Imaging for Proton Treatment Planning and Verification

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Uncertainties in Proton Therapy

• Localization Uncertainty
  * Analogous to x-ray treatment geometric uncertainties
  * Acts orthogonal to treatment beam direction
  * Countered with daily image guidance

• Range Uncertainty
  * Analogous to x-ray treatment heterogeneity uncertainties
  * Acts parallel to treatment beam direction
  * Determined from treatment planning CT scan
CT Simulation for Proton Therapy

- 3D (or 4D) model of the patient for geometric treatment planning
- Reference images for daily treatment guidance
- Substrate for basic dose calculation
- Material composition information for heterogeneity corrections
  - Relative electron density
  - Proton stopping power

Photon Planning: Relative Electron Density

- Scan commercial phantom with known RED
- Measure HU in scan
- Enter HU-RED curve in photon planning system

Proton Planning: Stopping Power

- Proton stopping power comes from Bethe-Bloch equation:
  \[ S = \frac{4\pi n e^2}{m_e c^2} \left( \frac{e^2}{4\pi e_0} \right)^2 \cdot \left[ \ln \left( \frac{2m_e c^2 \beta^2}{I} \right) - \beta^2 \right] \]
- \( n \) is electron density of the medium
- \( I \) is excitation energy of the medium
- HU-SP degeneracy
- Phantom materials are not like human tissues
- Stoichiometric Calibration Process
**Stoichiometric Calibration**

1. Measure HU of materials with known RED

   - Plugs have well known RED values
   - Elemental composition not tissue equivalent
   - Typically scan one plug at a time in center of phantom
   - Use fixed, clinical CT protocol

2. Parameterize CT Scanner by Fitting HUs

   - $Z$ and $\hat{Z}$ are material properties for photoelectric and Compton
   - Scanner parameters:
     * A: photoelectric
     * B: Compton
     * C: Klein-Nishina

3. Calculate Predicted HU for ICRU Tissues

   - $\hat{Z}$ and $\hat{\hat{Z}}$ can be calculated for tissues with physical properties published by ICRU
   - Scanner parameters:
     * A: photoelectric
     * B: Compton
     * C: Klein-Nishina
Stoichiometric Calibration

4. Calculate Relative Stopping Power for Reference Tissues

\[ S_p = \rho_p \frac{\ln \left( \frac{2m_e e^2 \beta^2}{U_{\text{max}}(1 - \beta^2)} - \beta^2 \right)}{\ln \left( \frac{2m_e e^2 \beta^2}{U_{\text{water}}(1 - \beta^2)} - \beta^2 \right)} \]

- I is ionization potential for material
- I is assumed to be ~75 eV for water
- More uncertainty in I for other materials

Schneider et al., PMB 1996

Stoichiometric Calibration

5. Plot Relative Stopping Power vs. Calc. CT

- Nominally fit to bilinear curve
- More segments used in soft tissue region to cover tissues with differing H composition

Schneider et al., PMB 1996

Uncertainties in HU to SP

- Degeneracy in SP values for tissues with same HU
- HU value uncertainty
  - Technique
  - Position in scanner
  - Artifact
- Uncertainties in mean excitation value
- Variations in human tissue composition
- Expected Range Uncertainty: ~3.5% + 1 mm
Potential Solutions for Better Range Accuracy

- **Dual Energy CT**
  - Potential to better characterize patient composition and stopping power

- **MVCT**
  - Reduction in scattering artifact

- **Proton CT**
  - Traverse the patient with a proton beam and measure residual energy at exit
  - Direct map of stopping power

Proton vs Photon Treatment Localization

- In the past 15 years IGRT for x-ray therapy has evolved and matured
  - EPID
  - kV Radiographic systems
  - CBCT
  - MR Linacs

- Proton therapy IGRT has lagged behind
  - Market size
  - Different needs, priorities in proton therapy

Proton IGRT Considerations

- Delivery system constraints
  - Gantry geometry

- Efficiency
  - Proton treatment rooms are expensive
  - Precise setup critical – protons more sensitive to changes in volume, pose

- Targeting goals
  - Anatomy targeting for protons different than for photons
Photons: Radiographic Localization

- Suitable for when bony anatomy is a good surrogate for target tissue, or when fiducials are placed
- Gantry mounted
  - MV EPID
  - kV Systems
- Fixed position imagers
  - BrainLab ExacTrac
  - Hokkaido RT-RT fluoroscopic system

Gantry Mounted Imagers

- Use of treatment beam for imaging
  - Imaging during treatment
  - BEV imaging – Important ‘Sanity Check’ on patient setup, other IGRT procedures
- Rotating gantry facilitates CBCT
BEV Imaging in Protons

- Small spot size important for scanning proton facilities
- X-ray tube in a scanning nozzle introduces atmospheric drift length; larger spot size
- Can’t image during proton treatment


Cone-beam Computed Tomography, Real-time tumor-monitoring, and gated proton spot-scanning beam therapy.

High precision positioning system (2D, 3D, and 4D)

- 2D, 3D positioning based on bony anatomy and soft tissue matching (radiography, CBCT)
- 4D positioning (real-time tumor-monitoring system)
- Verification
  - Fiducial migration (radiography, CBCT)
  - Inter-fractional variation of proton range (CBCT)

Gold marker

3 + 1 dimensional positioning (real-time tumor-monitoring system, Hokkaido University)
Limited Gantry Proton Systems

- Proton gantries are large and expensive
- Limited number of beam angles gives adequate plan quality for a number of treatment sites
- Lose the gantry support structure for imaging equipment

ProCure Fixed Beam Imaging

- Fast Intra-Tx imaging at any gantry/couch position
- Fluoroscopy capable
- Large FOV
- No moving parts – stable imaging isocenter
- 6 DOF matching software

Mayo Clinic Half Gantry

- Image from ProCure Website
Mayo Clinic Half Gantry

- Limited to two imaging angles
- FOV is 30 cm x 30 cm at isocenter – may not see center of tumor volume for non-isocentric plans

ProTom Robotic C-Arm

- Rotates to acquire radiographic projections for setup on 2D images
- Robotic arm allows for mobile imaging isocenter
- CBCT capable

ProTom Robotic C-Arm

- Imager Retracts to avoid interference with therapy nozzle, rotating couch

Courtesy of Sung Park
Mayo Clinic Half Gantry

- Limited to two imaging angles
- FOV is 30 cm x 30 cm at isocenter – may not see center of tumor volume for non-isocentric plans
- Not CBCT capable

Utility of CBCT for Protons

- Bony anatomy is often a poor surrogate for target/critical anatomy
- Fiducials or CT localization required in cases where we expect movement of soft tissues relative to radiographically evident bony anatomy
- Photons: Place target tissue at isocenter, don't worry about ‘upstream’ bony anatomy
- Protons: ??

CT Localization for Protons: Pelvis

- Change in position of bony anatomy alters dose distribution
- CT localization may be of limited use
CT Localization for Protons: Lung

- Change in position of rib causes minimal disturbance of dose distribution
- CT localization of lung tumors desirable for proton therapy

CBCT for Lung?

- Mayo proton facilities will be scanning beam only
- Treatments of mobile tumors will probably require gating/breath hold
- Free-Breathing CBCT imaging a poor reference for gated/breath held treatment
- Gated/breath held CBCT not impossible, but not easy

CBCT for Adaptive Protocols

- Proton dose calculation is extremely sensitive to CT number accuracy
- CT number accuracy / consistency not generally a priority in CBCT
- Increased scatter relative to helical CT degrades imaging performance
Helical/CBCT Phantom Images

Images Courtesy of T.J. Whitaker

CT on Rails

- Robot moves patient to imaging isocenter
- CT translates over patient for imaging
- Robot moves patient back to treatment isocenter while CT registration is performed
- Helical CT image quality
  - Images for adaptive imaging
- Fast image acquisition
- 4D imaging capability
Imaging Outside Treatment Room

• To increase throughput some imaging and treatment preparation has been moved outside the treatment room
• Patients should not be in the treatment room unless they're being aligned for treatment or being treated
• Various approaches
  • Immobilization/treatment preparation
  • Treatment localization
  • Imaging for adaptive planning protocols

Treatment Preparation

• Some treatment sites require difficult/time consuming preparation and immobilization
  • CSI
  • Brain cases – fluid in surgical sites
  • Head and Neck – changes in mask fit
• Immobilize and image patient outside treatment room to verify that patient pose is correct

Treatment Preparation Outside Tx Room

• 2 rooms with robotic positioners, lasers, and fixed orthogonal imagers
• Patient is immobilized and imaged
• Images are compared to DRRs to assess patient pose, not position
• Patient immobilization can be adjusted and re-imaged with little time pressure
• When pose is correct, transported to Tx room
Treatment Preparation Outside Tx Room

- Anesthesia Suite
- Imaging Rooms
- Beam Matched Tx Rooms

Treatment Localization Outside Room

- In some centers treatment localization is performed outside treatment room
  - Less work in treatment room
  - Access to various imaging modalities
- Imaging isocenter in one room tied to treatment isocenter in another
  - Careful, multiroom QA protocols
  - Precise patient transport systems
Remote patient positioning at PSI

1. Patient preparation: 5 minutes
2. Patient positioning checks: 5 minutes minimum
3. Transfer to treatment room: 2+2 minutes
4. Treatment delivery: 5-30 minutes
5. Transfer out of treatment room: 2+2 minutes

Patient Transporter

- Twin system for parallel operation
- Operable by one person
- Guided by optical tracks
- Connecting various predefined locations:
  - Preparation room
  - Anesthesia room
  - CT room
  - Gantry room
- Table coupling at CT and Gantry
- Reliable operation:
  - Increased comfort for patient
  - Decreased physical work for staff

Patient positioning: Remote Positioning at CT

Daily pre-treatment positioning at CT

- Horizontal and vertical scouts
- Compared against reference scouts (from treatment planning CT series)
- No axial CT scan acquired
- Online matching of anatomical landmarks:
  - Semi-automatically and/or manually
  - Offsets for table coordinates at Gantry (translations only)
- Linked to Gantry Control System (via RBB® interface)
- Software developed in-house ("ppp")
CT Gurney

Load Position

Handoff in the treatment room
Use of Fiducials

- Fiducial markers used to great effect in photon therapy in place of volumetric imaging
- Proton specific concerns with use of fiducials
  - CT artifact
  - Dose shadowing

CT Artifact from Fiducials

Huang et al., PMB 56 (2011) 5287

Dose Perturbations from Fiducials

Huang et al., PMB 56 (2011) 5287
Summary

- Dose-Volume uncertainties in proton therapy have some sources common to photon therapies, some unique
- CT simulation protocols require strict calibration and control
- Treatment localization imaging is maturing in proton therapy, responding to unique needs of the modality