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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

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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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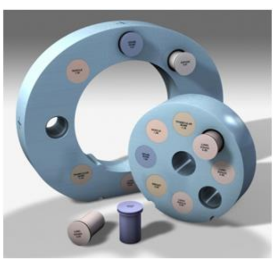
Photon Planning: Relative Electron Density



- 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:

$$S = \frac{4\pi}{m_e c^2}\cdot\frac{nz^2}{\beta^2}\cdot\left(\frac{e^2}{4\pi\epsilon_0}\right)^2\cdot\left[\ln\left(\frac{2m_e c^2\beta^2}{(I)\cdot(1-\beta^2)}\right)-\beta^2\right]$$

- 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

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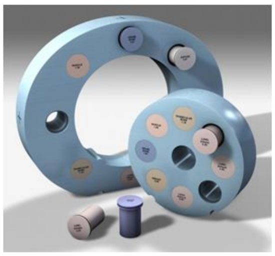
Stoichiometric Calibration

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

Schneider et al., PMB 1996

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Stoichiometric Calibration

2. Parameterize CT Scanner by Fitting HUs

$$\mathrm{HU}_{sc} = \rho_{e-}^{rel}(A \cdot \tilde{Z} + B \cdot \hat{Z} + C)$$

- $\tilde{Z}$ and $\hat{Z}$ are material properties for photoelectric and Compton
- 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

$$\mathrm{HU}_{sc} = \rho_{e-}^{rel}(A \cdot \tilde{Z} + B \cdot \hat{Z} + C)$$

- $\tilde{Z}$ and $\hat{Z}$ 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

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Stoichiometric Calibration

4. Calculate Relative Stopping Power for Reference Tissues

$$S_p = \rho_{e-}^{rel} \cdot \frac{\left\{ \ln\left[\frac{2m_e c^2 \beta^2}{\langle I_{mat} \rangle (1-\beta^2)}\right] - \beta^2 \right\}}{\left\{ \ln\left[\frac{2m_e c^2 \beta^2}{\langle I_{water} \rangle (1-\beta^2)}\right] - \beta^2 \right\}}$$

- 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

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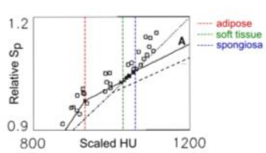
Stoichiometric Calibration

5. Plot Relative Stopping Power vs. Calc. CT



- Nominally fit to bi-linear 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

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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

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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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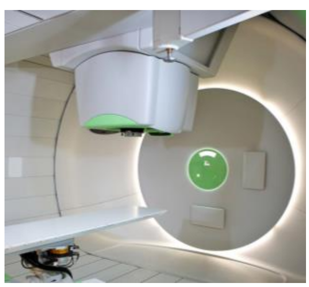
Gantry Mounted Imagers



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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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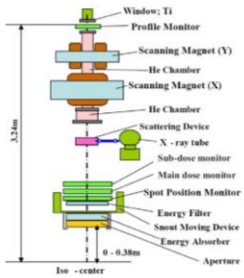
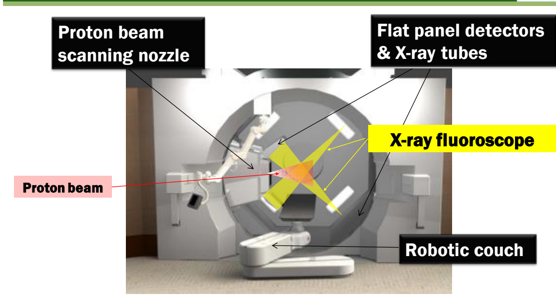
BEV Imaging in Protons

- 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



Gillin et al., Med Phys 37 (2010) p. 154

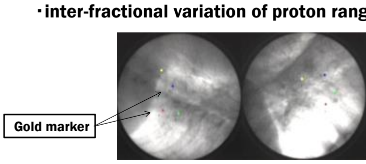
Cone-beam Computed Tomography, Real-time tumor-monitoring, and gated proton spot-scanning beam therapy.



Hokkaido University ; Supported by a grant from the Japan Society for the Promotion of Science (JSPS) through the "Funding for World-Leading Innovative R&D on Science and Technology"(FIRST program).

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)



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

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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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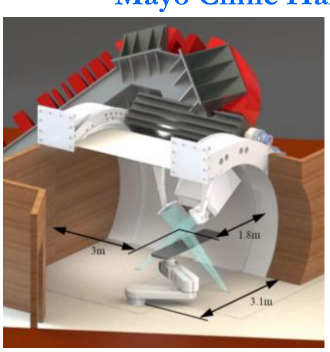
Mayo Clinic Half Gantry



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

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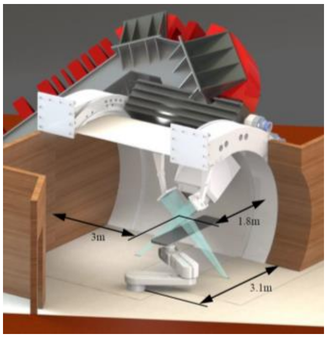
Mayo Clinic Half Gantry



- 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

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ProTom Robotic C-Arm

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

Courtesy of Sung Park

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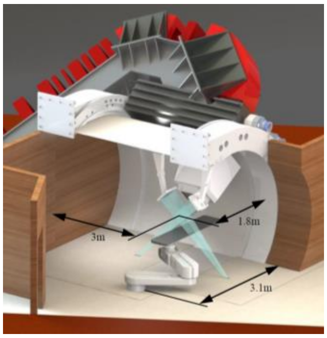
Mayo Clinic Half Gantry



- 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: ??

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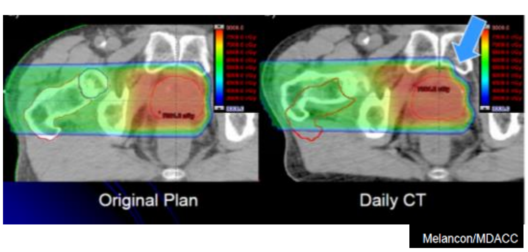
CT Localization for Protons: Pelvis

- Change in position of bony anatomy alters dose distribution
- CT localization may be of limited use



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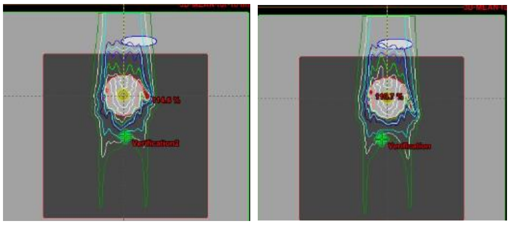
CT Localization for Protons: Lung

- 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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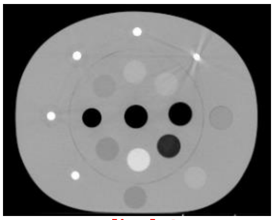
CBCT for Adaptive Protocols

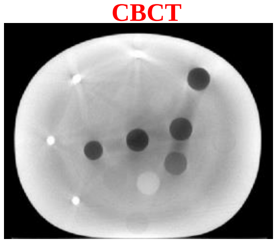
- Proton dose calculation is extremely sensitive to CT number accuracy
- CT number accuracy / consistency not generally a priority in CBCT
- Increased scatter relative to helical CT degrades imaging performance

Helical/CBCT Phantom Images



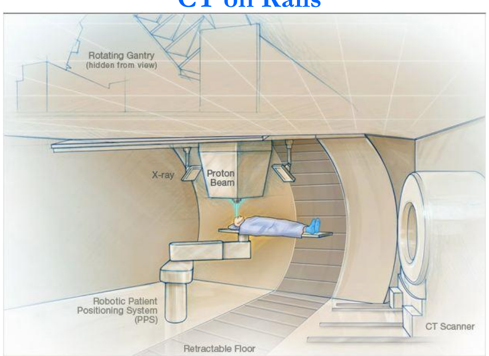
Helical CT

CBCT



Images Courtesy of T.J. Whitaker

CT on Rails



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

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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

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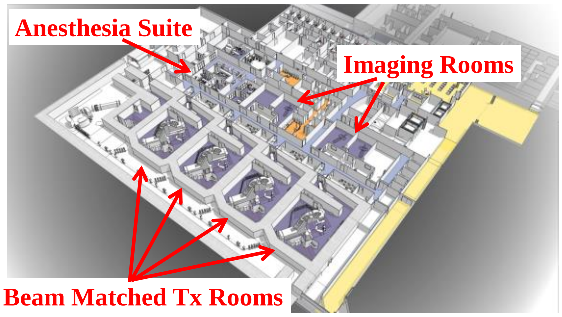
Treatment Preparation Outside Tx Room



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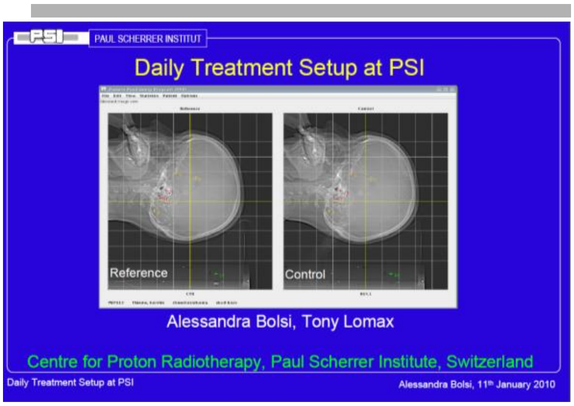
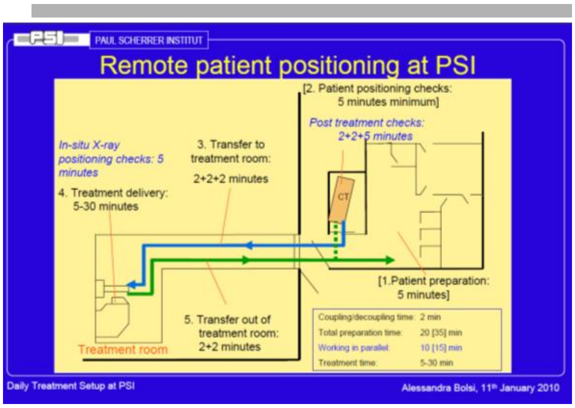
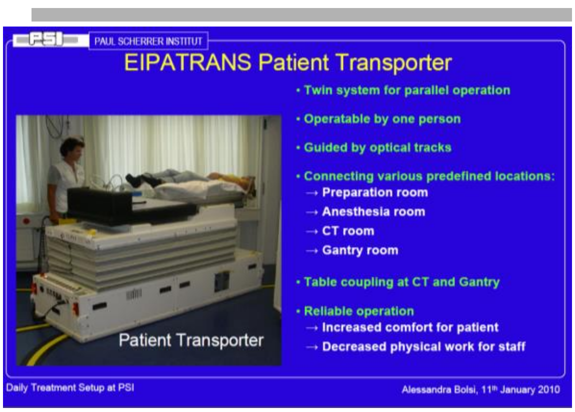
Treatment Localization Outside Room

- 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




PAUL SCHERRER INSTITUT
Remote patient positioning at PSI
[2. Patient positioning checks: 5 minutes minimum]
Post treatment checks: 2+2+5 minutes
In-situ X-ray positioning checks: 5 minutes
3. Transfer to treatment room: 2+2+2 minutes
4. Treatment delivery: 5-30 minutes
CT
[1.Patient preparation: 5 minutes]
5. Transfer out of treatment room: 2+2 minutes
Treatment room
Coupling/decoupling time: 2 min
Total preparation time: 20 [35] min
Working in parallel: 10 [15] min
Treatment time: 5-30 min
Daily Treatment Setup at PSI
Alessandra Bolsi, 11th January 2010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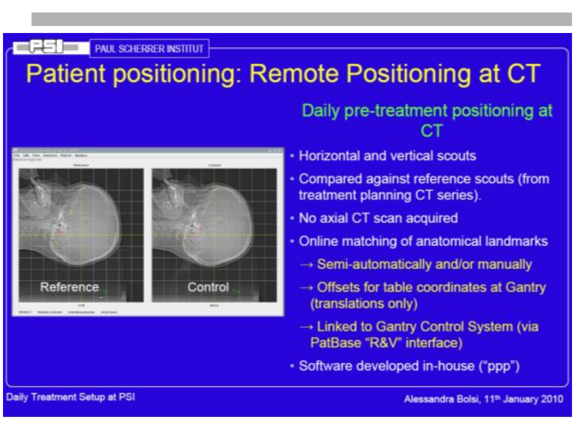
EIPATRANS Patient Transporter
Patient Transporter
• Twin system for parallel operation
• Operatable by one person
• Guided by optical tracks
• Connecting various predefined locations:
→ Preparation room
→ Anesthesia room
→ CT room
→ Gantry room
• Table coupling at CT and Gantry
• Reliable operation
→ Increased comfort for patient
→ Decreased physical work for staff
Daily Treatment Setup at PSI
Alessandra Bolsi, 11th January 2010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Patient positioning: Remote Positioning at CT
Daily pre-treatment positioning at CT
Reference
Control
• 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 PatBase "R&V" interface)
• Software developed in-house ("ppp")
Daily Treatment Setup at PSI
Alessandra Bolsi, 11th January 2010

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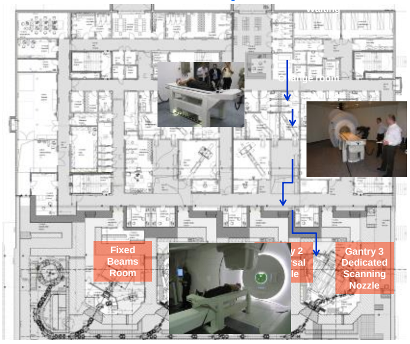
Multi Modality Remote Localization



WPE Essen

Courtesy of Jonathon Farr

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Multi Modality Remote Localization

PTC Prague

Courtesy of Jonathon Farr

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Multi Modality Remote Localization

PTC Prague

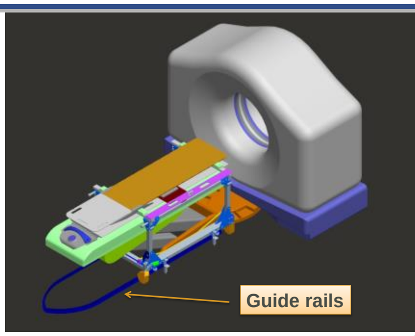
Courtesy of Jonathon Farr

CT Gurney

48

ProCure

Load Position



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ProCure

Handoff in the treatment room

50

ProCure

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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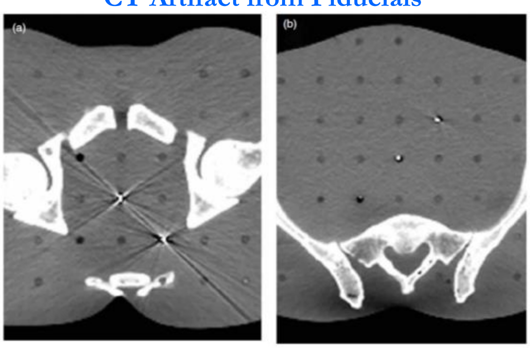
CT Artifact from Fiducials



Huang et al., PMB 56 (2011) 5287

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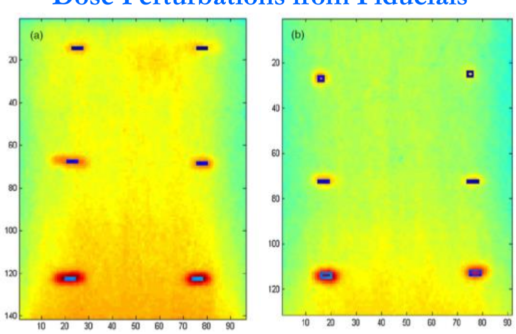
Dose Perturbations from Fiducials



Huang et al., PMB 56 (2011) 5287

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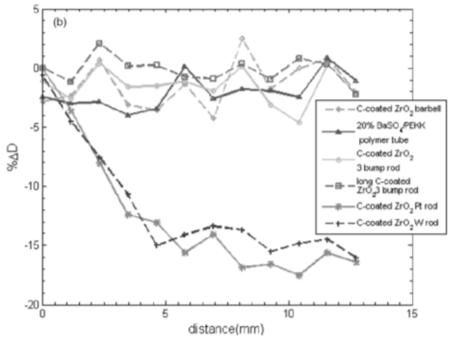
Dose Perturbations from Fiducials



Huang et al., PMB 56 (2011) 5287

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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