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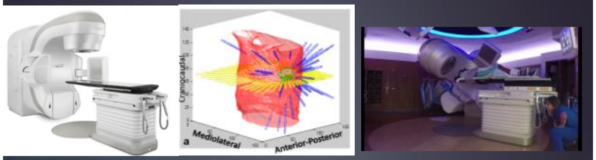
Explore New Dimensions in VMAT

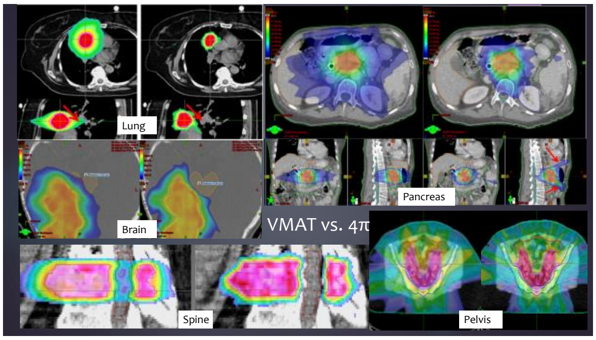
KE SHENG, PH.D., FAAPM
DIRECTOR OF PHYSICS RESEARCH
DEPARTMENT OF RADIATION ONCOLOGY
UNIVERSITY OF CALIFORNIA, LOS ANGELES

UCLA

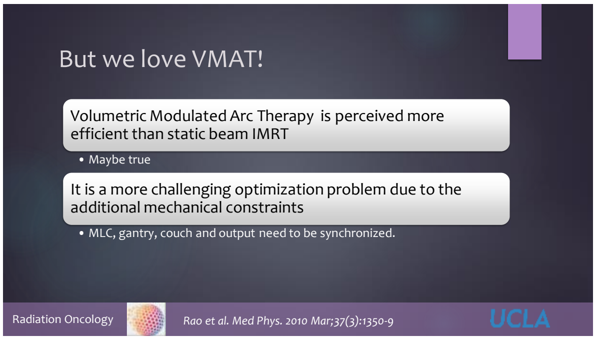
Non-coplanar 4π radiotherapy on C-arm gantry



Dong et al. IJROPB 2013, Dong et al. IJROBP 2013, Dong et al. PRO, 2014, Rwigema et al. IJROBP 2015, Yu et al. IJROBP 2018, Dong et al. Med. Phys. 2014, Nguyen et al, Med. Phys. 2014, Yu et al Med Phys. 2016, O'Connor et al. PMB 2018, Nguyen et al. Radiat. Onco. 2015, Woods et al. ARO 2016, Tran et al. Radiat. Onco. 2017, etc.



VMAT vs. 4π



But we love VMAT!

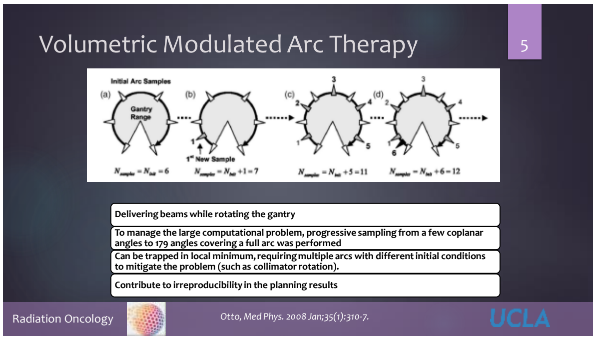
Volumetric Modulated Arc Therapy is perceived more efficient than static beam IMRT

- Maybe true

It is a more challenging optimization problem due to the additional mechanical constraints

- MLC, gantry, couch and output need to be synchronized.

Radiation Oncology *Rao et al. Med Phys. 2010 Mar;37(3):1350-9* UCLA



Volumetric Modulated Arc Therapy

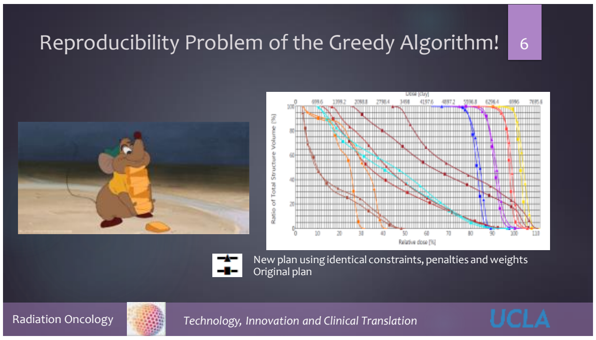
Delivering beams while rotating the gantry

To manage the large computational problem, progressive sampling from a few coplanar angles to 179 angles covering a full arc was performed

Can be trapped in local minimum, requiring multiple arcs with different initial conditions to mitigate the problem (such as collimator rotation).

Contribute to irreproducibility in the planning results

Radiation Oncology *Otto, Med Phys. 2008 Jan;35(1):310-7.* UCLA

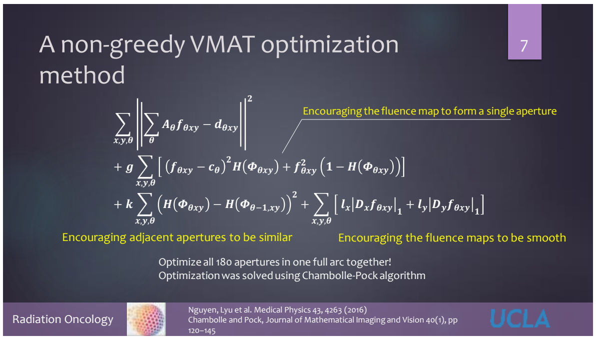


Reproducibility Problem of the Greedy Algorithm!

▲ New plan using identical constraints, penalties and weights

■ Original plan

Radiation Oncology *Technology, Innovation and Clinical Translation* UCLA



A non-greedy VMAT optimization method

$$\sum_{x,y,\theta}\left\|\sum_{\theta} A_\theta f_{\theta xy} - d_{\theta xy}\right\|^2$$
$$+\, g\sum_{x,y,\theta}\left[\left(f_{\theta xy}-c_\theta\right)^2 H(\Phi_{\theta xy}) + f_{\theta xy}^2\left(1-H(\Phi_{\theta xy})\right)\right]$$
$$+\, k\sum_{x,y,\theta}\left(H(\Phi_{\theta xy})-H(\Phi_{\theta-1,xy})\right)^2 + \sum_{x,y,\theta}\left[l_x\left|D_x f_{\theta xy}\right|_1 + l_y\left|D_y f_{\theta xy}\right|_1\right]$$

Encouraging the fluence map to form a single aperture

Encouraging adjacent apertures to be similar

Encouraging the fluence maps to be smooth

Optimize all 180 apertures in one full arc together!
Optimization was solved using Chambolle-Pock algorithm

Radiation Oncology

Nguyen, Lyu et al. Medical Physics 43, 4263 (2016)
Chambolle and Pock, Journal of Mathematical Imaging and Vision 40(1), pp 120–145

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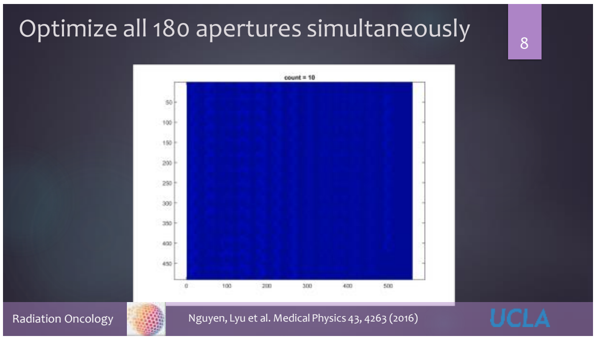

Optimize all 180 apertures simultaneously

Radiation Oncology

Nguyen, Lyu et al. Medical Physics 43, 4263 (2016)

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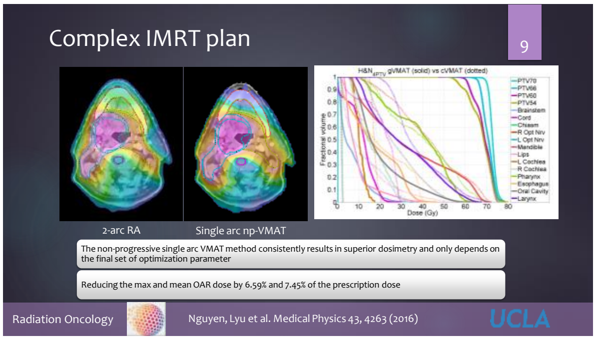

Complex IMRT plan

2-arc RA

Single arc np-VMAT

The non-progressive single arc VMAT method consistently results in superior dosimetry and only depends on the final set of optimization parameter

Reducing the max and mean OAR dose by 6.59% and 7.45% of the prescription dose

Radiation Oncology

Nguyen, Lyu et al. Medical Physics 43, 4263 (2016)

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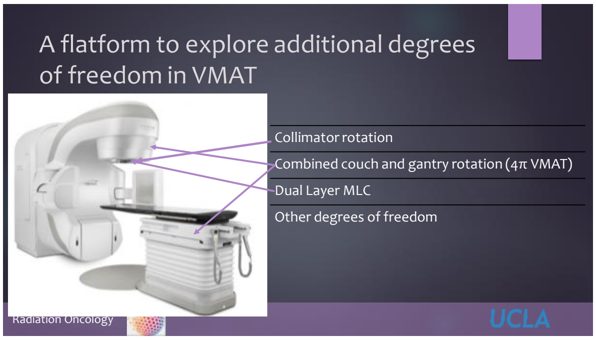
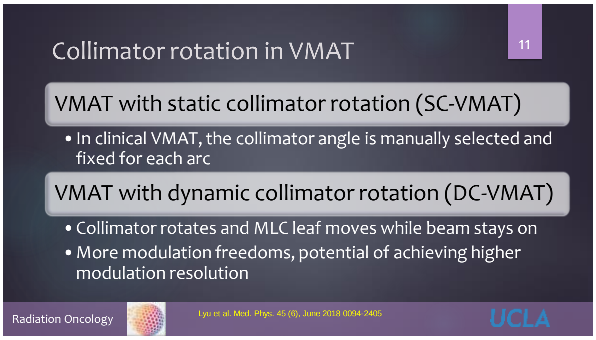


A flatform to explore additional degrees of freedom in VMAT

- Collimator rotation
- Combined couch and gantry rotation (4π VMAT)
- Dual Layer MLC
- Other degrees of freedom



Collimator rotation in VMAT

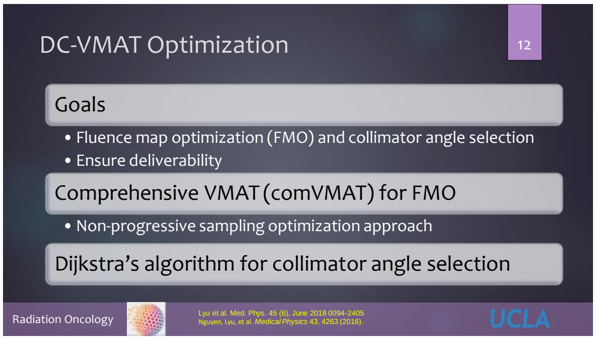
VMAT with static collimator rotation (SC-VMAT)

- In clinical VMAT, the collimator angle is manually selected and fixed for each arc

VMAT with dynamic collimator rotation (DC-VMAT)

- Collimator rotates and MLC leaf moves while beam stays on
- More modulation freedoms, potential of achieving higher modulation resolution

Lyu et al. Med. Phys. 45 (6), June 2018 0094-2405



DC-VMAT Optimization

Goals

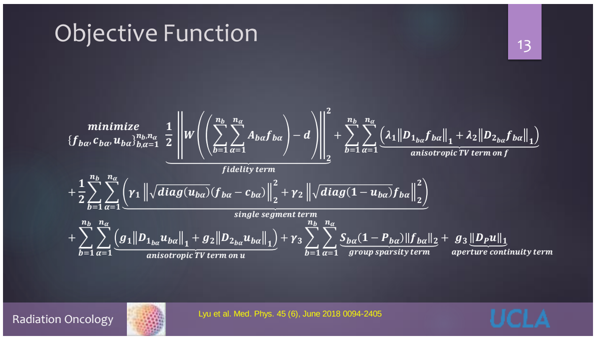
- Fluence map optimization (FMO) and collimator angle selection
- Ensure deliverability

Comprehensive VMAT (comVMAT) for FMO

- Non-progressive sampling optimization approach

Dijkstra's algorithm for collimator angle selection

Lyu et al. Med. Phys. 45 (6), June 2018 0094-2405
Nguyen, Lyu, et al. *Medical Physics* 43, 4263 (2016).



Objective Function

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$$\underset{\{f_{b\alpha},c_{b\alpha},u_{b\alpha}\}_{b,\alpha=1}^{n_b,n_\alpha}}{\text{minimize}} \underbrace{\frac{1}{2}\left\|W\left(\left(\sum_{b=1}^{n_b}\sum_{\alpha=1}^{n_\alpha}A_{b\alpha}f_{b\alpha}\right)-d\right)\right\|_2^2}_{fidelity\ term}+\sum_{b=1}^{n_b}\sum_{\alpha=1}^{n_\alpha}\underbrace{\left(\lambda_1\left\|D_{1_{b\alpha}}f_{b\alpha}\right\|_1+\lambda_2\left\|D_{2_{b\alpha}}f_{b\alpha}\right\|_1\right)}_{anisotropic\ TV\ term\ on\ f}$$

$$+\frac{1}{2}\sum_{b=1}^{n_b}\sum_{\alpha=1}^{n_\alpha}\underbrace{\left(\gamma_1\left\|\sqrt{diag(u_{b\alpha})}(f_{b\alpha}-c_{b\alpha})\right\|_2^2+\gamma_2\left\|\sqrt{diag(1-u_{b\alpha})}f_{b\alpha}\right\|_2^2\right)}_{single\ segment\ term}$$

$$+\sum_{b=1}^{n_b}\sum_{\alpha=1}^{n_\alpha}\underbrace{\left(g_1\left\|D_{1_{b\alpha}}u_{b\alpha}\right\|_1+g_2\left\|D_{2_{b\alpha}}u_{b\alpha}\right\|_1\right)}_{anisotropic\ TV\ term\ on\ u}+\gamma_3\sum_{b=1}^{n_b}\sum_{\alpha=1}^{n_\alpha}\underbrace{S_{b\alpha}(1-P_{b\alpha})\|f_{b\alpha}\|_2}_{group\ sparsity\ term}+\underbrace{g_3\|D_Pu\|_1}_{aperture\ continuity\ term}$$

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Lyu et al. Med. Phys. 45 (6), June 2018 0094-2405

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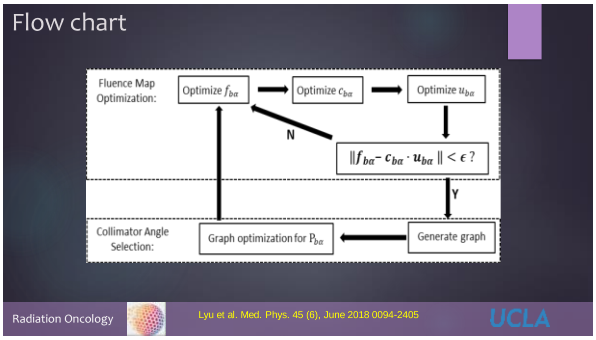

Flow chart

Fluence Map Optimization:

Optimize f_{ba} → Optimize c_{ba} → Optimize u_{ba}

$\|f_{ba} - c_{ba} \cdot u_{ba}\| < \epsilon$?

N

Y

Collimator Angle Selection:

Generate graph → Graph optimization for P_{ba}

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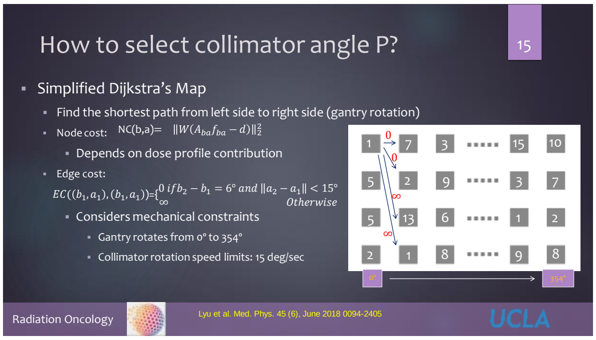

How to select collimator angle P?

15

- Simplified Dijkstra's Map
  - Find the shortest path from left side to right side (gantry rotation)
  - Node cost: NC(b,a)= $\|W(A_{ba}f_{ba}-d)\|_2^2$
    - Depends on dose profile contribution
  - Edge cost:

$EC((b_1,a_1),(b_1,a_1))=\{\begin{matrix}0\ if\, b_2-b_1=6°\ and\ \|a_2-a_1\|<15° \\ \infty\qquad\qquad\qquad\qquad Otherwise\end{matrix}$

    - Considers mechanical constraints
      - Gantry rotates from 0° to 354°
      - Collimator rotation speed limits: 15 deg/sec

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Lyu et al. Med. Phys. 45 (6), June 2018 0094-2405

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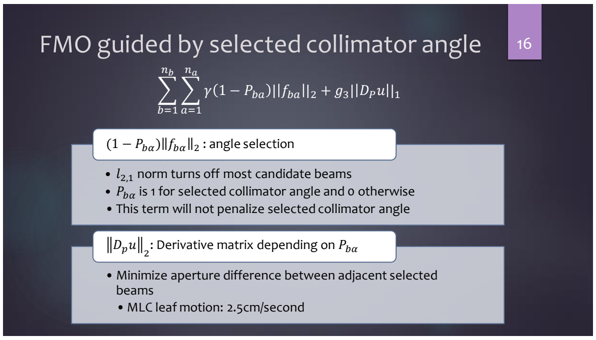


FMO guided by selected collimator angle

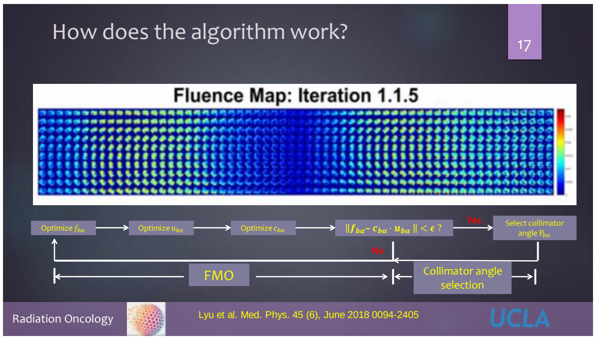
$$\sum_{b=1}^{n_b}\sum_{a=1}^{n_a}\gamma(1-P_{ba})||f_{ba}||_2+g_3||D_P u||_1$$

$(1-P_{b\alpha})||f_{b\alpha}||_2$: angle selection

- $l_{2,1}$ norm turns off most candidate beams
- $P_{b\alpha}$ is 1 for selected collimator angle and 0 otherwise
- This term will not penalize selected collimator angle

$\|D_p u\|_2$: Derivative matrix depending on $P_{b\alpha}$

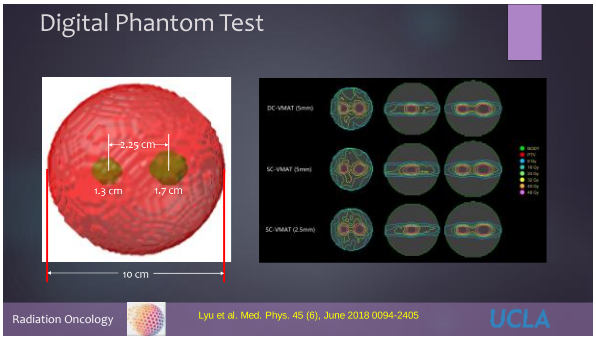
- Minimize aperture difference between adjacent selected beams
  - MLC leaf motion: 2.5cm/second



How does the algorithm work?

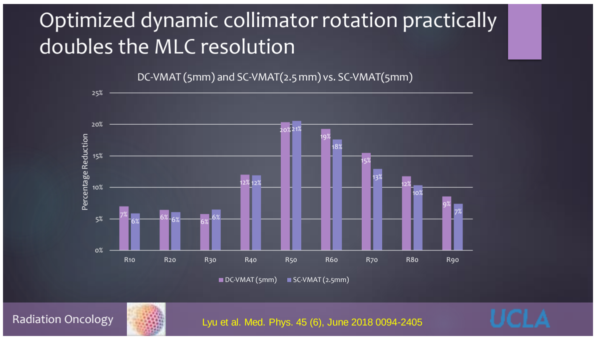
Fluence Map: Iteration 1.1.5

Lyu et al. Med. Phys. 45 (6), June 2018 0094-2405



Digital Phantom Test

Lyu et al. Med. Phys. 45 (6), June 2018 0094-2405



Optimized dynamic collimator rotation practically doubles the MLC resolution

Radiation Oncology

Lyu et al. Med. Phys. 45 (6), June 2018 0094-2405

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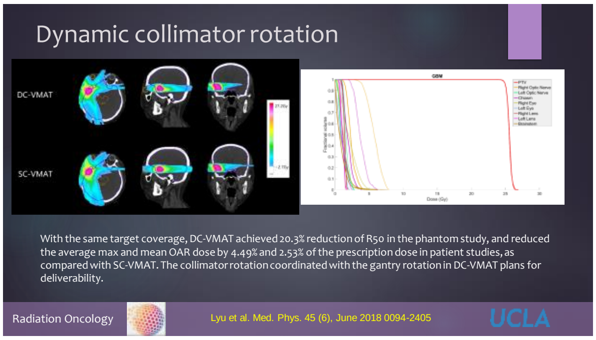

Dynamic collimator rotation

With the same target coverage, DC-VMAT achieved 20.3% reduction of R50 in the phantom study, and reduced the average max and mean OAR dose by 4.49% and 2.53% of the prescription dose in patient studies, as compared with SC-VMAT. The collimator rotation coordinated with the gantry rotation in DC-VMAT plans for deliverability.

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Lyu et al. Med. Phys. 45 (6), June 2018 0094-2405

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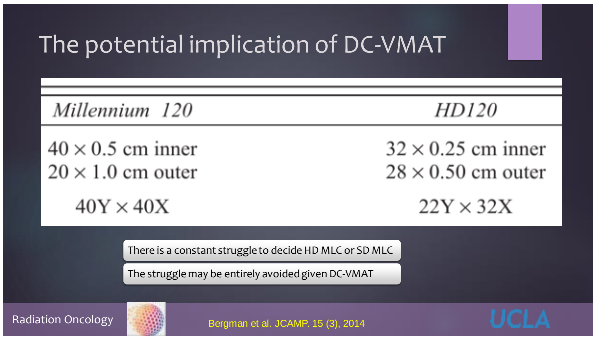


The potential implication of DC-VMAT

Millennium 120	*HD120*
40 × 0.5 cm inner 20 × 1.0 cm outer	32 × 0.25 cm inner 28 × 0.50 cm outer
40Y × 40X	22Y × 32X

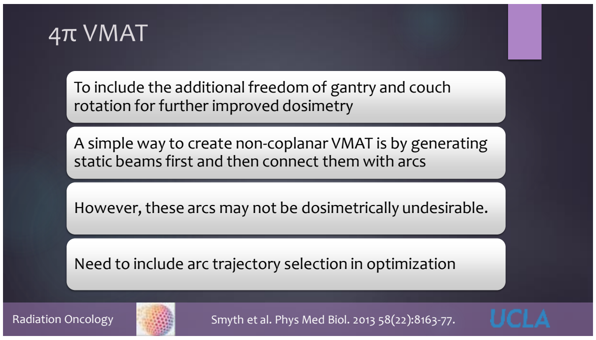
There is a constant struggle to decide HD MLC or SD MLC

The struggle may be entirely avoided given DC-VMAT

Radiation Oncology

Bergman et al. JCAMP. 15 (3), 2014

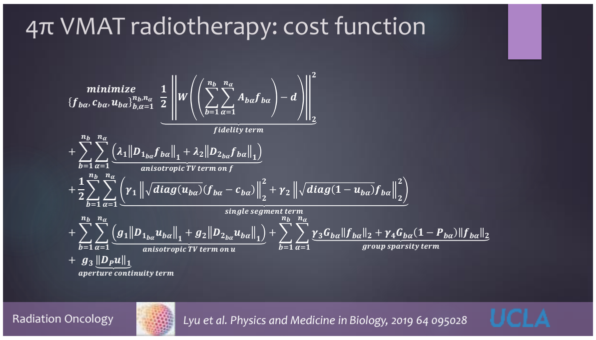
UCLA



4π VMAT

- To include the additional freedom of gantry and couch rotation for further improved dosimetry
- A simple way to create non-coplanar VMAT is by generating static beams first and then connect them with arcs
- However, these arcs may not be dosimetrically undesirable.
- Need to include arc trajectory selection in optimization

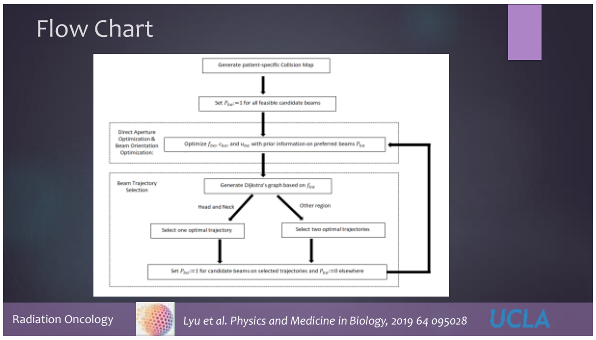
Radiation Oncology Smyth et al. Phys Med Biol. 2013 58(22):8163-77. UCLA



4π VMAT radiotherapy: cost function

$$\underset{\{f_{b\alpha}, c_{b\alpha}, u_{b\alpha}\}_{b,\alpha=1}^{n_b,n_\alpha}}{\mathit{minimize}} \underbrace{\frac{1}{2}\left\| W\left(\left(\sum_{b=1}^{n_b}\sum_{\alpha=1}^{n_\alpha} A_{b\alpha} f_{b\alpha}\right) - d\right)\right\|_2^2}_{\mathit{fidelity\ term}}$$
$$+ \sum_{b=1}^{n_b}\sum_{\alpha=1}^{n_\alpha} \underbrace{\left(\lambda_1 \|D_{1_{b\alpha}} f_{b\alpha}\|_1 + \lambda_2 \|D_{2_{b\alpha}} f_{b\alpha}\|_1\right)}_{\mathit{anisotropic\ TV\ term\ on\ f}}$$
$$+ \frac{1}{2}\sum_{b=1}^{n_b}\sum_{\alpha=1}^{n_\alpha} \underbrace{\left(\gamma_1 \left\|\sqrt{diag(u_{b\alpha})}(f_{b\alpha} - c_{b\alpha})\right\|_2^2 + \gamma_2 \left\|\sqrt{diag(1 - u_{b\alpha})} f_{b\alpha}\right\|_2^2\right)}_{\mathit{single\ segment\ term}}$$
$$+ \sum_{b=1}^{n_b}\sum_{\alpha=1}^{n_\alpha} \underbrace{\left(g_1 \|D_{1_{b\alpha}} u_{b\alpha}\|_1 + g_2 \|D_{2_{b\alpha}} u_{b\alpha}\|_1\right)}_{\mathit{anisotropic\ TV\ term\ on\ u}} + \sum_{b=1}^{n_b}\sum_{\alpha=1}^{n_\alpha} \underbrace{\gamma_3 G_{b\alpha} \|f_{b\alpha}\|_2 + \gamma_4 G_{b\alpha}(1 - P_{b\alpha}) \|f_{b\alpha}\|_2}_{\mathit{group\ sparsity\ term}}$$
$$+ \ g_3 \underbrace{\|D_P u\|_1}_{\mathit{aperture\ continuity\ term}}$$

Radiation Oncology *Lyu et al. Physics and Medicine in Biology, 2019 64 095028* UCLA



Flow Chart

Generate patient-specific Collision Map

Set $P_{b\alpha}$:=1 for all feasible candidate beams

Direct Aperture Optimization & Beam Orientation Optimization:

Optimize $f_{b\alpha}$, $c_{b\alpha}$, and $u_{b\alpha}$ with prior information on preferred beams $P_{b\alpha}$

Beam Trajectory Selection

Generate Dijkstra's graph based on $f_{b\alpha}$

Head and Neck

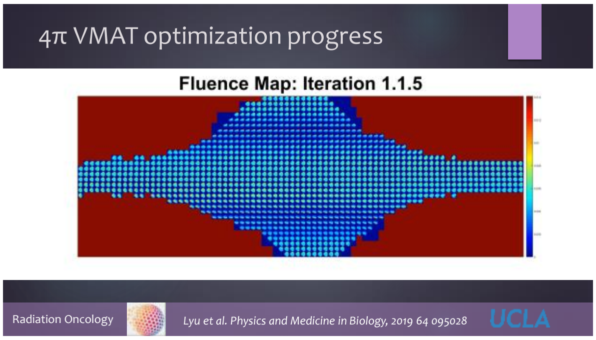
Other region

Select one optimal trajectory

Select two optimal trajectories

Set $P_{b\alpha}$:=1 for candidate beams on selected trajectories and $P_{b\alpha}$:=0 elsewhere

Radiation Oncology *Lyu et al. Physics and Medicine in Biology, 2019 64 095028* UCLA



4π VMAT optimization progress

Fluence Map: Iteration 1.1.5

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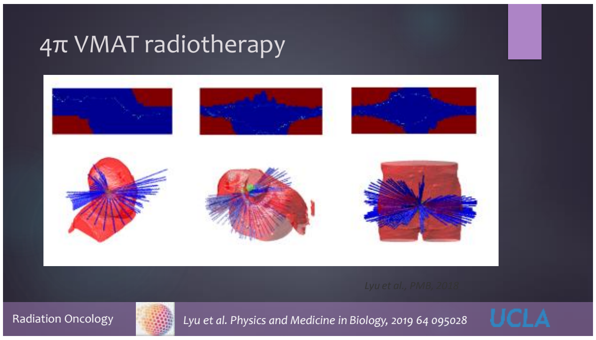
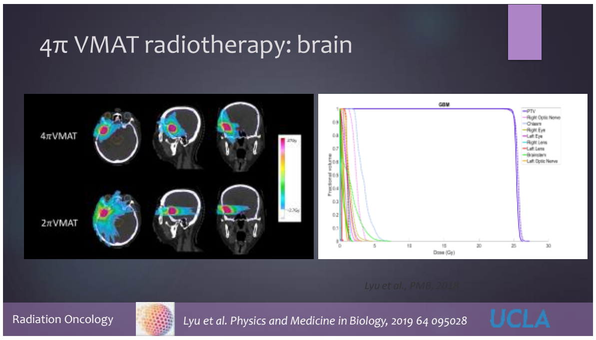


4π VMAT radiotherapy

Lyu et al., PMB, 2018

Radiation Oncology

Lyu et al. Physics and Medicine in Biology, 2019 64 095028



4π VMAT radiotherapy: brain

Lyu et al., PMB, 2018

Radiation Oncology

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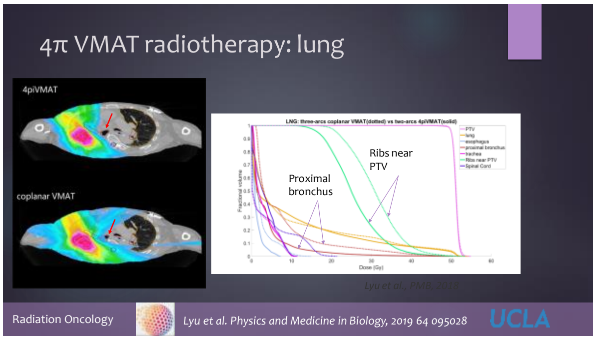


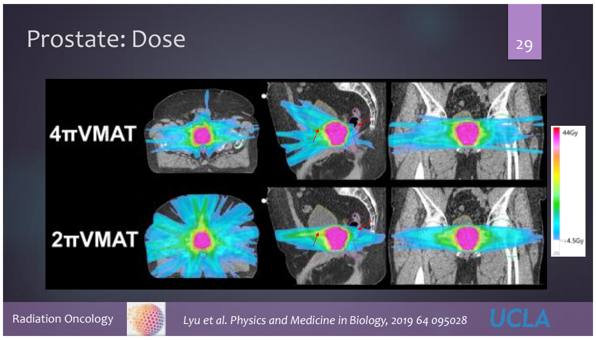
4π VMAT radiotherapy: lung

Ribs near PTV

Proximal bronchus

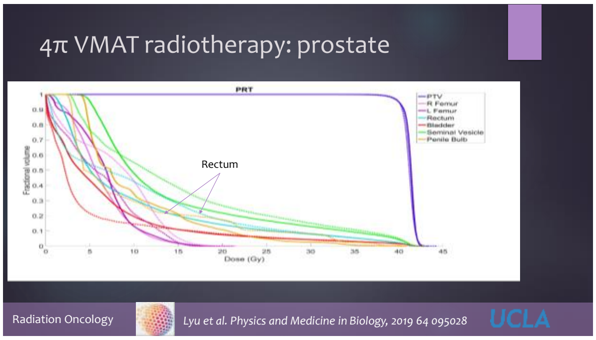
Lyu et al., PMB, 2018

Lyu et al. Physics and Medicine in Biology, 2019 64 095028



Prostate: Dose

Lyu et al. Physics and Medicine in Biology, 2019 64 095028



4π VMAT radiotherapy: prostate

Rectum

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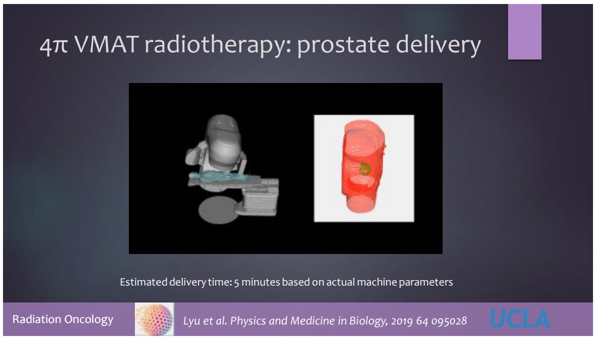

4π VMAT radiotherapy: prostate delivery

Estimated delivery time: 5 minutes based on actual machine parameters

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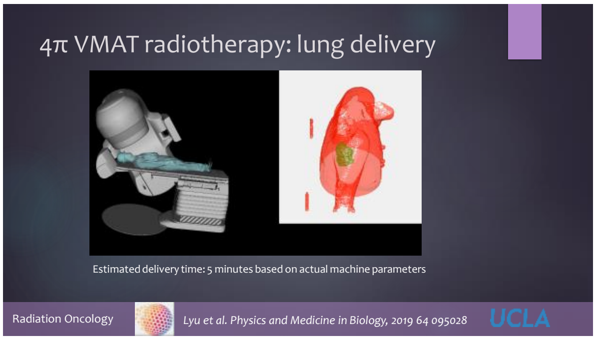

4π VMAT radiotherapy: lung delivery

Estimated delivery time: 5 minutes based on actual machine parameters

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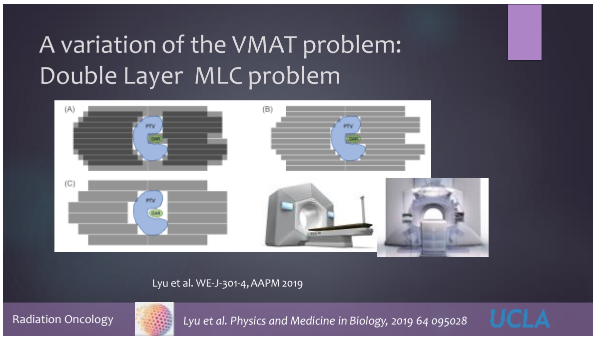

A variation of the VMAT problem: Double Layer MLC problem

Lyu et al. WE-J-301-4, AAPM 2019

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Lyu et al. Physics and Medicine in Biology, 2019 64 095028

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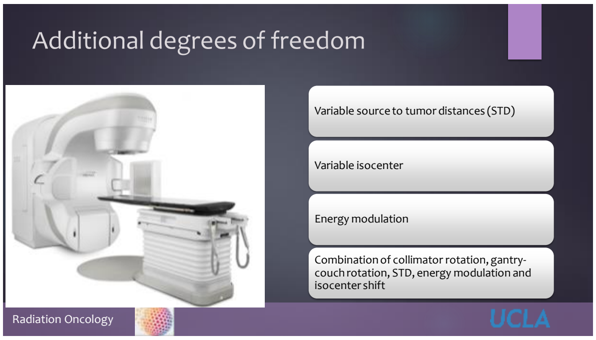
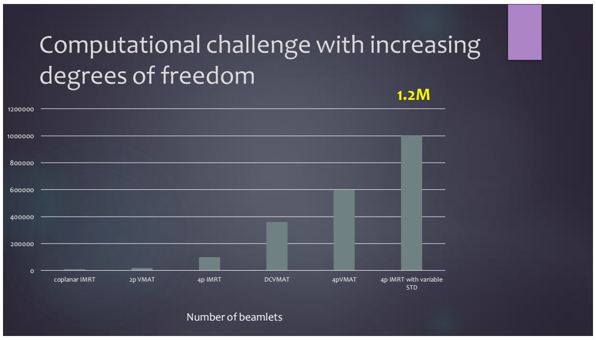


Additional degrees of freedom

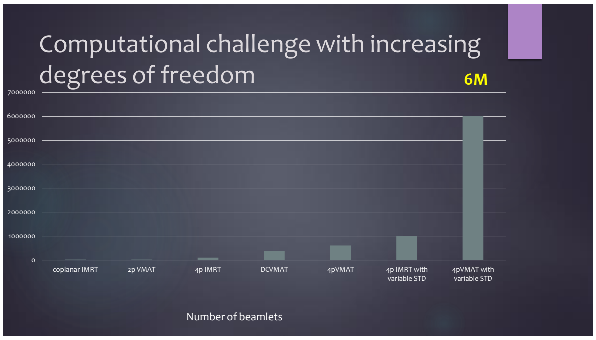
- Variable source to tumor distances (STD)
- Variable isocenter
- Energy modulation
- Combination of collimator rotation, gantry-couch rotation, STD, energy modulation and isocenter shift

Radiation Oncology

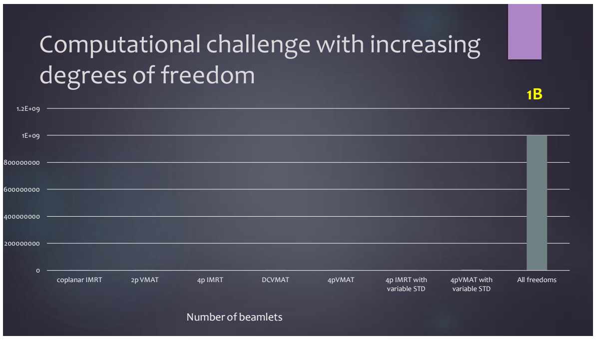
Computational challenge with increasing degrees of freedom



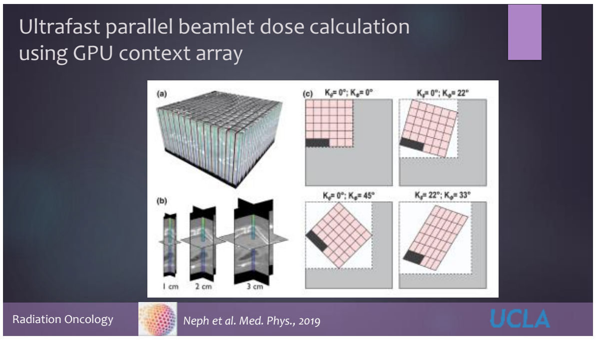
Computational challenge with increasing degrees of freedom



Computational challenge with increasing degrees of freedom



Computational challenge with increasing degrees of freedom

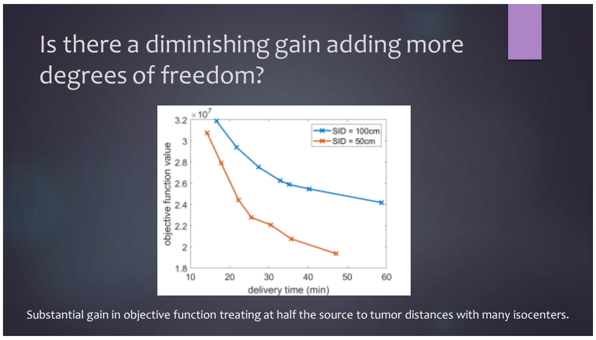


Ultrafast parallel beamlet dose calculation using GPU context array

Radiation Oncology

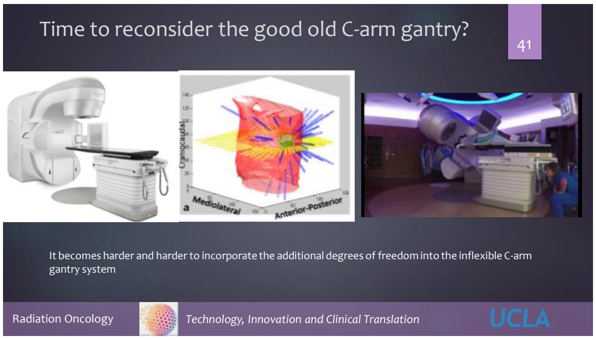
Neph et al. Med. Phys., 2019

UCLA



Is there a diminishing gain adding more degrees of freedom?

Substantial gain in objective function treating at half the source to tumor distances with many isocenters.



Time to reconsider the good old C-arm gantry?

It becomes harder and harder to incorporate the additional degrees of freedom into the inflexible C-arm gantry system

Time to move to a new platform for all degrees of freedom

http://shenglab.dgsom.ucla.edu/

2017

2018