Image Guidance for Proton Therapy

Brian Winey, Ph.D.
Medical Physicist, MGH
Assistant Professor, HMS

Acknowledgements

- Research grant from Elekta

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

San Diego, Maryland

U Penn, Texas, Greningen...

Knoxville, Austria, MGH...
3D Imaging options

- CT:
  - In Room
  - Outside room


Trento Dresden Mayo PSI

Needs: Anatomical Variations

Kevin Teo

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

<table>
<thead>
<tr>
<th>Site</th>
<th>2D Orthogonal X-Ray</th>
<th>CT/CBCT</th>
<th>Surface Imaging</th>
</tr>
</thead>
<tbody>
<tr>
<td>Head</td>
<td></td>
<td>3D (reconstructed)</td>
<td></td>
</tr>
<tr>
<td>CTV</td>
<td>Head may require multiple imaging sessions, prior knowledge to deformation</td>
<td>3D set (reconstructed)</td>
<td></td>
</tr>
<tr>
<td>2D</td>
<td></td>
<td>2D set (reconstructed)</td>
<td></td>
</tr>
<tr>
<td>Spine</td>
<td></td>
<td>2D set (reconstructed)</td>
<td></td>
</tr>
<tr>
<td>Extremities</td>
<td>2D ortho</td>
<td>2D set (reconstructed)</td>
<td></td>
</tr>
<tr>
<td>SBRT Lung</td>
<td>2D orthogonal</td>
<td>2D set (reconstructed)</td>
<td></td>
</tr>
<tr>
<td>SBRT Spine</td>
<td>1 mm accuracy challenge</td>
<td>2D set (reconstructed)</td>
<td></td>
</tr>
</tbody>
</table>

*Statements based on clinical experience, phantom publications, and proton publications.

Green = Good
Yellow = Possible
Orange = Inferior

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

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 Gantry: 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

**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)

Correction Methods

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

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

Correction Methods

- Deform versus a priori

Patient Dose Calculations
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)

CBCT Applications:

- Triage
CBCT Applications:

- Triage (U Penn)

![CBCT Image]

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

- New CT
- New Plan

Adaptive Workflow: Online Imaging

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

Replanning

- GPU Dose Calculation
- Reoptimize
Current Trends for Adaptive Proton Therapy

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

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