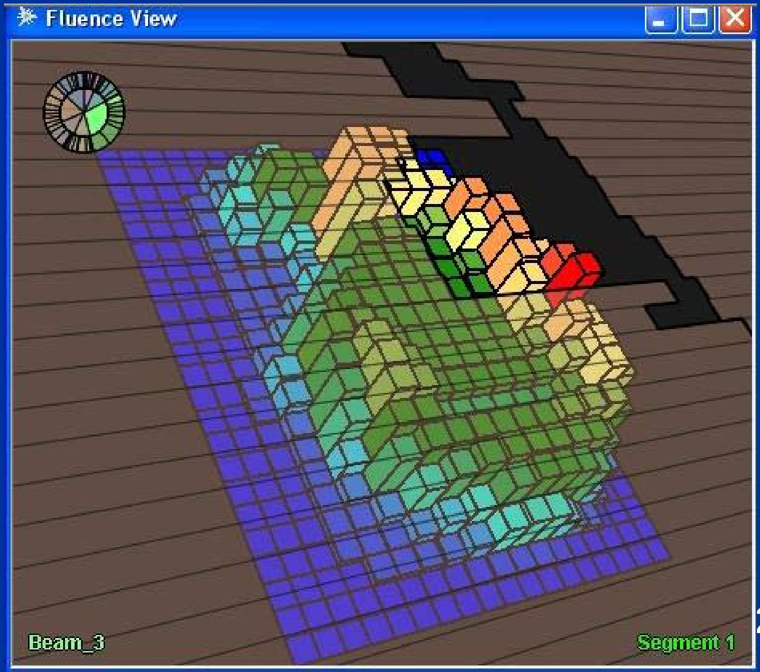
ROSWELL PARK CANCER INSTITUTE

Fluence Delivery

- MLC originally developed for field shaping
- In 1992, Convery & Rosenbloom published article on intensity modulation
- Showed how MLC can produce arbitrary intensity maps



Source: Varian



IMRT Delivery

- IMRT delivery with MLC involves two steps:
- Optimize intensity map for each field
- Determine leaf sequence to produce this map (step & shoot / dynamic)

Source: Elekta

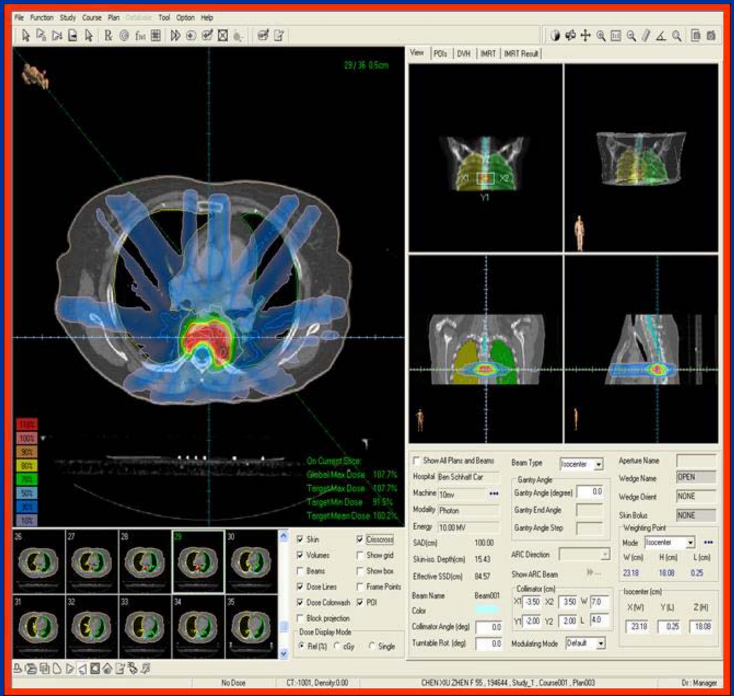
Tomotherapy

- Tomotherapy developed by Mackie *et al* in 1992-93
- Employed collimator system called MIMiC
- Delivered two parallel intensity-modulated fan beams

ROSWELL PARK CANCER INSTITUTE

Recent Issues

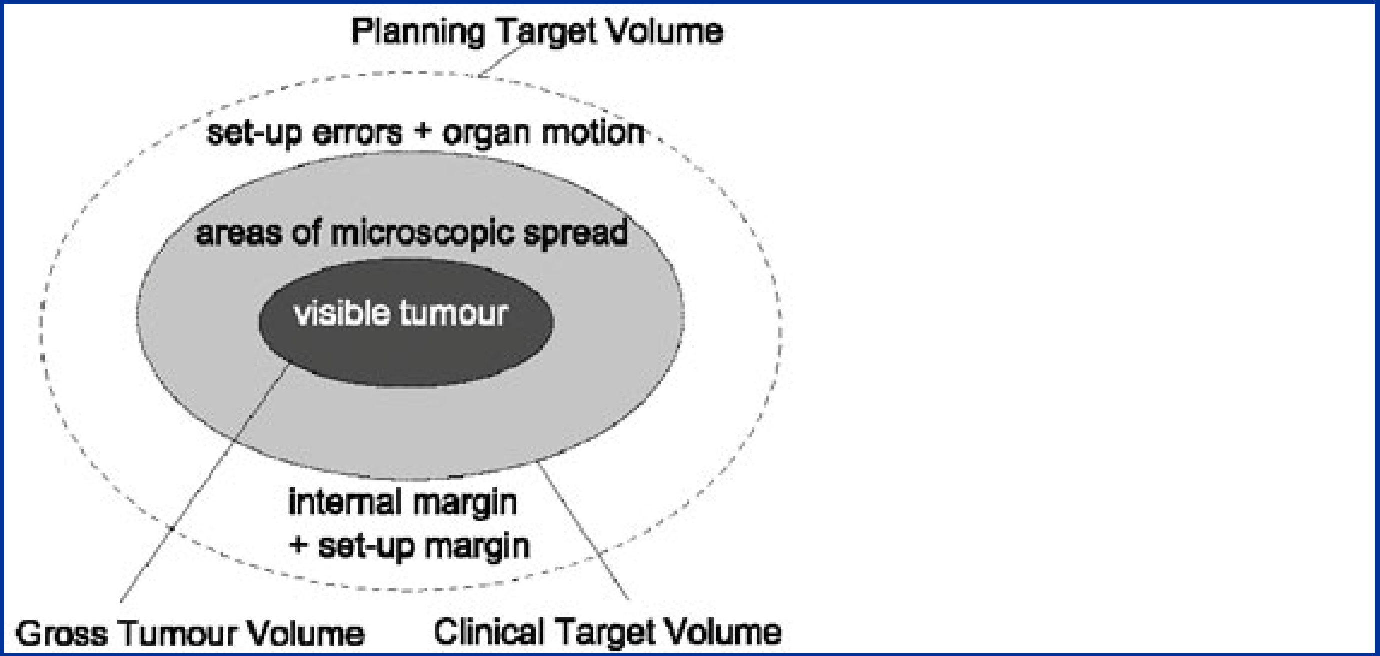
- Once IMRT matured, other issues could be addressed:
  - Uncertainties in patient set up
  - Patient motion
  - Single-criterion problem



ROSWELL PARK CANCER INSTITUTE

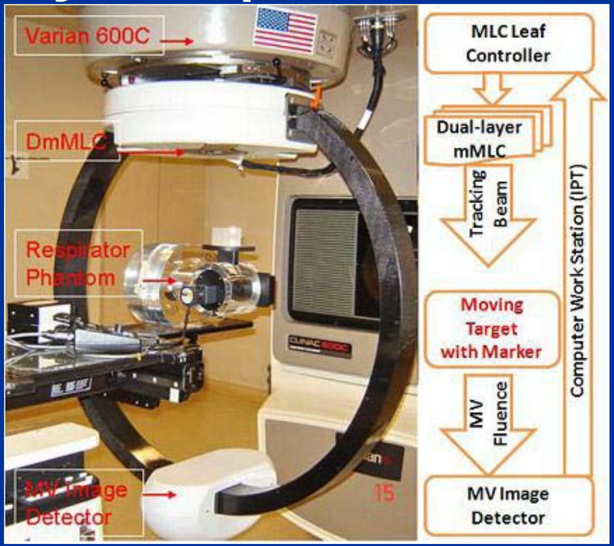
Uncertainty and Motion

- Positional uncertainties:
  - PTV ensures coverage assuming small uncertainties/motion
  - Reduction using image guidance or adaptive treatment techniques



Solution: Include in Optimization

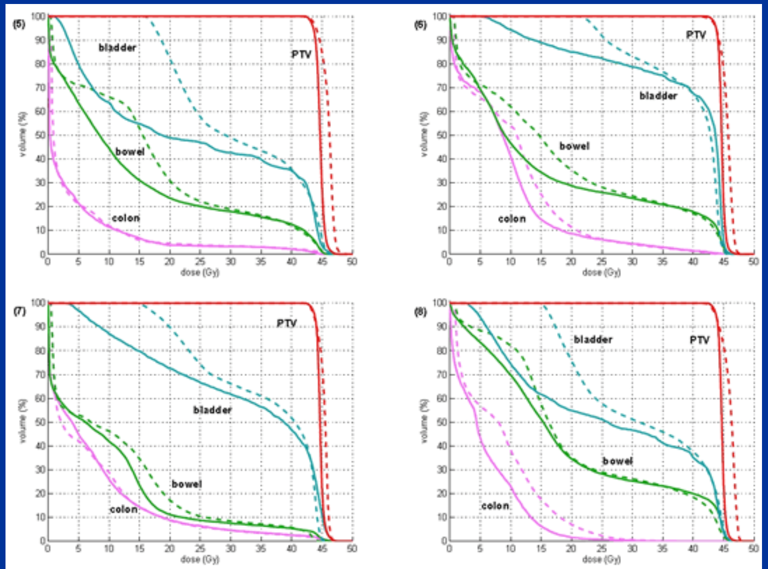
- Recently, work done in including uncertainty and motion in optimization problem
- Mathematical model accounts for these uncertainties
- Intensity maps include effects



Source: *JACMP*

Single Criterion

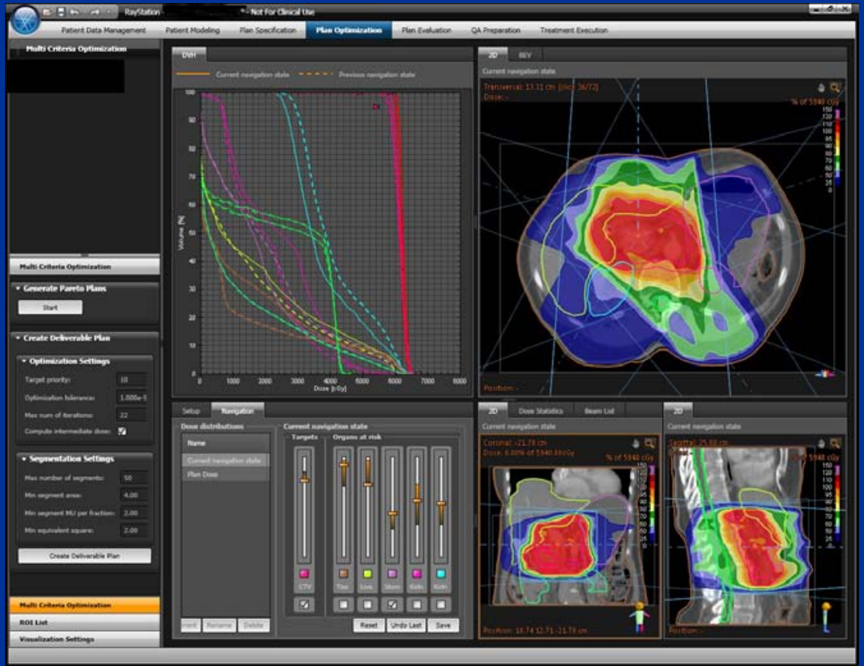
- Issue with IMRT planning: each plan characterized by single score
- May not faithfully reflect clinical decision process
- Current systems may yield plans mathematically optimal but clinically unacceptable



ROSWELL PARK CANCER INSTITUTE

Solution: Multicriteria Optimization

- First proposed for IMRT by Yu in 1997
- Instead of single score, define several objective functions
- For example – function for target and for each critical structure

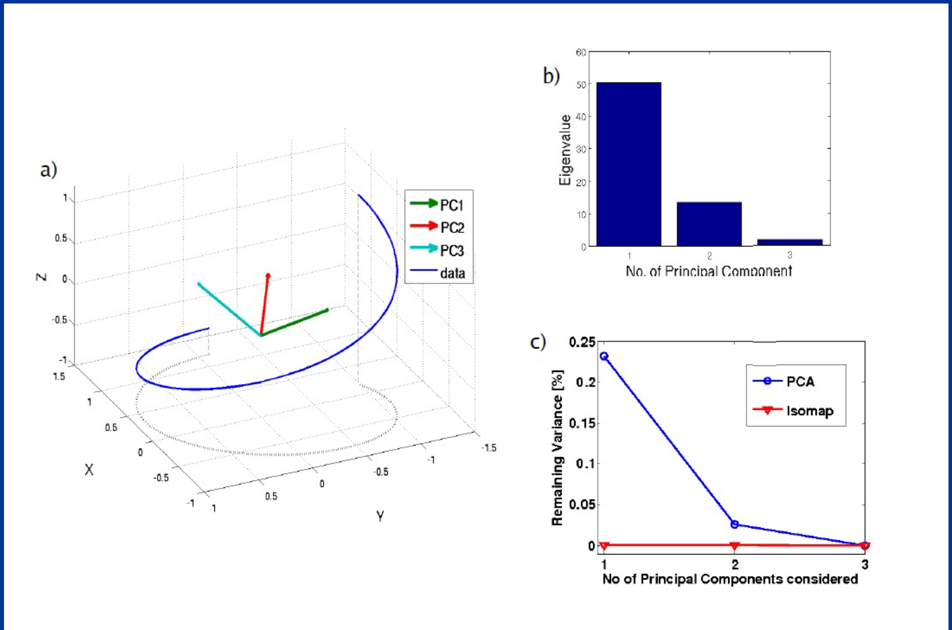


Source: Massachusetts General Hospital

ROSWELL PARK CANCER INSTITUTE

Solution: Multicriteria Optimization

- Optimization involves navigation along *Pareto surface*
- Does not require typical iterative process between physician, planner/TPS
- More clinically meaningful



ROSWELL PARK CANCER INSTITUTE

More to Come!

References

Orton, Bortfeld, Niemierko, Unkelbach, “The role of medical physicists and the AAPM in the development of treatment planning and optimization,” *Med. Phys.* 35 (2008)

Xiaochuan, Siewerdsen, La Riviere, Kalender, “Development of x-ray computed tomography: The role of *Medical Physics* and AAPM from the 1970s to present,” *Med. Phys.* 35 (2008)

Acknowledgments

Dr. Matthew Podgorsak

Sara Heidinger

Physics group at Roswell Park Cancer Institute

ROSWELL PARK CANCER INSTITUTE