Online adaptation of IMPT plans with GPU-MC dose calculation on CBCTs for head and neck

Brown bag seminar

Massachusetts General Hospital and Heidelberg University

May 1, 2017

General outline

Why is online adaptation needed?

Being the ultimate goal to better conform dose to the target...

- **Setup** uncertainties
- Patient **anatomy** inter-fractional variation

Why is online adaptation needed?

Being the ultimate goal to better conform dose to the target...

- **Setup** uncertainties
- Patient **anatomy** inter-fractional variation
- Protons are sensitive to geometry changes
- Target **coverage** may be compromised

Why is online adaptation needed?

Being the ultimate goal to better conform dose to the target...

- **Setup** uncertainties
- Patient **anatomy** inter-fractional variation
- Protons are sensitive to geometry changes
- Target **coverage** may be compromised
- Security **margins** increase high dose region

Why is online adaptation needed?

Being the ultimate goal to better conform dose to the target...

- **Setup** uncertainties
- Patient **anatomy** inter-fractional variation
- Protons are sensitive to geometry changes
- Target **coverage** may be compromised
- Security **margins** increase high dose region
- Higher dose to **OARs**

Why is online adaptation needed?

Being the ultimate goal to better conform dose to the target. . .

- **Setup** uncertainties
- Patient **anatomy** inter-fractional variation
- Protons are sensitive to geometry changes
- Target **coverage** may be compromised
- Security **margins** increase high dose region
- Higher dose to **OARs**
- A risky statement: **Robust planning** can not cover every possible scenario and increases high dose volume

Why is online adaptation needed?

Being the ultimate goal to better conform dose to the target...

- **Setup** uncertainties
- Patient **anatomy** inter-fractional variation
- Protons are sensitive to geometry changes
- Target **coverage** may be compromised
- Security **margins** increase high dose region
- Higher dose to **OARs**
- A risky statement: **Robust planning** can not cover every possible scenario and increases high dose volume

Online adaptation would allow margin reduction guaranteeing coverage and OAR sparing at before every fraction is delivered

The Head and Neck case

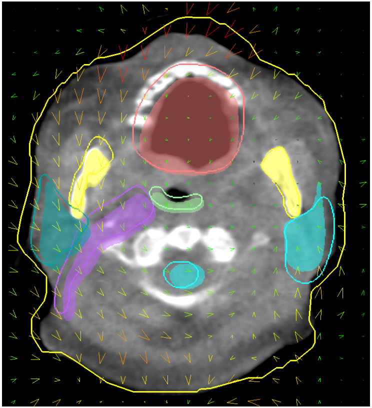


Fig : Head and neck patient geometry changes. The arrows represent the vector field.

Potential for increased treatment quality:

- OARs very close to the target
- Large inter-fractional anatomy changes
- Tissue interfaces make it sensitive

Objectives:

Aim: Change the IMPT fields to recover initial plan quality while the patient is on the couch

Goals:

- Develop an **online** adaptation algorithm
- Dose calculations with GPU-MC on CBCTs

Objectives:

Aim: Change the IMPT fields to recover initial plan quality while the patient is on the couch

Goals:

- Develop an **online** adaptation algorithm
- Dose calculations with GPU-MC on CBCTs

Steps:

- Plan set of patients with IMPT and no margin on CTV
- Study plan evolution *vs* anatomy changes on CBCT images
- Can we get away with plan adjustments as opposed to replanning?

What has been published?

Kurz 2016

- Offline
- Analytical dose calculation
- Full reoptimization
- Adaptation on vCT

Moriya 2017

- Range shifter of the day
- Passive scattering for lung

Jagt 2017

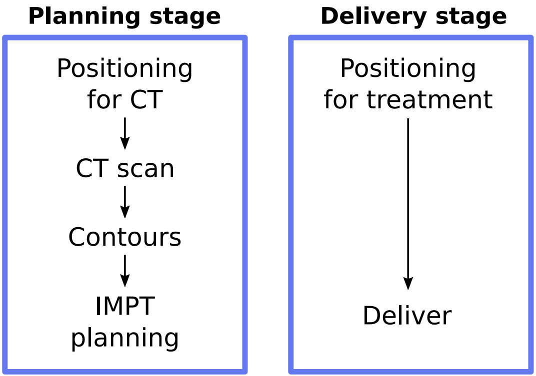
- Online (more or less)
- Analytical dose calculation
- Dose restoration
- Full reoptimization
- Original contours

Bernatowitz 2018

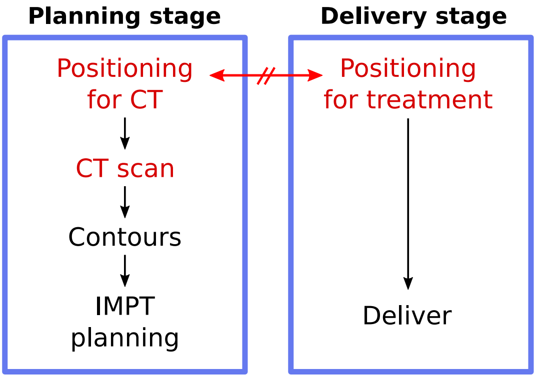
- Extension of *Jagt et al.* for robust optimization and others

General outline

Traditional workflow:



Traditional workflow:



Patient cohort planned without margin around CTV

Pat. No.	Location	No. beams	No. CBCTs	Plan CTV vol. (cm^3)	Average CTV vol. ratio (min, max)	Average CTV di
1	Oropharynx	4	6	22.3	1.00 (0.97, 1.05)	0.58 (0.50, 0.67)
2	Tonsil	2	6	9.0	1.02 (0.94, 1.12)	0.87 (0.83, 0.90)
3	Oropharynx	3	7	30.7	0.93 (0.90, 1.00)	0.82 (0.77, 0.88)
4	Neck	4	6	81.3	1.03 (0.98, 1.06)	0.79 (0.75, 0.84)
5	Hypopharynx	3	5	59.6	0.97 (0.95, 0.98)	0.89 (0.87, 0.91)
6	Mouth	3	7	116.5	0.78 (0.75, 0.82)	0.87 (0.83, 0.90)
7	Larynx	3	6	25.0	1.21 (1.08, 1.34)	0.84 (0.77, 0.88)
8	Tongue	4	5	79.9	1.06 (1.04, 1.11)	0.87 (0.82, 0.91)
9	Tonsil	2	6	12.0	0.98 (0.95, 1.00)	0.87 (0.83, 0.93)
10	Oropharynx	3	7	95.9	0.96 (0.91, 1.02)	0.89 (0.85, 0.92)
Summary:	-	-	61	63.22 ± 45.1	0.98 ± 0.11	0.83 ± 0.09

Table : Patient cohort summary

What are we facing?

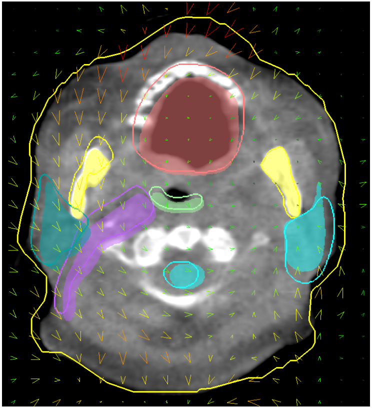


Fig : Head and neck patient geometry changes. The arrows represent the vector field.

What are we facing?

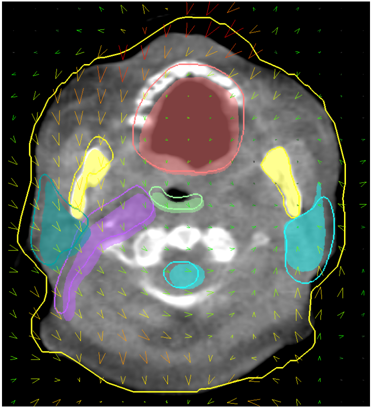
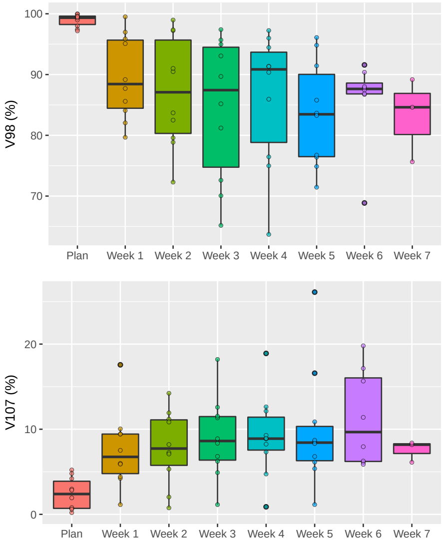
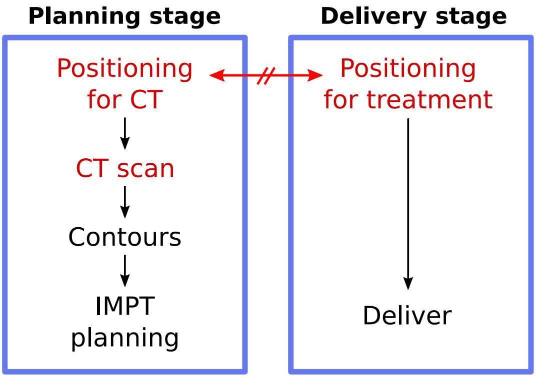


Fig : Head and neck patient geometry changes. The arrows represent the vector field.



Traditional workflow:



Adaptation workflow:

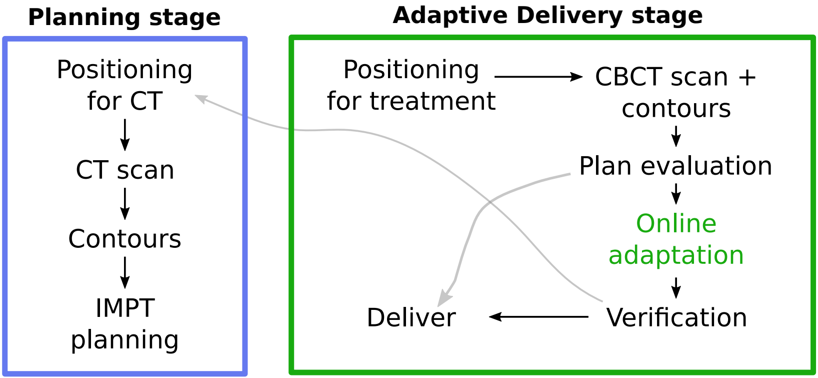
Planning stage

Positioning for CT
↓
CT scan
↓
Contours
↓
IMPT planning

Adaptive Delivery stage

Positioning for treatment → CBCT scan + contours
↓
Plan evaluation
↓
Online adaptation
↓
Verification → Deliver

Adaptation workflow:



Necessary tools

Cone Beam CT (CBCT)

A priori CT-based scatter correction WEPL error $< 2\%$ in head cases.

Park et al., Med Phys. 2015;42(8), Kim et al., Phys Med Bio. 2017;62(1)

Fast GPU MC: gPMC

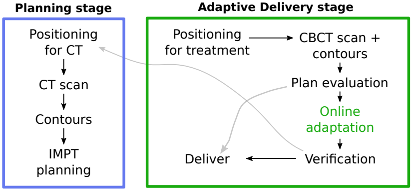
Accurate dose calculation engine.

Qin et al., Phys Med Biol. 2016;61(20)

Image Registration: Plastimatch

Register planning CT to CBCT. Rigid and deformable (DIR), GPU B-spline

Shackleford et al., Phys Med Biol. 2010;55(21)



Adaptation steps

Adaptation steps:

1. **Geometrical adaptation:** spots are moved following a VF and the energy is adjusted after raytracing
2. **Weight adaptation:** tune spot weights to correct for the unbalance created by the geometrical adaptation

Adaptation steps

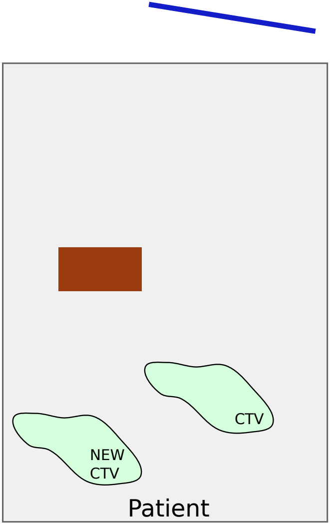
Adaptation steps:

1. **Geometrical adaptation:** spots are moved following a VF and the energy is adjusted after raytracing
2. **Weight adaptation:** tune spot weights to correct for the unbalance created by the geometrical adaptation

Why does this study not include setup uncertainties and what does it mean?

Geometrical adaptation: basics

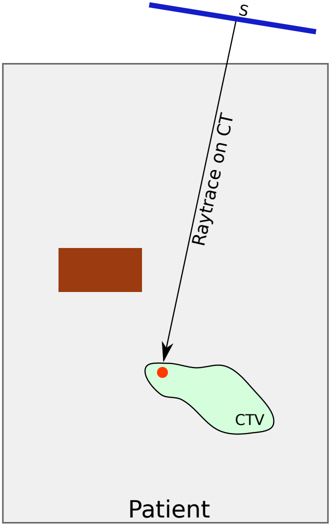
Per spot $s_i = (x_0, y_0, E_0)$:



Geometrical adaptation: basics

Per spot $s_i = (x_0, y_0, E_0)$:

1: **Raytrace** s_i in CT (r_i)

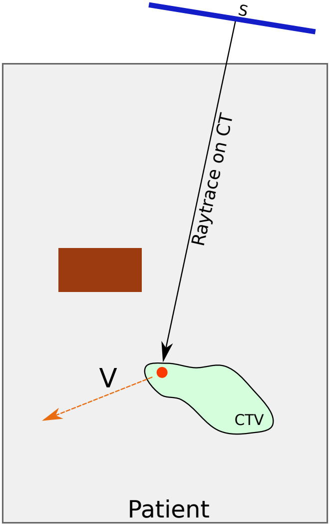


Geometrical adaptation: basics

Per spot $s_i = (x_0, y_0, E_0)$:

1: **Raytrace** s_i in CT (r_i)

2: **Probe** VF at r_i coords: v_i



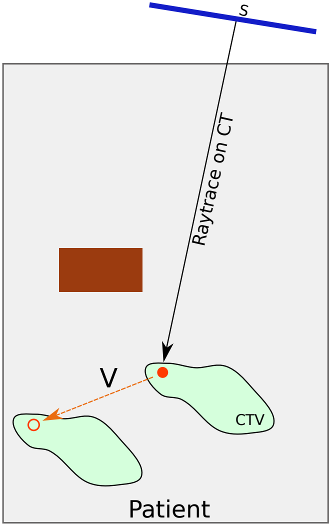
Geometrical adaptation: basics

Per spot $s_i = (x_0, y_0, E_0)$:

1: **Raytrace** s_i in CT (r_i)

2: **Probe** VF at r_i coords: v_i

3: **Apply** v_i **to** r_i coords: position where the r_i should be in the CBCT



Geometrical adaptation: basics

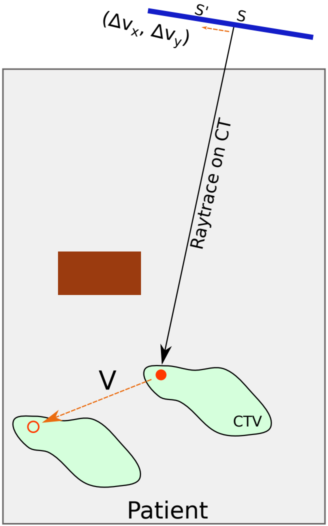
Per spot $s_i = (x_0, y_0, E_0)$:

1: **Raytrace** s_i in CT (r_i)

2: **Probe** VF at r_i coords: v_i

3: **Apply** v_i **to** r_i coords: position where the r_i should be in the CBCT

4: **Apply** v_i **to** $s \rightarrow$ $s_i' = (x_0 + \Delta v_x, y_0 + \Delta v_y, E_0)_i$



Geometrical adaptation: basics

Per spot $s_i = (x_0, y_0, E_0)$:

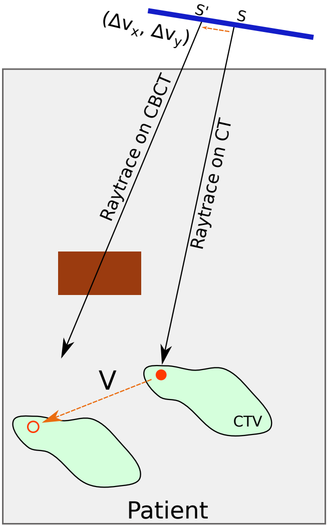
1: **Raytrace** s_i in CT (r_i)

2: **Probe** VF at r_i coords: v_i

3: **Apply** v_i **to** r_i coords: position where the r_i should be in the CBCT

4: **Apply** v_i **to** $s \rightarrow s'_i = (x_0 + \Delta v_x, y_0 + \Delta v_y, E_0)_i$

5: **Raytrace** s'_i in CBCT



Geometrical adaptation: basics

Per spot $s_i = (x_0, y_0, E_0)$:

1: **Raytrace** s_i in CT (r_i)

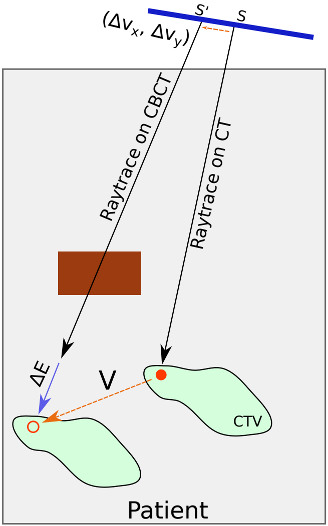
2: **Probe** VF at r_i coords: v_i

3: **Apply** v_i **to** r_i coords: position where the r_i should be in the CBCT

4: **Apply** v_i **to** $s \rightarrow$ $s'_i = (x_0 + \Delta v_x, y_0 + \Delta v_y, E_0)_i$

5: **Raytrace** s'_i in CBCT

6: **Get** ΔE_i



Geometrical adaptation: basics

Per spot $s_i = (x_0, y_0, E_0)$:

1: **Raytrace** s_i in CT (r_i)

2: **Probe** VF at r_i coords: v_i

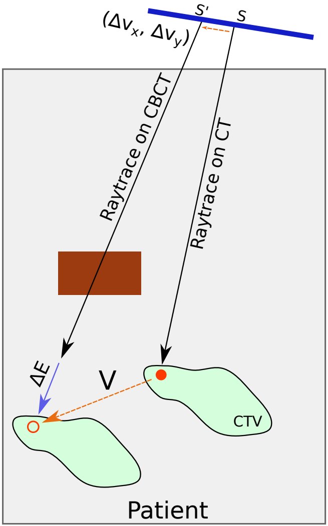
3: **Apply** v_i **to** r_i coords: position where the r_i should be in the CBCT

4: **Apply** v_i **to** $s \rightarrow$ $s'_i = (x_0 + \Delta v_x, y_0 + \Delta v_y, E_0)_i$

5: **Raytrace** s'_i in CBCT

6: **Get** ΔE_i

Spot adaptation: $(\Delta v_x, \Delta v_y, \Delta E)_i$



Geometrical adaptation: constraints

Constraints:

- Free: No constraints on spots movement $(\Delta v_x, \Delta v_y, \Delta E)_i$
- Constrained:
  - *Couch/isocenter shift*: Average VF in the CTV
  - *Range-shifter-of-the-day*: Average energy shift
  - *Both*

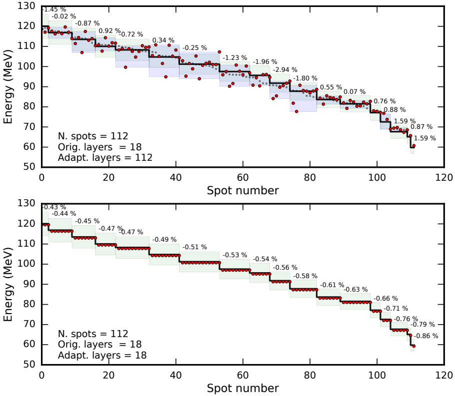
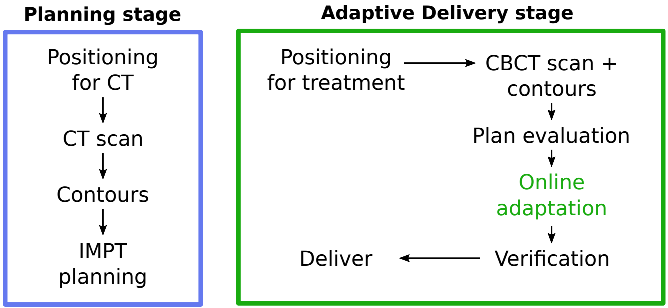


Fig : Distortion and conservation of plan energy layers

Weight tuning:

Taking the proposed workflow into account. . .



How can we gather significant information of individual spots **fast**?

Adaptation workflow:

Use information from the initial plan: on average, 8.2% of the spots deliver at least 50% of the dose

Adaptation workflow:

Use information from the initial plan: on average, 8.2% of the spots deliver at least 50% of the dose

Weight tuning:

1. Run the **geometrical adaptation** with gPMC
2. Define **region of interest** during simulation
3. Score the **dose per spot** in ROI
4. **Select set** of spots giving 50% of the dose, being at least 10% of the total spots
5. Accumulate adapted dose without the set
6. Calculate **remaining dose** for coverage in target
7. **Tune set weights** to fill the remaining dose with Opt4D

General outline

What does the deformation look like?

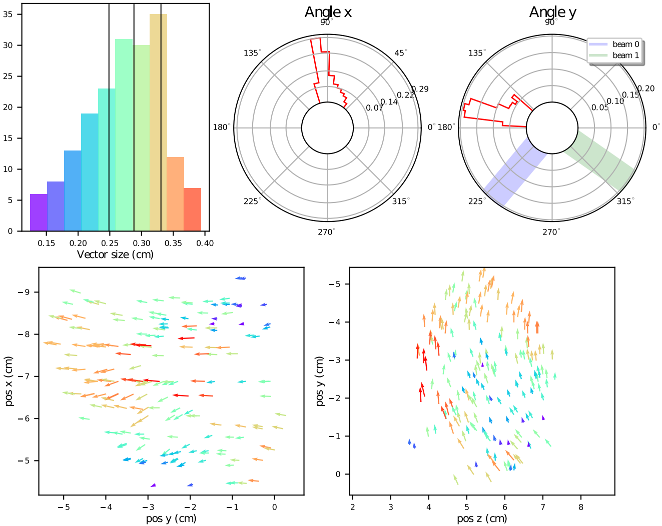


Fig : Deformation field of patient 9, fraction 1

What does the deformation look like?

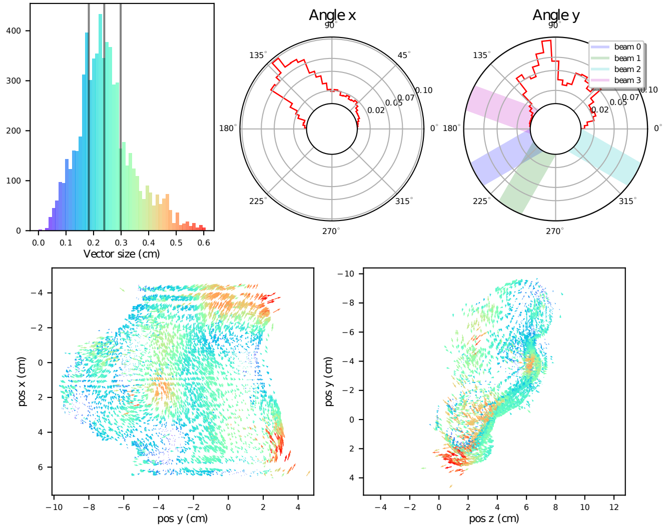


Fig : Deformation field of patient 4, fraction 1

How do the spot parameters change?

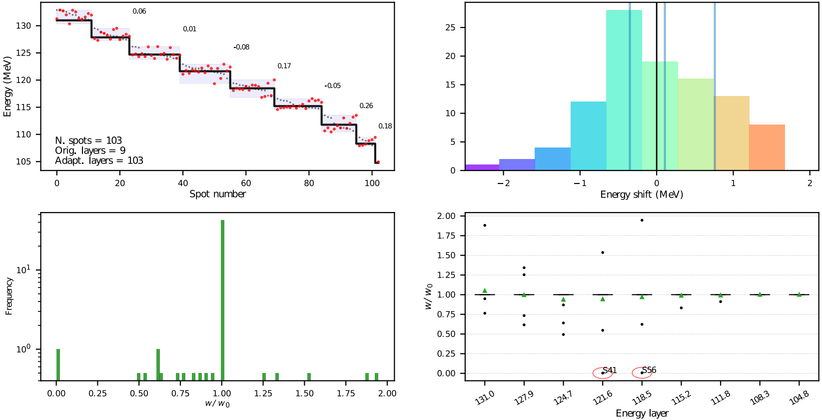


Fig : Fluence map changes: Patient 2, fraction 1, beam 1

How do the spot parameters change?

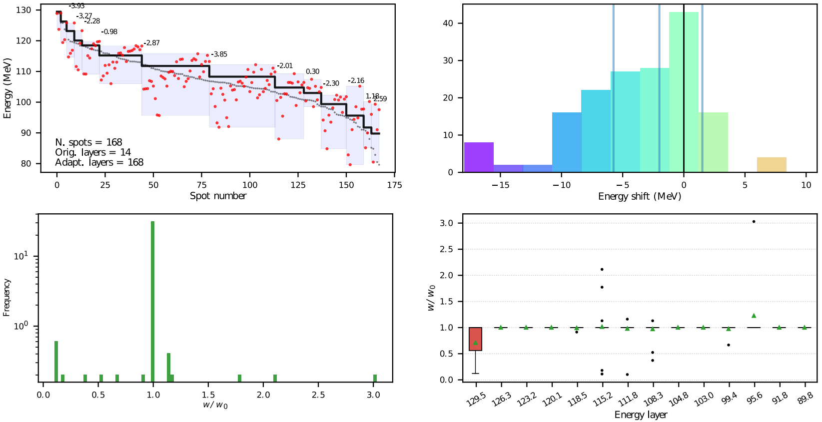


Fig : Fluence map changes: Patient 7, fraction 4, beam 2

Results: what has not worked

Geometric-only approaches:

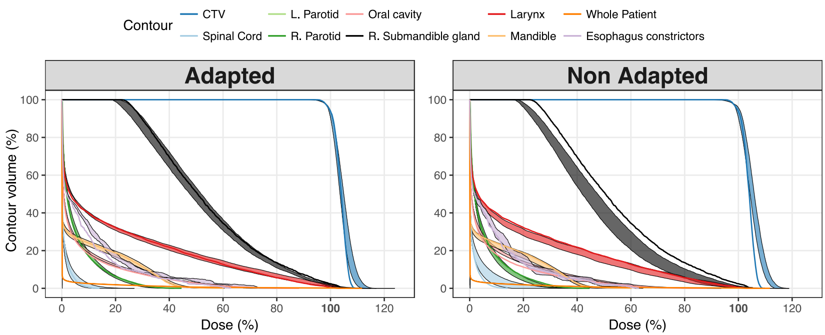
- Not in the general case
- Divergences in the VF
- Bragg peaks changes
- Unbalance of spot doses
- Under-represented areas
- Constraints too strict

Results: what has not worked

Geometric-only approaches:

- Not in the general case
- Divergences in the VF
- Bragg peaks changes

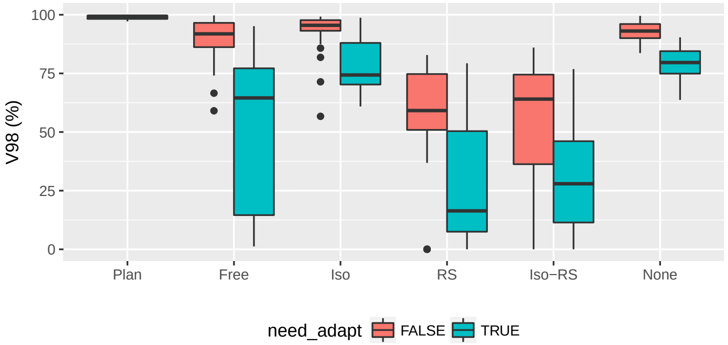
- Unbalance of spot doses
- Under-represented areas
- Constraints too strict



Results: what has not worked

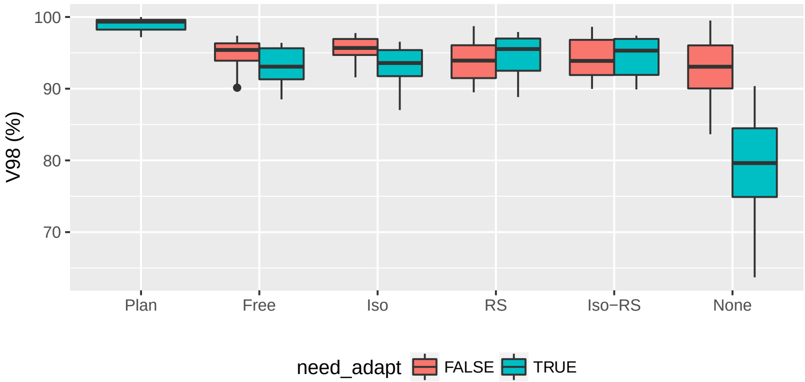
Geometric-only approaches:

- Not in the general case
- Divergences in the VF
- Bragg peaks changes
- Unbalance of spot doses
- Under-represented areas
- Constraints too strict



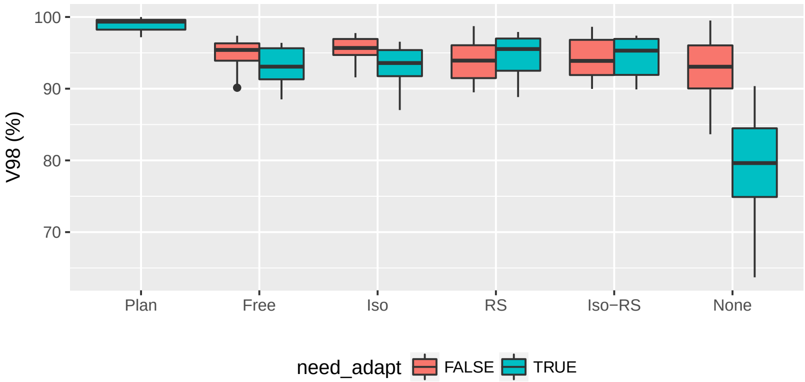
Results with weight tuning: CTV

Adjusting the weights shows improved results:



Results with weight tuning: CTV

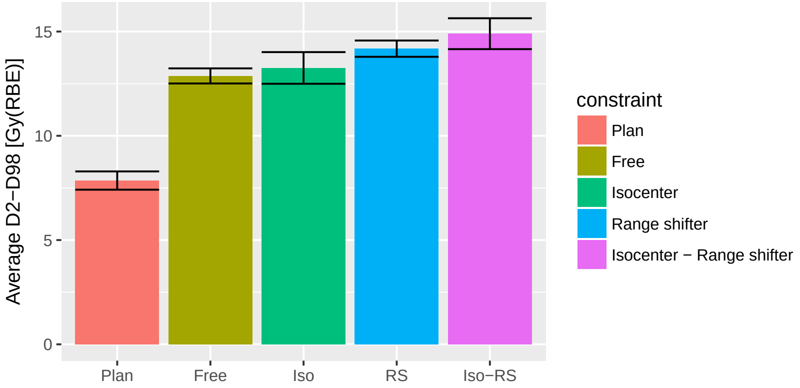
Adjusting the weights shows improved results:



Which one is better? Normalize and check homogeneity!!

Results with weight tuning: CTV

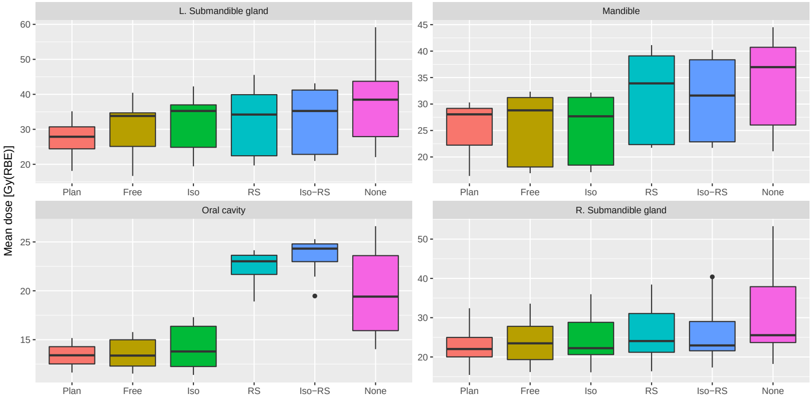
Normalized to V98 $= 98\%$:



... hard to tell between *Free* and *Isocenter shift*. Maybe the OARs show a clearer pattern?

Results with weight tuning: OARs

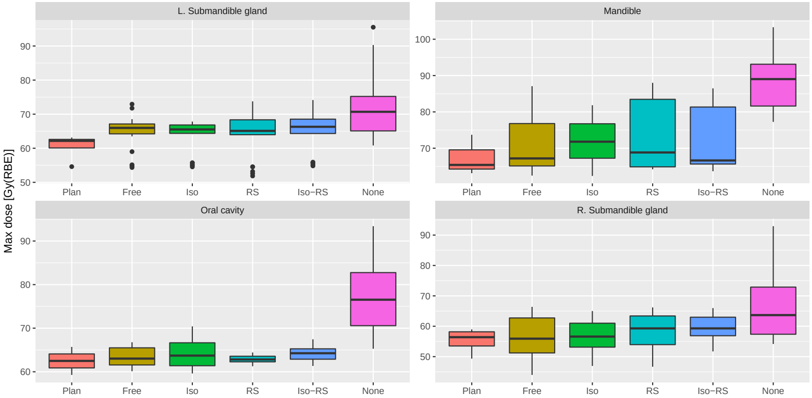
The free strategy *seems* slightly better than the isocenter strategy.



The DVHs are normalized to V98 = 98%.

Results with weight tuning: OARs

The free strategy *seems* slightly better than the isocenter strategy.



The DVHs are normalized to $V98 = 98\%$.

Results overview

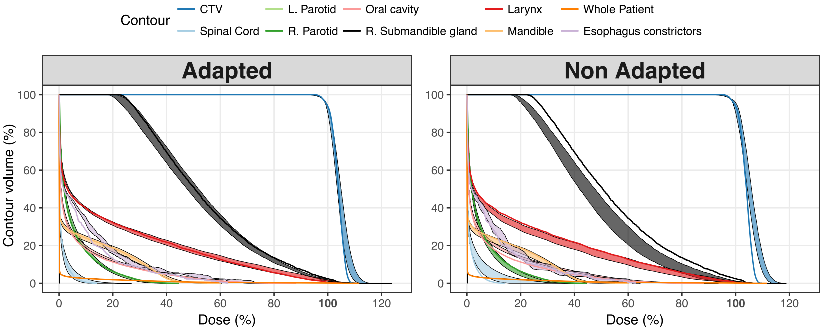


Fig : Patient 9, adaptation vs plan

Results overview

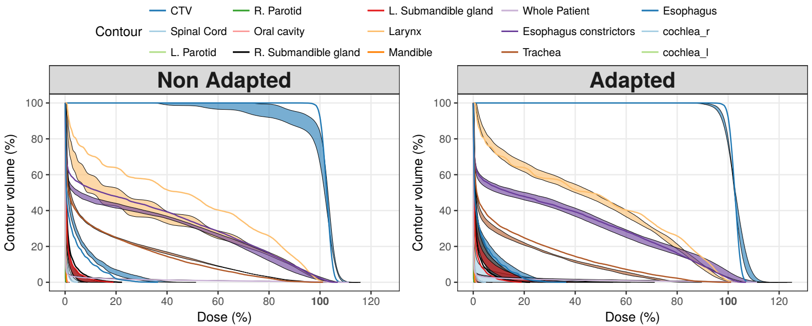


Fig : Patient 7, adaptation vs plan

Results overview

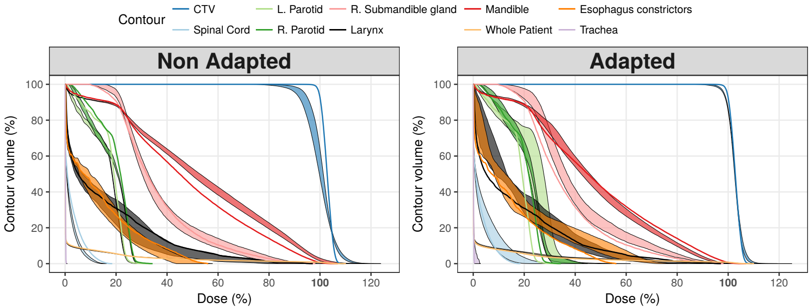


Fig : Patient 8, adaptation vs plan

Results overview

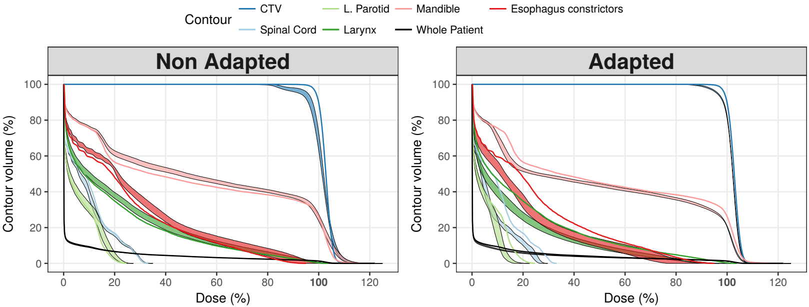


Fig : Patient 6, adaptation vs plan

A quick peek into the next studies

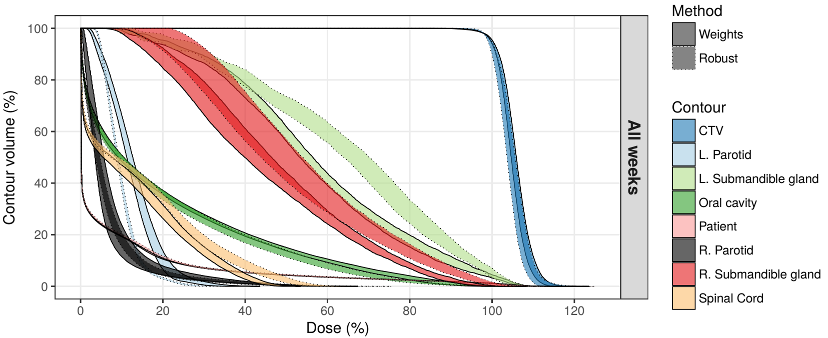


Fig : Patient 1, **adaptation vs ideal robust optimization**

Timing, timing, timing!!

	Minimum	Average	Maximum	Expected
Geometrical adapt.	11.7	16.9	26.57	$\sim 1-5$
gPMC validation	115.6	261.9	419.2	~ 30
Weight tuning	12.0	44.8	198.0	??
Total	-	322.7	-	~ 60
D_{ij} size (MB)	4.1	77.9	312.0	50%

Table : Current and expected times

Improvements:

- Geometrical adapt.: VF masks, binnings, multithreading...
- gPMC validation: Multiple GPUs, unified codes, optimal stopping, kernel occupancy, thread variance reduction...
- Opt4D optimization: I am not a great expert, but the dose matrices can be smaller

Conclusions and outlook

Conclusions:

- We have developed and online adaptation algorithm using GPU-MC
- The algorithm is able to recover good plan quality
- This tool might be useful to allow uncertainty margin reduction

Conclusions and outlook

Conclusions:

- We have developed and online adaptation algorithm using GPU-MC
- The algorithm is able to recover good plan quality
- This tool might be useful to allow uncertainty margin reduction

Future work:

- Improve spot selection
- Flexible number of particles per spot in gPMC
- Compare against robust optimization
- Include uncertainties


THANK
YOU
GRACIAS
ARIGATO
SHUKURIA
DANKSCHEEN
TASHAKKUR ATU
YAQHANYELAY
SUKSAMA
EKHMET
MEHRBANI
GRAZIE
MAAKE
KOMAPSUMNIDA
GOZAIMASHITA
EFCHARISTO
JUSPAXAR
PALDIES
BOLZÏN
MERCI
BÏYAN
SHUKRIA
TINGKI