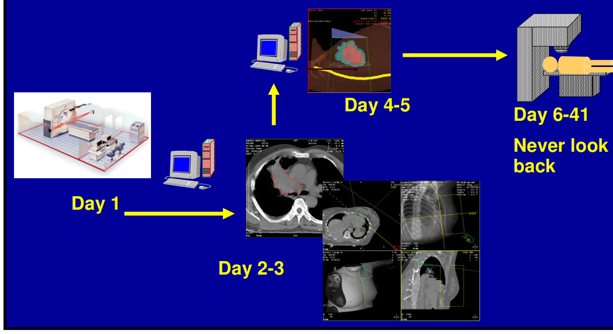
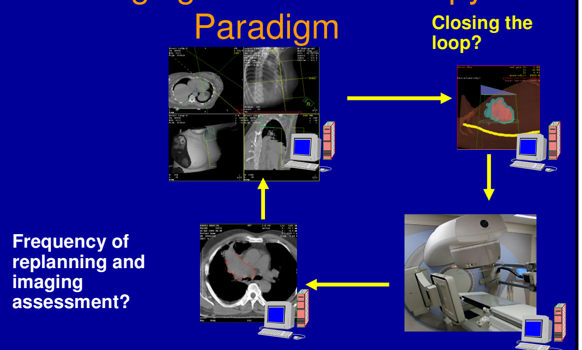
"On Critical Needs for Computation in Radiation Therapy"

Jatinder R. Palta, Ph.D.
University of Florida
Gainesville, FL

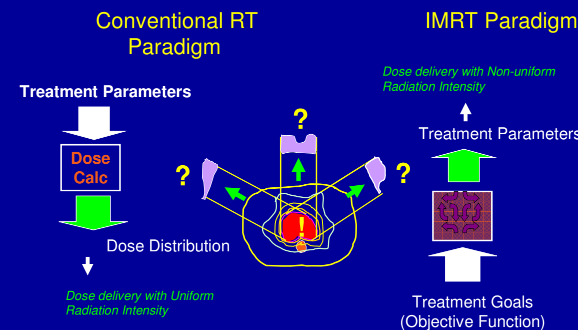
Conventional Radiation Therapy Paradigm



Emerging Radiation Therapy Paradigm

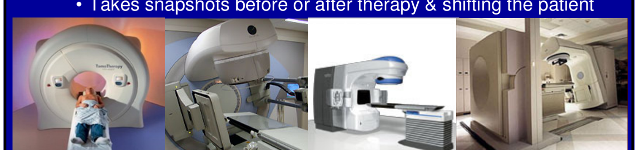


Radiation Therapy Planning Process



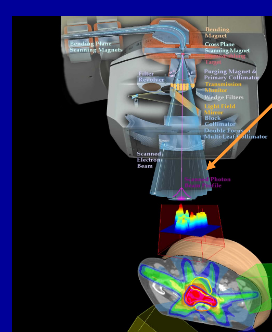
Radiation Therapy Delivery Systems

- Megavoltage photon and electron beams
  - Uniform and intensity–modulated radiation delivery
- Onboard volumetric imaging
  - Takes snapshots before or after therapy & shifting the patient



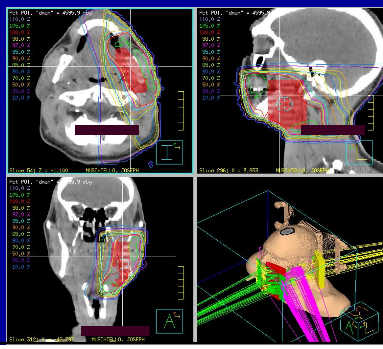
Current technology has no ability to account for intra-fraction motions!

IMRT delivery

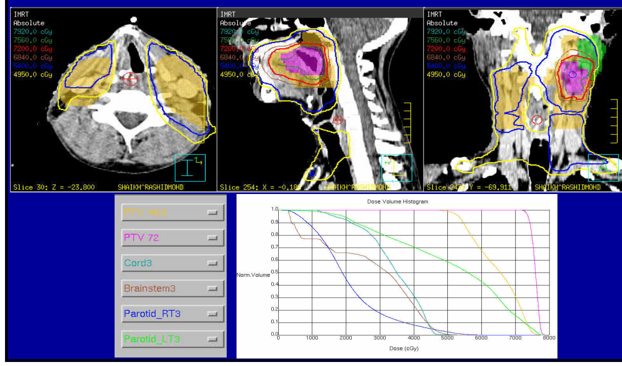


Beams of radiation are subdivided into small, yet finite, beams called beamlets; Each Beamlet can have a different fluence (intensity)

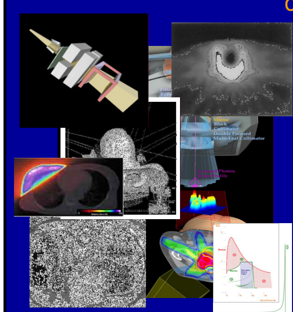
Conventional Radiation Therapy



Intensity Modulated Radiation Therapy



Great progress in optimizing dose delivery to static objects



Technology Evolution

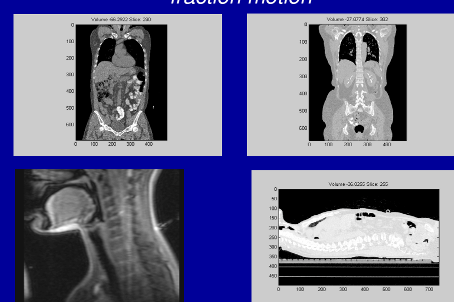
CT Sim
Convolution
IMRT Optimization
Monte Carlo
IMPT
etc.

We have perfected the optimization of dose to static objects

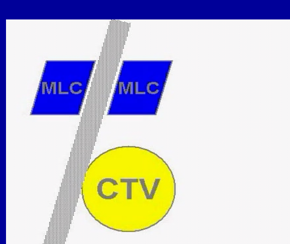
However…

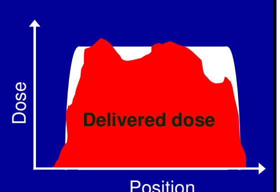
The Clinical Challenge

How to manage dose delivery uncertainties due to inter-/intra-fraction motion

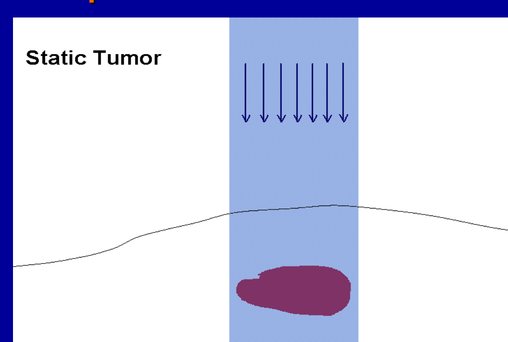


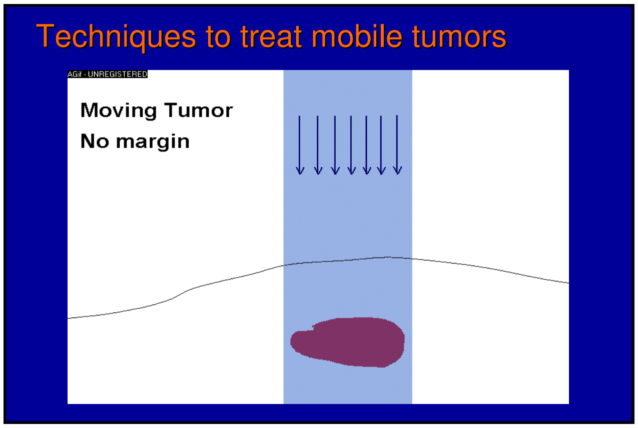
Motion in Radiation Therapy?

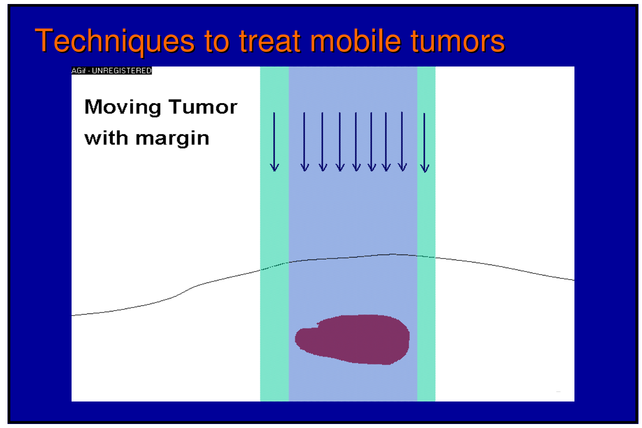


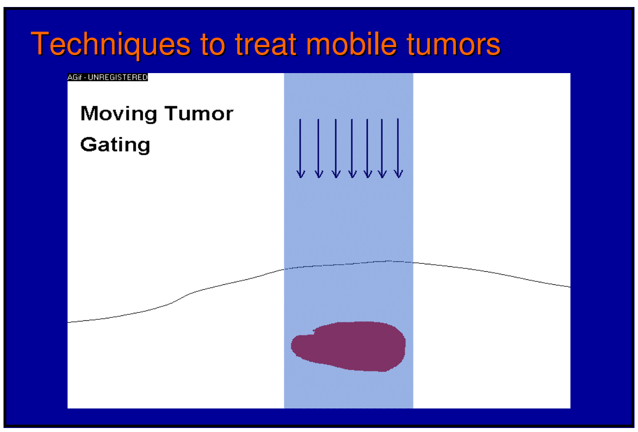


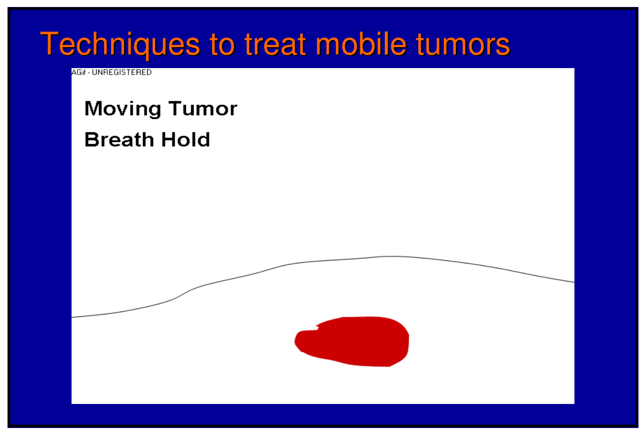
Techniques to treat mobile tumors

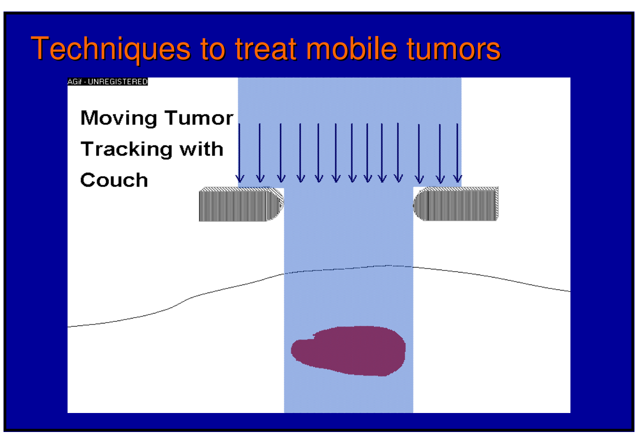


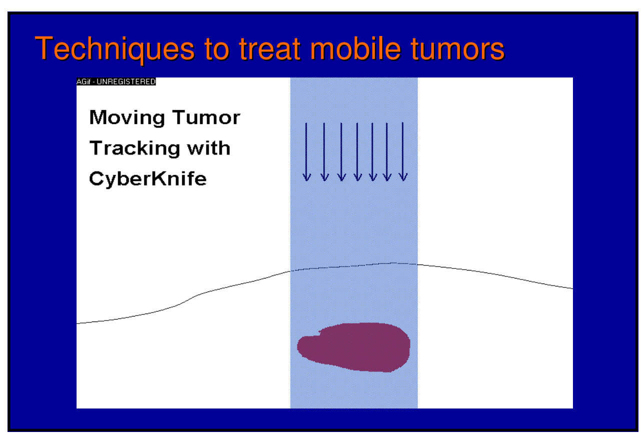

Techniques to treat mobile tumors
Moving Tumor
No margin


Techniques to treat mobile tumors
Moving Tumor
with margin

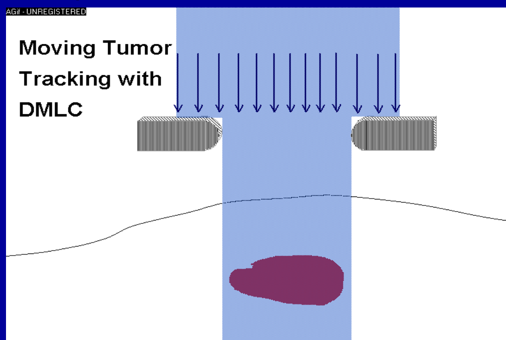

Techniques to treat mobile tumors
Moving Tumor
Gating


Techniques to treat mobile tumors
Moving Tumor
Breath Hold

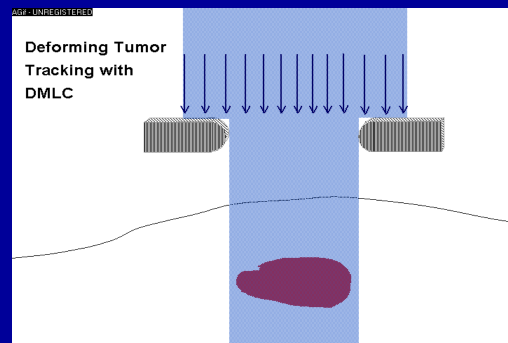

Techniques to treat mobile tumors
Moving Tumor
Tracking with
Couch


Techniques to treat mobile tumors
Moving Tumor
Tracking with
CyberKnife

Techniques to treat mobile tumors



Techniques to treat mobile tumors

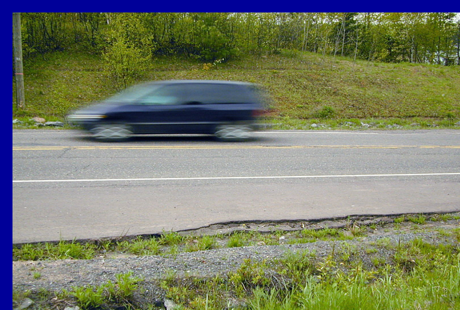


Effects and Artifacts of Motion in Radiation Therapy

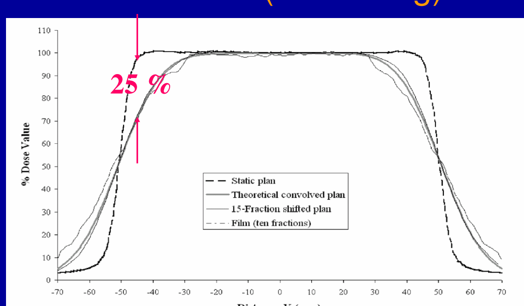
Intrafraction motion can be caused by the respiratory, skeletal muscular, cardiac and gastrointestinal systems. However, respiratory motion is the most dominant. Its effects are:

1. Motion blurring (smoothing)
2. Dose deformation (interface effects)
3. Interplay effects

Motion blur

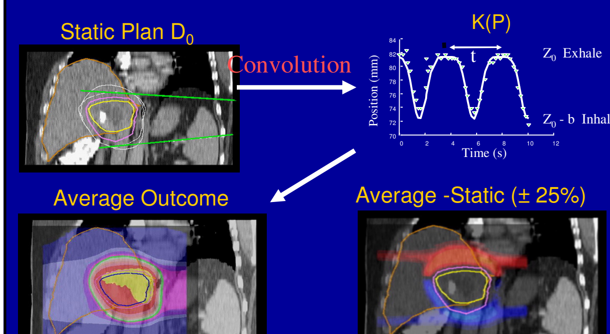


Motion blur (smoothing)



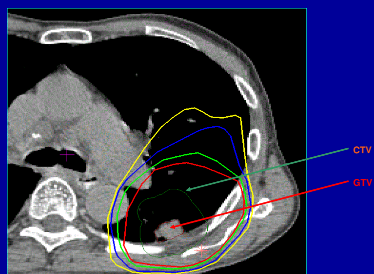
McCarter & Beckham, PMB, 45, 2000

Motion blur of dose distribution

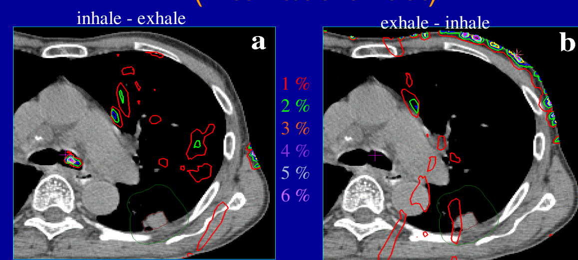


Courtesy; Ten Haken, University of Michigan

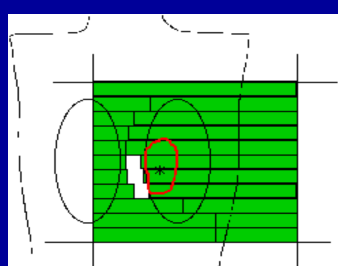
Dose deformation (Interface Effects)



Dose deformation (interface effect)



Interplay effects between organ motion and MLC movement

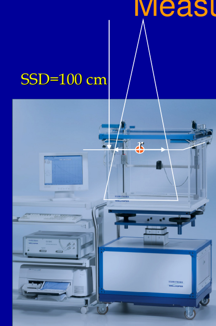


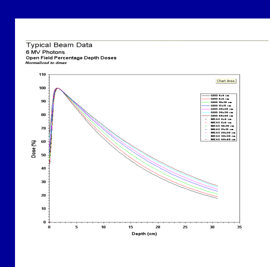
Sources of Uncertainty in Treatment Planning Process

- Patient localization
  - Patient/organ motion during imaging and treatment
- Imaging
  - Problems in transfer, conversion, geometrical distortion, and multi-modality image registration
- Definition of anatomy
  - Inaccuracy and intra-observer variation in definition of the anatomical model of the patient
- Establishment of beam geometry and dose calculations
  - Poor modeling of the physical situation
- Dose display and plan evaluation
  - Dependency of DVH on grid size resolution and volume calculations

State-of-the art in Dose Calculation Algorithm

Radiation Beam Characteristics are Measured in water



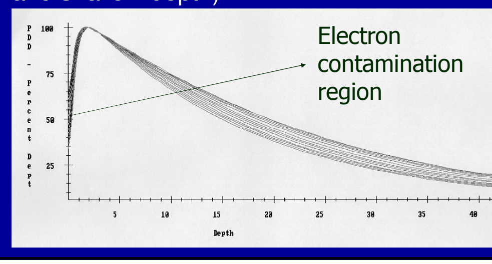


Measurement -Based Algorithms

- Use measured data directly when computing dose, or use a set of empirical functions (fitting functions)
- Apply correction factors to account for differences between the patient and the measurement (i.e. beam modifiers, patient contour, inhomogeneities etc).

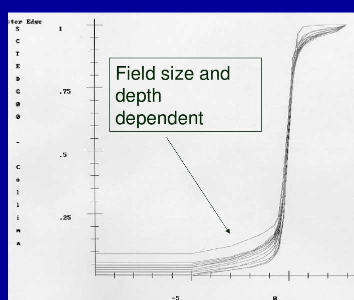
Limitation of Model

- Dose in the buildup region (Surface Dose and shallow depth)



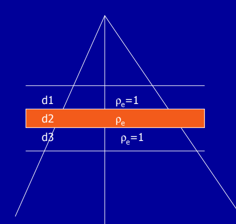
Limitation of Model

- Dose in the penumbra region
- Dose outside the field

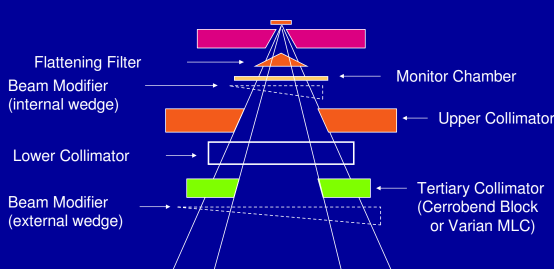


Limitation of Model

- Tissue inhomogeneities



Sources of Extra-Focal Radiation

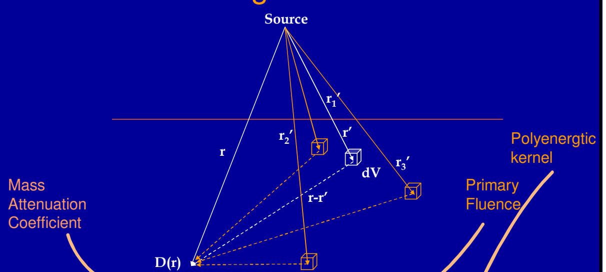


Measurement-based algorithms cannot account for changing magnitude of extra-focal radiation

Model-Based Algorithms

- Use physical and measured data to define the energy fluence distribution from the LINAC.
- Use cross sectional data to compute distribution of scatter.
- Calculate dose to a patient by means of radiation transport computation.

Formalism of Model-Based Algorithm



$$D(\vec{r}) = \sum \left\{ \frac{\mu}{\rho}(\vec{r}_1')\Psi(\vec{r}_1')K(\vec{r}-\vec{r}_1') + \frac{\mu}{\rho}(\vec{r}_2')\Psi(\vec{r}_2')K(\vec{r}-\vec{r}_2') + \ldots \right\}$$

Primary Energy Fluence: $\psi(\vec{r}\,')$

Affected by:

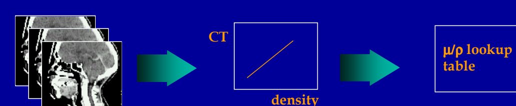
- Differential hardening/softening
  - flattening filter
  - beam modifiers
  - patient
- field size or aperture opening
- transmission through collimation
- finite source size

Primary Energy Fluence: $\psi(\vec{r}\,')$

includes:

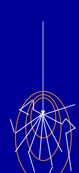
- photons from target
- photons scattered from primary collimator
- photons scattered from flattening filter
- photons scattered from secondary & tertiary collimation
- electron contamination

Mass Attenuation Coefficient: μ/ρ



$$D(\vec{r}) = \int_V \frac{\mu}{\rho}(\vec{r}\,')\Psi(\vec{r}\,')K(\vec{r}-\vec{r}\,')dV$$

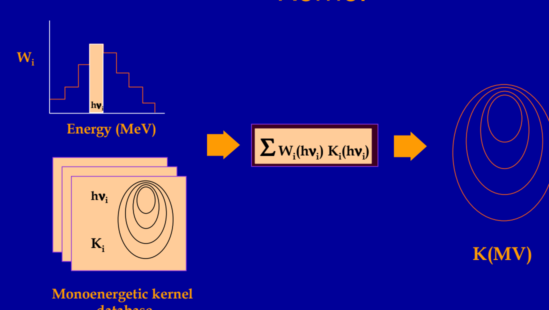
Convolution: Kernel Generation



Monte Carlo simulation of photons of a given energy interacting at a point in water. The resulting energy released at the target point is absorbed in the medium in a “drop-like” pattern called a *dose deposition kernel*

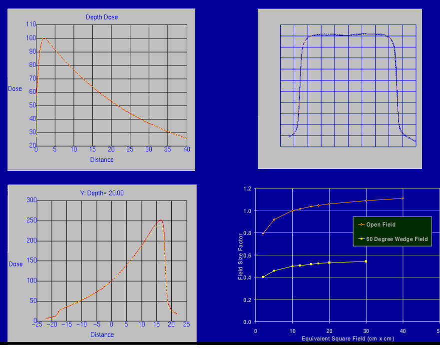
$$D(\vec{r}) = \int_V \frac{\mu}{\rho}(\vec{r}\,')\Psi(\vec{r}\,')K(\vec{r}-\vec{r}\,')dV$$

Convolution: Polyenergetic Kernel

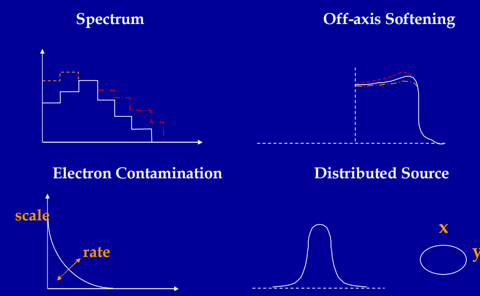


3-D RTPS Commissioning

Measure a self-consistent data set for beam modeling.
- Depth doses, cross-beam profiles in water and in air

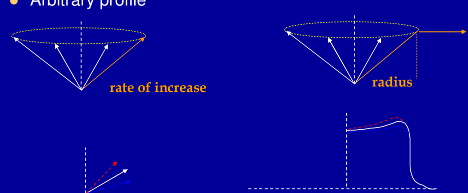


3-D RTPS Commissioning



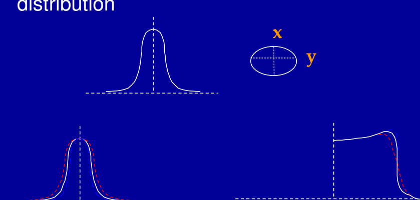
Photon Model Parameters

- Cone: Models primary fluence and is depth independent
- Cone rate of increase and radius
- Arbitrary profile

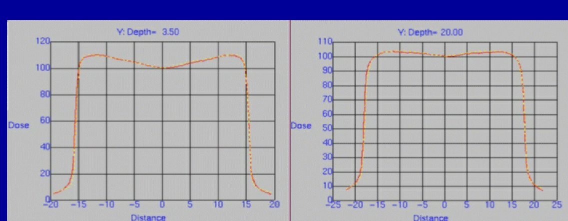


Photon Model Parameters

- Distributed source: Models the geometrical penumbra
- Gaussian kernel is convolved with energy fluence distribution

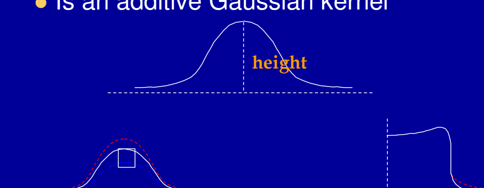


Profile Modeling for 20 MV Open Beam at 3.5 and 20 cm Depths for 30 cm Square Field



Photon Model Parameters

- Head Scatter: Models the stray scatter from the head of the Linac
- Is an additive Gaussian kernel

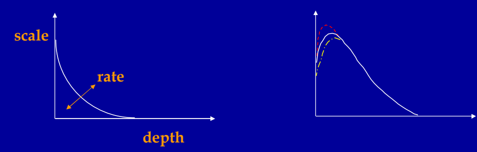


Photon Model Parameters

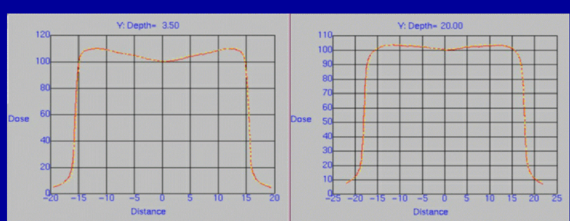
- Off axis softening is depth dependent
- Models the change in spectrum (in turn the μ/ρ) at off axis distances

Photon Model Parameters

- **Electron contamination is a post calculation additive function**
- **Determines the shape of the depth dose in the buildup region**

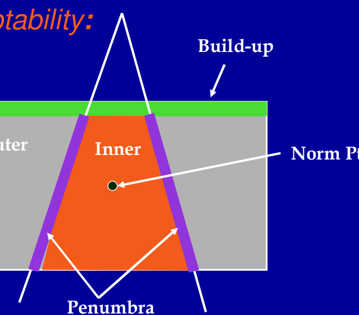


Profile Modeling for 20 MV Open Beam at 3.5 and 20 cm Depths for 30 cm Square Field



3-DRTPS Commissioning

Criteria for Acceptability:



3-DRTPS Commissioning

* Criteria for Acceptability

Absolute Dose @ Normalization Point (%)	**1.0**
Central-Axis (%)	**1.0 - 2.0**
Inner Beam (%)	**2.0 - 3.0**
Outer Beam (%)	**2.0 - 5.0**
Penumbra (mm)	**2.0 - 3.0**
Buildup region (%)	**20.0 - 50.0**

***Criteria for acceptability must be increased for inhomogeneous media (2-3 fold)**

Tissue Inhomogeneities

- Loss of lateral electron equilibrium when high energy photon traverses the lung - broaden penumbra
- Loss of lateral scatter electron for high energy photon beam - reduction in dose on the beam axis
- The effect is significant for small field size (<6x6 cm) and high energies (> 6MV)

Dose Computation Challenges in Radiation Therapy

- Understanding the dose calculation algorithms and its clinical limitations is essential in the safe implementation of TPS
- There is no perfect beam modeling. Therefore, understand the model limitation and make the best judgement in choice of parameters.
- It is impossible to test all aspects of a TPS dose calculation algorithm. Therefore, vigilance and careful evaluation of every treatment plan by a qualified physicist is essential