CBCT for image guidance and dose calculations

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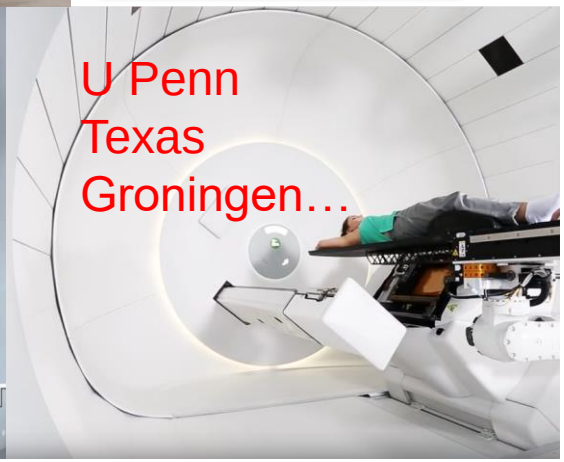
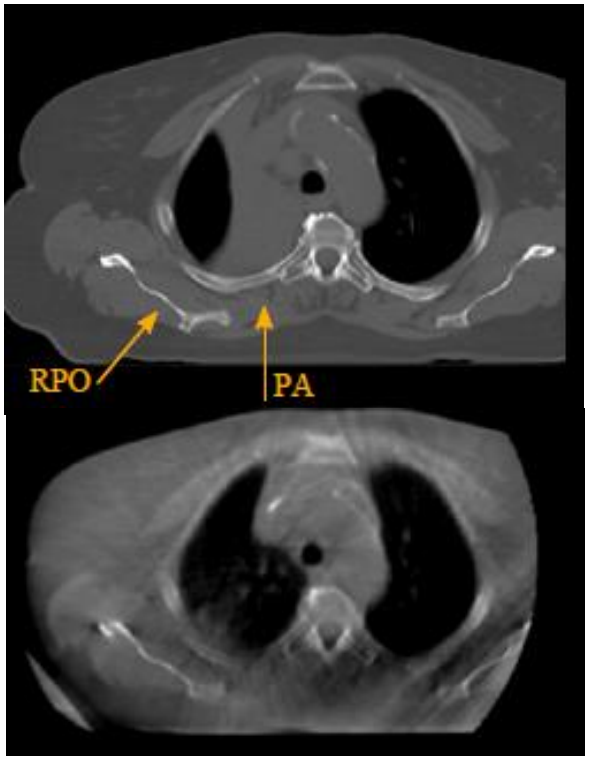
CBCT Imaging options

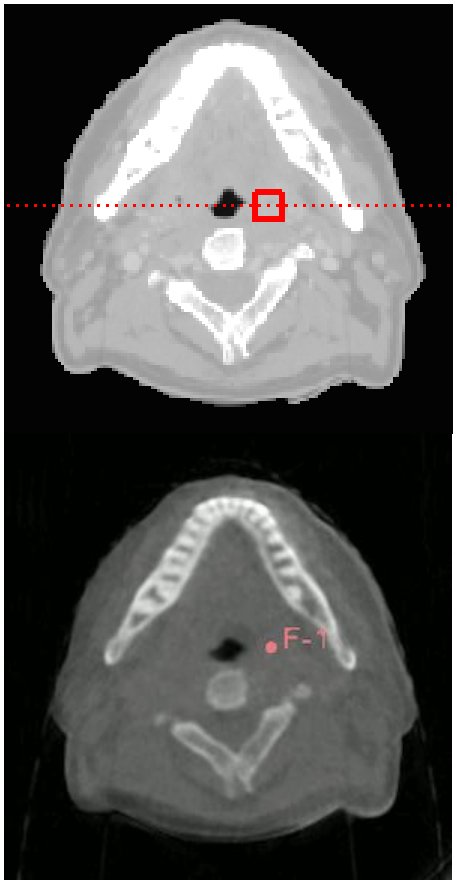
- Varian
- IBA
- MedPhoton
- Forte

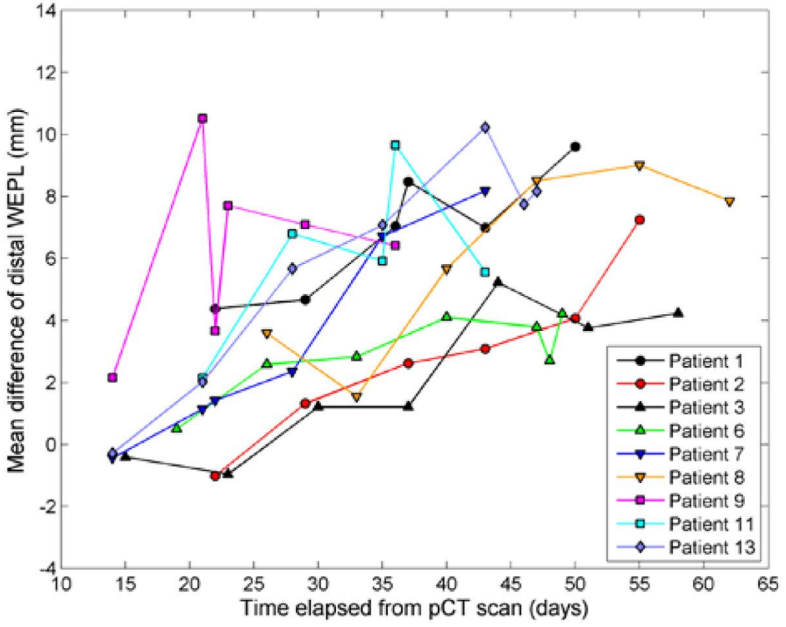


Anatomical Variations



Kevin Teo





- Geometric alignment does not guarantee dosimetric delivery
- Need to understand the WEPL

CBCT

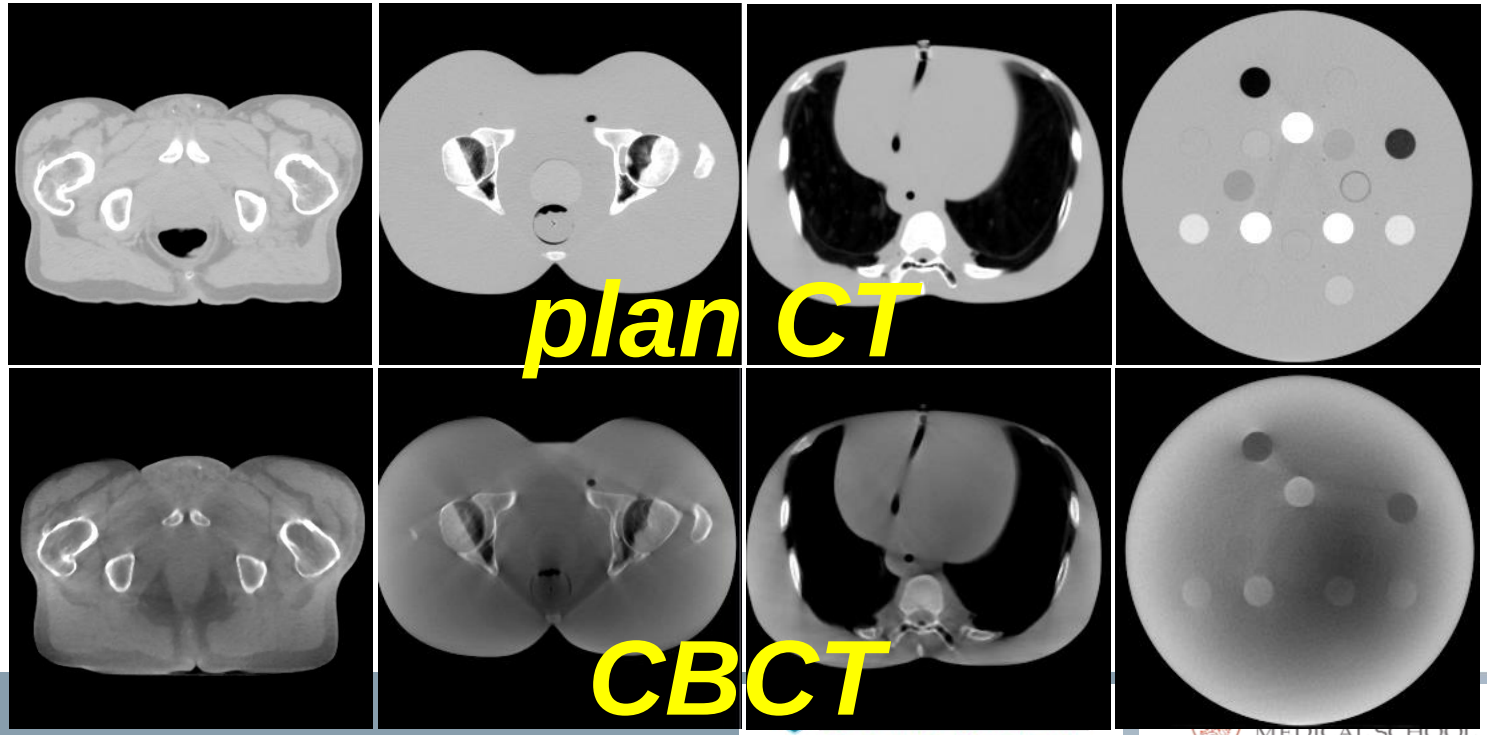
- Workflow, time
- Treatment position (or close)
- Imaging and Tx isocenter coincidence
- Lower image quality
- HU to RSP for dose calculations?
- 4D Imaging is challenging

CBCT Workflow and Time

- Ring (couch mounted)
  - Faster than Gantry rotation
  - Not limited to a single imaging position
  - Large FOV (>70cm)
  - Complex calibration
  - Image during Tx
- Gantry Mounted
  - Simple Calibration
  - Half-rotation small FOV

CBCT Image Quality

- Artifacts: streaks, scatter, beam hardening
- HU Accuracy
- Geometric Accuracy/Gantry Flex
- Motion



CBCT Developments

- Scatter reduction
- HU calibration
- Diagnostic Scanners (Toshiba 16 cm axial FOV scanner)
- Gantry isocenter callibrations

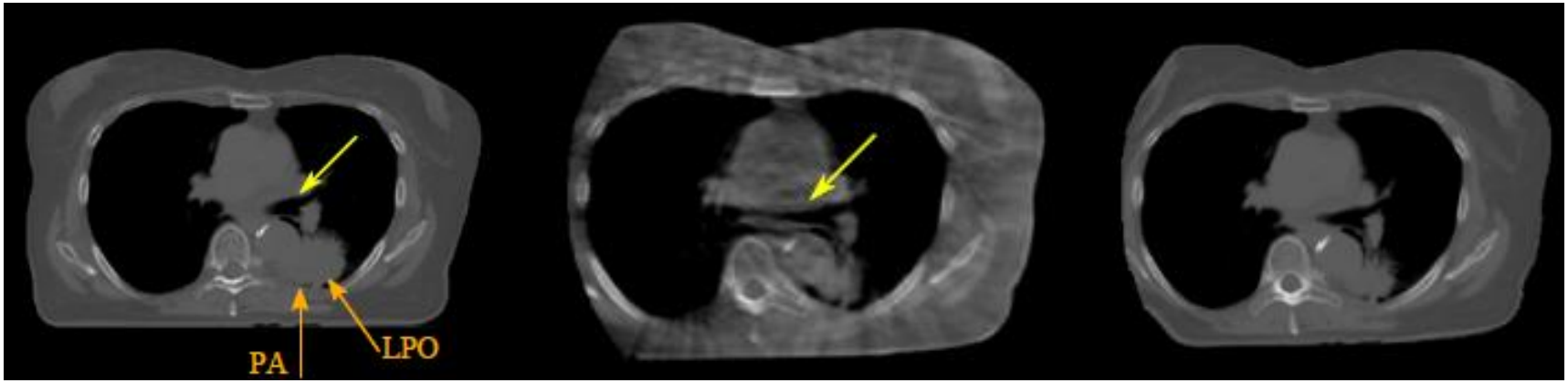
Aquilion ONE ViSION
0.5 mm x 320 detector
640 slices every rotation
16 cm of every rotation
0.275 sec/rotation

Artifact Correction Methods

- Deform CT to CBCT
- Scatter Model (low frequency)
- HU Look Up Table (LUT)
- *A priori* CT scatter correction
  - Analytic model
  - Machine learning
    - GAN and CNN

Correction Methods

- Deform CT: Data from Kevin Teo (Penn)
  - Multiple publications (Penn and LMU Munich)



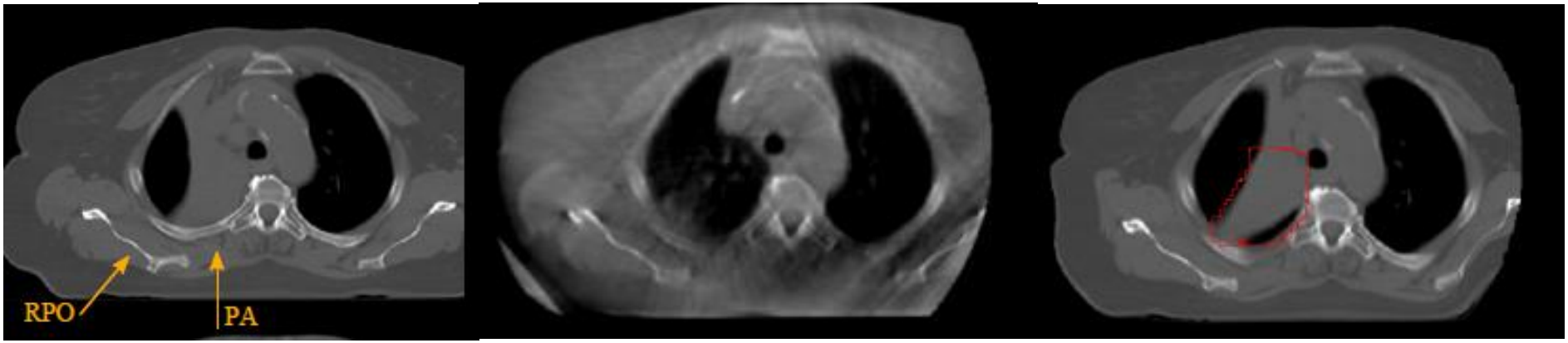
CT **CBCT** **dCT**

Veiga *et al IJROBP* 2016

Veiga *et al Biomed Phys Eng Exp* 2017

Correction Methods

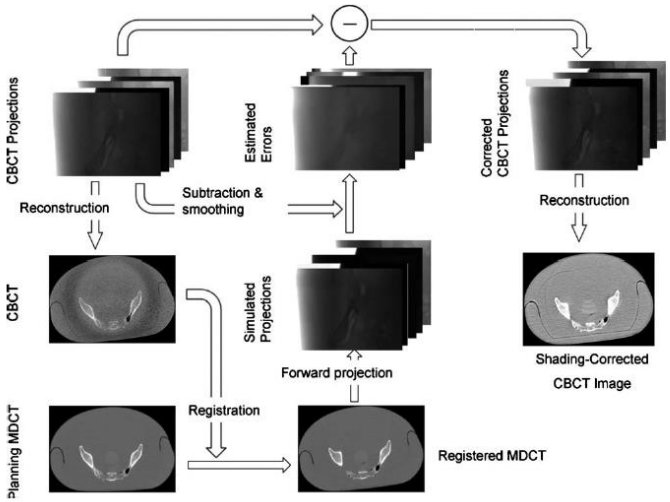
- Deform CT
  - Challenges when anatomy changes too much, especially with air cavities



CT **CBCT** **dCT**

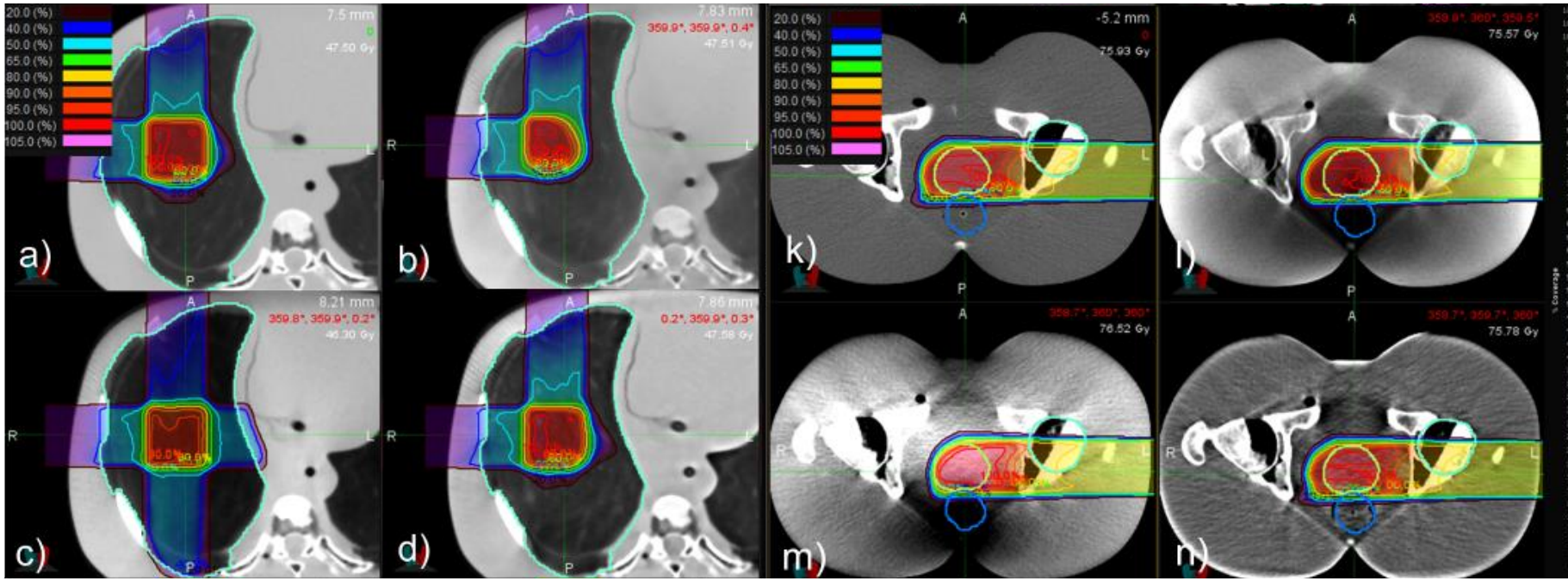
A priori Method

- Niu et al (Med Phys 2010) using *a priori* CT information and scatter kernel
- Reconstructions with RTK
- Compared to a uniform scatter correction model and baseline CBCT



Park *et al Med Phys* 2015

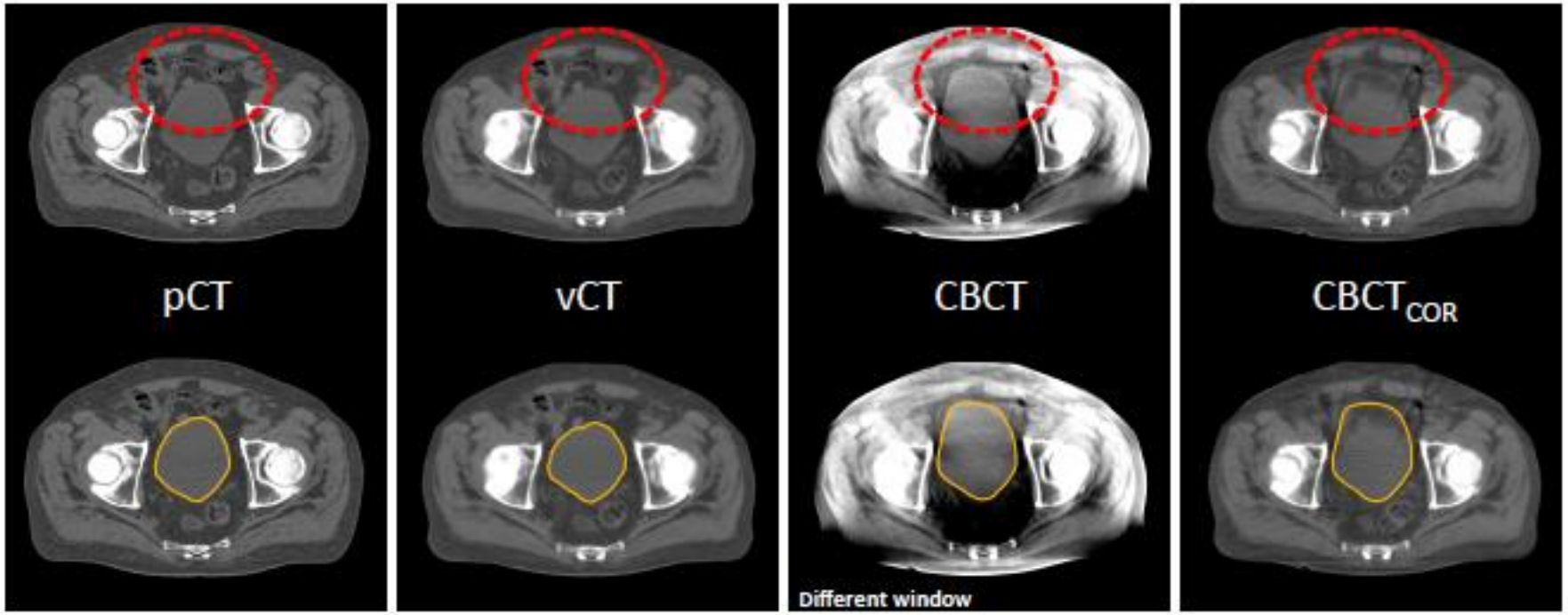
Dose Comparison: Phantoms



Park *et al Med Phys 2015*

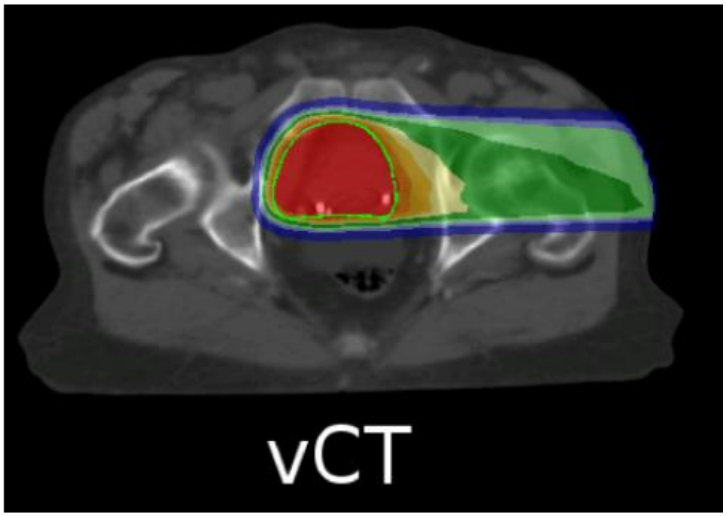
Correction Methods

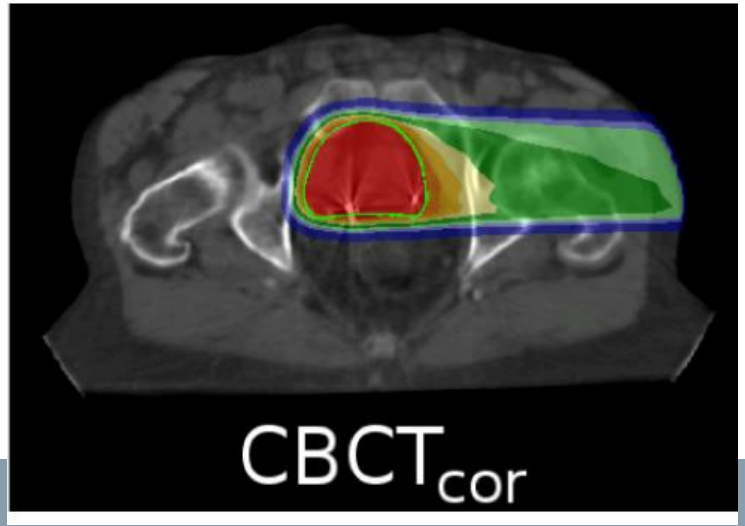
- Deform versus *a priori*

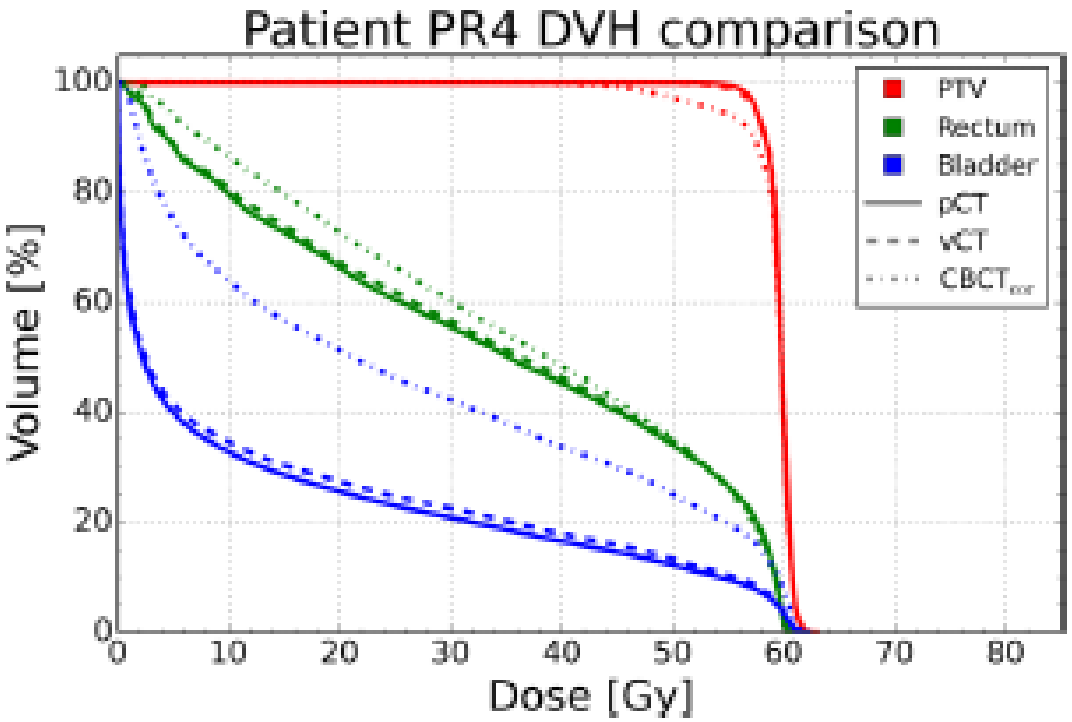


Kurz et al *Med Phys 2016*

Patient Dose Calculations





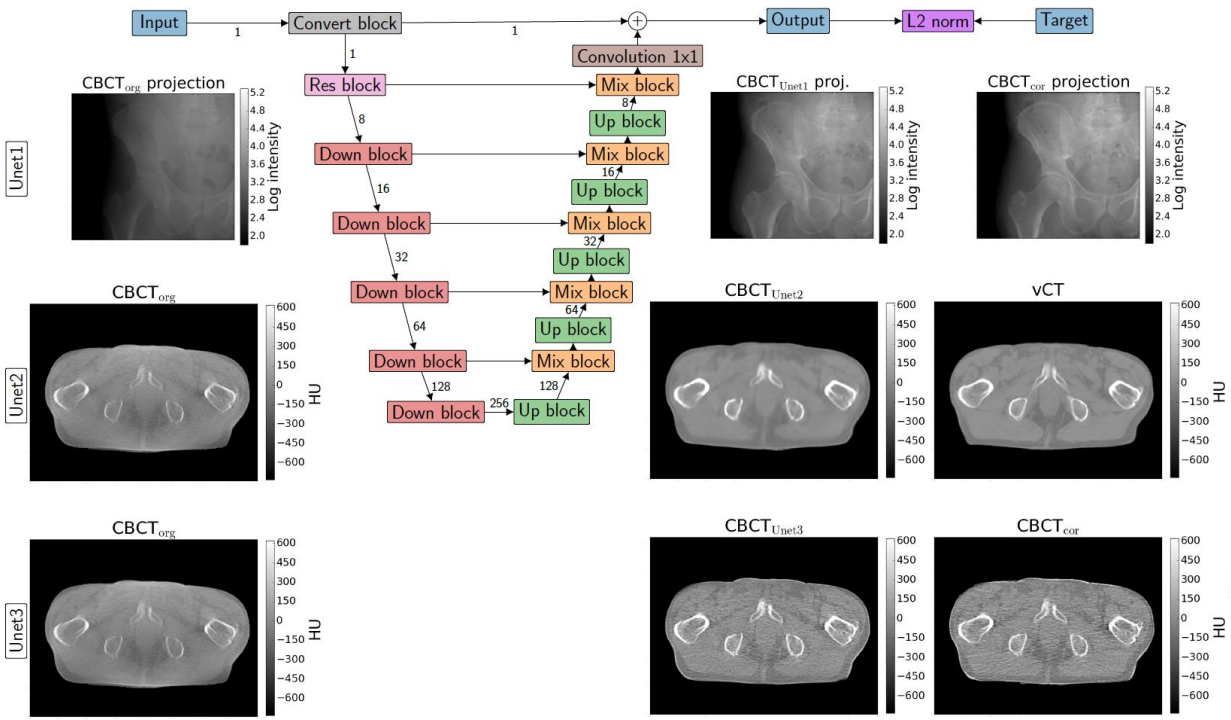


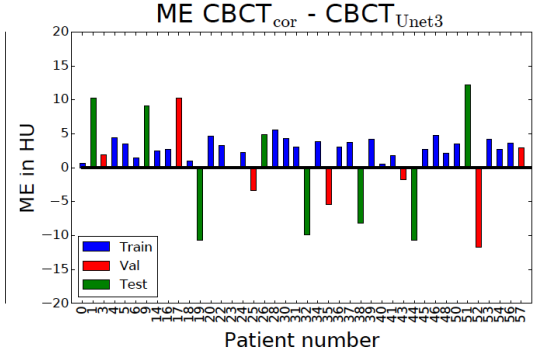
Kurz *et al* *Med Phys* 43(10): 5635, 2016.

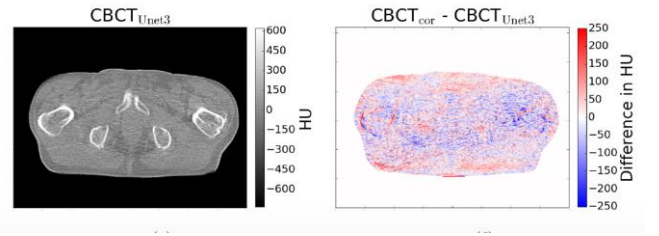
A Priori Method

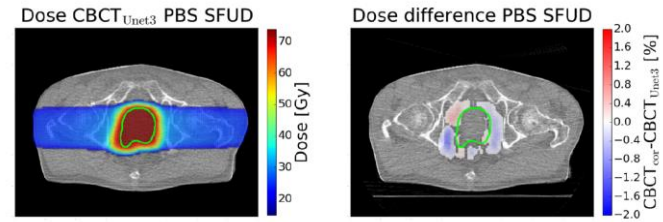
- Current Limitation is time
- Generally found to have HU accuracy and WEPL accuracy within 2-3 mm.
- ML methods have potential to dramatically increase the speed and the accuracy

Machine Learning



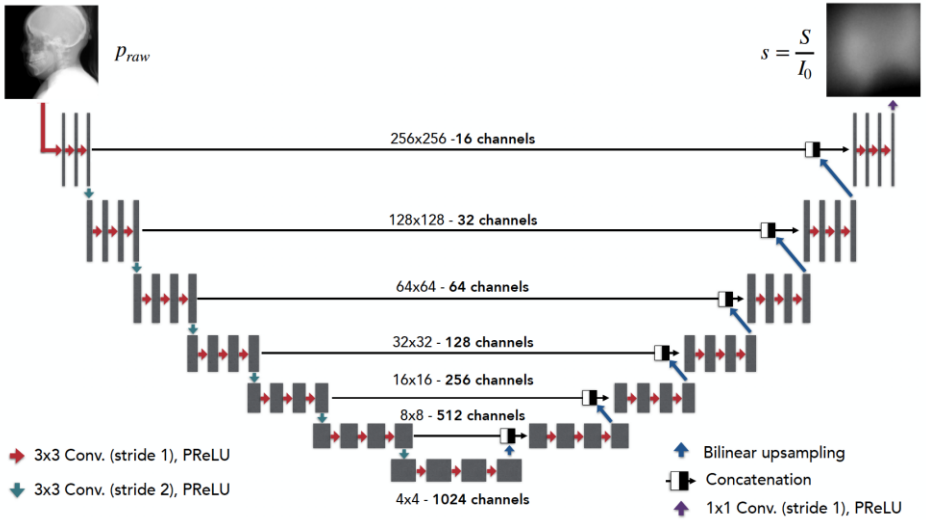


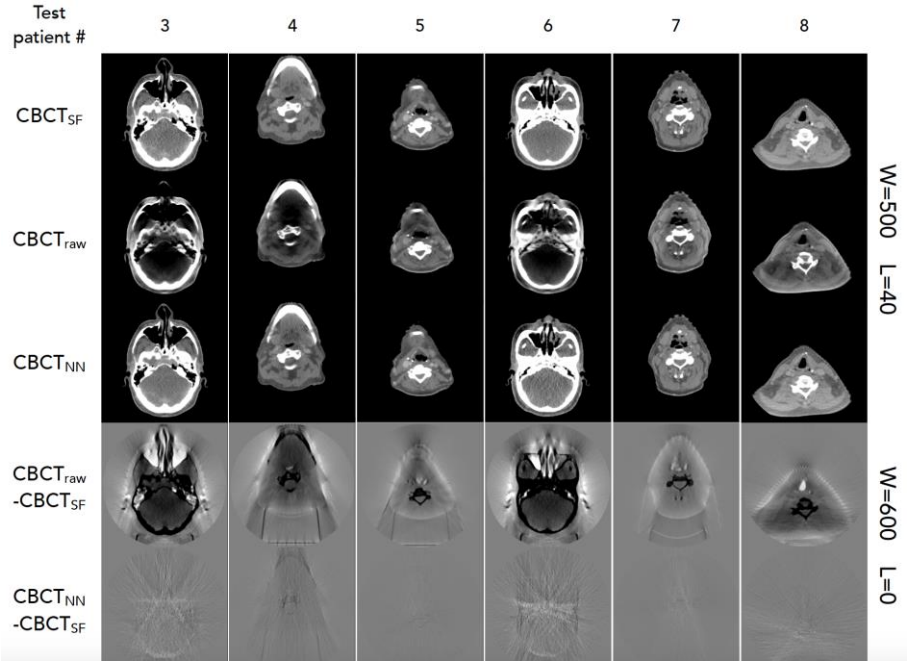


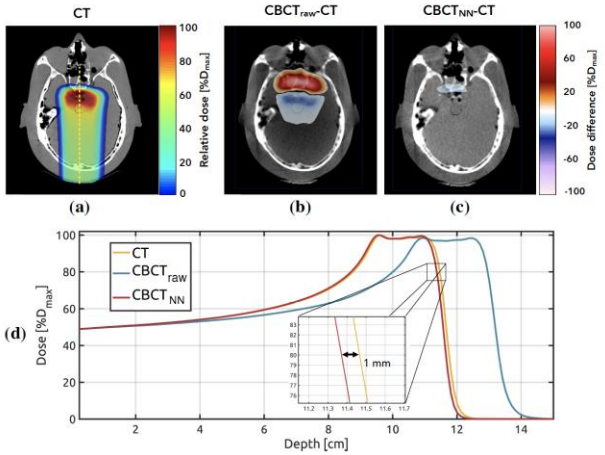


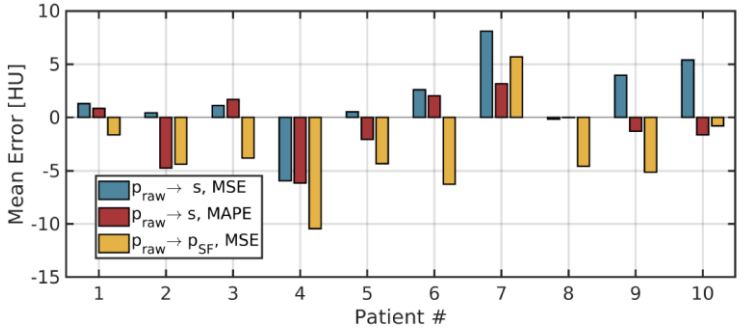
Landy *et al* *PMB* 2018.
Hansen *et al Med Phys* 2018
https://github.com/dchansen/ScatterNet

DCNN



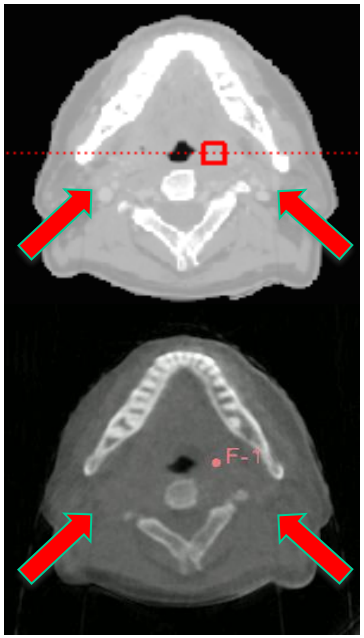




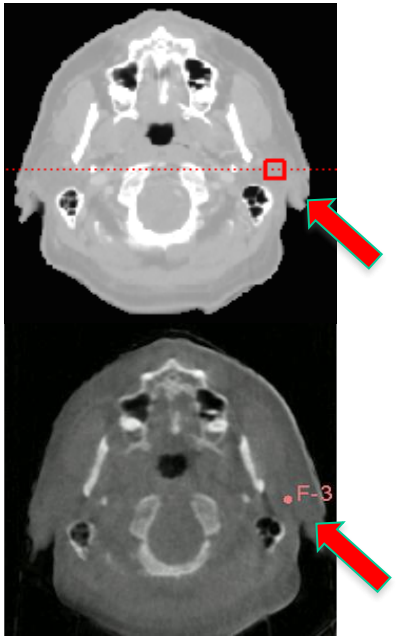


CBCT ranges within 1 mm/1%

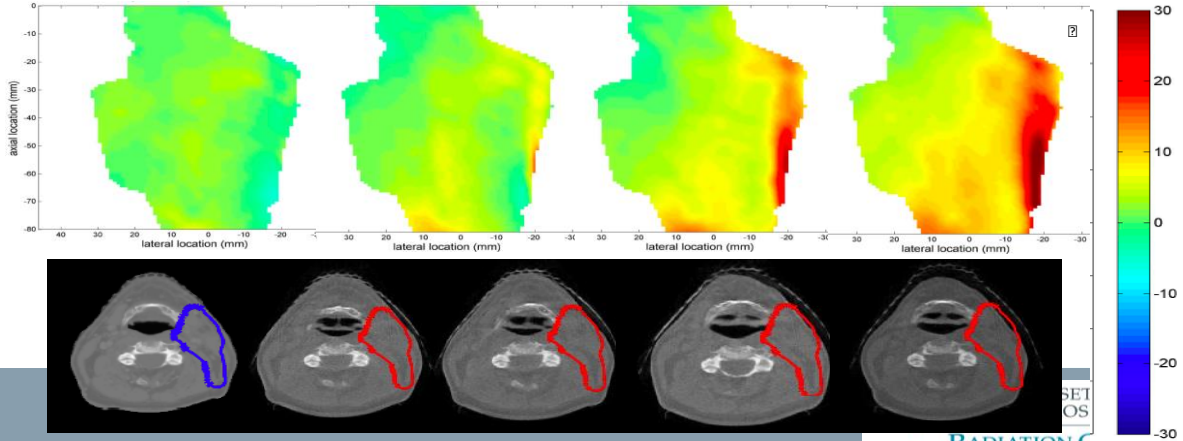
Head and Neck Variations



Weekly variations (current clinical imaging protocol)



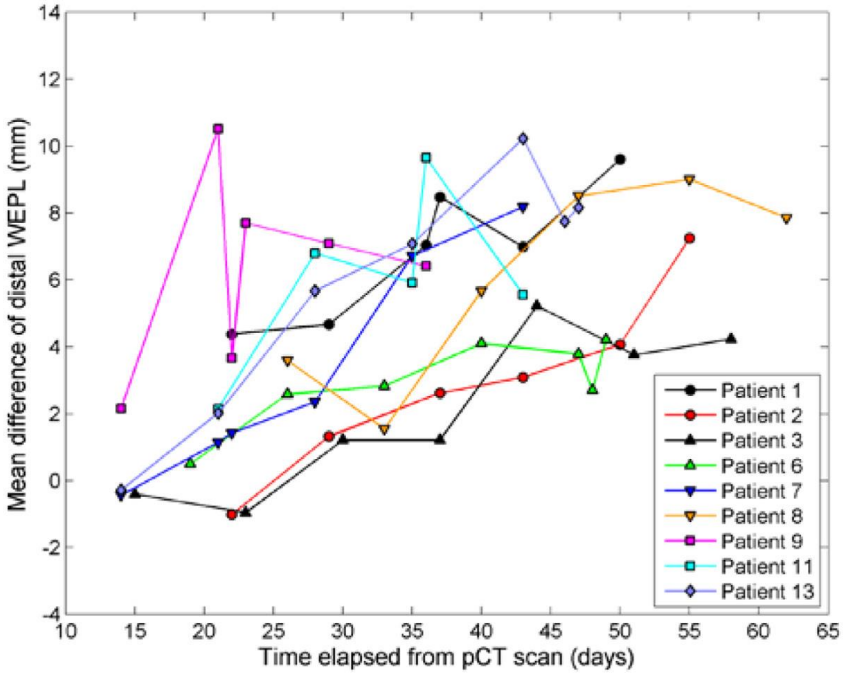
Patient	1	2	3	4	5	6
Day 1	1.0	-4.1	-2.4	-3.4	4.1	4.2
Day 2	2.7	-1.9	0.0	2.4	2.3	13.0*
Day 3	5.2	0.3	3.4	-0.4	3.0	4.7
Day 4	5.3	1.8	2.6	0.3	6.1	5.1
Day 5	7.1	0.8	0.2	4.5	8.9	7.1
Day 6	8.3	9.0	3.0	6.4	7.6	5.5
Day 7			1.4			6.2
Day 8						5.1

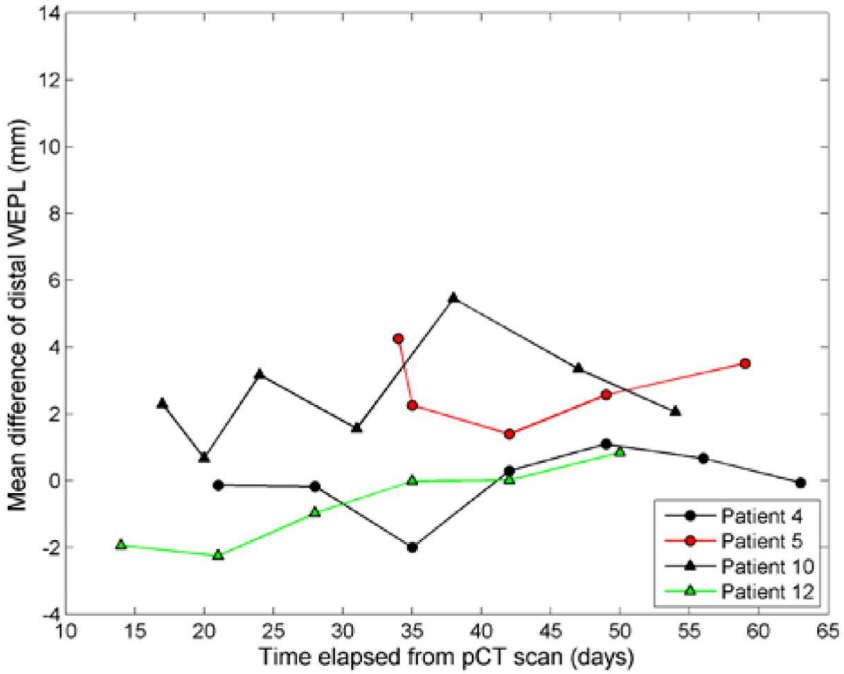


Kim *et al PMB 2017*

CBCT Applications:

- Triage

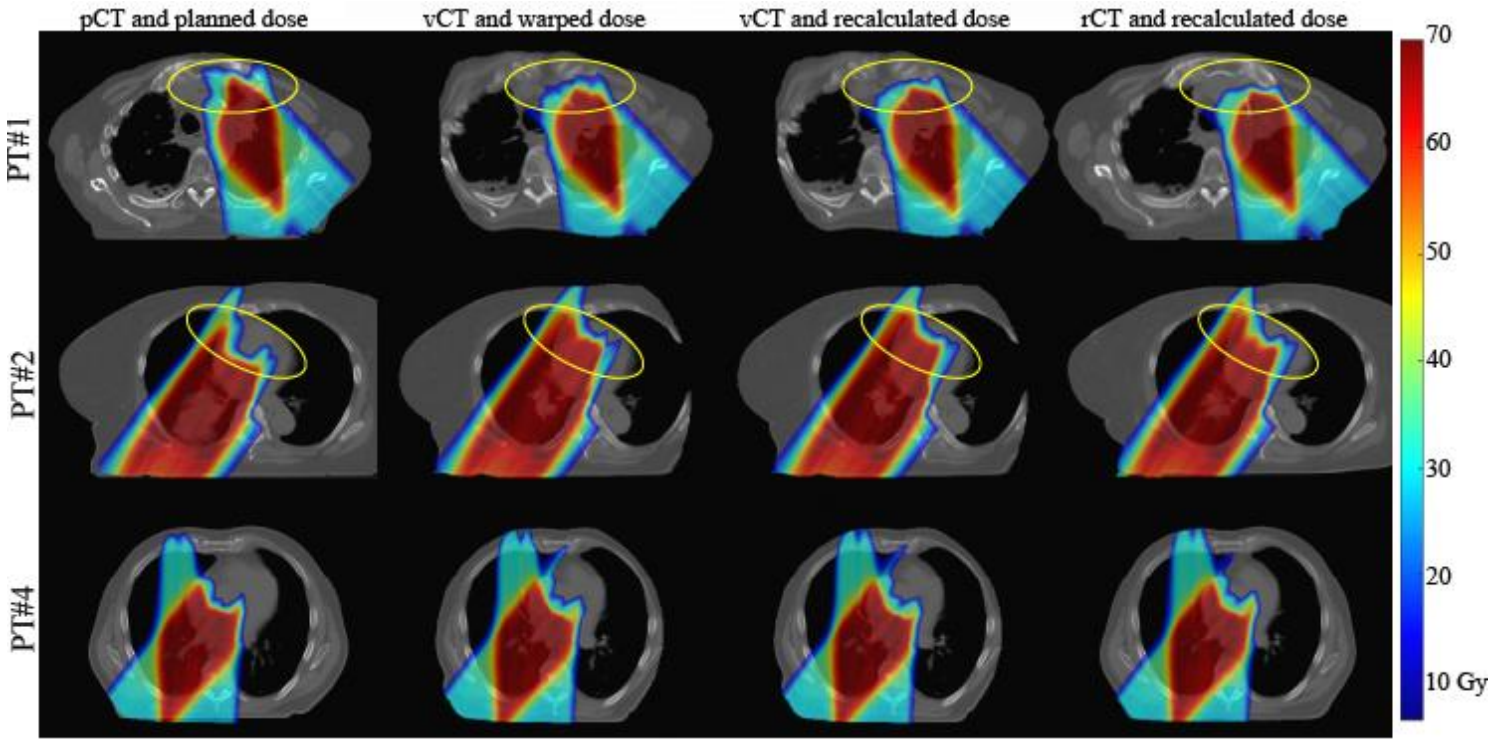




Kim *et al PMB 2017*

CBCT Applications:

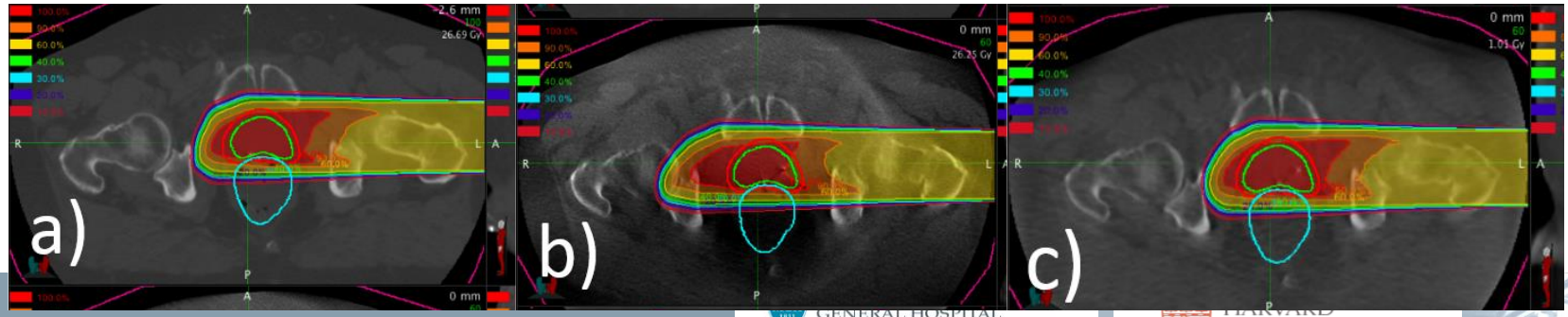
- Triage (U Penn)



Veiga *et al IJROBP 2016*

CBCT Applications:

- Triage (multiple possibilities)
- Dose Calculation
- Range verification
- Replanning… *Not yet*

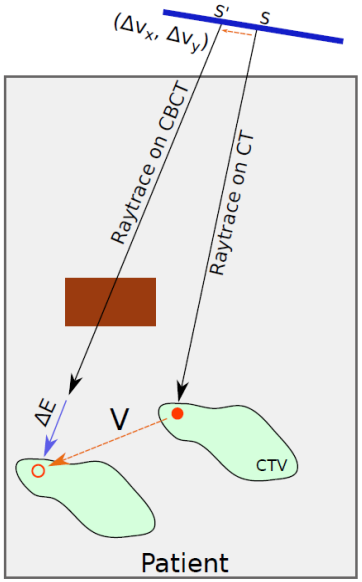


Replanning

- GPU Dose Calculation
- Reoptimize?

A vector field (VF) from DIR links CT and CBCT.
The VF is employed to:

1. Transport contours to new geometry
2. Warp IMPT plan (not dose). Per spot $s_i = (x_0, y_0, E_0)$:
   1: **Raytrace** central axis of s_i in CT to end of range (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



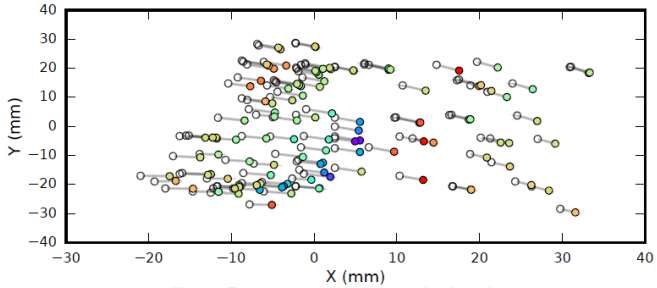


Fig: Plan positions shifted

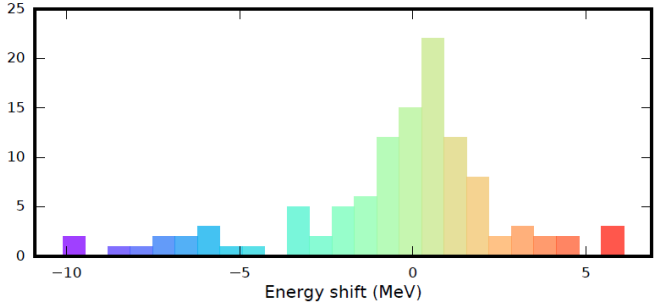
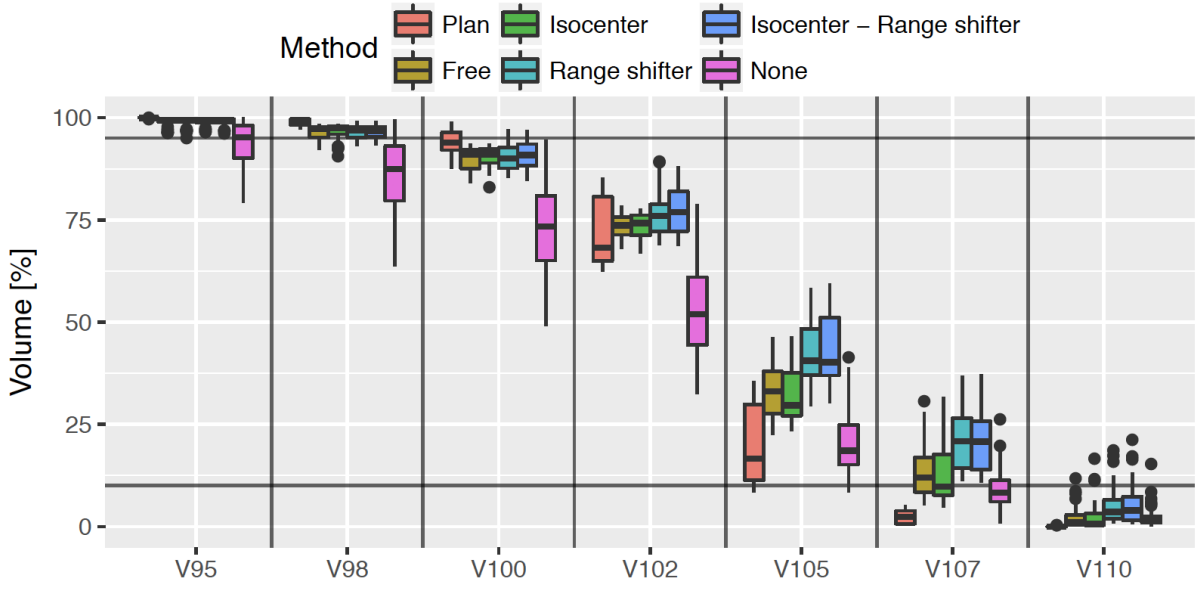


Fig: Energy shifts histogram.

Botas *et al PMB* 2018

Replanning

- Degrees of reoptimization
- Prioritize Targets/OARs (MCO role?)
- Match original or improve?

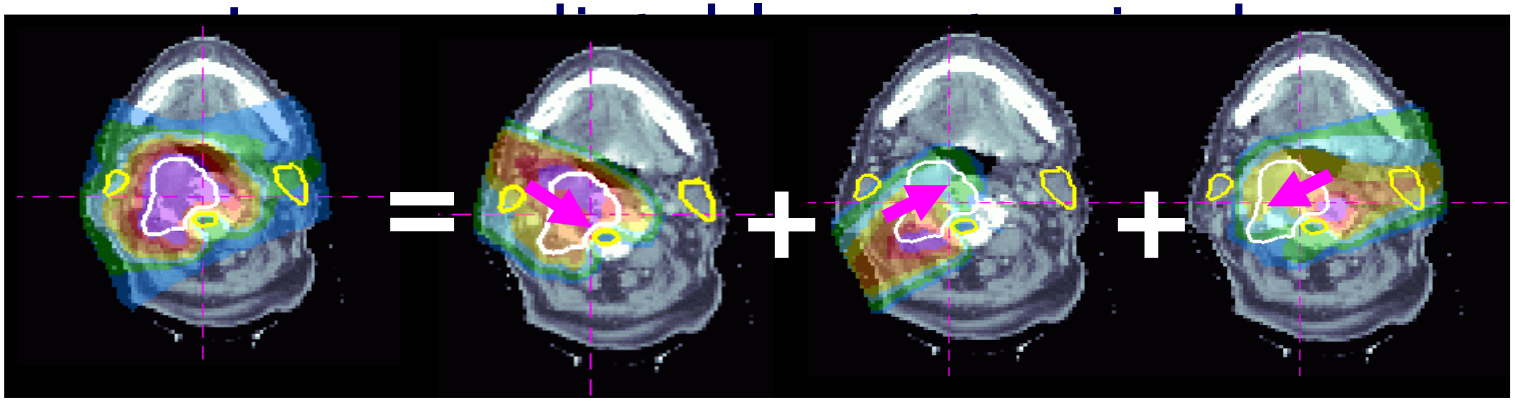


Current CBCT Daily Adaptation

- Daily adaptation with CBCT is close
- Rapid reconstruction with ML: 30 s
- Rapid GPU dose calculations (20-40 s)
- Reoptimization: seconds-minutes
- Contours?
- QA: ?

Robustness

- Is adaptive proton therapy required?
- What are the limits of robust planning?
- Uncertainty models: range and setup
- Motion? Deformations? Weight loss?



Trofimov et al

Conclusions

- CBCT is becoming more available and demonstrated as useful tools for setup and adaptive proton therapy: dose calculations, planning
- CBCT is now useable for WEPL and dose calculations with 1 mm/1% uncertainties
- Further research is needed for CBCT, 4D imaging, workflows, efficiency

Thank You!

http://gray.mgh.harvard.edu