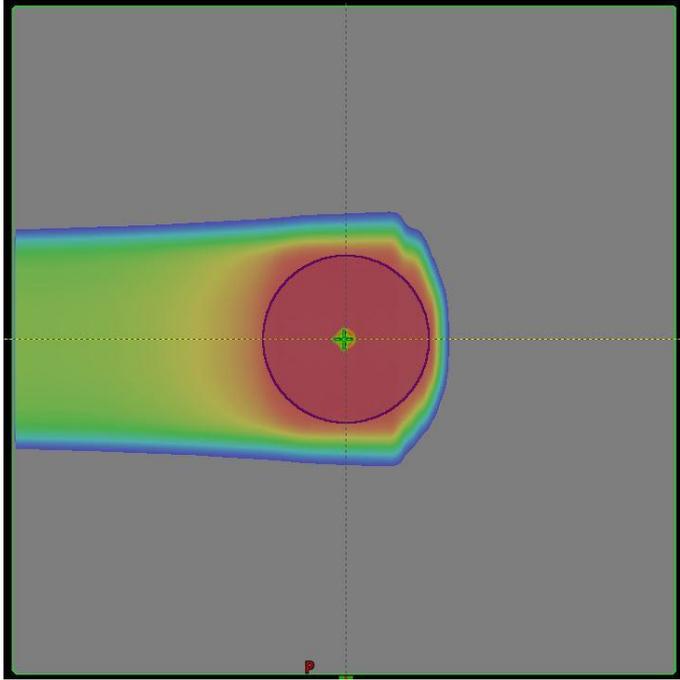# Proton Workflows for In-Room CT
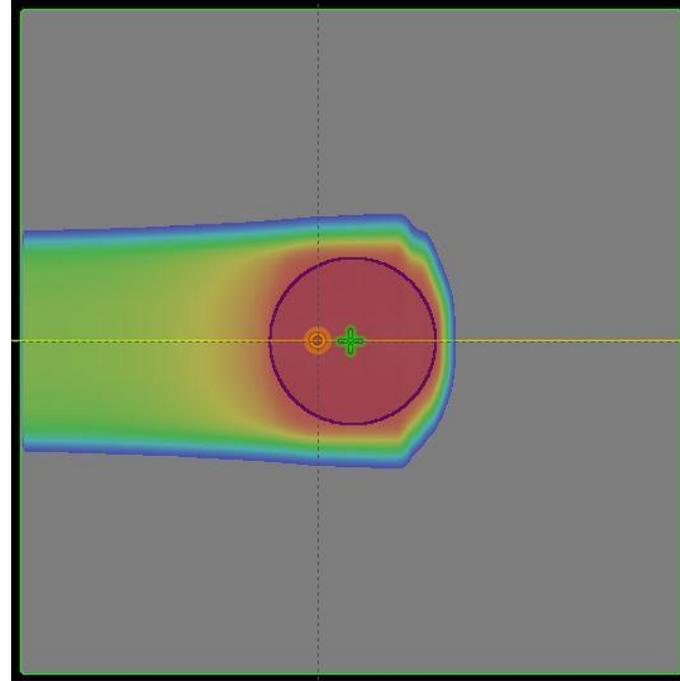
Jon J. Kruse
Mayo Clinic, Rochester MN
AAPM Annual Meeting, 2020

# Range and Tumor Depth
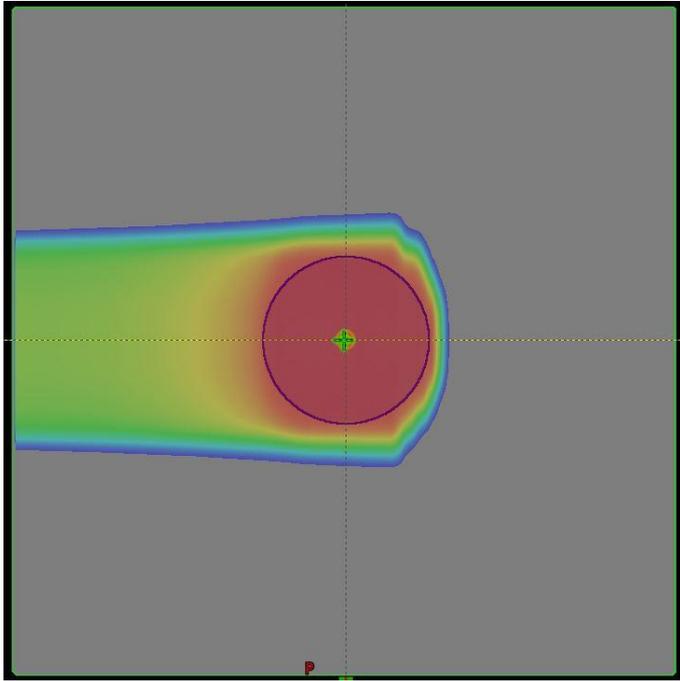


**Nominal Plan**

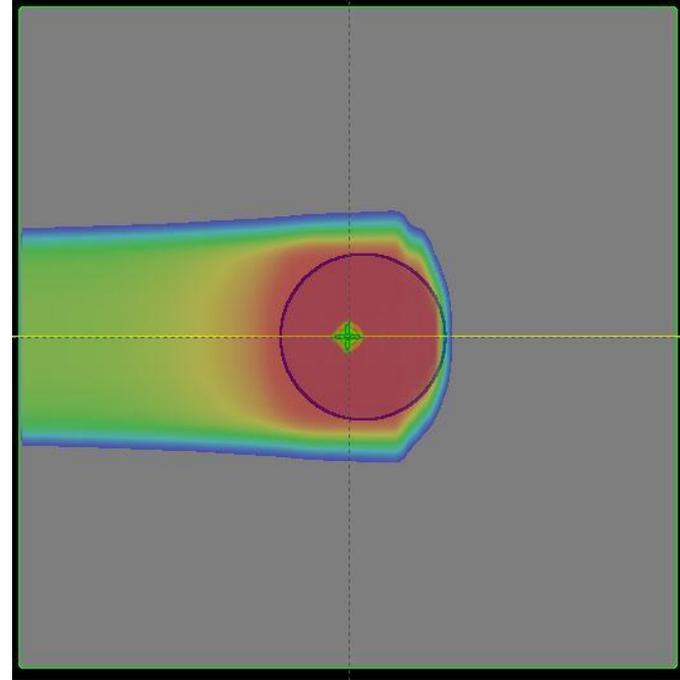**Long Shift in BEV**

# Range and Tumor Depth
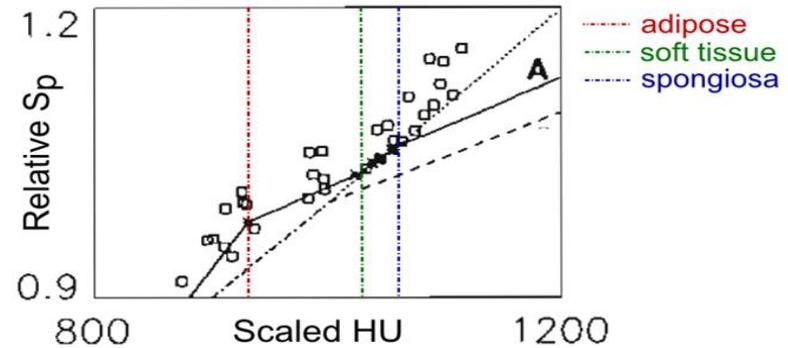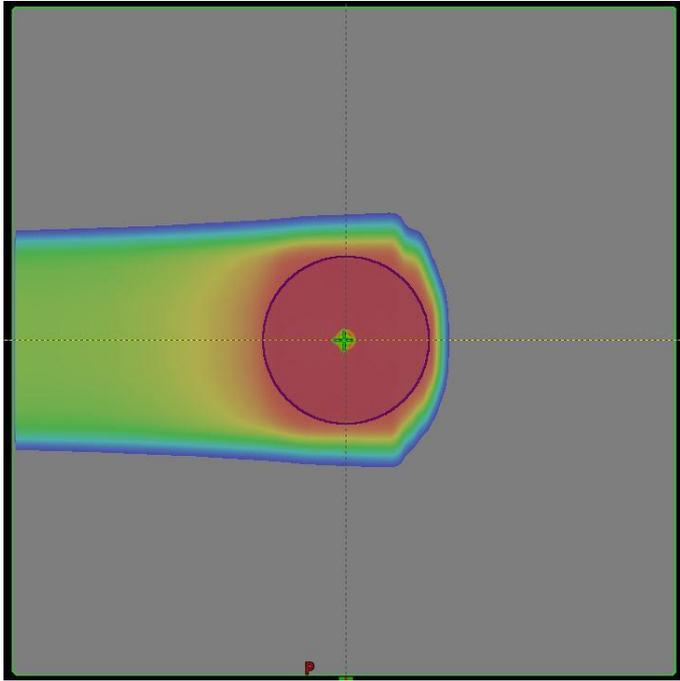


**Nominal Plan**



**Internal Target Shift**

# CT Number to rSP
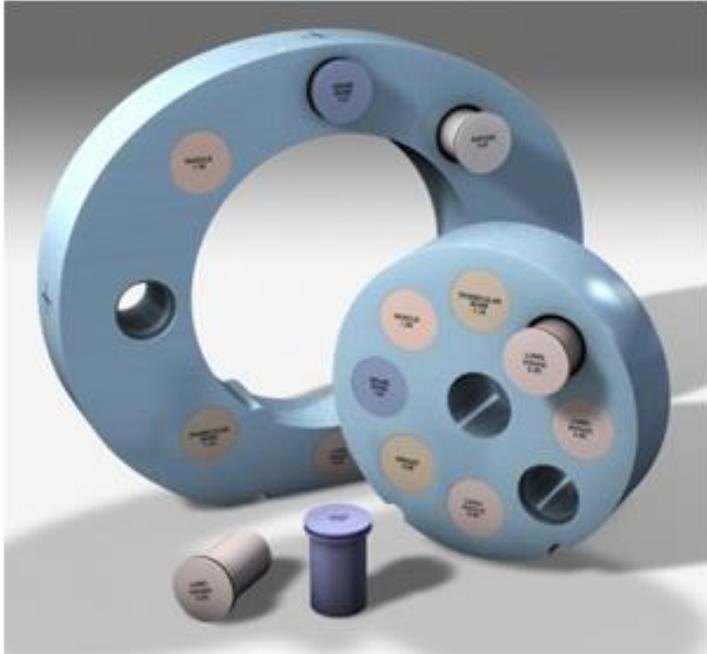


$$S = \frac{4\pi}{m_e c^2} \cdot \frac{nz^2}{\beta^2} \cdot \left(\frac{e^2}{4\pi\epsilon_0}\right)^2 \cdot [\ln\left(\frac{2m_e c^2 \beta^2}{\langle I \rangle \cdot (1-\beta^2)}\right) - \beta^2]$$

# Range and Tumor Depth



**Nominal Plan**
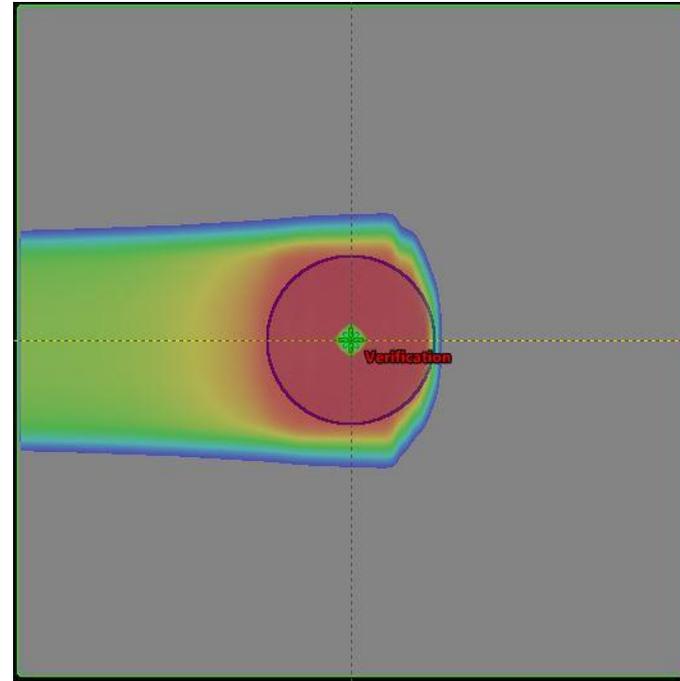
**3% Error in RSP**

# 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
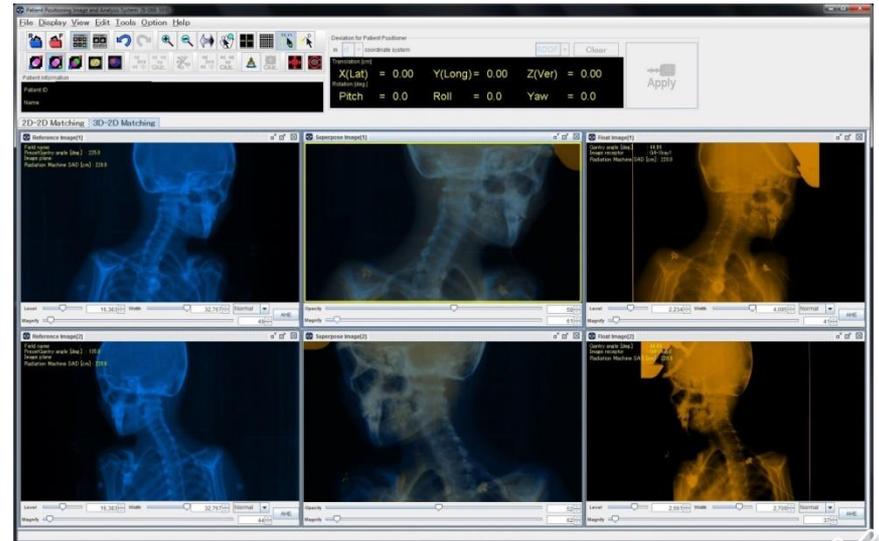
# IGRT Systems



VisionRT Surface Imaging
- 3 PODs
- Surface Guided Setup
- Live Patient Monitoring
- Verify Couch Motions
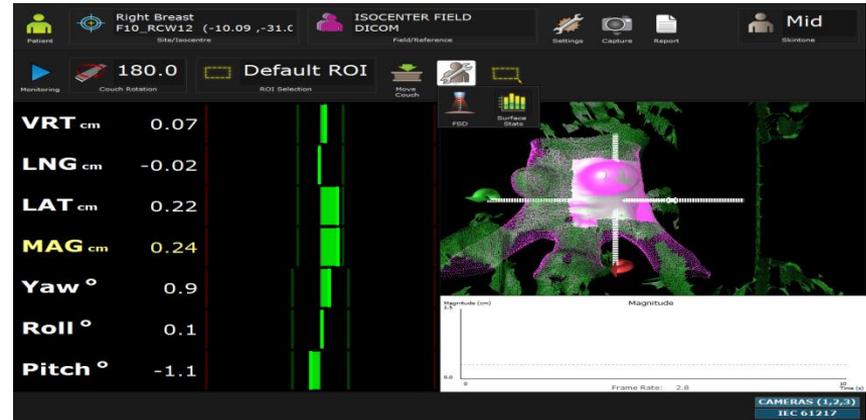
# IGRT Systems

# CT Localization Step 1: 2D Imaging



- Adjust Patient Pose
- Localize Bony Anatomy, Fiducial Markers
- Establish Reference Couch Coordinates

# CT Localization Step 2: Surface Imaging
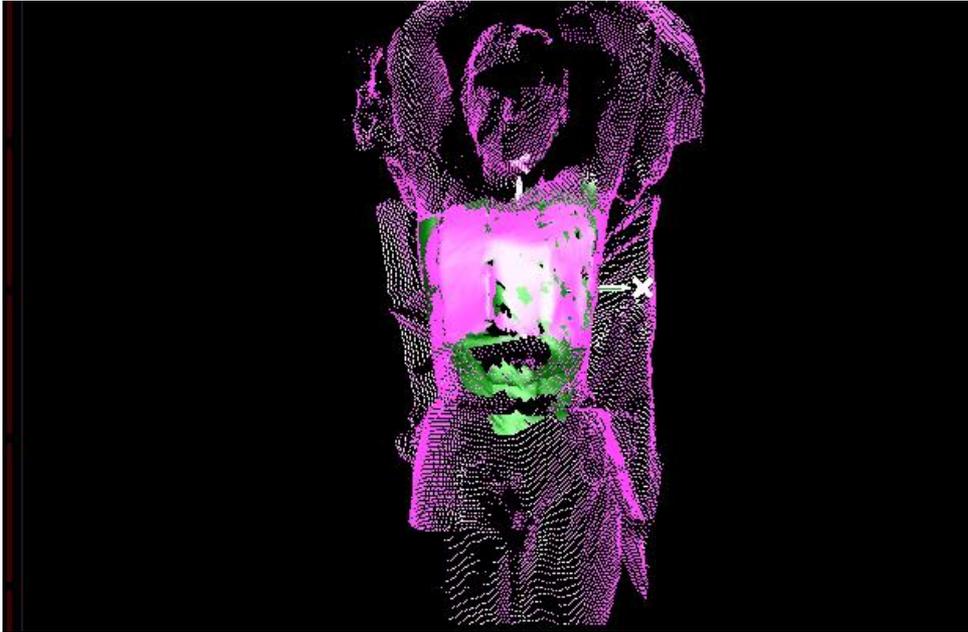


- Capture Reference Surface Image After 2D Localization

# 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
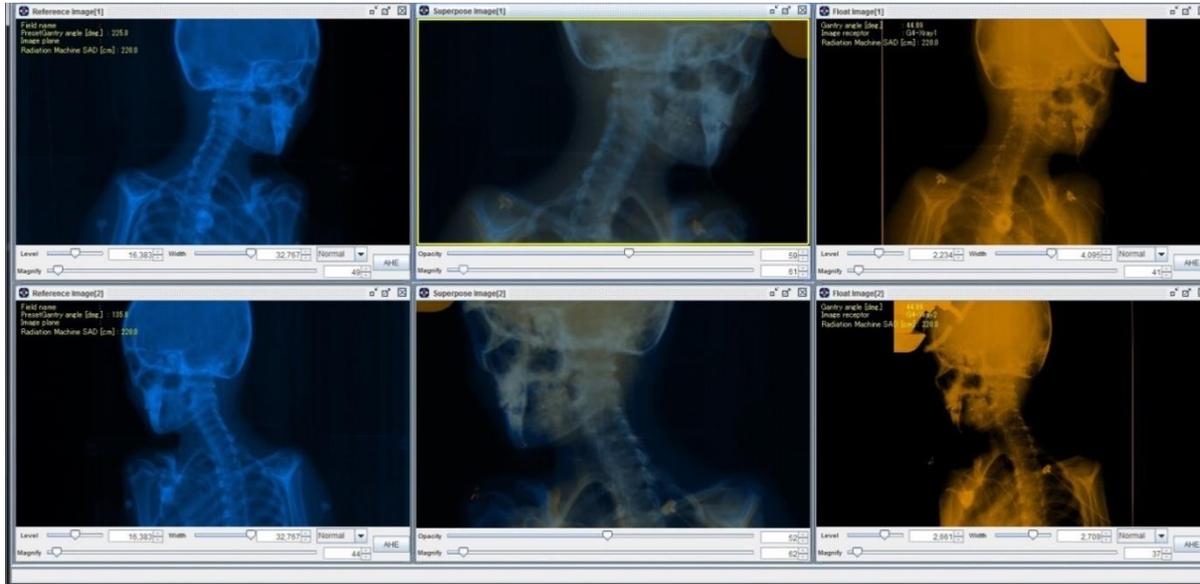


- Move Patient Back to Tx Iso During Registration
- Acquire Surface Image to Verify Correct Couch Position, Patient Pose
- Apply 6 DOF Corrections
- Acquire New Surface Reference
- Treat

# 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 locolization 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
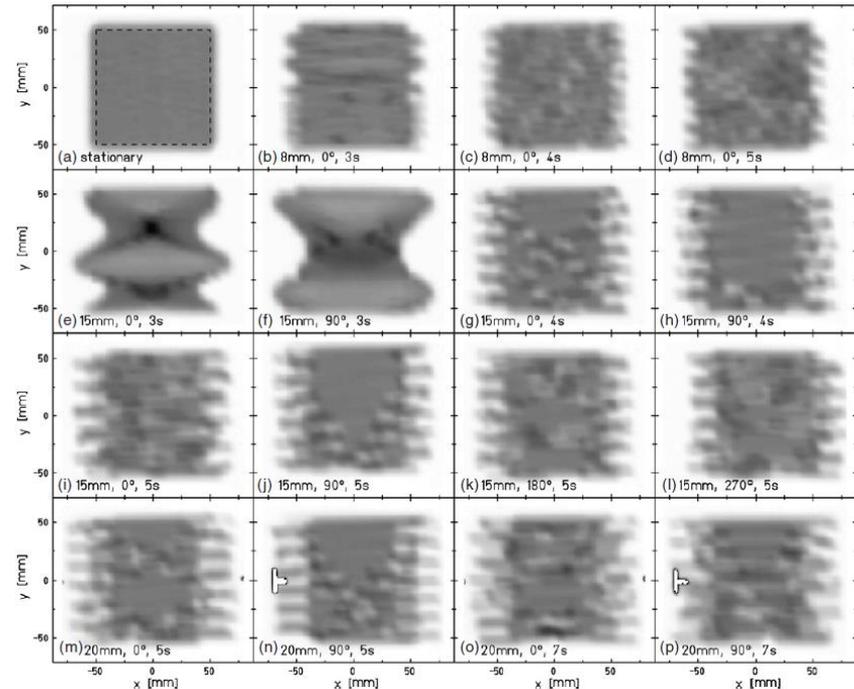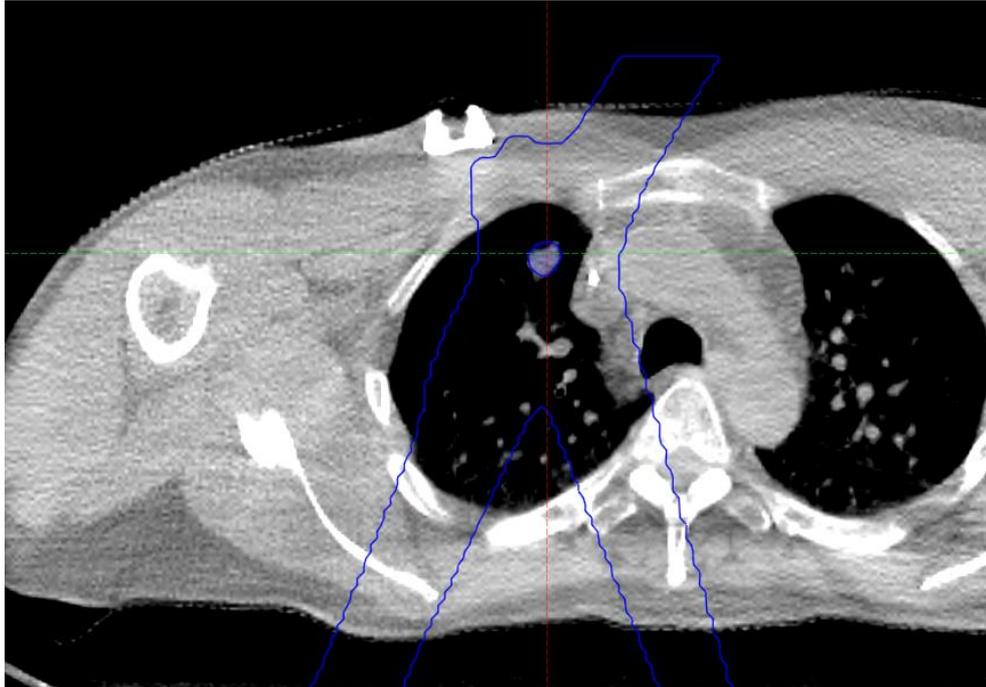


*Bert et al., PMB 53 (2008)*

# 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

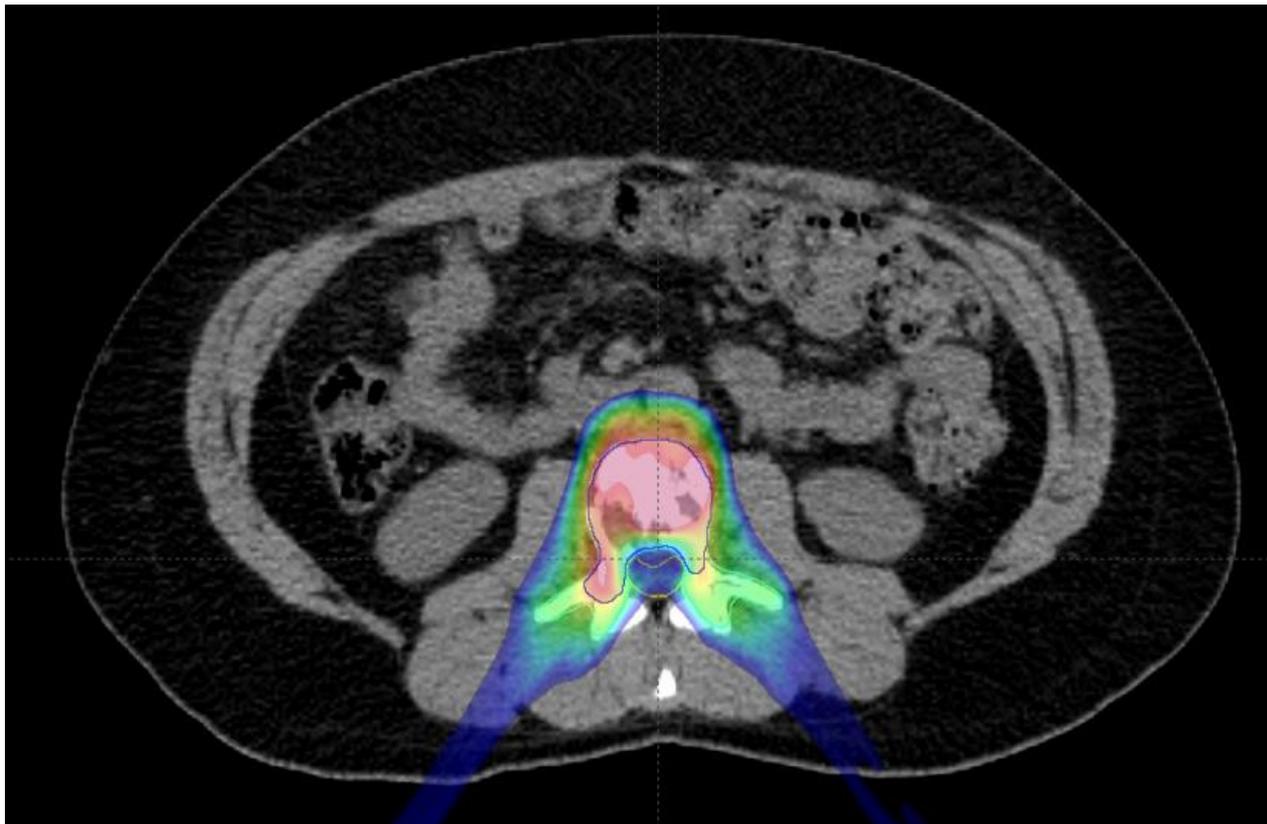- Tumor depth can vary by several cm or more, systematically or day by day
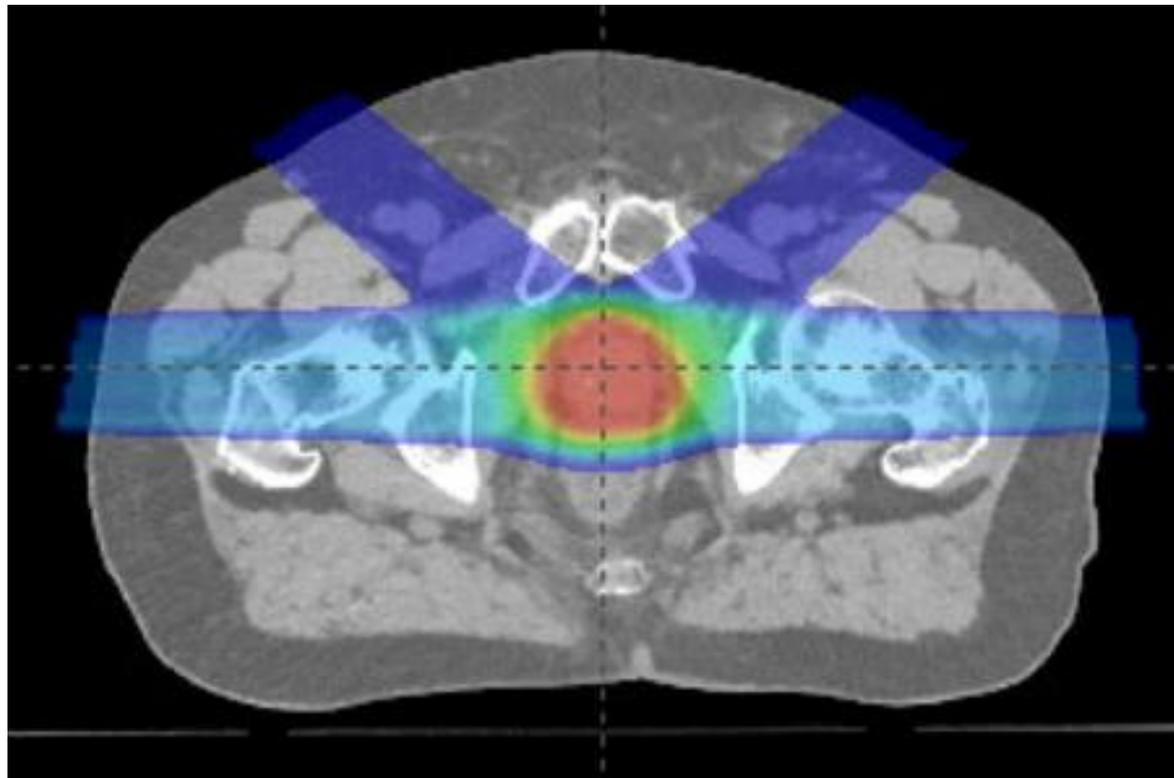
# CT Guided SBRT
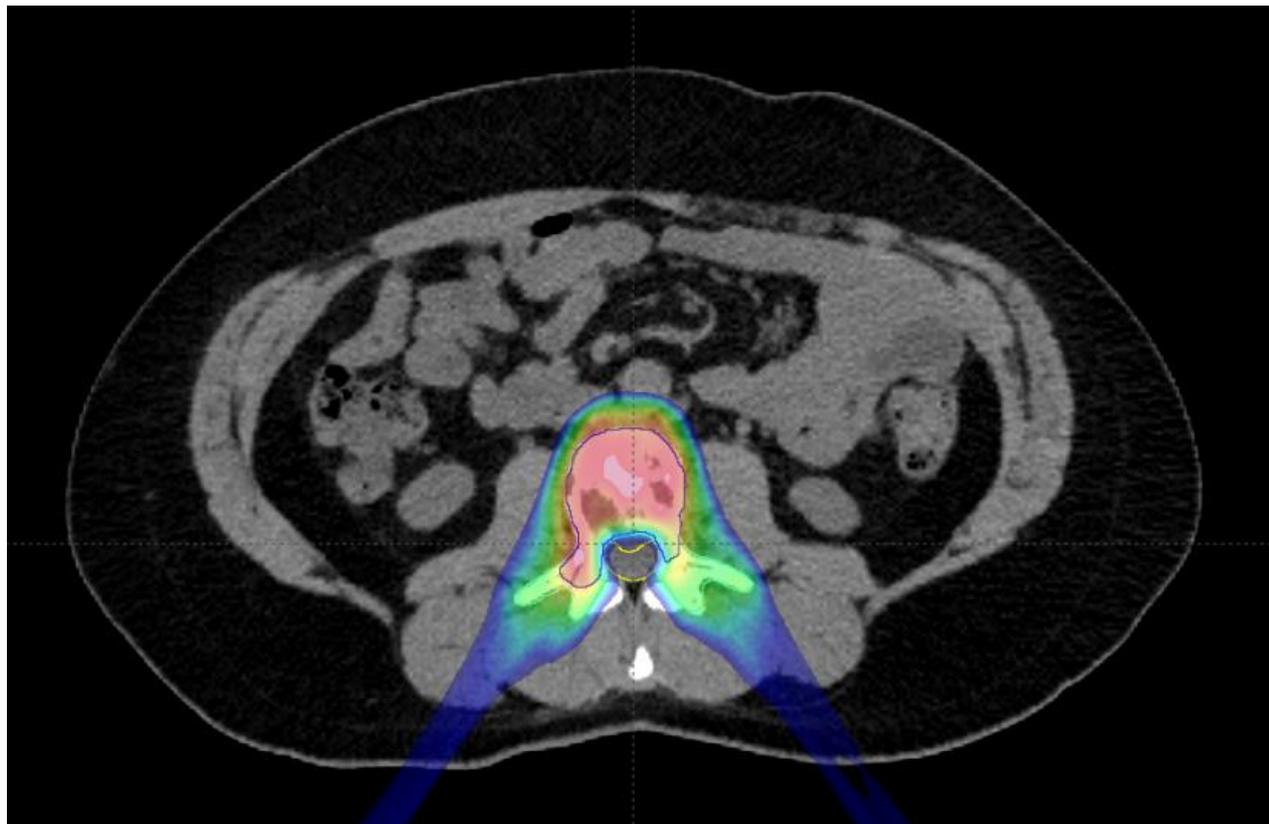
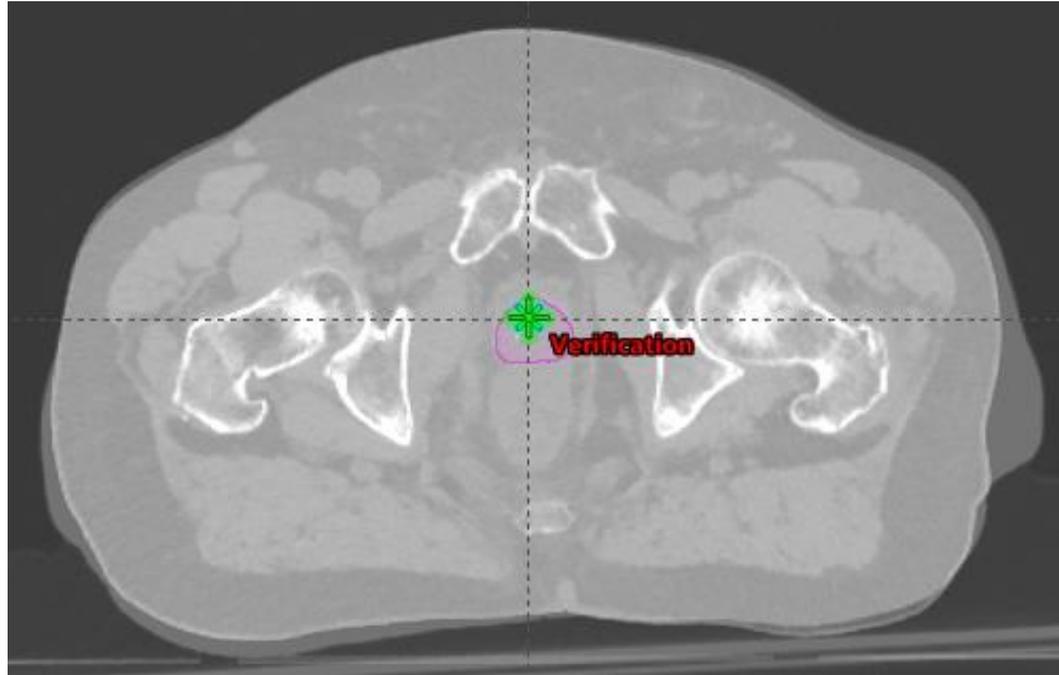# CT Guided SBRT

# CT Guided SBRT
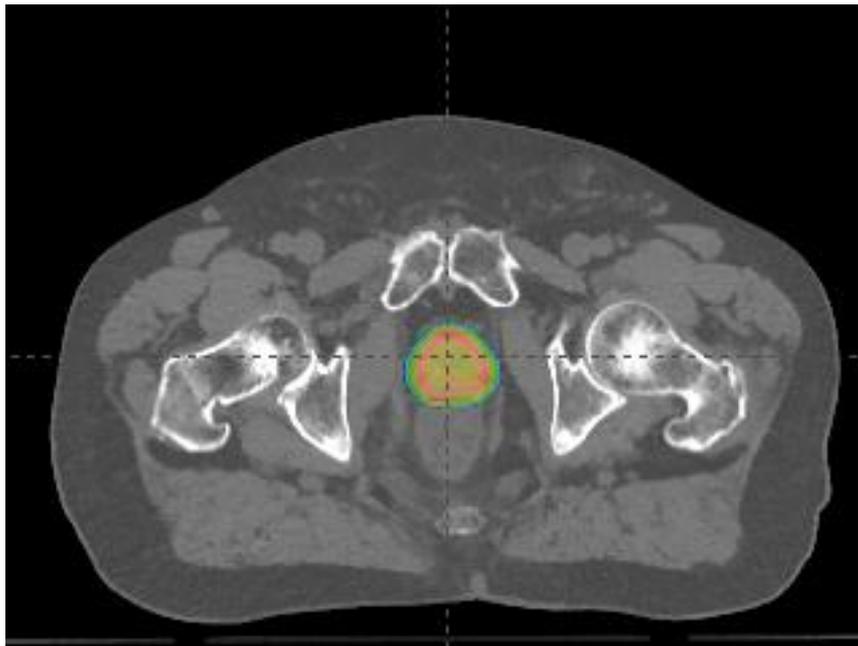


## Verification Dose

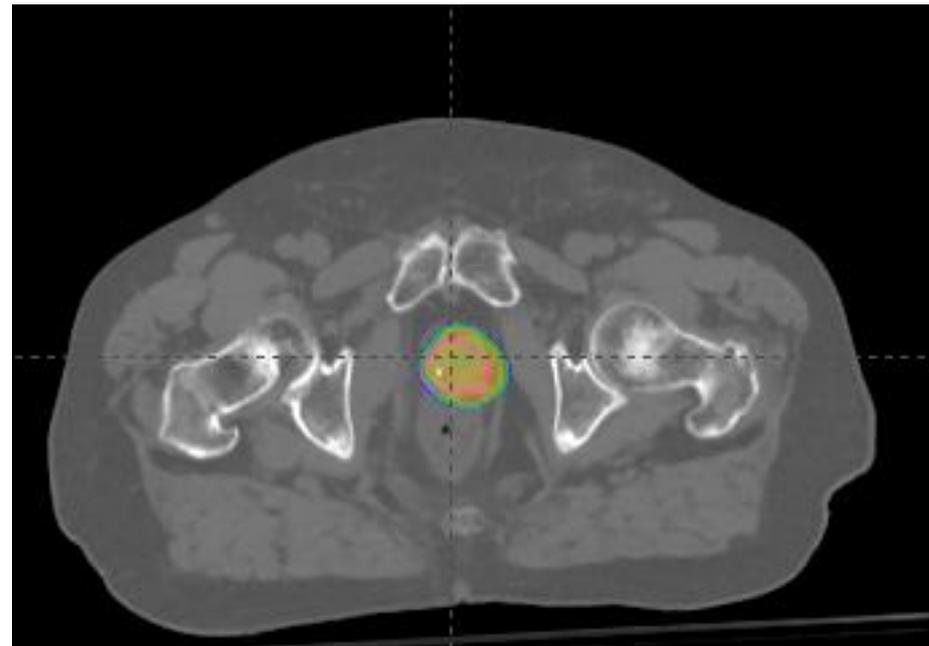# Prostate SABR

# Prostate SABR



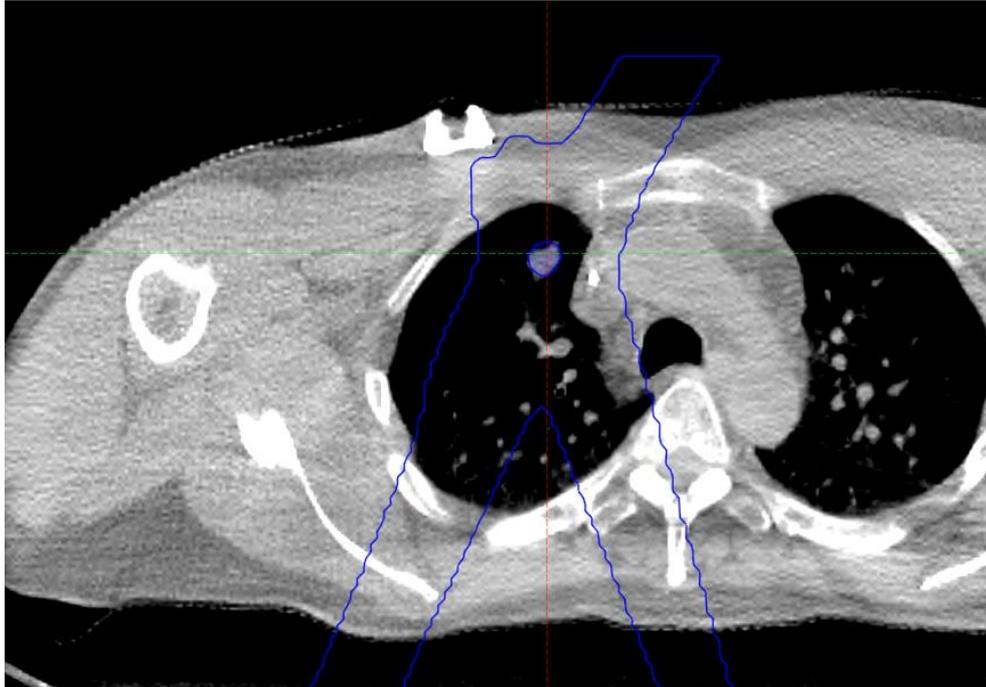## Pre-Treatment Registration

# 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
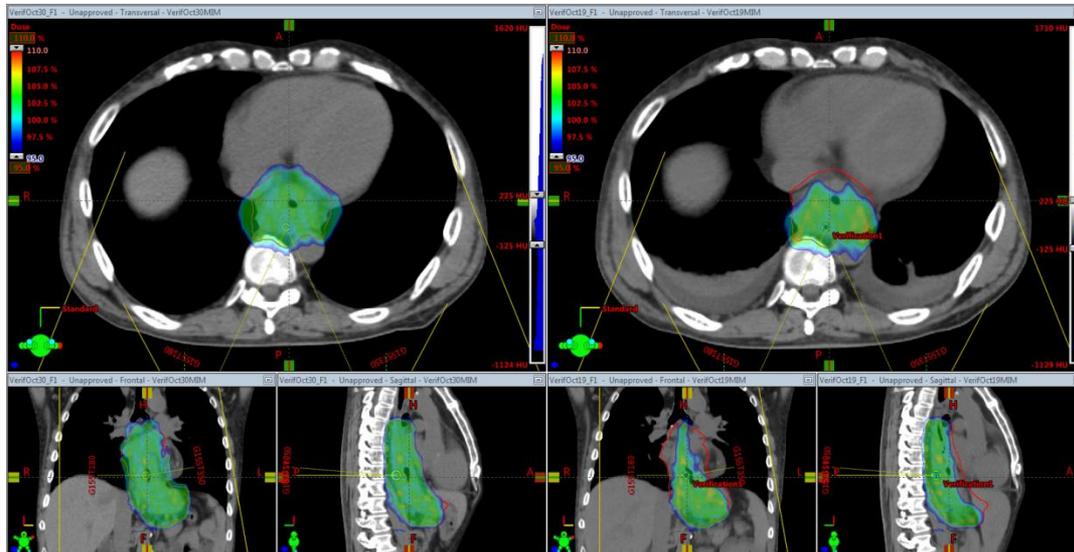


- Repeat CT scans over course of treatment, re-calculate dose to verify coverage
- Patient pose is often the dominant factor in dosimetric integrity
- Difficult to achieve in CT simulator
- Post-treatment CT on Rails can be acquired in actual treatment position

# Treatment Plan Adaptation by Site



**Percent of Patients Replanned by Site**

Percent of Patients Replanned (%)

- 2.17
- 5.56
- 12.12
- 15.45
- 17.14
- 17.46
- 22.22
- 28.95
- 34.62
- 35.71
- 39.47
- 47.56

**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) |
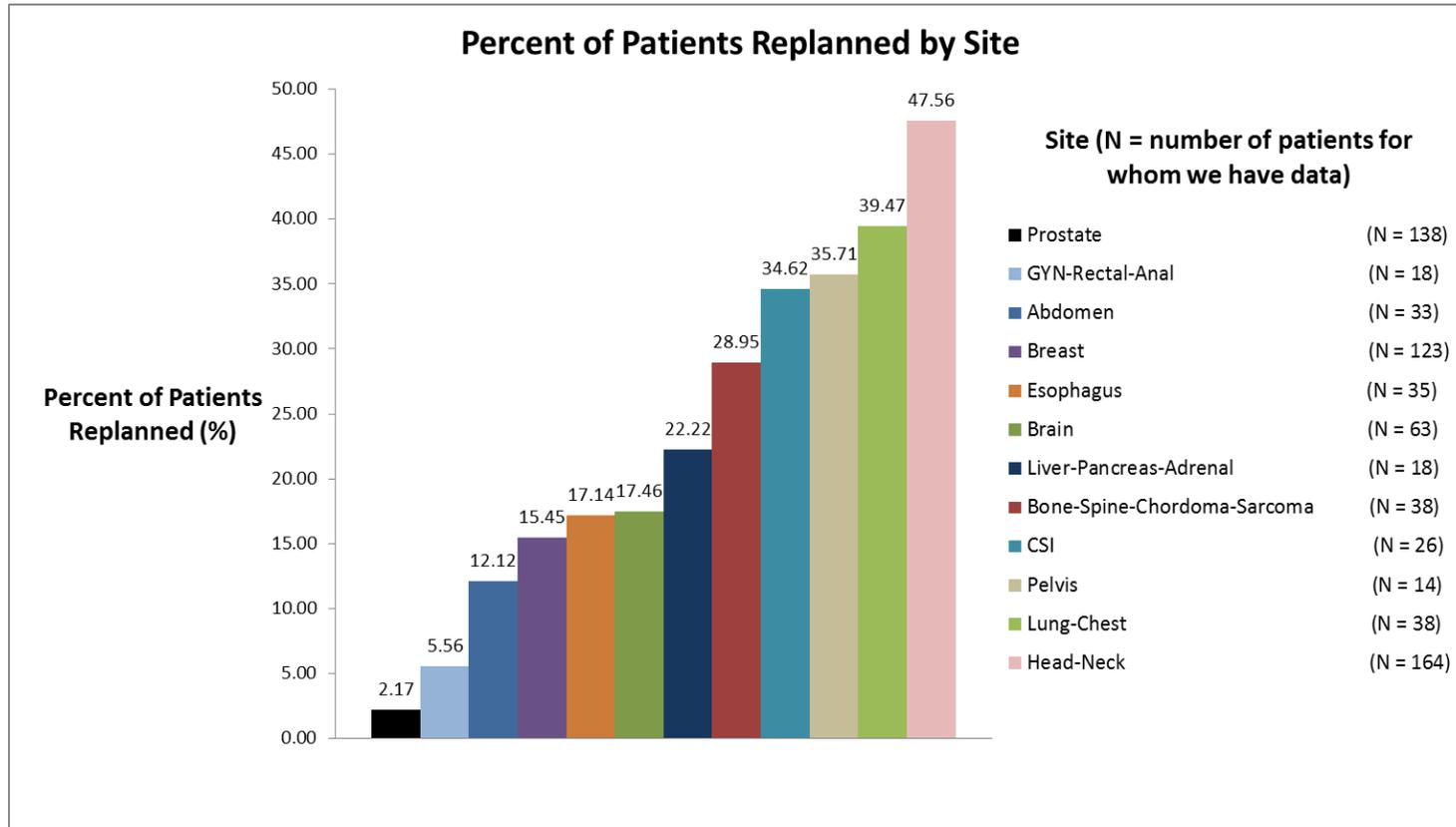
# Near Future of CT on Rails: Pre-Tx Dose Validation



Small Anatomical Change: Large Dosimetric Impact
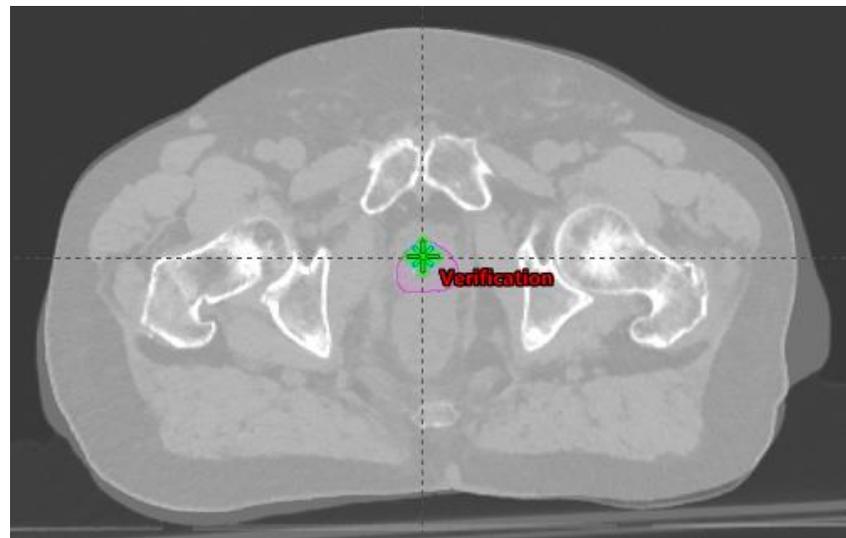
Large Anatomical Change: Small Dosimetric Impact

# 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
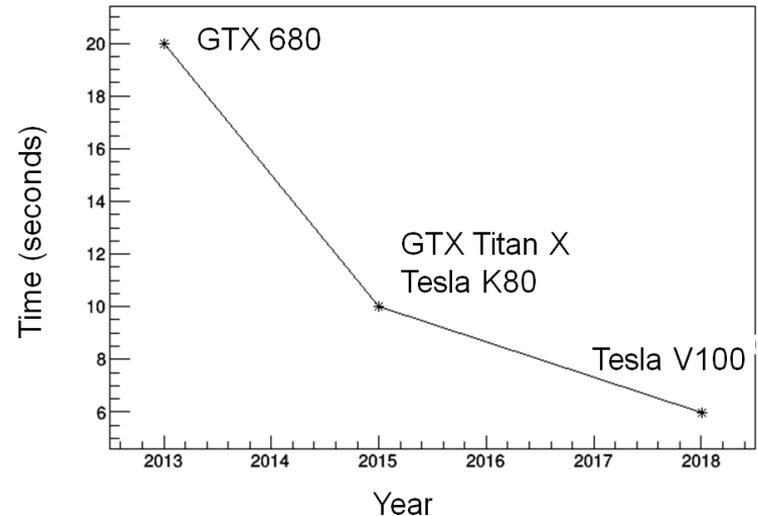


Calculation time per $10^7$ proton histories on 1 GPU

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
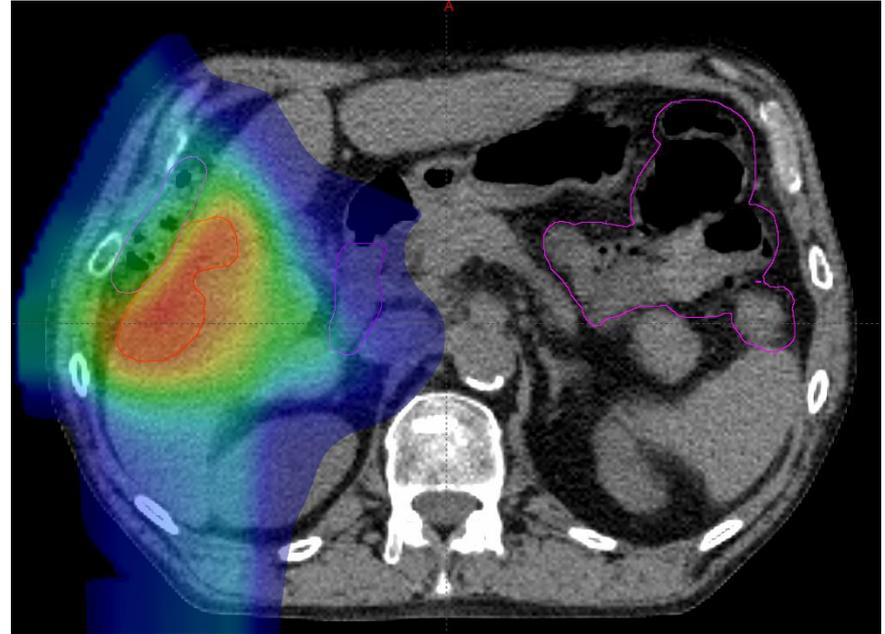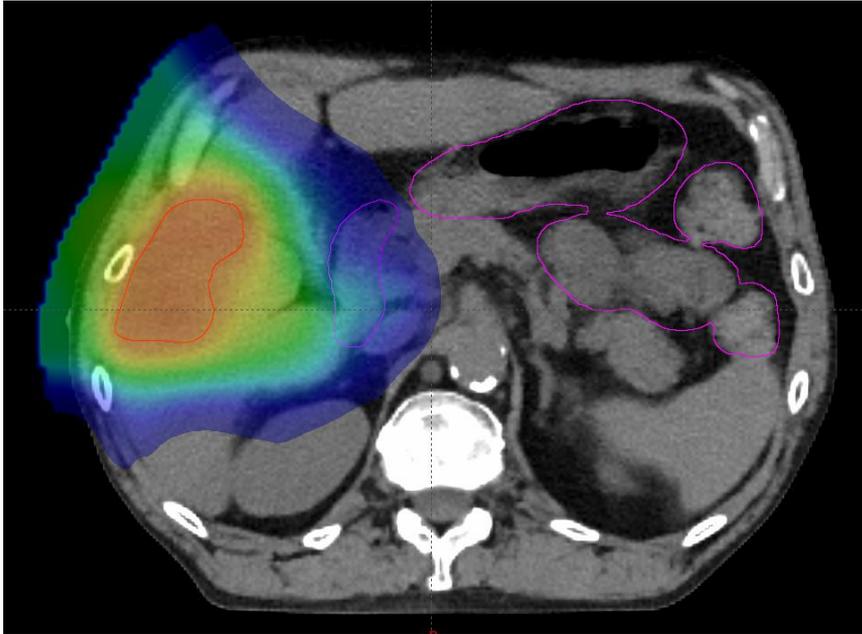  - Pretreatment analysis of magnet settings and beam energies

# On-Line Plan Adaptation: Liver Treatment
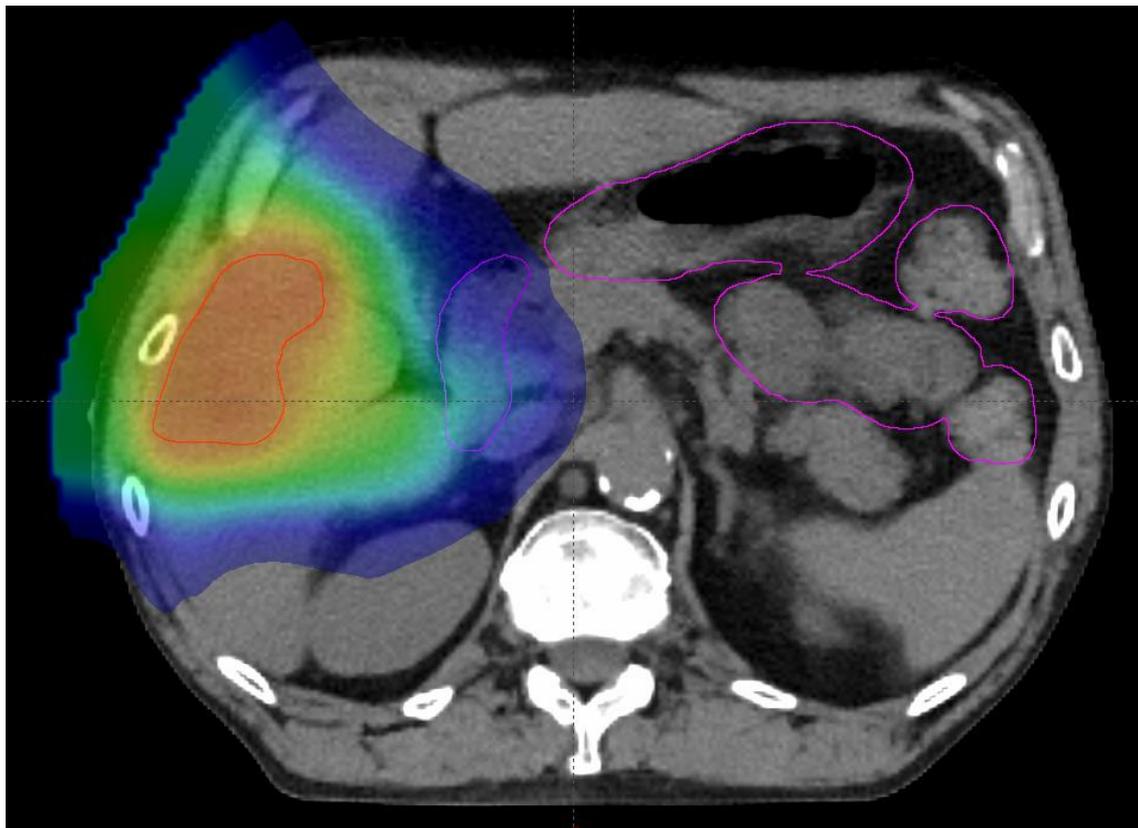
# On-Line Plan Adaptation: Two Anatomy Presentations
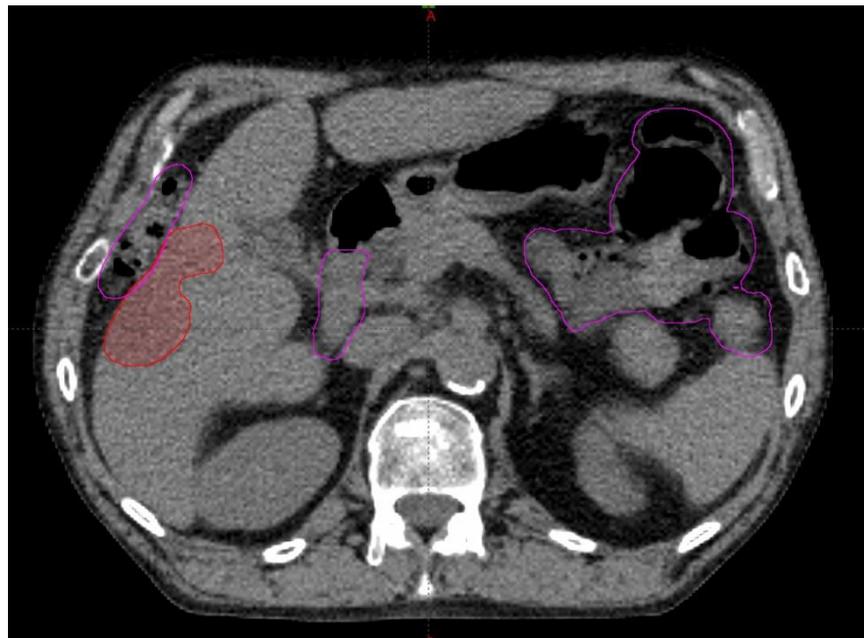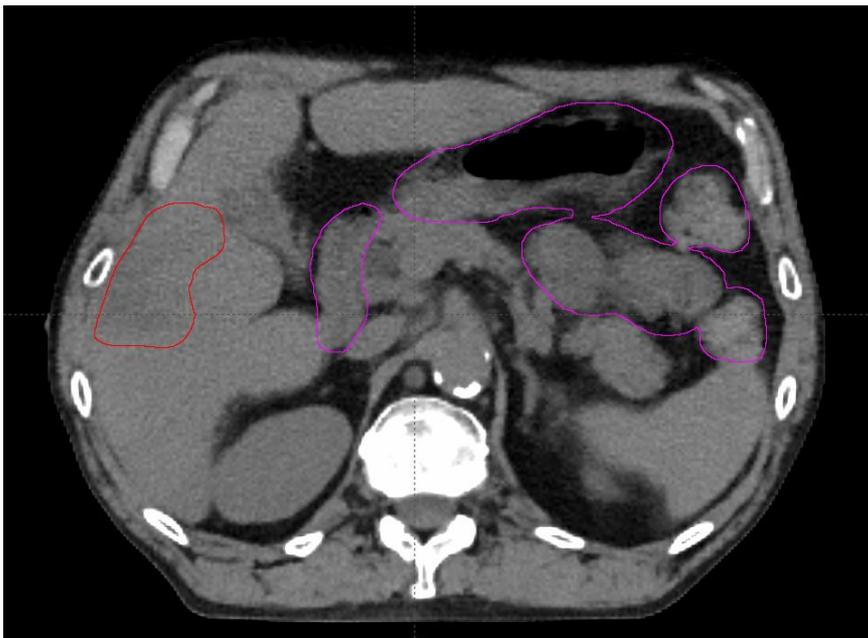
# On-Line Plan Adaptation: Two Treatment Plans



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