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4π radiotherapy

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8/4/2016 @AAPM

1

Aim of therapy physics research

Find practical ways to maximize the radiation dose to tumor and minimize radiation dose to normal tissues

We optimize delivery variables

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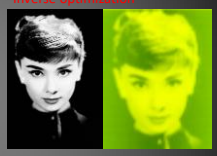
Intensity modulated radiotherapy

Forward optimization

Tape Art by Mark Khaisman

Inverse optimization



Portrait using MLC on EBT2 by Hairong Shi

Stacking discretized shots to conform to certain pattern

$$\arg\min \| D - \sum_{i=1}^{N} w_i A x_i \|_2^2$$

3

Need for safe dose escalation: Locally advanced lung cancer

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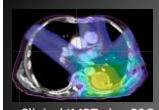
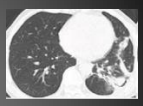
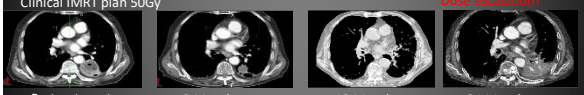


Clinical IMRT plan 50Gy



Dose escalation?



Pretreatment | 3 Month post | 12 Month post | 24 Month post

The majority of stage III lung cancer patients die from local in field disease progression. Garg et al . Pract Radiat Oncol. 2013 Oct-Dec;3(4):287-93, 2014 Sep-Oct;4(5):342-8
High BED is essential to achieve tumor local control for large locally advanced lung cancer. Zhao et al. IJROBP Volume 68, Issue 1, 1 May 2007, Pages 103–110

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Need for better OAR sparing: Bone marrow sparing RT

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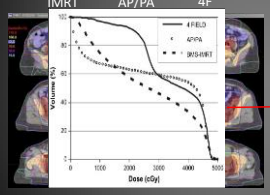
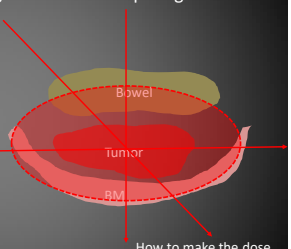
IMRT AP/PA 4F





How to make the dose more compact?

Mell et al, Int J Radiat Oncol Biol Phys. 2008 Aug 1;71(5):1504-10

Non-coplanar radiotherapy is not new

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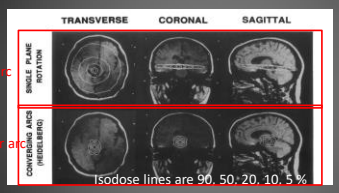
Coplanar arc

Non-Coplanar arcs



Isodose lines are 90, 50, 20, 10, 5 %

Podgorsak et al. IJROBP Volume 16, Issue 3, March 1989, Pages 857–865

- Non-coplanar beams and arcs show definitely advantages for intracranial SRS and are ubiquitously used in these treatments
- Non-coplanar beams are less systematically used for extracranial treatment

From fluence map optimization to beam orientation optimization

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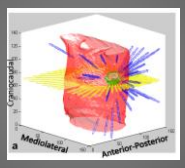

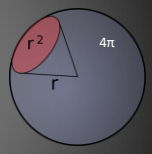

Forward optimization of non-coplanar beams and arcs becomes increasing difficult and inefficient

Need to develop inverse 4π optimization of beam orientations

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Integrated beam orientation and fluence map optimization

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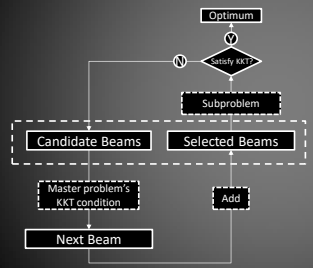

- Pre-compute beamlet doses for all candidate beams (~600-1000)
- Column generation used to select beams and optimize fluence
- Efficient to solve the large scale combined beam orientation and fluence map optimization problem

Karush–Kuhn–Tucker (KKT)-conditions for optimality
Romeijn, H.E., et al.. Siam Journal on Optimization, 2005. **15**(3): p. 838-862.

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New Beam orientation optimization based on global optimization approach

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$$\underbrace{\sum_{b=1}^{n} w_b \|x_b\|_2}_{\text{group sparsity}} + \underbrace{\frac{\mu}{2}\|(d_0 - A_0 x)_+\|_2^2}_{\text{PTV}} + \underbrace{\sum_{i=0}^{N} \frac{\alpha_i}{2}\|(A_i x - d_i)_+\|_2^2}_{\text{OARs}} + \underbrace{\sum_{i=1}^{N} \frac{\beta_i}{2}\|A_i x\|_2^2 + \eta\|Dx\|_1^{(\gamma)}}_{\text{additional guidance}}$$

Global optimization to avoid heuristics and improve results
O'Connor et al. 2016 AAPM TH-EF-BRB-5

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Lung SBRT

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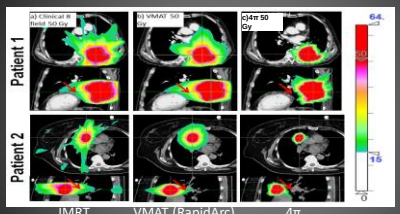

IMRT VMAT (RapidArc) 4π

Reduce R_{50} by 54%, Reduce EUD of heart, esophagus, trachea, bronchus and spinal cord were reduced by 44%, 74%, 40%, 42%, and 51%

Dong et al. IJROBP 2013 July 1; 86 (3):407–413.

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Larger non-coplanar solution space help avoid beam overlapping

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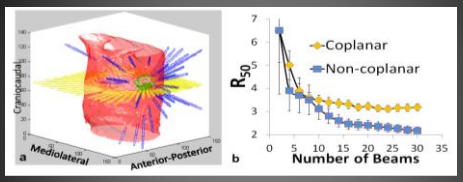

- R50 is the ratio between 50% isodose volume and the PTV volume, it is a measurement of the dose compactness.
- There is an intrinsic advantage in the dose compactness using non-coplanar beams

Dong et al. IJROBP 2013 July 1; 86 (3):407–413.

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Potential for *no* penalty tumor dose escalation

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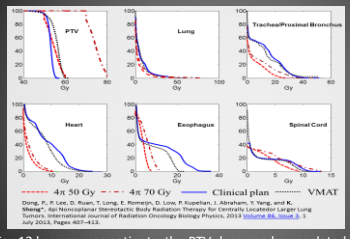

For 12 lung cancer patients, the PTV dose can be escalated by 40% without increasing normal tissue dose

Dong et al. IJROBP 2013 July 1; 86 (3):407–413.

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Potential for safe dose escalation

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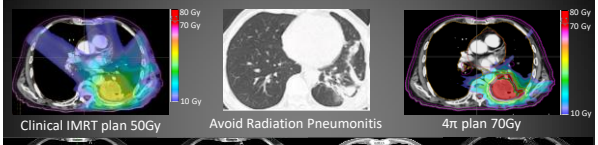
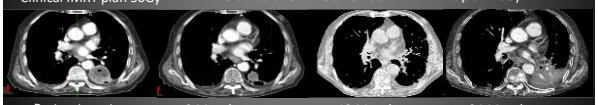


Clinical IMRT plan 50Gy | Avoid Radiation Pneumonitis | 4π plan 70Gy



Pretreatment | 3 Month post | 12 Month post | 24 Month post

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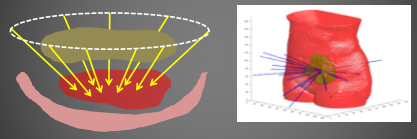
Overcoming the coplanar geometrical limitation



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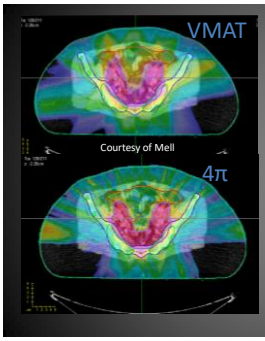
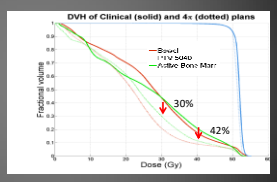
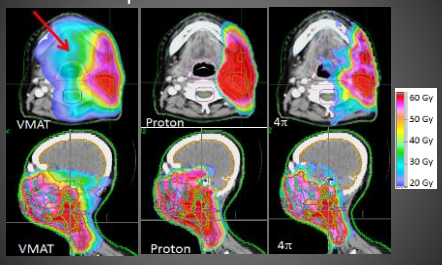
Bone Marrow Sparing





Irreversible bone marrow conversion happens at 30-40 Gy

4π vs. proton for unilateral HN



Sheng et al. Current Cancer Therapy Reviews, 2014, 10(4), 343 - 352

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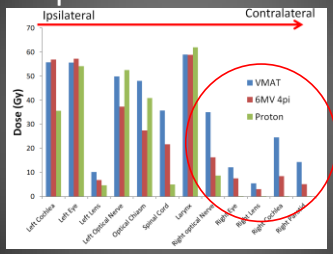
4π vs. proton for unilateral HN



Significantly reduce the distal organ dose while maintaining proximal dose conformality

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Improved dose compactness benefits wide range of disease sites

- Lung
- Liver
- Prostate
- Breast
- Brain
- Pancreas
- GYN
- Head and neck

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Spine SBRT using 4π

4π improves the dose gradient by 80%
Reduce max and mean cord dose by 22% and 42% compared to 2 ARC VMAT
Yu et al. 2016 AAPM TH-EF-BRB-3

Cortex sparing with 4π

VMAT cortex sparing compromises target homogeneity and hippocampus
Substantial cortex sparing without sacrificing PTV dose homogeneity
Woods et al. 2016 AAPM Best in Physics TH-EF-BRB-1

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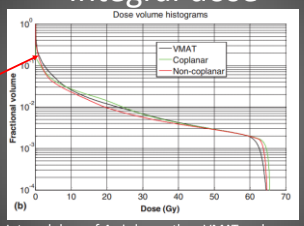
Integral dose



4π increase the volume receiving 2 Gy or lower

Integral dose of 4π is lower than VMAT and comparable to coplanar IMRT

Nguyen et al, Med. Phys. 41, 011905 (2014)

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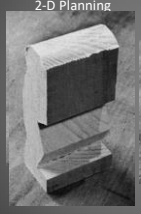
IMRT Dose sculpting

2-D Planning



3-D Conformal

IMRT

You have seen this……

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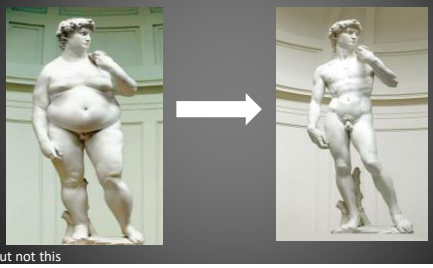
Compact dose distribution



……but not this

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Manual 4π delivery

Total treatment time 45-50 minutes

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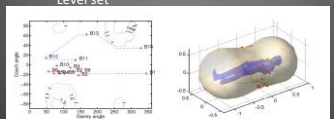
Path to safe automated delivery

Collision space modeling
- Optical camera 3D surface measurement
- Yu 2016 AAPM

Path navigation
- Level set



optimized control path patient-centric view

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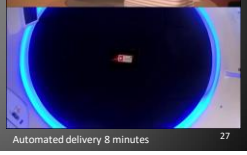
Manual vs. automated delivery

Manual: total treatment time 45 minutes

With remote couch: 28 minutes



Automated delivery 8 minutes

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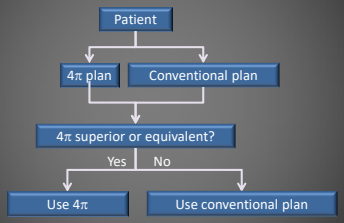
Phase I 4π clinical trial study design



Aims: Safety, tolerance, treatment time and intrafractional motion

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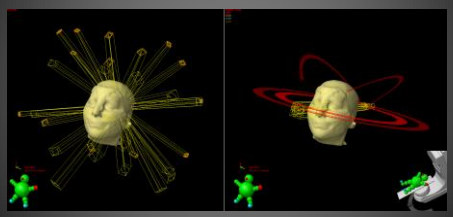
4π radiotherapy vs VMAT



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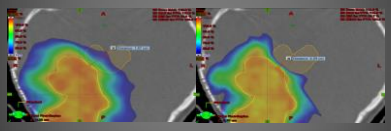
4π trial results update

- 4π plan was recalculated in Eclipse to generate a clinical plan
- Composite plan of the original and the new recurrent plans



VMAT 4π

- 4π enables uncompromised PTV dose coverage
- 8/10 patient treated using 4π
- Prospective 4π spine SBRT ongoing

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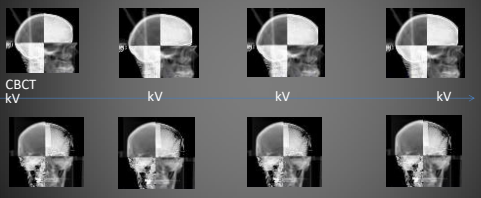
Intrafractional motion monitoring



Intrafractional head motion <1 mm for most treatment fractions
Patient position corrected for >1 mm motion
Main discomfort from the tight radiosurgical mask

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Summary

- Use 4π for conformal + compact radiotherapy
- Consistent reduction in critical organs doses allows more aggressive tumor dose escalation
- The integral dose does not increase with 4π radiotherapy
- Exploring the dosimetric benefits from additional degrees of optimization freedom including gantry and couch angles, source to tumor distances, collimator rotation and energies
- Automated delivery with robust collision avoidance needs to be developed and rigorously QA'd

Digital linacs enable exploration of the additional freedom

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A new delivery platform?

Woods et al. 2016 AAPM **TH-EF-BRB-7**

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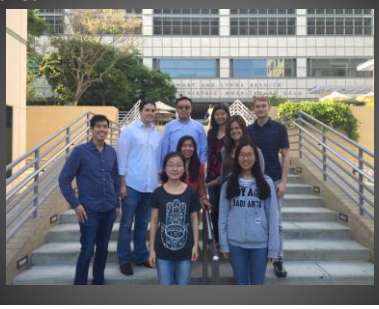
The 4π Team



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NIH R21CA144063

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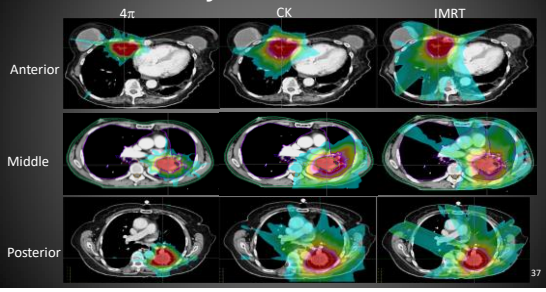
4π vs. CyberKnife vs. IMRT



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