Explore New Dimensions in VMAT
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Non-coplanar 4π radiotherapy on C-arm gantry

But we love VMAT!

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

- Maybe true

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- Maybe true

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

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

Volumetric Modulated Arc Therapy

Delivering beams while rotating the gantry

To manage the large computational problem, progressive sampling with a few angular steps to 179 angles covering a full arc was performed

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

Contribute to irreproducibility in the planning results.

Reproducibility Problem of the Greedy Algorithm!

Original plan

New plan using identical constraints, penalties and weights
A non-greedy VMAT optimization method

\[
\sum_{\Phi} \left( \sum_{\Phi_{\text{ap}} = \Phi} d_{\text{ap}} \right)^2
\]

Encouraging fluence map to form a single aperture

\[
+ \alpha \left( \sum_{\Phi} \left( f_{\Phi_{\text{ap}}} - c_{\Phi_{\text{ap}}} \right)^2 \right)
\]

Encouraging all apertures to be similar

\[
+ \beta \left( \sum_{\Phi} \left( H(\Phi_{\text{ap}}) - H(\Phi_{\text{ap} + 1}) \right)^2 \right)
\]

Encouraging the fluence maps to be smooth

Optimization was solved using Chambolle-Pock Algorithm

Optimize all 180 apertures in one full arc together.

Optimize all 180 apertures simultaneously

Complex IMRT plan

Two arc IMRT

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 parameters.

Reducing the area and mean OAR dose by a 12% and 4% of the prescription dose.
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A platform to explore additional degrees of freedom in VMAT

Collimator rotation
Combined couch and gantry rotation (ext-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

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
Objective Function

\[
\minimize \quad \frac{1}{2} \left( \sum_{i=1}^{n} (s_i - f_i)^2 \right) + \sum_{i=1}^{n} \left( \frac{1}{2} \left( \sum_{j=1}^{m} (s_{ij} - f_{ij})^2 \right) + \frac{1}{2} \sum_{j=1}^{m} (s_{ij} - f_{ij})^2 \right)
\]

\[
= \sum_{i=1}^{n} \left( \frac{1}{2} \left( \sum_{j=1}^{m} (s_{ij} - f_{ij})^2 \right) + \frac{1}{2} \sum_{j=1}^{m} (s_{ij} - f_{ij})^2 \right)
\]

\[
= \sum_{i=1}^{n} \sum_{j=1}^{m} (s_{ij} - f_{ij})^2 + \frac{1}{2} \sum_{i=1}^{n} \sum_{j=1}^{m} (s_{ij} - f_{ij})^2
\]

Flow chart

How to select collimator angle P?

- Simplified Dijkstra’s Map
  - Find the shortest path from left side to right side (gantry rotation)
  - Edge cost: \( NC(b,a) = W[A_b - A_a] + f_b^2 \)
  - Node cost: \( E_D(b,a) = \frac{1}{2} |A_b - A_a|^2 \)
  - Consider mechanical constraints
  - Gantry rotation: \( 0^\circ \) to \( 354^\circ \)
  - Collimator rotation speed limit: \( 15^\circ / \text{sec} \)

\[
NC(b,a) = W[A_b - A_a] + f_b^2
\]

\[
E_D(b,a) = \frac{1}{2} |A_b - A_a|^2
\]
FMO guided by selected collimator angle

\[ FMO \text{ guided by selected collimator angle} \]

\[ \sum_{\alpha=1}^{A} \sum_{\beta=1}^{B} \gamma (1 - P_{\alpha \beta}) ||f_{\alpha \beta}||_2 + \beta ||D_{\beta \alpha}||_2 \]

- \( (1 - P_{\alpha \beta}) ||f_{\alpha \beta}||_2 \): angle selection
  - \( P_{\alpha \beta} \) is 1 for selected collimator angle and 0 otherwise
  - This term will not penalize selected collimator angle

- \( ||D_{\beta \alpha}||_2 \): Derivative matrix depending on \( P_{\alpha \beta} \)
  - Minimize aperture difference between adjacent selected beams
  - MLC leaf motion: 2.5 cm/second

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How does the algorithm work?

**Fluence Map: Iteration 1.1.5**

- Optimization
- Selection
- MLC
- Collimator angle

**FMO**

**Digital Phantom Test**

Radiation Oncology

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

UCLA
Optimized dynamic collimator rotation practically doubles the MLC resolution

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.

The potential implication of DC-VMAT

There is a constant struggle to decide HD MLC or SD MLC. The struggle may be entirely avoided given DC-VMAT.
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

![Flow Chart](image_url)

**Flow Chart**

- Start with planning setup
- Generate static beams
- Connect beams with arcs
- Include arc trajectory selection
- Optimize dosimetry
- Account for group sparsity and aperture continuity
4π VMAT radiotherapy: prostate delivery

Estimated delivery time: 5 minutes based on actual machine parameters

4π VMAT radiotherapy: lung delivery

Estimated delivery time: 5 minutes based on actual machine parameters

A variation of the VMAT problem:
Double Layer MLC problem

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

Computational challenge with increasing degrees of freedom

- Number of beamlets
- coplanar IMRT
- 2p VMAT
- 4p IMRT
- DCVMAT
- 4pVMAT
- 4p IMRT with variable STD
- Number of beamlets
- 600k
- 1.2M
Computational challenge with increasing degrees of freedom

- coplanar IMRT
- 2p VMAT
- 4p IMRT
- DCVMAT
- 4p VMAT with variable STD
- 4p IMRT with variable STD
- All freedoms

Number of beamlets

Ultrafast parallel beamlet dose calculation using GPU context array

Radiation Oncology
Nagh et al. Med. Phys., 2019
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