On the implementation of the plan-class specific reference field concept using multidimensional clustering of plan features

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IDOS 2019 – Small Field Dosimetry
Tuesday, June 18th, 2019
Background

- **Project motivation:**
  - External beam radiotherapy
    - Numerous multi-leaf collimator (MLC) defined fields
  - Modulate dose to maximize target dose
    - Minimize dose to healthy tissue by conforming radiation to patient anatomy
  - Modulated treatments with small and irregular fields
    - Difficult dosimetry measurements

1. (Image source) Varian Medical Systems, Palo Alto, CA, USA, [www.variantruebeam.com](http://www.variantruebeam.com)
2. (Image source) Varian Medical Systems, Palo Alto, CA, USA, [www.newsroom.varian.com](http://www.newsroom.varian.com)
4. (Video source) The National Cancer Institute, Bethesda, MD, USA, [www.cancer.gov](http://www.cancer.gov)
Project motivation:

- External beam radiotherapy
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References:
2008 IAEA formalism\(^1\) introduced two intermediate fields

- Machine-specific reference (msr) fields
  - Machines unable to achieve conventional reference field conditions

- Plan-class specific reference (pcsr) fields
  - Reliable dosimetry from reference field conditions
  - Representative set of modulations from a group of clinical plans

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Plan-class specific reference fields

- “...a class of combinations of fields in a configuration that is as close as possible to the final clinical delivery scheme, but delivers a homogeneous absorbed dose...”\(^3\)

- Reference conditions → Intermediate calibration → Group of clinical plans
  - No quantitative guidelines or representative data provided\(^4\)

“Representative” VMAT prostate field

Similarly modulated VMAT prostate plans

1. (Image source) W. Cao, G.J. Lim, Y. Li, X.R. Zhu et al., Cancers 7(2) (2015)
2. (Image source) V. Pyshniak, I. Fotina, A. Zverava et al., JACMP 15(4) (2014)
Specific goal

To determine whether distinct plan clusters can be distinguished using a multidimensional feature analysis to help guide the creation of representative plans.
Clinical database of past IMRT treatments
- Metrics calculated for every beam from every plan

Seek plan clusters based on complexity metrics
- Approach 1: Manually sort plans by site of treatment and evaluate differences between groups
- Approach 2: Search for plan clusters using an objective algorithm
Complexity metrics list

- Aperture Area (AA)
- Number of Active MLC Pairs (NAP)
- Aperture perimeter (AP)
- Edge Metric\(^1\) (EM)
- Average Leaf Pair Opening\(^2\) (ALPO)
- Complete Irradiation Area Outline (CIAO)
- Aperture Area Variability\(^3\) (AAV)
- Leaf Segment Variability\(^3\) (LSV)
- Aperture Irregularity\(^4\) (AI)
- Unique Opening Index (UOI)
- Cross-Axis Score (CAS)
- Small Aperture Score (SAS)
- Mean Aperture Displacement (MAD)
- Perimeter Area Ratio (PAR)
- Modulation Complexity Score\(^3\) (MCS)
- Leaf Travel Index\(^5\) (LTI)
- Leaf Travel Index Modulation Complexity Score\(^5\) (LTMCS)
- Closed Leaf Score (CLS)

1. K. Younge et al., Med Phys 39(11), 2012
UW Hospital network database cases

- Varian TrueBeam™ STx
  - 627 VMAT plans
  - 2180 beams
  - 193161 control points

- Varian Clinac® iX
  - 131 modulated plans
    (92 step-and-shoot and 39 VMAT plans)
  - 834 beams
  - 27140 control points

Approach 1: Site-based groupings of treatments

- **TrueBeam plans site-based groups**
  - abdomen (27)
  - brain (154)
  - breast (12)
  - chest wall (3)
  - esophagus/mediastinum (34)
  - extremities (3)
  - head and neck (22)
  - liver (14)
  - lung (227)
  - pelvis (22)
  - prostate (85)
  - spine (24)

- **Clinac plans site-based groups**
  - abdomen (5)
  - brain (4)
  - breast (6)
  - chest wall (7)
  - head and neck (19)
  - lung (20)
  - pelvis (12)
  - prostate (57)
  - spine (1)
Box plot of the Clinac beam-averaged AAV across multiple sites of treatment with individual data points for both VMAT and step-and-shoot beams overlaid.
Approach 1 methods and conclusions

- Groupings made based on site of treatment

- Nonparametric statistical tests used to perform multiple comparisons across all metrics
  - Groups did not show high levels of distinction from one another
  - Primarily due to high variability of metric distributions within groups

- Results too inconclusive to form definitive plan clusters
  - Motivated alternate approach
Clustering using $k$-means algorithm

- $k$-means clustering group plans based on shared characteristics
  - Use principal components of 21 features

- Iterative refinement classifies data
  - Alternates between assignment and update steps
  - Stops when assignments no longer change

1. (Animation Source) [http://shabal.in/visuals/kmeans/1.html](http://shabal.in/visuals/kmeans/1.html), accessed on 9/20/18
Clustering and optimization

- **k-means clustering**
  - Requires number of clusters to seek beforehand
  - Optimal number of clusters unknown

- **Caliński-Harabasz criterion**
  - Determine “optimal” number of clusters
  - \[ CH(k) = \left[ \frac{B(k)}{W(k)} \times \frac{n-k}{k-1} \right] \]
  - Maximize between cluster variance and minimize within cluster variance
Results: Caliński-Harabasz values

Clinac beam-averaged data

Clinac plan-averaged data

TrueBeam beam-averaged data

TrueBeam plan-averaged data
Results: Clinac clustering

Clinac beam-averaged data clustering results

Clinac plan-averaged data clustering results
Results: TrueBeam clustering

TrueBeam beam-averaged data clustering results

TrueBeam plan-averaged data clustering results
Clinac beam-averaged data clustering results

Clinac plan-averaged data sorted by delivery modality
Results: Principal component biplots

Clinac beam-averaged data

- Features most directly affecting first principal component:
  - Aperture irregularity (AI)
  - Unique opening index (UOI)
  - Small Aperture Score 10mm (SAS_{10mm})

Clinac plan-averaged data

- Features most directly affecting first principal component:
  - Aperture irregularity (AI)
  - Number of active MLC pairs (NAP)
  - Unique opening index (UOI)

1. Du et al., Med Phys 41(2), 2014
Conclusions

- Quantitative complexity metrics provide some basis for establishing plan clusters

- Feature distinction at specificity of site being treated was not observed
  - Inherent variability among modulated plans, even for a well-defined site like prostate

- Objective clustering algorithms were able to distinguish VMAT and step-and-shoot plans
  - Focus calibration efforts at level of plan modality
Acknowledgements

- Dr. Wesley Culberson
- Dr. Larry DeWerd
- UWMRRC students and staff
  - Special thanks to:
    - Dan Anderson
    - Keith Kunugi
    - John Micka
- UW Carbone Cancer Center
  - Dr. Zacariah Labby
- UW Accredited Dosimetry Calibration Lab customers
  - Continued support helps fund student research

Thank you for your attention!

Questions are welcome