UNIVERSITY of MARYLAND MEDICAL SYSTEM
MARYLAND PROTON TREATMENT CENTER

Using Multiple CT Images to Aid Robust IMPT Optimization

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Disclosure

- None

Learning Objectives

- Understand the unique sensitivity of proton doses to anatomic changes;
- Review recent progress on multiple CT (mCT) robust optimization(RO) for intensity modulated proton therapy (IMPT):
  - Methods for mCT IMPT optimization;
  - mCT RO for thoracic, sinonasal, and pelvic IMPT;
  - Benefits and challenges of mCT IMPT optimization

Introduction

- More interests in proton therapy (PT);

https://www.ptcog.ch/

Proton Facilities	Total	USA
In operation	67	27
Under construction	42	10
In planning stage	20	4

* as of July 19, 2018

Introduction

- More interests in proton therapy (PT);
- Uncertainties in PT:

RBE	Patient Setup	Proton Range	Motion	Anatomy variation
Multi-beam RBE-opt.	Margin	Margin	ITV + margin Re-painting Etc.	Adaptive RT Beam angle

Introduction

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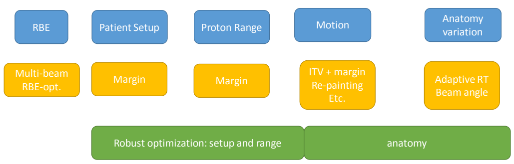
- Uncertainties in PT:

RBE	Patient Setup	Proton Range	Motion	Anatomy variation
Multi-beam RBE-opt.	Margin	Margin	ITV + margin Re-painting Etc.	Adaptive RT Beam angle

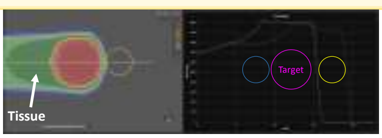
Robust optimization: setup and range

Introduction

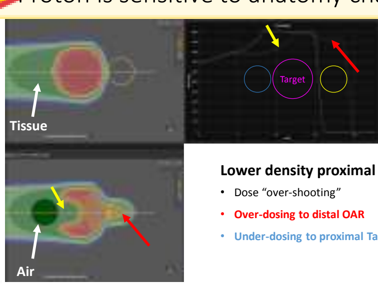
- More interests in proton therapy (PT);
- Uncertainties in PT:



Proton is sensitive to anatomy changes



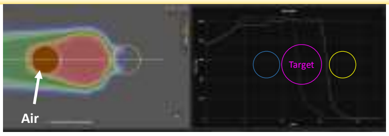
Proton is sensitive to anatomy changes



Lower density proximal to target:

- Dose "over-shooting"
- Over-dosing to distal OAR
- Under-dosing to proximal Target

Proton dose is sensitive to anatomy changes



Proton dose is sensitive to anatomy changes

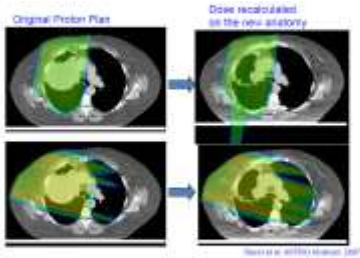
Higher density proximal to target:

- Dose "pulling-back"
- **Under-dosing to distal Target**
- Over-dosing to proximal OAR

Patient Anatomy changes

- Thoracic
  - Tumor shrinkage
  - Patient weight change
  - Pulmonary fluid
- Sinonasal
  - Cavity filling
- Pelvic
  - Bowel filling

Lung IMPT: anatomy changes dramatically



Lung IMPT: anatomy changes dramatically

Table 1

Patient number	Age (y)	PCT CTV (cm³)	ACT CTV (cm³)	Interval (days)	Tumor location
1	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
2	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
3	[illegible]	[illegible]	[illegible]	[illegible]	Left
4	[illegible]	[illegible]	[illegible]	[illegible]	Right
5	[illegible]	[illegible]	[illegible]	[illegible]	Right
6	[illegible]	[illegible]	[illegible]	[illegible]	Left
7	[illegible]	[illegible]	[illegible]	[illegible]	Left
8	[illegible]	[illegible]	[illegible]	[illegible]	Middle

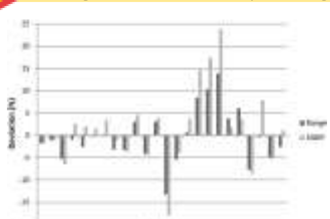
Wang, *et al.*, Radiother Oncol. (2017)

30% re-planning

Between PCT and ACT:

- Negligible variation of CTV volume

Lung IMPT: anatomy change dramatically



Wang, *et al.*, Radiother Oncol. (2017)

30% re-planning

Between PCT and ACT:

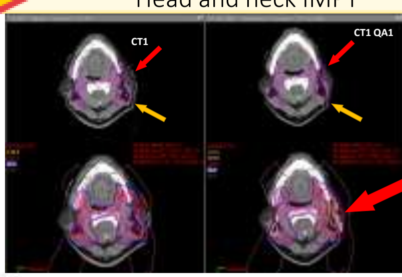
- Negligible variation of CTV volume
- **Large difference of Range and SOBP**

Dosimetric consequence

Re-plan is required

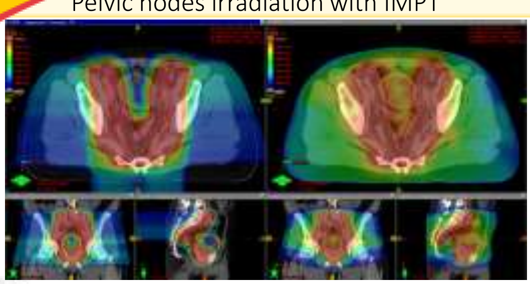
Wang, *et al*., Radiother Oncol. (2017)

Head and neck IMPT

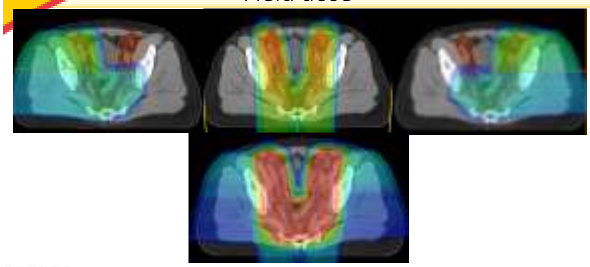


127% hot spot

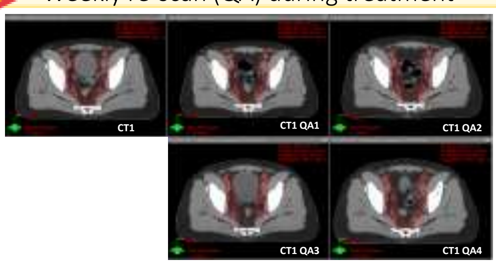
Pelvic nodes irradiation with IMPT



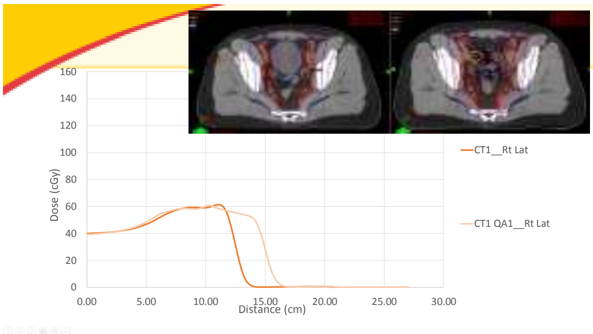
Field dose

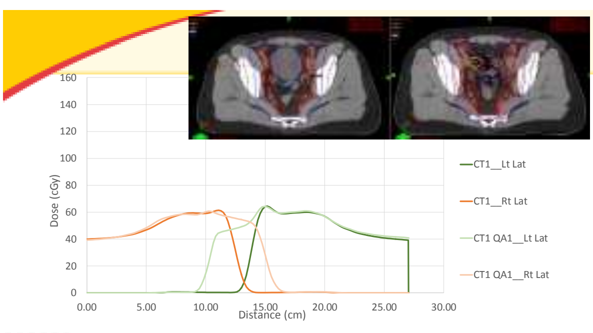


Weekly re-scan (QA) during treatment



Hot spots on re-scans


160
140
120
100
80
60
40
20
0
Dose (cGy)
0.00
5.00
10.00
15.00
20.00
25.00
30.00
Distance (cm)
CT1__Rt Lat
CT1 QA1__Rt Lat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Distance (cm)
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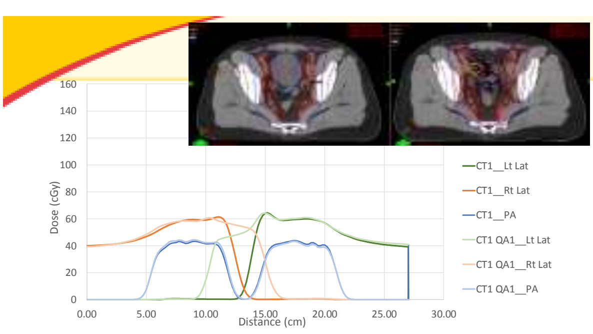
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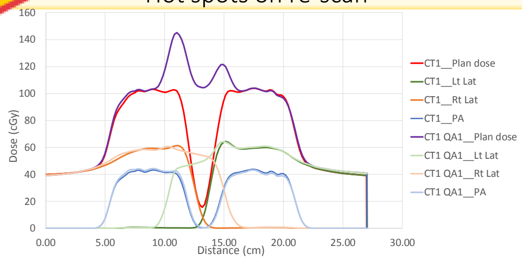
40
20
0
Dose (cGy)
0.00
5.00
10.00
15.00
20.00
25.00
30.00
Distance (cm)
CT1__Lt Lat
CT1__Rt Lat
CT1__PA
CT1 QA1__Lt Lat
CT1 QA1__Rt Lat
CT1 QA1__PA

Hot spots on re-scan



Global maximum doses

Pt. #	# of QA CTs	Without RO		
		Nominal plan Dmax	QA plan Dmax Range	
			Min	Max
1	3	105.8%	106.0%	121.2%
2	4	105.4%	105.5%	131.6%
3	4	106.7%	107.0%	122.5%
4	4	105.3%	108.1%	144.4%
5	5	106.2%	107.6%	133.4%
6	5	105.2%	107.3%	140.7%
7	5	105.9%	109.7%	121.2%
8	4	104.3%	107.2%	128.1%
9	5	105.7%	105.6%	122.3%
10	4	108.3%	108.3%	120.5%

- Hot spots up to 144% can be seen on re-scan CTs;
- Usually small and random;
- Hasn't trigger re-planning;
- However it is a concern

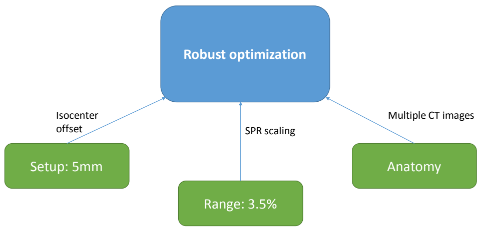
IMPT is uniquely sensitive to patient anatomy change

- Undesired dosimetric consequence
- Unpredictable dosimetric consequence

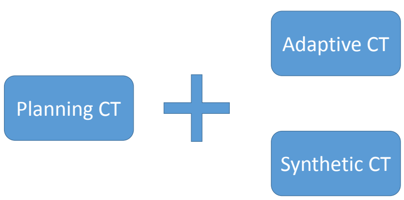
- Mitigation strategy: frequent re-scan and re-plan
  - Resource intensive
  - Suboptimal treatment

- **Question: Is it possible/how to proactively take it into account in plan optimization?**

Multiple CT optimization



Types of multiple CTs



mCT for lung IMPT

- 8 patients with 4D scans,
- PCT: planning CT
- ACT: adaptive CT
- IGTV+8mm → CTV
- CTV+5mm → PTV

Wang, *et al.*, Radiother Oncol. (2017)

Dosimetric comparison

P-ACT

A-ACT

Wang, *et al.*, Radiother Oncol. (2017)

Dosimetric comparison

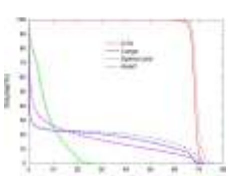
P-ACT

A-ACT

M-ACT

Wang, *et al.*, Radiother Oncol. (2017)

DVH comparison



Solid: P-PCT
Dashed: M-PCT

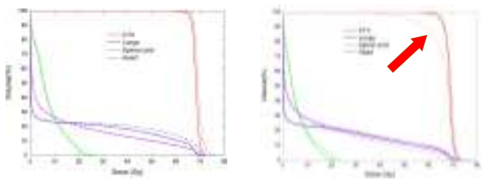
mCT plan:

Slightly higher CTV dose

Slightly higher Lung V20

Wang, *et al.*, Radiother Oncol. (2017)

DVH comparison

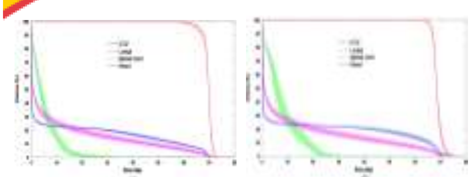


Solid: P-PCT
Dashed: M-PCT

Solid: A-ACT
Dashed: M-ACT
Dotted: P-ACT

Wang, *et al.*, Radiother Oncol. (2017)

Robustness comparison



PCT

mCT

Wang, *et al.*, Radiother Oncol. (2017)

mCT RO for lung IMPT

- Using 2 patient scans: PCT and ACT
- Include both CTs in optimization
- On PCT:
  - Similar coverage
  - Slightly higher lung dose
  - Similar robustness
  - No statistically difference in heart or spinal cord dose

Wang, *et al.*, Radiother Oncol. (2017)

mCT for lung IMPT

- Using 2 patient scans: PCT and ACT
- Include both CTs in optimization
- **On ACT:**
  - **Reduced cold spot—improve tumor control**
  - **Could potentially reduce re-planning frequency**

- mCT RO for lung IMPT is feasible

Wang, *et al.*, Radiother Oncol. (2017)

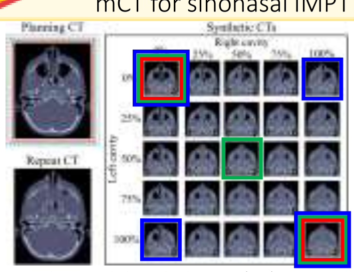
mCT for sinonasal IMPT

Planning CT + Synthetic CTs

- 5 patients
- 25 synthetic CT images per patient
- Each with a different density override in cavities
- Compared with SFUD and adaptive plans

van de Water, *et al.*, Phys. Med. Biol. **63** 025020 (2018)

mCT for sinonasal IMPT



Planning CT +

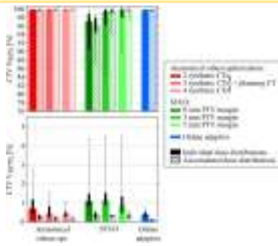
2 synthetic CTs

3 synthetic CTs

4 synthetic CTs

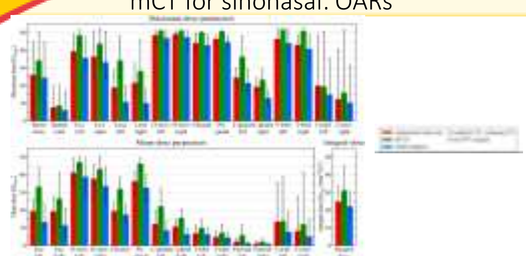
van de Water, *et al.*, Phys. Med. Biol. **63** 025020 (2018)

mCT for sinonasal: CTV



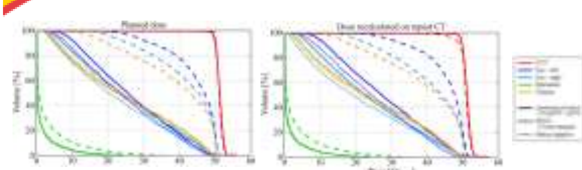
van de Water, *et al.*, Phys. Med. Biol. **63** 025020 (2018)

mCT for sinonasal: OARs



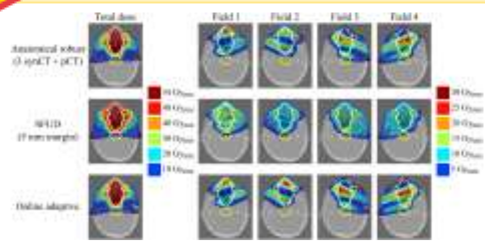
van de Water, *et al.*, Phys. Med. Biol. **63** 025020 (2018)

mCT for sinonasal



van de Water, *et al.*, Phys. Med. Biol. **63** 025020 (2018)

mCT for sinonasal



van de Water, *et al.*, Phys. Med. Biol. **63** 025020 (2018)

mCT RO for sinonasal cancer

- Better target coverage than SFUD (+ margin);
- Lower OAR dose than SFUD (+ margin);
- Online adaptation is the best, but implementation is not realistic;
- mCT RO plans are anatomically robust under conditions of large cavity filling variation, therefore can be an alternative to the online adaptation;

van de Water, *et al.*, Phys. Med. Biol. **63** 025020 (2018)

IMPT for pelvic nodal targets

Pt. #	# of QA CTs	Without RO		
		Nominal plan Dmax	QA plan Dmax Range Min	Max
1	3	105.8%	106.0%	121.2%
2	4	105.4%	105.5%	131.6%
3	4	106.7%	107.0%	122.5%
4	4	105.3%	108.1%	144.4%
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- Hot spots up to 144% can be seen on re-scan CTs;
- Usually small and random;
- Hasn't trigger re-planning;
- However it is a concern

Solution: Robust optimization with different density variation

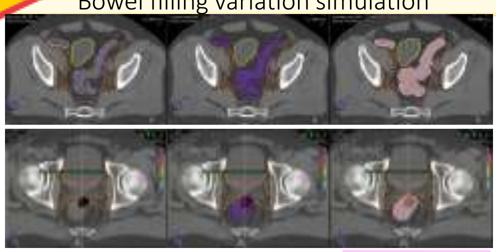
mCT for Pelvic IMPT

Planning CT + Synthetic CTs

- 10 previously treated patients
- Used the same planning CT;
- Two copies of the planning CT are created
- RO optimization with all 3 CTs,
- Evaluate on the QA CTs;

Zhu, *et al*, ASTRO 2017

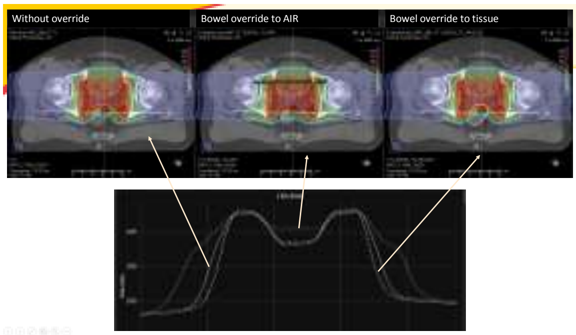
Bowel filling variation simulation



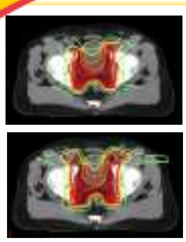
Native CT # and density | Purple: Override to Air | Pink: Override to Muscle

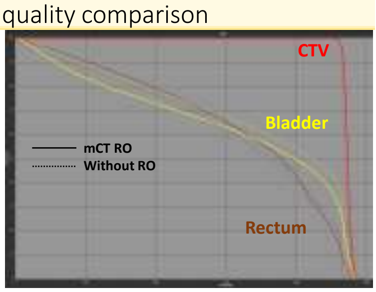
mCT RO for pelvic IMPT

- Patient position:
  - 0.5cm
  - 7 scenarios
- Range Uncertainty:
  - 3.5%
  - 3 scenarios
- Image sets:
  - 3 CTs
- Total: 63 scenarios

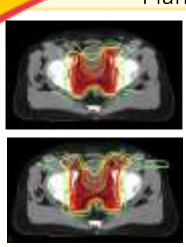


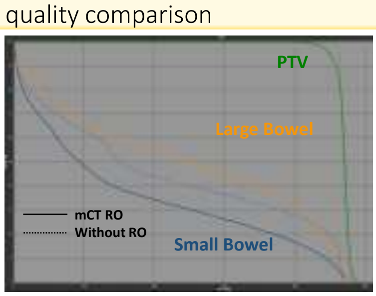
Plan quality comparison



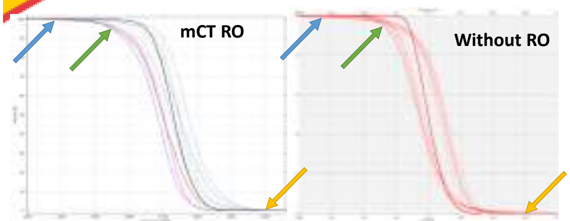


Plan quality comparison

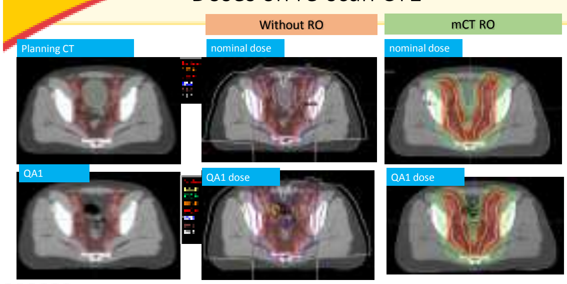




CTV robustness comparison



Doses on re-scan CT1



Global maximum dose on re-scan CTs

Pt. #	# of QA CTs	Without RO			With RO		
		Nominal plan Dmax	QA plan Dmax Range		Nominal plan Dmax	QA plan Dmax Range	
			Min	Max		Min	Max
1	3	105.8%	106.0%	121.2%	106.6%	106.6%	107.9%
2	4	105.4%	105.5%	131.6%	107.0%	107.4%	109.2%
3	4	106.7%	107.0%	122.5%	105.9%	[illegible]	108.0%
4	4	105.3%	108.1%	144.4%	[illegible]	[illegible]	109.4%
5	5	106.2%	107.6%	133.4%	[illegible]	[illegible]	108.9%
6	5	105.2%	107.3%	140.7%	105.5%	[illegible]	109.1%
7	5	105.9%	109.7%	121.2%	106.0%	105.9%	109.0%
8	4	104.3%	107.2%	128.1%	106.5%	107.0%	108.6%
9	5	105.7%	105.6%	122.3%	107.9%	108.0%	109.1%
10	4	108.3%	108.3%	120.5%	105.1%	107.6%	107.7%

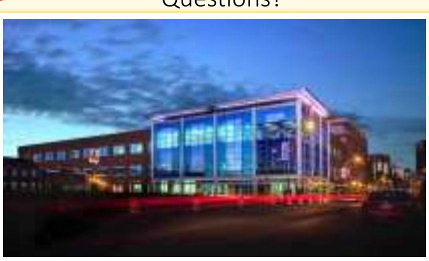
Clinically implementation

- All prostate patients are planned with this method;
- The frequency of re-scan reduced by 50%:
  - From weekly scans to every other week;
- Haven't observe concerning hot spots on the re-scan CTs so far;
- This method can be used for other disease sites
  - GYN
  - Bladder
  - Anal/rectal
  - Head and neck
  - etc…

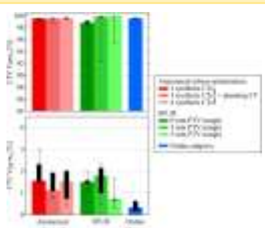
Summary

- Anatomy changes during treatment
  - Under cover target
  - Over dosing OAR
  - Require frequent adaptive scan/planning
- mCT robust optimization
  - Additional CT (re-scan or synthetic)
  - Include anatomy variation in optimization
    - Improve target coverage
    - May also reduce dose to normal tissue

Questions?



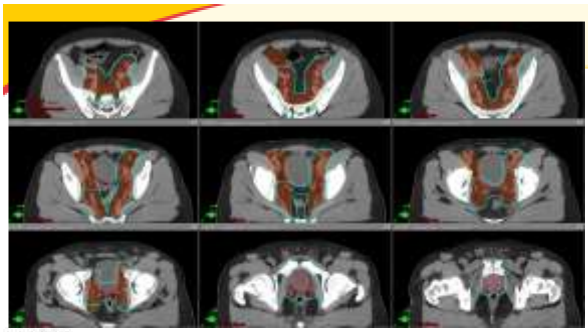
mCT for sinonasal

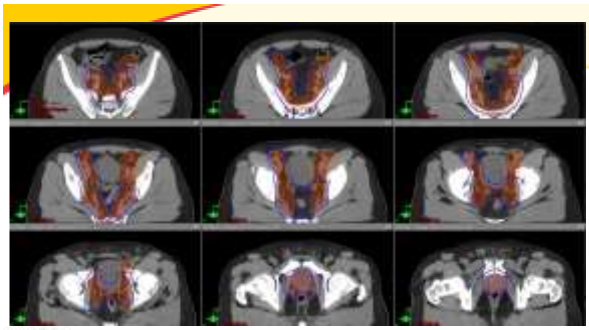


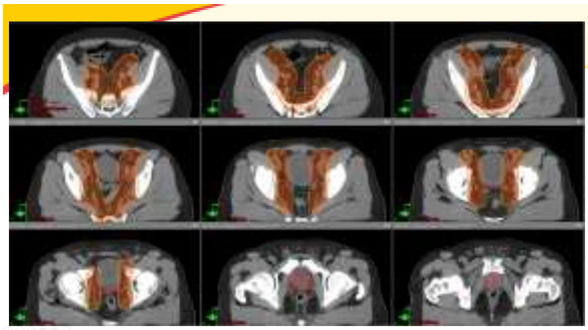
van de Water, et al., Phys. Med. Biol. **63** 025020 (2018)

MPTC method—previously

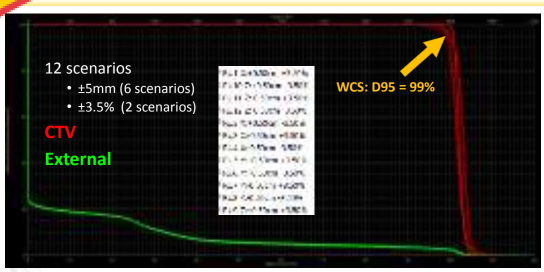
- Without Robustness Optimization
  - Feb. 2016 – June 2017
- 3 fields:
  - Left lateral
  - Right lateral
  - PA
- Split field target to better spare OARs
- Multiple field optimization;



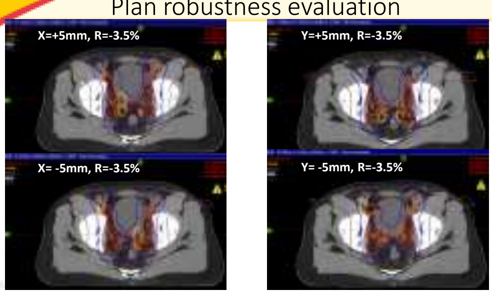




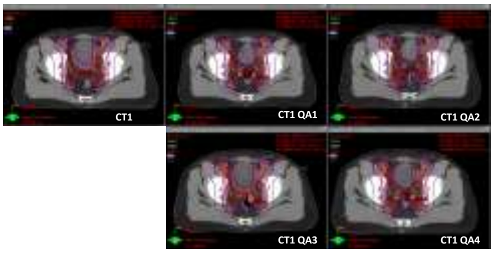
Plan robustness evaluation



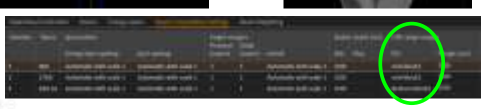
Plan robustness evaluation



Hot spots on re-scan

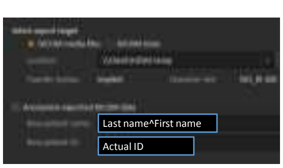


Using OAR margin to split field



CT image preparation

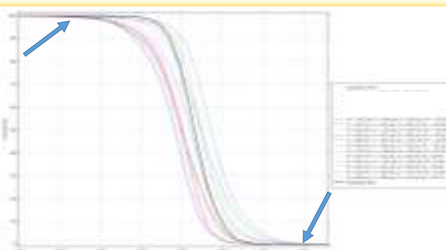
- Once all the contours are completed, export the planning CT with RT structure, anonymized to the same Patient ID and Name;



CT image preparation

- Once all the contours are completed, export the planning CT with RT structure, anonymized to the same Patient ID and Name;
- Import the anonymized CT+RT structure to the same patient/case;
- Co-register the two CTs by manually "set identity"

Robustness evaluation



CT image preparation

- Once all the contours are completed, export the planning CT with RT structure, anonymized to the same Patient ID and Name;
- Import the anonymized CT+RT structure to the same patient/case;
- Co-register the two CTs by manually "set identity"
- Contour the material override structure only on the copied CT;
- Assign material accordingly

Optimization objective functions

Dmax on QA CTs