Image Guidance for Proton Therapy

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Acknowledgements

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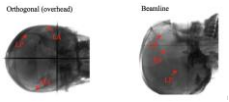
Introduction

- Current Imaging Technologies
  - 2D
  - 3D: CT and CBCT
- Review Current Imaging/Adaptive Workflows
  - Adaptive workflows
  - Adaptive: Methods, imaging, planning

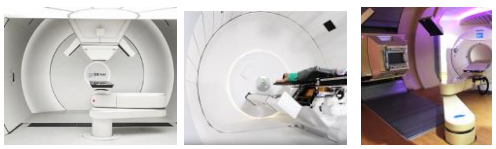
Current Imaging Technologies

- 2D Imaging
  - Anatomy: 2D/2D
  - Fiducials (Cranial/Prostate)
  - Gray Scale: 2D/3D
- CBCT
- CT
- Surface



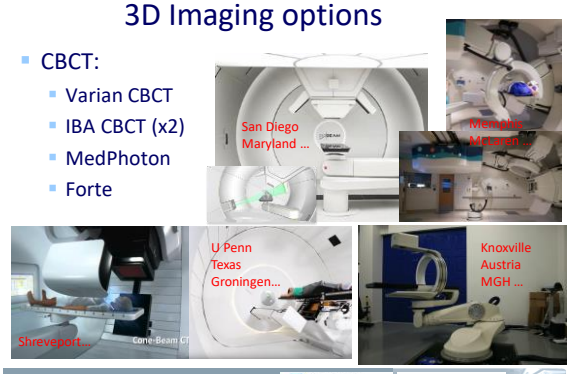
2D Imaging Options

- All proton therapy centers have 2D imaging capabilities
  - Fixed to room, Couch, or Gantry
  - Remains the most common imaging technique



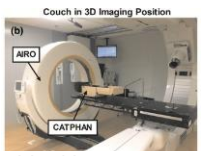
3D Imaging options

- CBCT:
  - Varian CBCT
  - IBA CBCT (x2)
  - MedPhoton
  - Forte



3D Imaging options

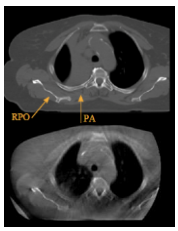
- CT:
  - In Room
  - Outside room



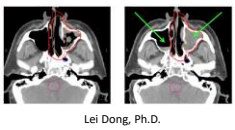
J Appl Clin Med Phys. 2017 May; 18(3): 130–136.

MEVION AND MEDPHOTON BRING ADVANCED CONE BEAM CT IMAGING TO PROTON THERAPY

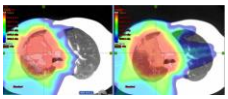
Needs: Anatomical Variations



Kevin Teo



Lei Dong, Ph.D.



Needs: Image Guidance

- In photon therapy, geometric alignment of anatomy is generally a good surrogate for dose
- In proton therapy, geometric alignment does not guarantee dosimetric delivery
- Need to understand the WEPL

Patient Needs/Demonstrated Benefits

- Imaging benefits and technological requirements vary with patients, motion extent, disease site, margins, clinical endpoints, reproducibility, immobilization, etc
- Benefits of various imaging techniques:
  - Treatment accuracy (3D>2D for many locations)
  - Real-time monitoring of patient/lesion positions
  - Adapting treatment

What should we do?

- Imaging Priorities: Variable for Patients/Sites
  - Accuracy
  - Image Quality: Bones or soft tissue?
  - Margins
  - Robust planning
- Patient Logistics and Comfort
  - Timing
  - Workflow

Green = Good
Yellow = Possible
Orange = inferior

Only CT/CBCT can provide WEPL information to the target. Surface and 2D imaging require a surrogate model based on a reference 3D image.

*Statements based upon clinical experience, photon publications, and proton publications

Site	2D Orthogonal X-Ray	CT / CBCT	Surface Imaging
Breast	Chest wall with bony surrogate, **Use Surface Imaging**	*Dose concern: lower dose CT/CBCT protocols*	Regular Use
CNS- Pediatrics	2D/3D alignment	*Dose concern: lower dose CT/CBCT protocols*	Open Masks, Supine
CNS- elsewhere	2D/3D alignment		Open Masks, Supine
CSI	Bony surrogates	*Dose concern: lower dose CT/CBCT protocols*	Demonstrated, Prone
H&N	2-3 mm uncertainty with bony surrogates, Limited knowledge of deformations	Soft tissue beneficial for deformations	Open Masks
Lung	Bony anatomy is poor surrogate unless target is fixed	Soft tissue visualization necessary, *Motion Artifacts*	Gating Only
GI	With implanted fiducials	Soft tissue visualization necessary, *Motion Artifacts*	Gating Only
Spine	Bony target well localized		Poor Surrogate, Monitor Position
Prostate	With implanted fiducials	Soft tissue visualization necessary, *but challenging*	Poor Surrogate, Monitor Position
Extremities	Well localized by bony surrogate but difficult to align	Prefer 3D imaging with large field of view for setup	Demonstrated
SRS	2D/3D alignment		Open Masks
SBRT Lung	Bony anatomy is poor surrogate, large margins	Soft tissue visualization necessary	Gating Only
SBRT Spine	1 mm accuracy challenge		Poor Surrogate

What should we do?

- In-room, each with impact on workflow:
  - kV systems: fluoro tracking, 2D/2D, 2D/3D
  - Surface Imaging
  - CT (on wheels/tracks, on rails)
  - CBCT: C-arm, Gantry, Couch mounted
- Out of room:
  - CT: challenge of timing and position accuracy

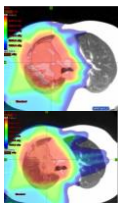
Best Imaging for Proton Therapy?

- Toward the goal of adaptive proton therapy, volumetric imaging is required*.
- CT and CBCT are the current best options for accurate setup and adaptive workflows
- Supplemented by 2D and surface imaging

**Ultrasound and MR not yet demonstrated for proton dose calculations or geometric accuracy*

CT

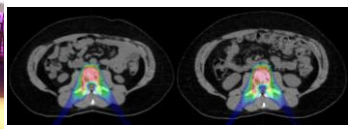
- CT: In room or outside Tx room
  - High Image Quality, 4D options
  - Workflow, time, robotic motions
  - Non treatment position
  - Commissioning similar to CTs:
    - **Calibration of isocenters**
    - **Robotic/CT motion accuracy**
  - Hardware shutdown?
- Use in Adaptive workflows has been published: MDACC and utilized at many centers (PSI and Mayo in room. Penn, MGH, MDACC, etc offline)



Lei Dong

CT In the Room

- Mayo: CT on Rails
- Frequently used for patient setup and plan assessment
- Surface imaging to track patient
- 2D at iso when needed



Jon Kruse

CBCT

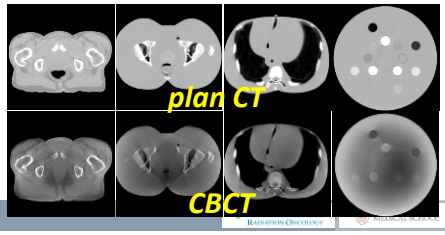
- CBCT:
  - Workflow, time
  - Lower image quality
  - Treatment position (or close)
  - Same isocenter (typically)
  - 4D Imaging is challenging
  - Commissioning similar to photon clinic:
    - **Biggest difference is Proton/CBCT isocenter coincidence-> Film or scintillator**
    - **HU to RSP for dose calculations?**
    - **Couch mounted: Robotic accuracy**

CBCT Workflow and Time

- Couch mounted
  - Faster than Gantry rotation
  - Not limited to a single imaging position
  - Large FOV
  - Complex calibration
  - Image during Tx
- Gantry Mounted
  - Simple Calibration
  - Half-rotation Gantries: 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
- Motion: iterative, etc

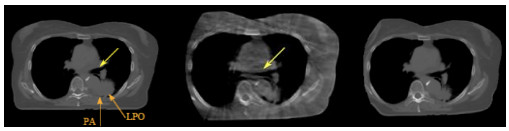
Aquilion ONE ViSION
0.5 mm x 320 detector
640 slices every rotation
16 cm of every rotation
0.275 sec/rotation

Artifact Correction Methods

- Software
  - Deform CT to CBCT
  - *A priori* CT scatter correction
  - Scatter Model (low frequency)
  - HU Look Up Table (LUT)
- Hardware
  - Anti scatter grids
  - Filtration

Correction Methods

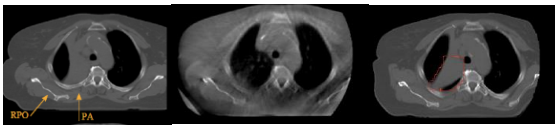
- Deform CT: Data from Kevin Teo (Penn)
  - Multiple publications (Penn and LMU Munich)



CT **CBCT** **dCT**

Correction Methods

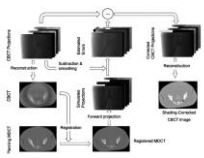
- Deform CT
  - Challenges when anatomy changes too much, especially with air cavities



CT **CBCT** **dCT**

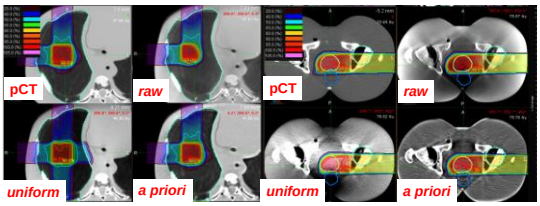
A priori Method*

- 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



*Portions of this study have been published in *Med Phys*

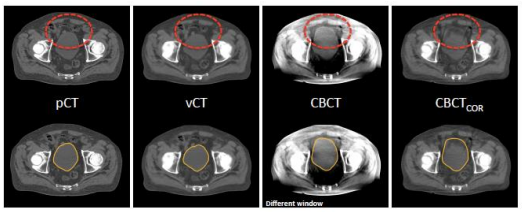
Dose Comparison: Phantoms



Park *et al Med Phys 2015*

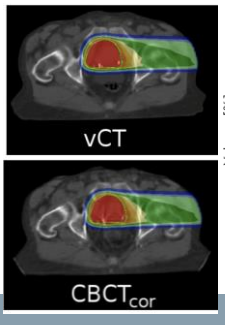
Correction Methods

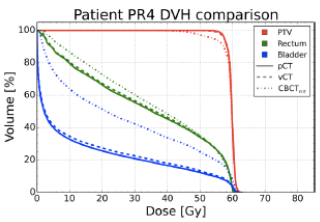
- Deform versus *a priori*



Kurz et al *Med Phys 2016*

Patient Dose Calculations



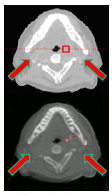


Kurz *et al Med Phys* 43(10): 5635, 2016.

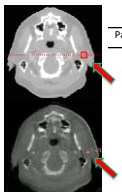
A Priori Method

- Current Limitation is time
- Generally found to have HU accuracy within 3% and WEPL accuracy within 2-3 mm.
- Beam hardening still needs addressed

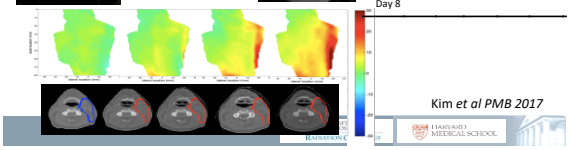
CBCT Applications: Head and Neck Variations



Weekly variations (current clinical imaging protocol)



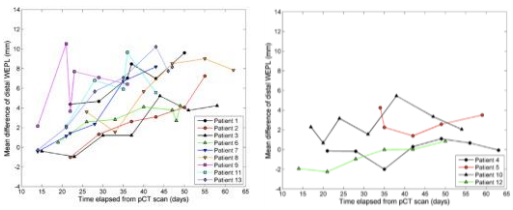
Patient	1	2	3	4	5
Day 1	1.0	-4.1	-2.4	-3.4	4.1
Day 2	2.7	-1.9	0.0	2.4	2.3
Day 3	5.2	0.3	3.4	-0.4	3.0
Day 4	5.3	1.8	2.6	0.3	6.1
Day 5	7.1	0.8	0.2	4.5	8.9
Day 6	8.3	9.0	3.0	6.4	7.6
Day 7			1.4		
Day 8					



Kim *et al PMB 2017*

CBCT Applications:

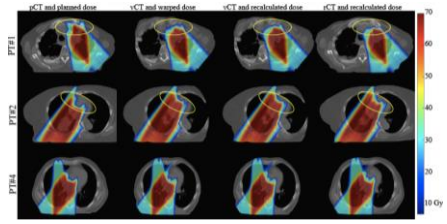
- Triage



Kim *et al PMB 2017*

CBCT Applications:

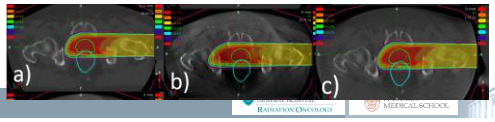
- Triage (U Penn)



Veiga *et al IJROBP 2016*

CBCT Applications:

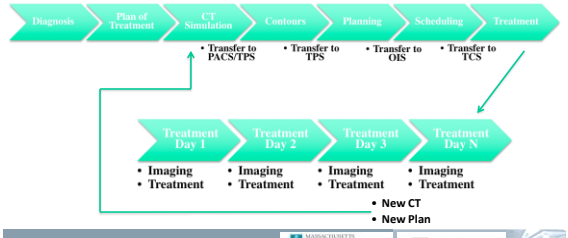
- Triage (multiple possibilities)
- Dose Calculation
- Range verification
- Replanning… *Not yet*



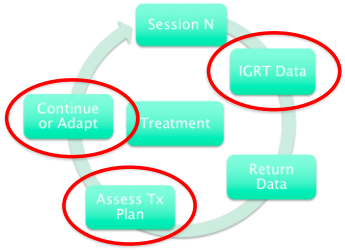
Needs for Adaptive Proton Therapy

- Framework to support imaging and replanning
- Imaging information
- Treatment planning
  - Rapid dose calculation (GPU now validated)
  - Rapid optimization (Research projects, easier once an optimized plan exists)

Workflow: Quasi Adaptive (aka Brute Force) Offline Imaging



Adaptive Workflow: Online Imaging



Examples from Penn and Mayo!

We have addressed the dose delivery assessment and have begun to look at optimization methods

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 $s \rightarrow s'_i = (x_0 + \Delta v_x, y_0 + \Delta v_y, E_0)$.
   5. **Raytrace** s'_i in CBCT
   6. Get ΔE.

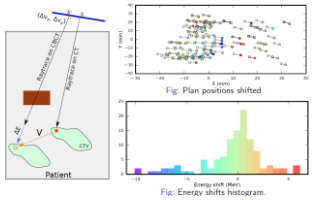


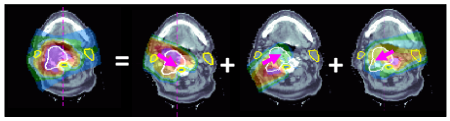
Fig: Plan positions shifted

Fig: Energy shifts histogram.

Botas et al

Current Trends for Adaptive Proton Therapy

- Robust treatment planning: reduce the need for adaption
- Imaging: 3D and tracking
- In vivo range imaging: feedback



Trofimov et al

Robustness

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

Conclusions

- CT and CBCT are becoming more available and demonstrated as useful tools for setup and adaptive proton therapy: Imaging (CT and CBCT, dose calculations, planning)
- CBCT is now useable for WEPL and dose calculations with 2-3 mm uncertainties
- Further research is needed for CBCT, 4D imaging, workflows, efficiency

Thank You!

http://gray.mgh.harvard.edu