Proton Workflows for In-Room CT

Jon J. Kruse
Mayo Clinic, Rochester MN
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Range and Tumor Depth

Nominal Plan

Long Shift in BEV
Range and Tumor Depth

Nominal Plan

Internal Target Shift
CT Number to rSP

\[ S = \frac{4\pi}{m_e c^2} \cdot \frac{n e^2}{\beta^2} \cdot \left( \frac{e^2}{4\pi \varepsilon_0} \right)^2 \cdot \left[ \ln \left( \frac{2 m_e c^2 \beta^2}{\langle \| \rangle \cdot (1 - \beta^2)} \right) - \beta^2 \right] \]
Range and Tumor Depth

Nominal Plan

3% Error in RSP
Range and Tumor Depth

Proper target coverage in proton therapy requires:

1. Target at planned location relative to isocenter
2. Target at planned location IN patient
3. Water Equivalent Depth of target is correct – Relative Stopping Power of tissues correctly determined from CT numbers
IGRT Systems
IGRT Systems

Orthogonal X-ray Panels
• Rapid, low dose imaging
• 6 DOF Adjustment
• Fluoroscopy capable
IGRT Systems

VisionRT Surface Imaging
- 3 PODs
- Surface Guided Setup
- Live Patient Monitoring
- Verify Couch Motions
IGRT Systems
CT Localization Step 1: 2D Imaging

- Adjust Patient Pose
- Localize Bony Anatomy, Fiducial Markers
- Establish Reference Couch Coordinates
CT Localization Step 2: Surface Imaging

- Capture Reference Surface Image After 2D Localization
CT Localization Step 3: CT Scan

- Move Patient ~1m from Tx Iso to CT Iso
- Motion takes ~60 seconds
- Acquire Scout Image
- Scan
- Send CT Image to IGRT System
CT Localization Step 4: 3D3D Registration

- Move Patient Back to Tx Iso During Registration
- Acquire Surface Image to Verify Correct Couch Position, Patient Pose
- Apply 6 DOF Corrections
- Acquire New Surface Reference
- Treat
Downsides of CT on Rails Localization

• Must move patient ~1m each way for imaging
  • Potential for patient motion, inaccurate couch motions
    • Robotic couch mechanical accuracy QA better than 0.5 mm
    • Patient position on couch verified with surface imaging
• Added treatment time
  • Compared to 2D IGRT protocols, CT on Rails localization adds ~5 minutes to a treatment session
  • Typical appointment slots 30 to 45 minutes
Advantages of CT on Rails Localization

- Diagnostic Image Quality
  - Large field of view
  - Superior image quality compared to CBCT
  - Mayo Rochester RadOnc has 4 CT simulators, 2 CT on Rails
  - CT on Rails are the same scanner model as the sim
  - HU to rSP calibration for CT on Rails matches calibration for sims
    - 1 Calibration curve in planning system for all 6 scanners
    - Accurate calculation of proton treatment plans
Advantages of CT on Rails Localization

- Spot scanning proton plans have time-dependent delivery
- Mobile targets at Mayo are treated with breath-hold or phase gating
- Free-breathing average CT image is a poor medium for localizing breath-held or gated treatments

Bert et al., PMB 53 (2008)
Respiratory-Managed Imaging

- Breath-held Treatment: Breath-held Helical CT easy to acquire
- Phase-gated Treatment: Acquire 4DCT, reconstruct only exhale phase for localization
4DCT for Localization

- Proton plan optimized on average of phases within the respiratory gate
- Sub-average image serves as the reference for localization, comparison to exhale 4D acquired at treatment
- Target contour from exhale phase displayed on reference for localization
Range Errors in Proton Therapy

- HU to rSP Errors
  - Errors in HU-rSP Calibration
  - Image Artifact
  - Variations in HU from x-ray hardening
  - Deviation of human tissue from ICRU standard
  - Uncertainty in mean excitation energies

  - Typically ≤ 3% (3 mm for a target depth of 10 cm)

- Anatomical Changes in Target Depth
  - Variations in posterior tissue on immobilization device
  - Weight gain/loss
  - Tumor volume changes
  - Variation in patient pose

- Tumor depth can vary by several cm or more, systematically or day by day
CT Guided SBRT

Original Plan
CT Guided SBRT

Tx Image Registration
CT Guided SBRT

Verification Dose
Prostate SABR
Prostate SABR

Pre-Treatment Registration
Prostate SABR Variation

Original Plan

Verification Plan
Evaluating Anatomy Changes Pre-Tx

- Display contours of target, critical normal anatomy
- Convert 500 cGy Isodose to structure, display pre-Tx to evaluate external contour at beam entry points
- Plan robustness is documented in patient chart
- Compare variations in external to range robustness of treatment plan
Verification Plans: Off-line Adaptive Proton Therapy

- Repeat CT scans over course of treatment, re-calculate dose to verify coverage
- Patient pose is often the dominant factor in dosimetric integrity
- Difficult to achieve in CT simulator
- Post-treatment CT on Rails can be acquired in actual treatment position
Treatment Plan Adaptation by Site

Percent of Patients Replanned by Site

Site (N = number of patients for whom we have data)

- Prostate (N = 138)
- GYN-Rectal-Anal (N = 18)
- Abdomen (N = 33)
- Breast (N = 123)
- Esophagus (N = 35)
- Brain (N = 63)
- Liver-Pancreas-Adrenal (N = 18)
- Bone-Spine-Chordoma-Sarcoma (N = 38)
- CSI (N = 26)
- Pelvis (N = 14)
- Lung-Chest (N = 38)
- Head-Neck (N = 164)
Near Future of CT on Rails: Pre-Tx Dose Validation

Small Anatomical Change: Large Dosimetric Impact

Large Anatomical Change: Small Dosimetric Impact
Pre-Treatment Dose Validation

- Mayo Clinic has an in-house GPU cluster for rapid Monte Carlo dose calculation of proton plans.
- CT on Rails will send localization images to IGRT system, and to GPU cluster in Tx room.
- After registration, SRO sent to GPU cluster for localization of proton beams.
- Dose calculated and displayed before patient position is applied.

Calculation time per $10^7$ proton histories on 1 GPU

Tseung et al., Med Phys 2015
Future of CT on Rails: Online Adaptive Proton Therapy

• Acquire CT image immediately before treatment
• Register to planning image, deform contours
  • AI Assisted
• Calculate dose on anatomy of the day
  • GPU Monte Carlo
• Adapt treatment plan to account for anatomy changes
  • AI Assisted
• Validate treatment plan and deliver
  • Pretreatment analysis of magnet settings and beam energies
On-Line Plan Adaptation: Liver Treatment
On-Line Plan Adaptation: Two Anatomy Presentations
On-Line Plan Adaptation: Two Treatment Plans

Pre-Treatment Imaging used to localize patient AND select treatment plan
CT on Rails Summary

• Disadvantages (time and patient motion) can be controlled
• Several distinct advantages relative to CBCT
  • Diagnostic image quality
  • 4D capability
  • Excellent HU accuracy
  • Dose calculation and plan adaptation without any other image processing
• On-line plan validation and adaptation on the near horizon