UNIVERSITY OF WISCONSIN
SCHOOL OF MEDICINE AND PUBLIC HEALTH

JOZEF STEFAN INSTITUTE

TomoTherapy: Combining Imaging and Therapy

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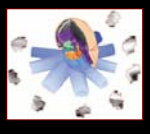
Radiotherapy (RT)

- **Conventional RT:**
  - Jaws are used to shape the beams (rectangular around tumor)

- **Conformal RT (CRT):**
  - MLCs are used to shape the beams (conformal to tumor shape)



- **Intensity modulated RT (IMRT):**
  - MLCs are used to shape the beams *and* modulate intensity

Intensity modulated radiotherapy

- **Cone beam (non-rotational) IMRT**
  - Treating cone by cone (port by port)
  - Using dynamic MLC
  - Techniques:
    - Step-and-shoot (multiple static field) technique
    - Sliding window (dynamic MLC) technique
    - Several alternative techniques (e.g., IMAT, dynamic arc therapy)

Intensity modulated radiotherapy

- Fan beam (rotational) IMRT
  - Treating slice by slice
  - Using binary MLC
  - Techniques:
    - Serial tomotherapy (NOMOS)
    - **Helical tomotherapy (TomoTherapy)**

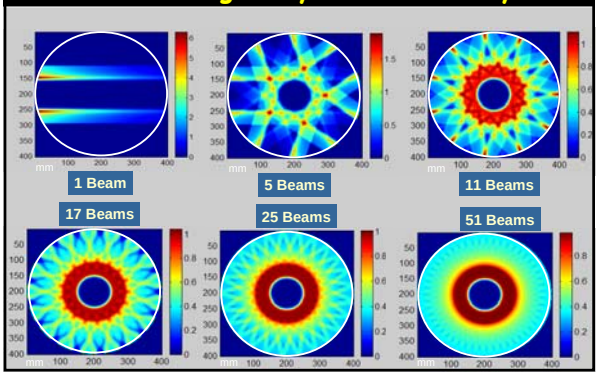
Helical tomotherapy – design basis

- Helical fan-beam IMRT delivery is simple, fast and effective
- CT is the most important imaging modality for radiotherapy
- Linac on a CT is better than a CT on a linac
  - ring gantry is more stable than a C-arm gantry
  - CT gantry allows faster rotation
  - no possibility of rotational collisions
  - coplanar delivery is simpler
- Single energy sufficient
- Simple binary MLC modulating the fan beam
- Accurate CT couch

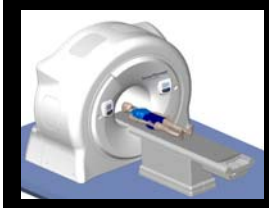
Helical tomotherapy

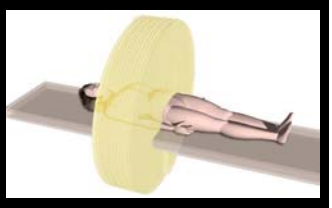
Helical tomotherapy components

More Beams = more homogeneity and conformity

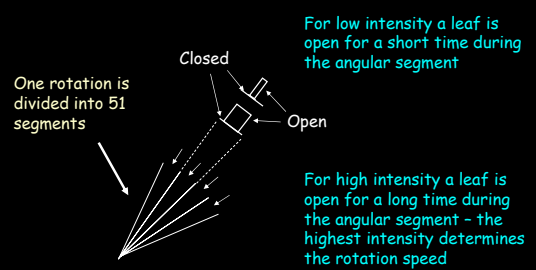


Helical scan/delivery





Intensity modulation in helical tomotherapy

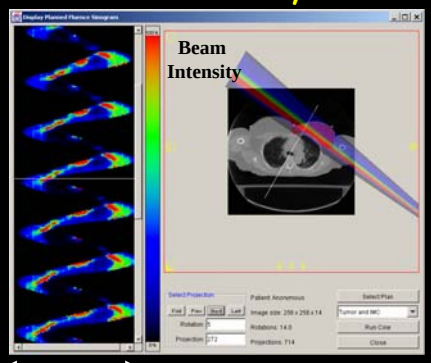


One rotation is divided into 51 segments

For low intensity a leaf is open for a short time during the angular segment

For high intensity a leaf is open for a long time during the angular segment – the highest intensity determines the rotation speed

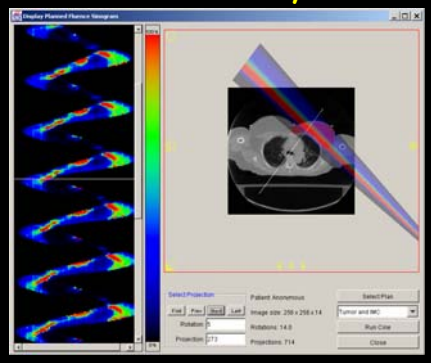
Beam delivery



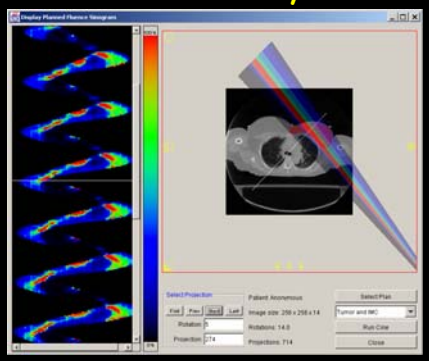
Beam direction & couch position

Leaf #

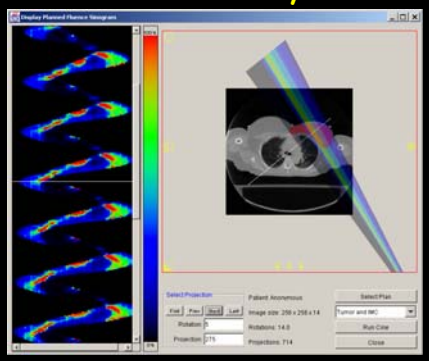
Beam delivery



Beam delivery

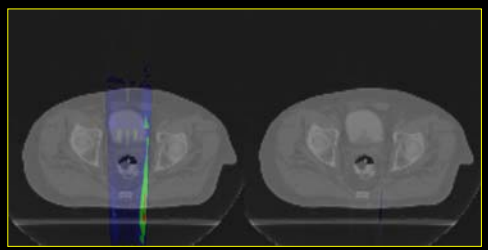


Beam delivery

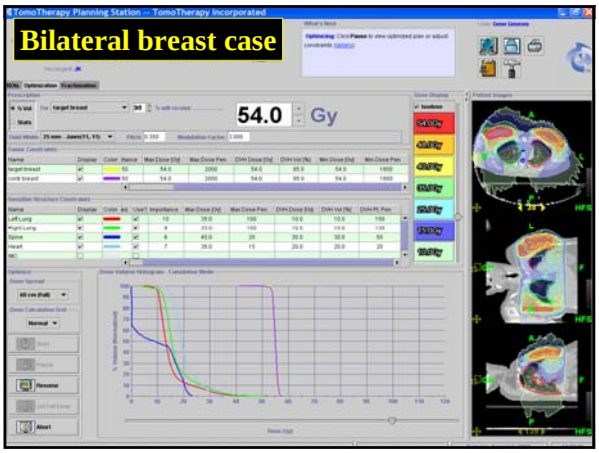


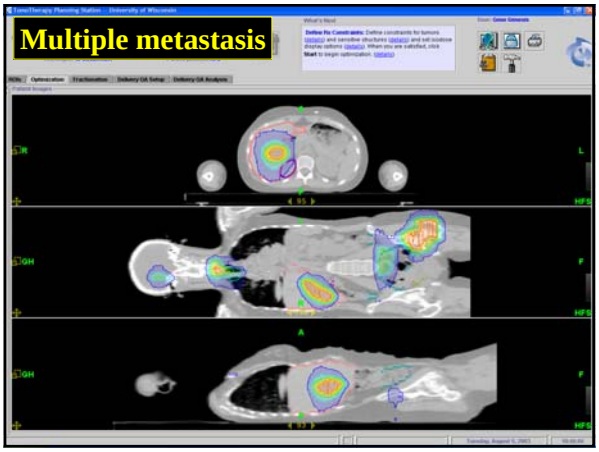
Prostate treatment delivery

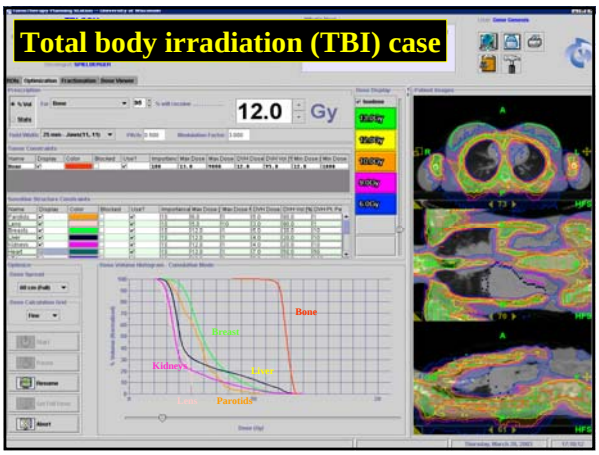
Dose Rate Cumulative Dose



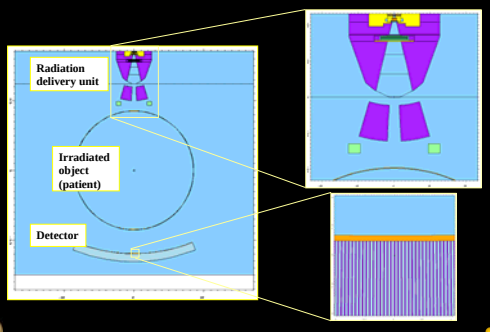
0 to 30% 30 to 90% 90 to 100%


Bilateral breast case
54.0
Gy

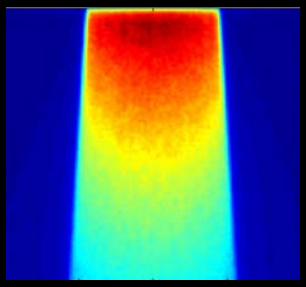

Multiple metastasis


Total body irradiation (TBI) case
12.0
Gy
Bone
Breast
Kidneys
Liver
Parotids

Helical tomotherapy MC model

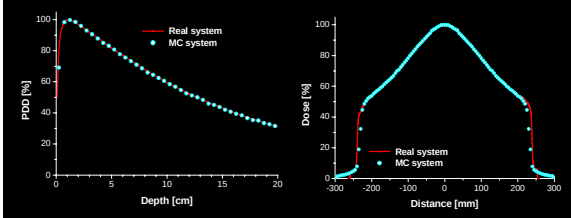


Static tomotherapy beam



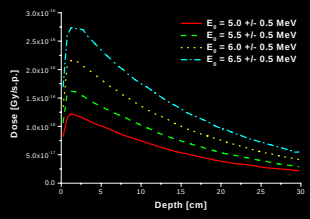
The beam is not flat because helical tomotherapy does not have a flattening filter - no need for IMRT

Single beam



The first step in Monte Carlo modeling is to tune the MC model to match the measurements

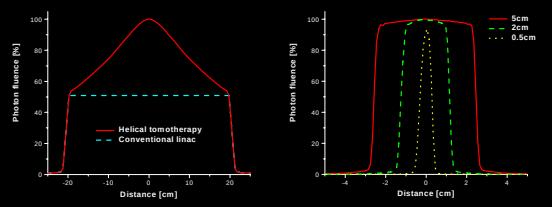
Beam energy dependence



$$D \propto E_0^3 \ln\left(\frac{2E_0}{m_e c^2}\right)$$

Strong dependence of the depth dose curve with energy, but not significant %DD dependence – not very sensitive to commissioning

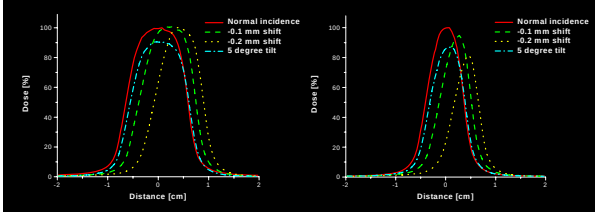
Beam profiles



The lateral beam profile has a characteristic "cone" profile - ~2-times higher in the center

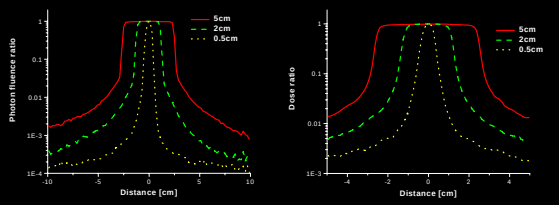
The axial beam profile has a very sharp penumbra

Lateral field sensitivity



The beam profile is very sensitive to the linac electron beam position – particularly for narrow fields

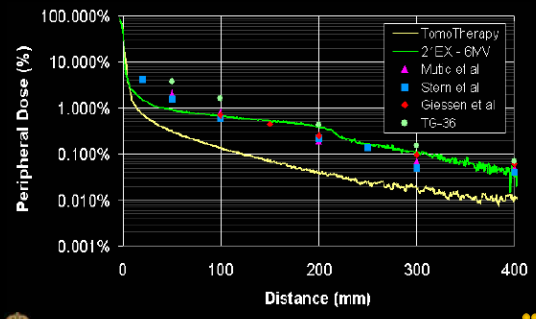
Shielding - leakage



Helical tomotherapy was designed to increase shielding in the forward direction

» 10^4 attenuation at 10 cm for narrow fields

Leakage compared to other systems



Ramsey *et al*, J App Clin Med Phys 7, 2006, 11

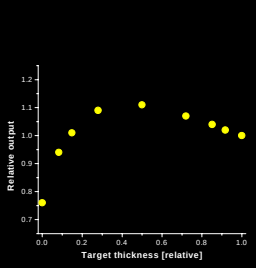
IMRT Integral Dose

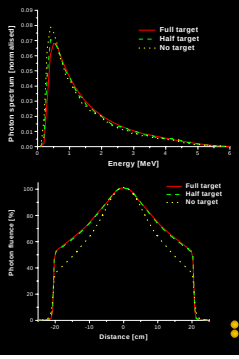
	In-Field (Aoyama)	Photon Out-Field (Ramsey and Reft)	Neutron (Reft)	Total	Change From 6MV 3D CRT
6 MV 3D CRT	122.9	3.4	0	126.3	0 %
6 MV IMRT	116.7	16.9	0	133.6	+6 %
20 MV 3D CRT	113.4	4.2	1.1	118.8	-6 %
20 MV IMRT	109.1	21.2	5.6	135.9	+8 %
Tomo (6 MV)	117.9	3.0	0	120.9	-4 %

Units are in Gy-liter

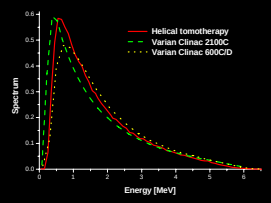
Courtesy of Thomas R. Mackie, University of Wisconsin, Madison, WI

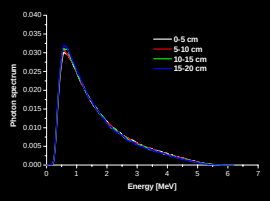
No flattening filter – radiation safety concern





Helical tomotherapy spectral characteristics

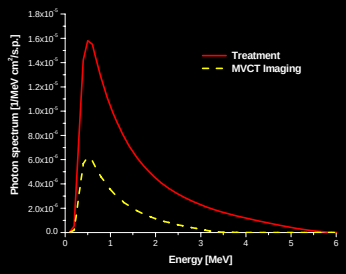




Helical tomotherapy has a very comparable spectrum to other linacs (6 MV)

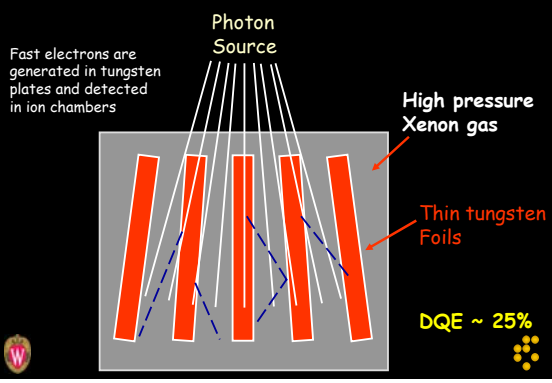
There is very insignificant in-field spectral change (no flattening filter)

Treatment and imaging beams



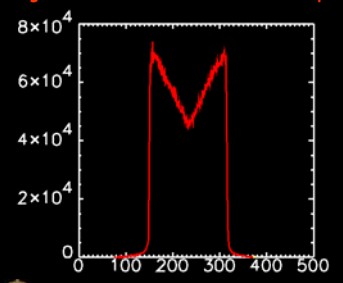
Helical tomotherapy creates the imaging beam by reducing energy (from ~6 MeV to 3.5 MeV)

Detector system

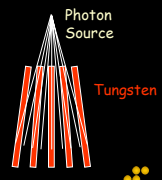


Detector response across the detector

Signal at the detectors for one linac pulse

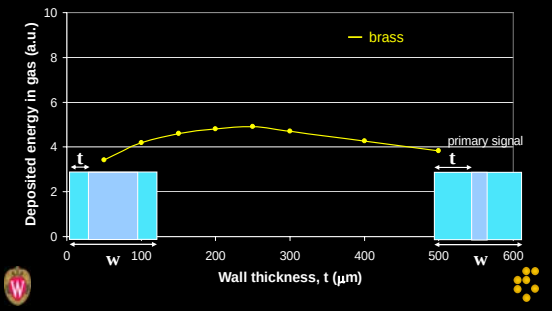


The detector response increases from the center of the detector due to an increased cross-section of tungsten.



Optimization of the detector design (primary signal)

Simulations for a fixed detector element width (w = 1.5mm)



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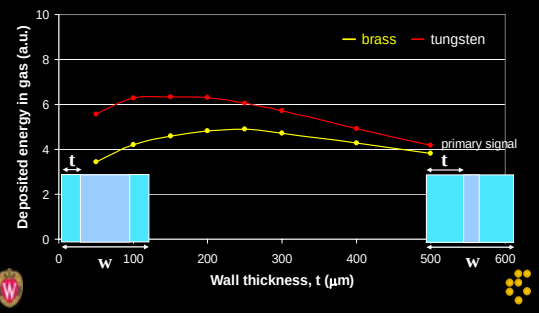
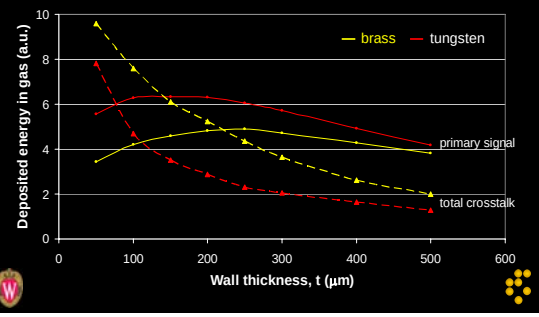
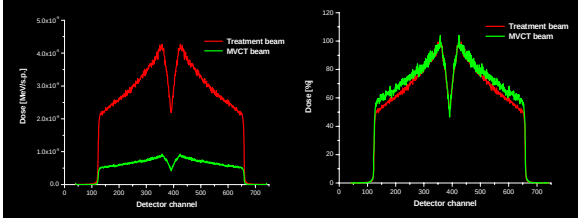


Optimization of the detector design (cross-talk)

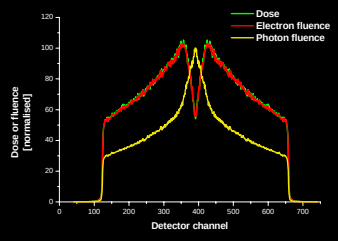


MC simulations of the detector



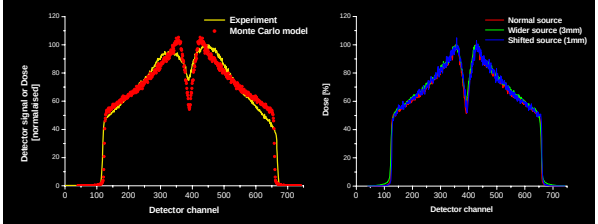
Detector signal is the lowest in the center (low septa plate cross-section), but the approximately follows the photon profile

Monte Carlo provides useful "immeasurable" information



Detector signal is directly proportional to the electron fluence; photon and electron fluences similar in the septa plates, not in the gas

Comparison to experiment



Agreement with the experiment is not good. Why?

- source description
- detector geometry
- transport physics

Sensitivity studies!

Comparison of tomotherapy with CBCT

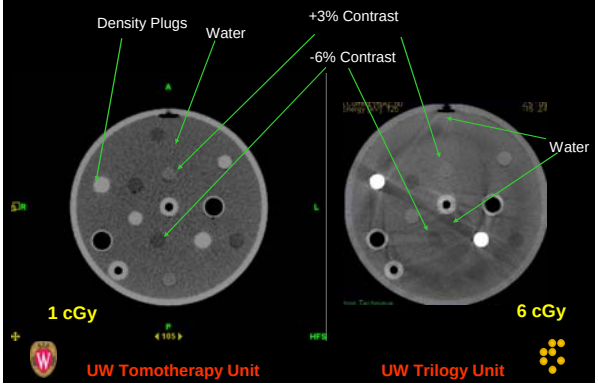


Image registration

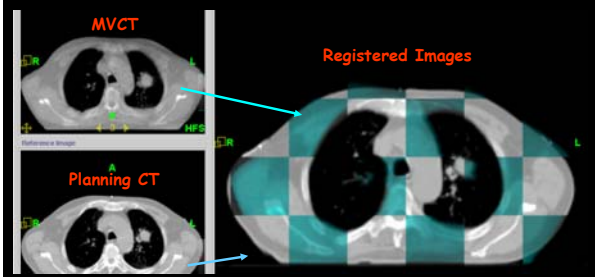
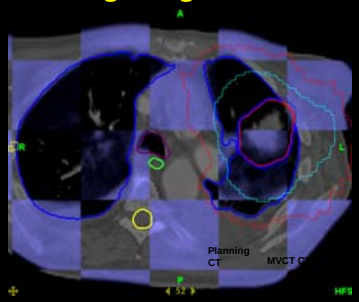


Image registration



Superposition of the planned dose distribution over the daily CT enables optimal conformity of the dose to the daily anatomy

Internal anatomy is changing

Start of treatment

7 days later

2 weeks later

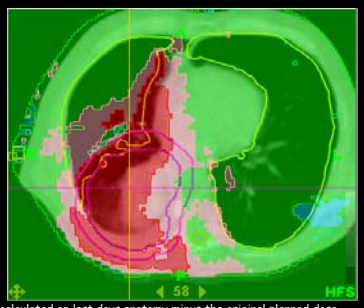
3 weeks later

1 month later

Courtesy of Tim Holmes, St. Agnes Cancer Center, Baltimore, MD

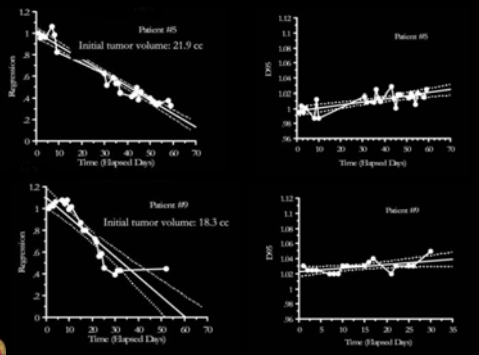
Treatment dose ≠ planned dose

Difference between the planned dose and actual delivered dose is significant and can, at least in principle, be compensated for with treatment adaptation



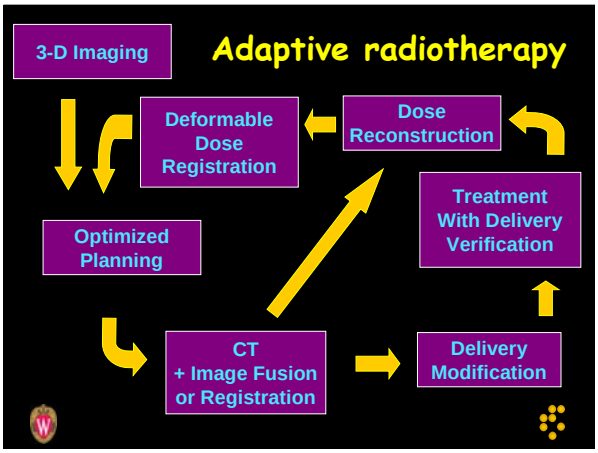
Dose calculated on last days anatomy minus the original planned dose
Green = no difference in planned vs. treatment dose
Red = difference in planned vs. treatment dose
Courtesy of Tim Holmes, St. Agnes Cancer Center, Baltimore, MD

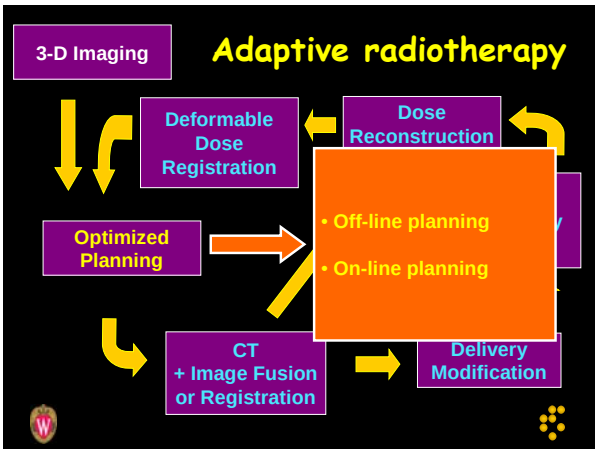
Tumor shrinkage

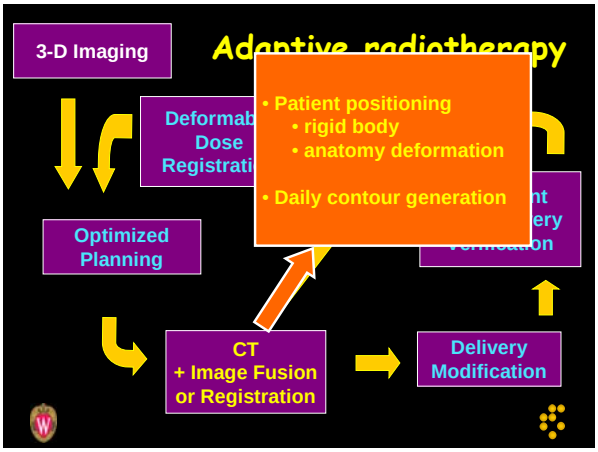


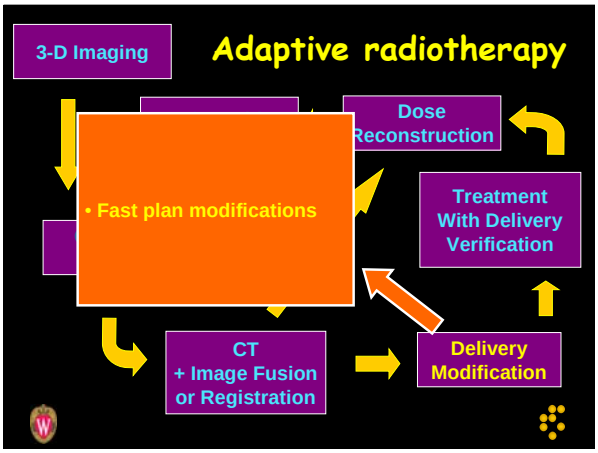
Kupelian *et al*, Int J Rad Oncol Biol Phys 63, 2005, 1024

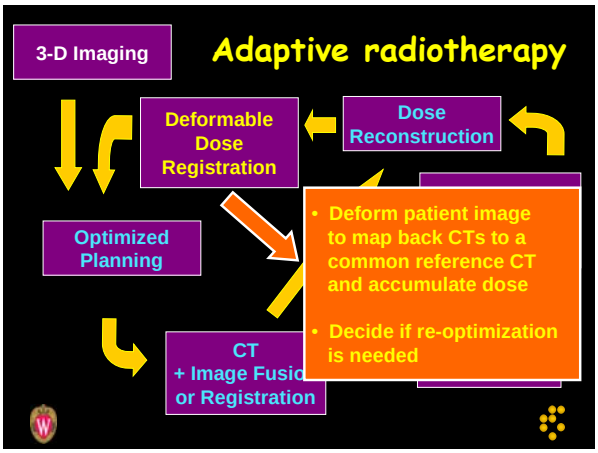
Adaptive radiotherapy

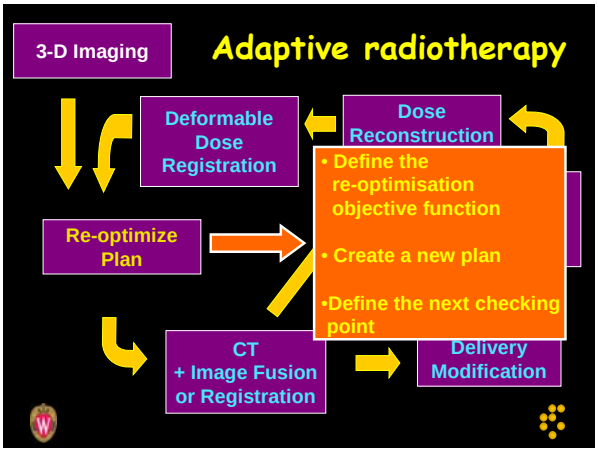



3-D Imaging
Adaptive radiotherapy
Deformable Dose Registration
Dose Reconstruction
Optimized Planning
• Off-line planning
• On-line planning
CT + Image Fusion or Registration
Delivery Modification


3-D Imaging
• Patient positioning
• rigid body
• anatomy deformation
• Daily contour generation
Optimized Planning
CT + Image Fusion or Registration
Delivery Modification


3-D Imaging
Adaptive radiotherapy
Dose Reconstruction
• Fast plan modifications
Treatment With Delivery Verification
CT + Image Fusion or Registration
Delivery Modification





Conclusions

- Helical tomotherapy is a designed image-guided radiotherapy system
- Monte Carlo simulations of the complete system include both, characterization of the treatment beam and imaging beam
- Monte Carlo simulations are invaluable in understanding and optimization of such a complex system
- Many challenges and opportunities for Monte Carlo simulations in the future

Thank you for your attention