AAPM 2018 JUL 29–AUG 2
BEYOND THE FUTURE!
60th ANNUAL MEETING & EXHIBITION | NASHVILLE, TN

Understanding IMPT and Delivery Uncertainties

Mark Pankuch PhD
Director of Medical Physics and Dosimetry
Northwestern Medicine Chicago Proton Center

Session Objectives

- Review of treatment safety margins and how they relate to proton therapy
- Discuss IMPT Optimization methods
- Introduce the concept of "Robustness"
- Define intra-treatment concerns specifically important to IMPT

An important statement from the AAPM:

The essential responsibility of the Medical Physicist to assure the safe, effective and consistent delivery of radiation*

Acceptance Testing **Quality Assurance**

Commissioning **Procedural Guidelines**

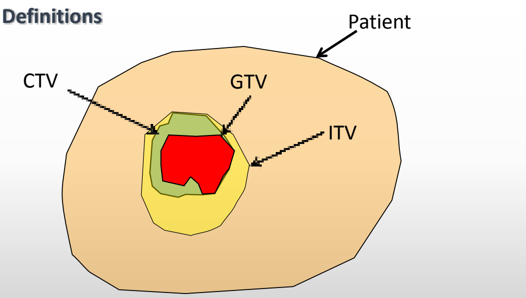
* AAPM Scope of Practice for a Qualified Medical Physicist

With Regards to Treatment Planning……..

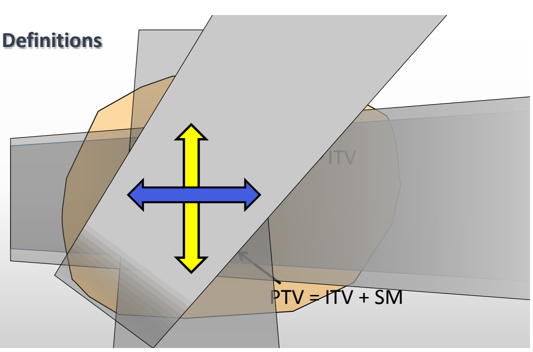
Safe Effective Consistent

Standardization of Target Definitions → **Quantification of Safety Margins**

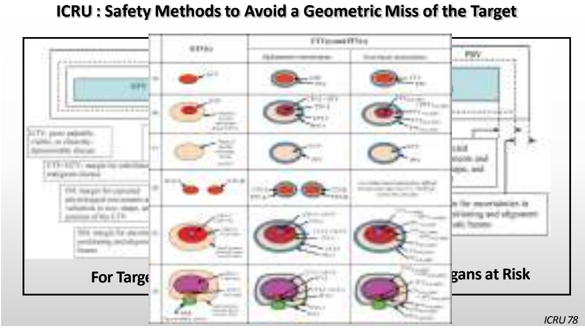
ICRU Definitions



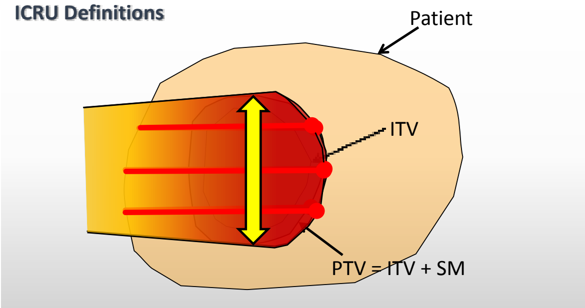
ICRU Definitions



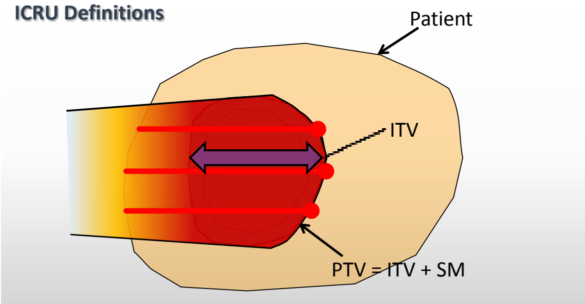
ICRU : Safety Methods to Avoid a Geometric Miss of the Target



ICRU Definitions



ICRU Definitions

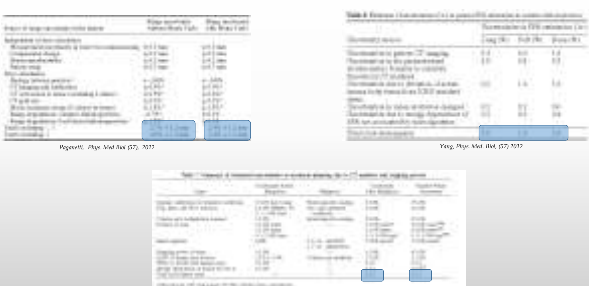


Safe **Effective** **Consistent**

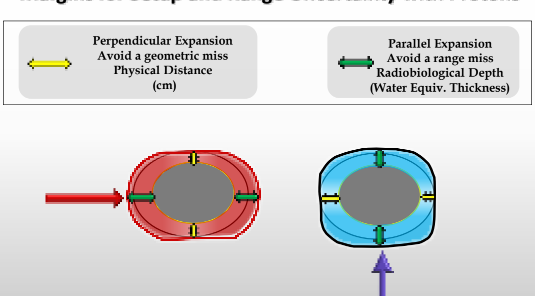
Are there other safety considerations that need to be considered for the distal edge margins??

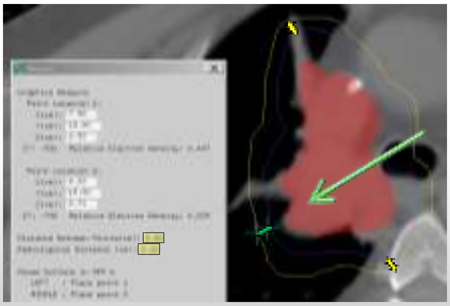
Proton Range Uncertainties

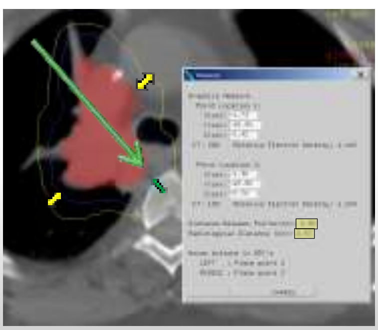
With Protons : We must always consider for Range Uncertainty



Margins for Setup and Range Uncertainty with Protons



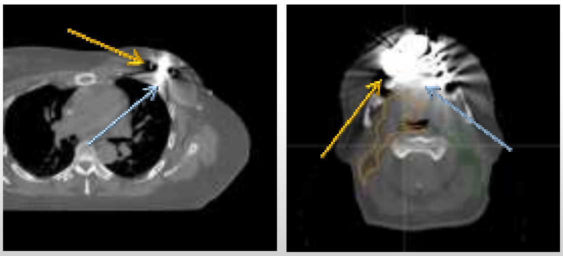




Using a CT as the Patient "Map" is an Area of Specific Concern for Protons

- Trying to make our CT scanner a spectrometer
  - Two tissues can have same HU but different RSP
- CT scans are not perfect
  - Noise
  - Beam hardening
- Stoichiometric Method is valid for tissue type materials. Anything not natural can have large errors.
  - Contrast
  - Fillings
  - Implants

Artifact caused by the Filling Port of a Chestwall Expander / Dental Fillings



HU to RSP Conversion Errors in a Silicone Breast Prosthesis

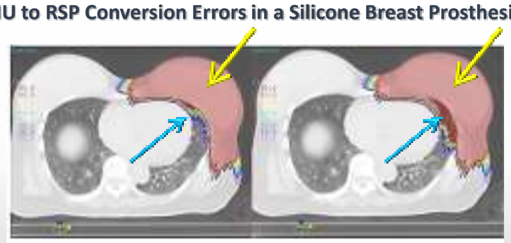
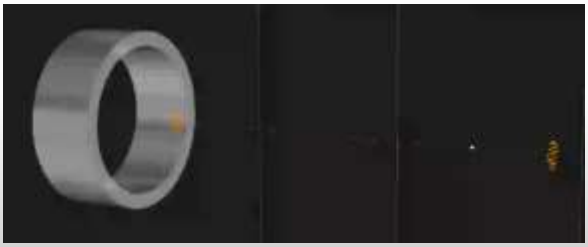


Fig. 3: Treatment plan for patient with silicone breast prosthesis. (a) Planned dose distribution without RLSP reassignment. (b) Delivered dose distribution if planned without proper pRLSP assignment.

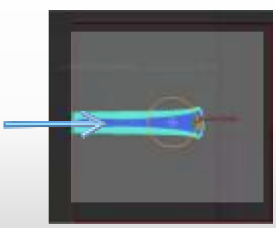
Moyers et.al Med Dosim. 2014 Spring;39(1):98-101.

Delivery of a Sphere of Dose using PBS

Delivery of a Sphere of Dose using PBS



Spot / Layer Patterns for a Sphere



Dose Distribution

Beam's Eye View

How can we obtain these complex, 3-D spot patterns?

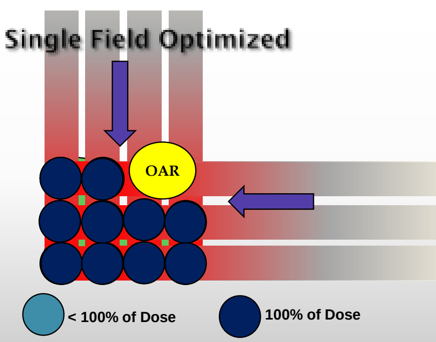
Inverse planning techniques

- Iterative minimization of an objective function.
  - Cover target areas
  - Minimize dose to organs at risk
- Exceptional potential for computing and mathematical "tricks"
  - Minimizing the effects of positional errors and range errors directly into the cost function (Robust Optimization)
  - Including effects of motion into the cost function (4-D Optimization)
  - Multi Criteria Optimization (MCO)
- Two different optimization methods used to guide the objective function

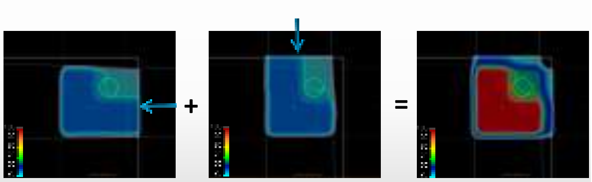
Commonly used IMPT Optimization Methods

Single Field Optimization (SFO)	Multi Field Optimization (MFO)
Uniform Dose is delivered to the entire target by each field individually	Spot weights of all fields are optimized together. The spot weight of one field will rely on another field's dose to create an integrated uniform target dose
Less sparing of critical structures	Better for sparing critical structures
Less sensitive to Set-up/Range errors	More sensitive to Set-up/Range errors

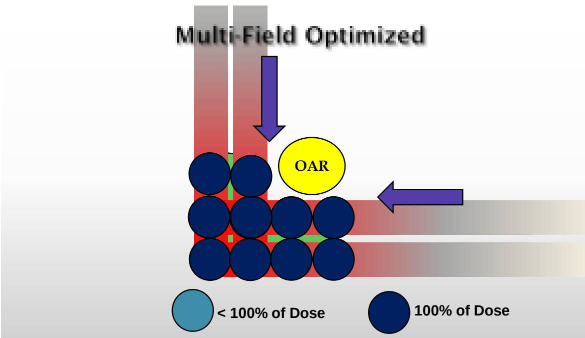
Single Field Optimized

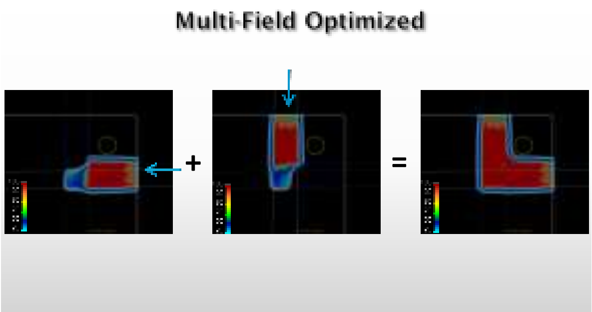


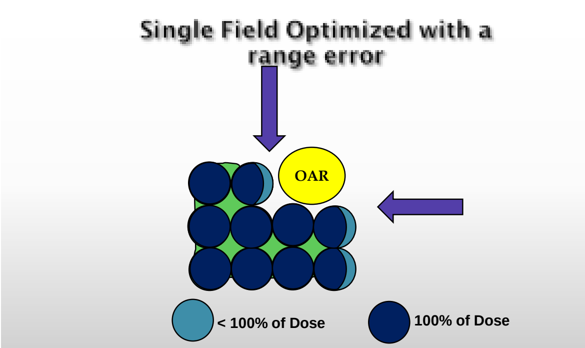
Single Field Optimized



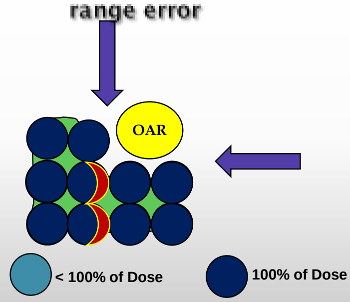
Clinical Radiation Oncology, 3rd Addition


Multi-Field Optimized
OAR
< 100% of Dose
100% of Dose


Multi-Field Optimized
+
=
Clinical Radiation Oncology, 3rd Addition


Single Field Optimized with a range error
OAR
< 100% of Dose
100% of Dose

Multi Field Optimized with a range error



The physicist is tasked to

Quantify the effects of:

- Non-ideal set-up
- Intra-fraction motion
  - Respiratory motion

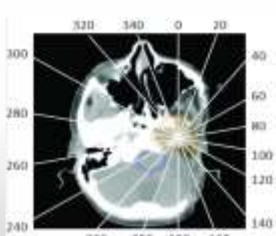
"Robustness"

- Range uncertainty
- Inter-fraction motion
  - Anatomical consistency

Prospective Robust Planning

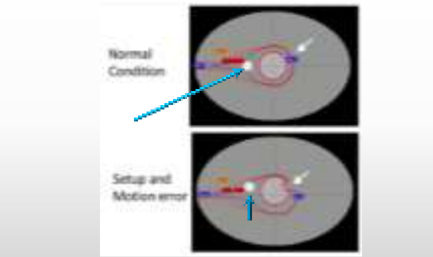
Beam Angle Optimization prior to Spot optimization

- **Evaluate path-lengths and the effect of range error and set-up uncertainties**
- **Concept can be expanded to 4-D evaluations**



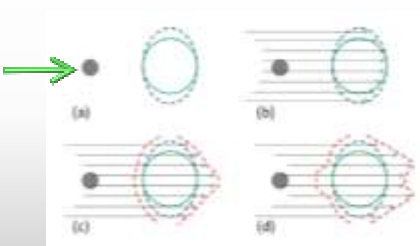
Cao et.al Med Phys. 2012 Aug; 39(8): 5248–5256. MDA

The Effect of Set-up Errors on SFO Plan



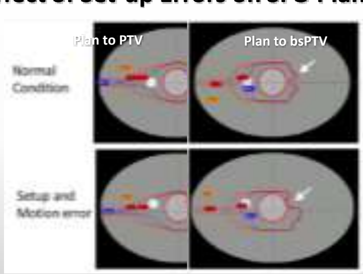
Park et al. Int J Radiat Oncol Biol Phys. 2012

For SFO: Beam Specific PTV : bs(PTV)



P. Park et al Int J Radiat Oncol Biol Phys. 2012

The Effect of Set-up Errors on SFO Plan



Park et al. Int J Radiat Oncol Biol Phys. 2012

What about MFO methods?

Robust Optimization

- Add penalties into the cost function for robustness
- Allow the planning system to score robustness on a spot to spot basis AND how one spot will effect the overall sensitivity to potential plan degradation.
- Spots with “poor” robustness (high sensitivity to plan degradation) will be penalized by iteratively decreasing, and potentially, eliminating their intensity
- There is potential for LET / Biological Dose Optimization

Robust Optimization

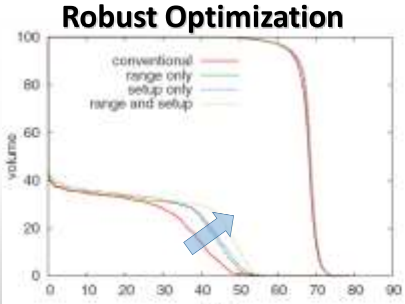
- **Range Uncertainties and Set-up Errors**

1) Probabilistic approach
   - Range and positional errors are parameterized and incorporated into the objective function
   - spot range/position/weight is a random variable

2) Optimize on “worst case” scenarios

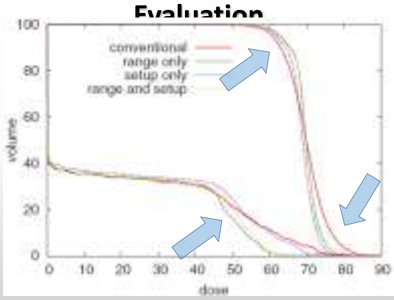
Unkelbach Phys. Med. Bio. 2007,Med Phys 2009

Robust Optimization



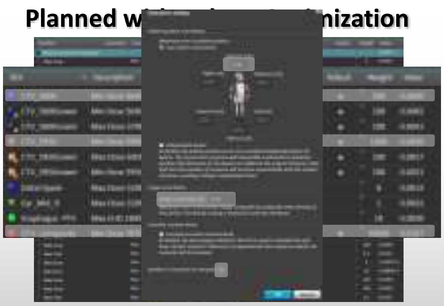
(Unkelbach Med. Phys. 2009)

Robust Optimization Evaluation

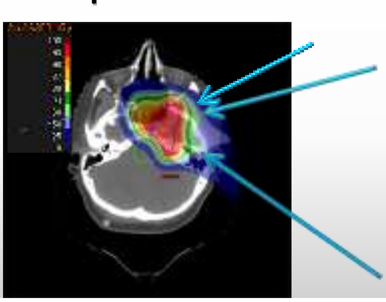


(Unkelbach Med. Phys. 2009)

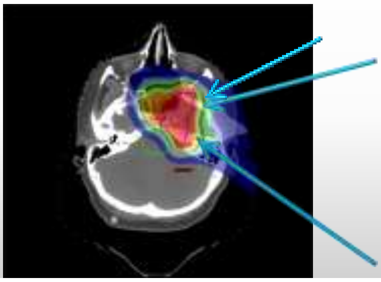
Planned w … nization



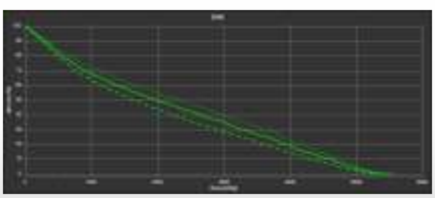
Robust Optimization for OAR



Robust Optimization for OAR



Robust Optimization for OAR



Dose	ROI/POI	Clinical goal	Value
Plan dose: To 61 G...	BrainStem	At most 5700 cGy dose at 0.0 cm³ volume	[illegible]
Perturbed dose: CT...	BrainStem	At most 5700 cGy dose at 0.0 cm³ volume	[illegible]
Perturbed dose: CT...	BrainStem	At most 5700 cGy dose at 0.0 cm³ volume	5545 cGy

The balancing act of trade-offs

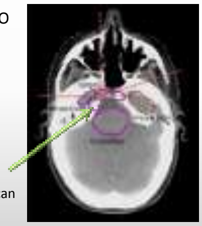
Multi-Field Optimized ——— Single Field Optimized

Target Coverage ——— Critical Organ Dose

High Quality plan ——— Robustness

Degeneracy within IMPT plans Which is best?

- Multi-Criteria Optimization MCO
  - Database of plans each emphasizing different planning objectives are pre-calculated to approximate the Pareto surface
  - Pareto surfaces are navigated to find the optimal balance
  - Range and Set-up uncertainties can be included



Chen et al. Phys. Med. Biol. 2012

The physicist is tasked to "Robustness"

Quantify the effects of:

- Non-ideal set-up
- Intra-fraction motion
  - Respiratory motion

Robustness Evaluation

- Range uncertainty
- Inter-fraction motion
  - Anatomical consistency

Important note : Robust Optimization does not guarantee a robust plan

Robustness Evaluation

Quantify the differences in quality between the planned and the delivered dose in the presence of uncertainties

Robust Plan Evaluation includes :

- Calculation and Evaluation of many "Worst case" scenarios
  - Systematic offset of HU conversion (-3.5% , + 3.5%)
  - Systematic offset of set-up error (x= +/- 5mm, y= +/- 5mm, z= +/- 5mm)

Lomax Phys. Med. Biol 2008

Robustness Evaluation

The concept of "Robust Evaluation" really has limitations

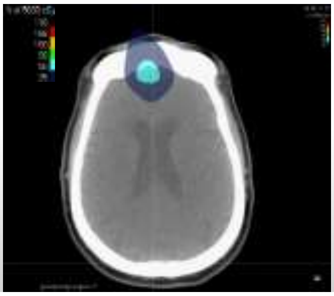
- Impossible to look at all potential scenarios
- In reality there is a combinations of Random AND Systematic errors
  - Set-up errors are random
  - Range errors are systematic
    - Beam Hardening
    - Tissue Dependent
    - Range errors are NOT uniformly distributed
- It is essential to have clear communication between physics and physicians of potential target coverage limitations and possible OAR doses.
- Only as good as the patient model that you give it.
  - What if the patient changes.....

Adaptive Planning

All radiation treatment delivery is sensitive to anatomical changes

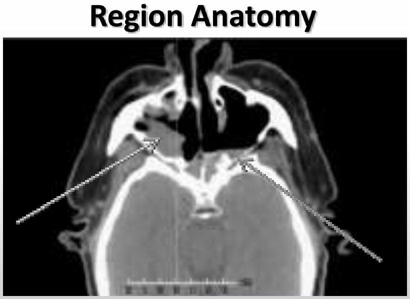
- Especially in particle therapy, a clear understanding of the magnitude and potential consequences of any anatomical change needs to be defined
- IMPT delivery, especially MFO optimized plans , can be very sensitive to anatomical changes.
- Workflows need to be in place to detect, evaluate and correct unexpected anatomical changes.

Adaptive Planning : Naso-pharynx to 56Gy$_{(RBE)}$

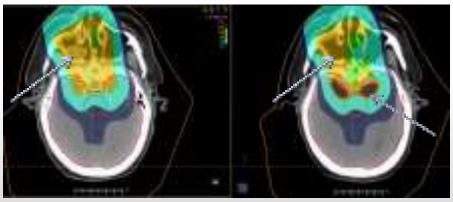


Approved Plan : Naso-pharynx

Large Change in Target Region Anatomy



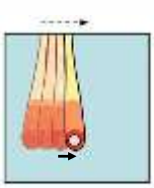
Calculation of Initial Plan on New Image Set



Initial Plan On Treatment Evaluation

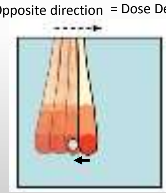
DVH with modified anatomy

Interplay Effects Due to Motion and Delivery Timing



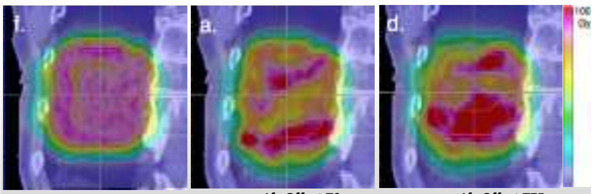
Motion in same direction = Dose Increase

Motion in Opposite direction = Dose Decrease



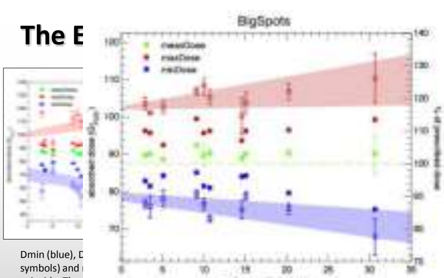
ICRU 78

IMPT delivery has a time structure
The Effects of Respiratory Motion



C. Grassberger et al. Int J Radiat Oncol Biol Phys. 2014

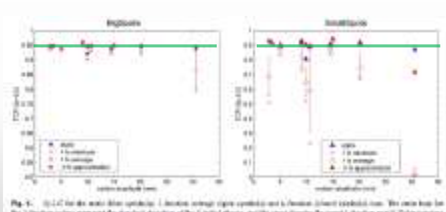
The E



Dmin (blue), D
symbols) and
coincide. The
initial phases. The shaded areas represent a linear fit through the maximum and minimum values of to guide the eye.

C. Grassberger et al. Int J Radiat Oncol Biol Phys. 2014

Daily Under-dosing and 2y-LC



C. Grassberger et al. Int J Radiat Oncol Biol Phys. 2014

Motion effects mitigation

Treatment Delivery

- **Repainting**
- **Gating**
- **Breath Hold / Compression**
- **Beam Tracking**

Treatment Planning

- **Planning Methods**
  - **Using more Fields**
  - **More fractions (>5)**
- **4-D Robust Optimizations**
- **4-D Dose Evaluation**

Strategies for addressing Motion : Repainting

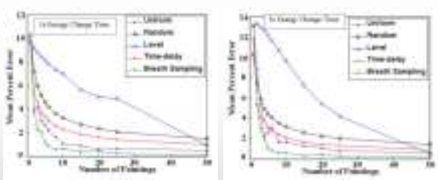


Figure 4. Number of paintings required to reduce the dosimetric effect of motion (breathing period: 4.4 s, motion trajectory: sin4, 30 fractions), 1 s and 5 s energy change time.

J Seco et al. Phys. Med. Biol. (2009)

In Summary

- IMPT is an essential tool in the effort to reach the full potential of particle planning. IMPT methods generate better plans and to more treatment sites.
- IMPT methods are sensitive to range errors, set-up errors, motion and anatomical variances. (Robustness)
- Robust Optimization methods can be used to minimize these sensitive effects along with Robust Evaluations to quantity the consequences.
- IMPT planning is a trade off of many variables. Careful planning with effective communication is necessary between the physics and physician teams.


THANK
YOU