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

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^V Photon Planning: Relative Electron Density



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

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Proton Planning: Stopping Power

• Proton stopping power comes from Bethe-Bloch equation:

$$S = \frac{4\pi}{m_e c^2} \cdot \frac{n z^2}{\beta^2} \cdot \left(\frac{e^2}{4\pi\epsilon_0}\right)^2 \cdot \left[\ln\left(\frac{2m_e c^2\beta^2}{\langle \mathbf{l}\rangle\cdot(\mathbf{1}-\beta^2)}\right) - \beta^2\right]$$

- 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



Schneider et al., PMB 1996

 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

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Stoichiometric Calibration

2. Parameterize CT Scanner by Fitting HUs

- \widetilde{Z} and \widehat{Z} are material properties for photoelectric and $HU_{sc} = \rho_{s=-}^{rel} (A \cdot \widetilde{Z} + B \cdot \widehat{Z} + C)$
 - Scanner parameters:
 - A: photoelectric
 - B: Compton
 - C: Klein-Nishina

Schneider et al., PMB 1996

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Stoichiometric Calibration

3. Calculate Predicted HU for ICRU Tissues

HU _{sc}	=	$\rho_{e-}^{\text{rel}}(A$	•	\tilde{Z}	+	В	•	Ź	+	C)

• Ž and Ż can be calculated for tissues with physical properties published by ICRU

- Scanner parameters:
 - A: photoelectric
 - B: Compton
 - C: Klein-Nishina

Schneider et al., PMB 1996

MAYO CLINIC Stoichiometric Calibration

4. Calculate Relative Stopping Power for Reference Tissues



- 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

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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

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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

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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

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Gantry Mounted Imagers





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Photon 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

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- 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

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ning Magnet (Y) He Chambe anning Magnet (X) He Chamber ttering Device X - ray tube Sub-dose monito Main dose m ot Position Monito Energy Filter out Moving Devic Energy Absorber Aperts Gillin et al., Med Phys 37 (2010) p. 154

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Profile Mor









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

FIRST

- \checkmark 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)



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

Advanced Radiation Therapy Project - Real-time Tumor-tracking with Molecular Imaging Technique

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

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ProCure Fixed Beam Imaging



Image from ProCure Website

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Mayo Clinic Half Gantry



- 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



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

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ProTom Robotic C-Arm



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

Courtesy of Sung Park

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

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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

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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

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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







Images Courtesy of T.J. Whitaker





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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

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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

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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 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









Patient positioning: Remote Positioning at CT



Daily pre-treatment positioning at

CT Horizontal and vertical scouts Compared against reference 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 PatBase "R&V" interface)

Software developed in-house ("ppp")

Daily Treatment Setup at PSI

Alessandra Bolsi, 11th January 2010





MAYOCLINIC Multi Modality Remote Localization



PTC Prague

Courtesy of Jonathon Farr

MAYO CLINIC Multi Modality Remote Localization



PTC Prague

Courtesy of Jonathon Farr

CT Gurney



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ProCure

Load Position





Handoff in the treatment room



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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

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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