In-room Use of Volume Alignment (Online Volumetric IGRT)

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Acknowledgement

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Learning Objectives:

- Learn about the rationales and procedures for in-room CT-guided radiotherapy.
- Suggest the design of computer-aided image processing algorithms.
- Demonstrate workflow and clinical applications.

Outline

- Rationale of soft-tissue volumetric imaging
- Workflow
- Manual alignment
- Automatic alignment
- Other factors for on-line applications

What is “Volumetric” Imaging?

- 3D representation of patient’s anatomy
  - Voxel-by-voxel
  - Both tumor target and critical normal structures
  - Potential for radiation dose calculation
- Equivalent to “CT simulation in a treatment room”
- Examples
  - CT-on-rails
  - Mega-voltage CT (tomotherapy)
  - Cone-beam CT (KV and MV)
  - MRI
  - US (?)
  - PET/SPECT
  - Digital Tomosysthesis

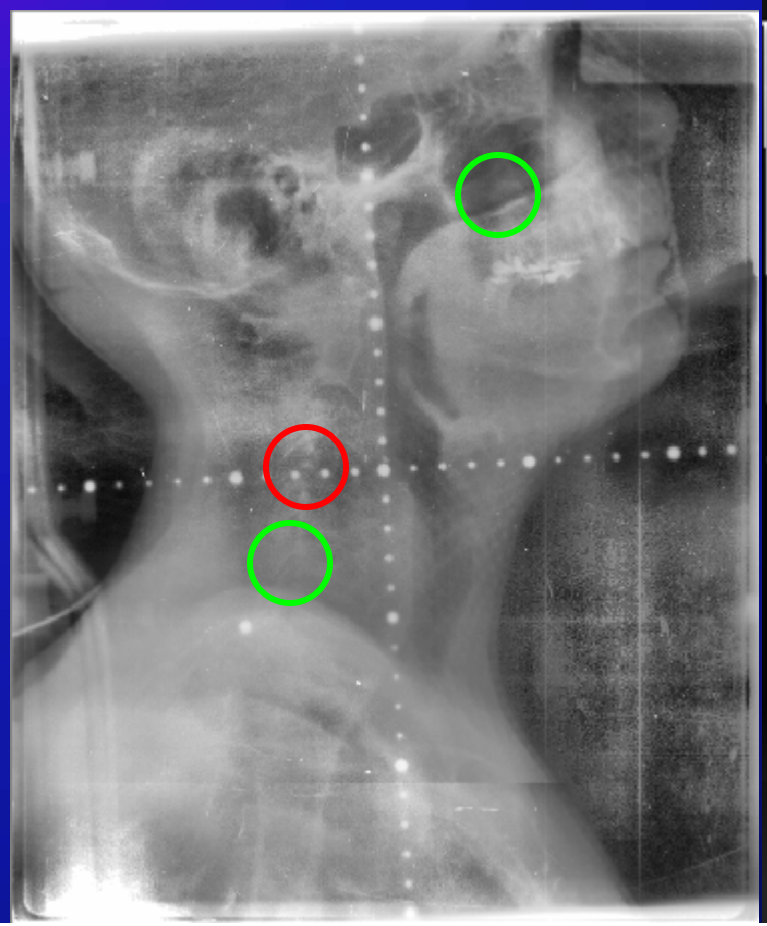
Ideal IGRT System?

- Ling CC et al. From IMRT to IGRT: Frontierland or neverland? Radiother Oncol 2006;78:119-122.
  - 3D volumetric representations of soft tissue organs and tumors
  - Efficient acquisition and comparison of 3D volumetrics
  - An efficacious process for clinically meaningful intervention.

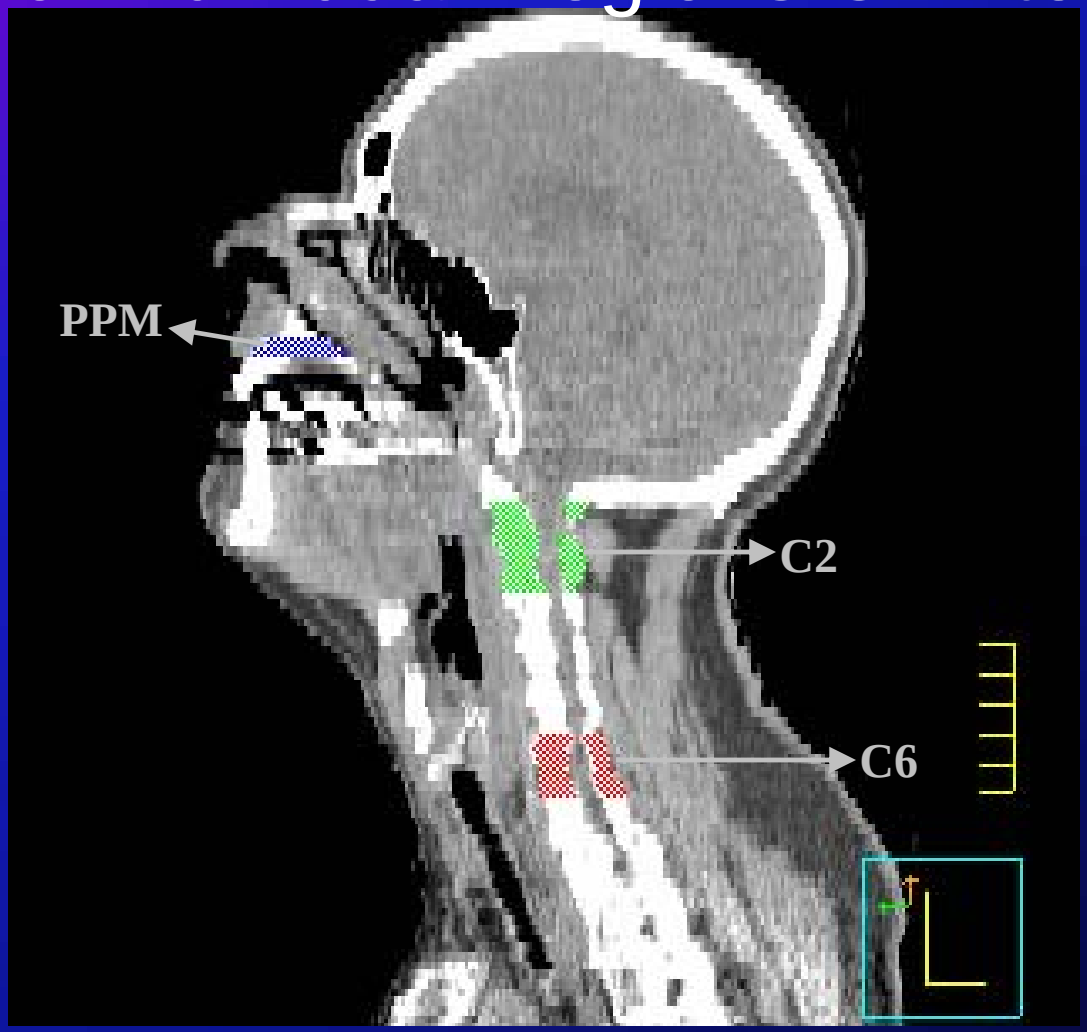
What are the main differences for 2D/3D alignments

- Direct soft-tissue target imaging
  - Alternatives: surrogates of the target:
    - Implanted fiducials
    - Bony alignment
- Unique identification of a 3D object

- Example
  - Traditional alignment assumes rigid-body for the entire H&N region
  - Can you combine multiple 2D ROI for a 3D ROI?
    - 2 x 2D = 3D?

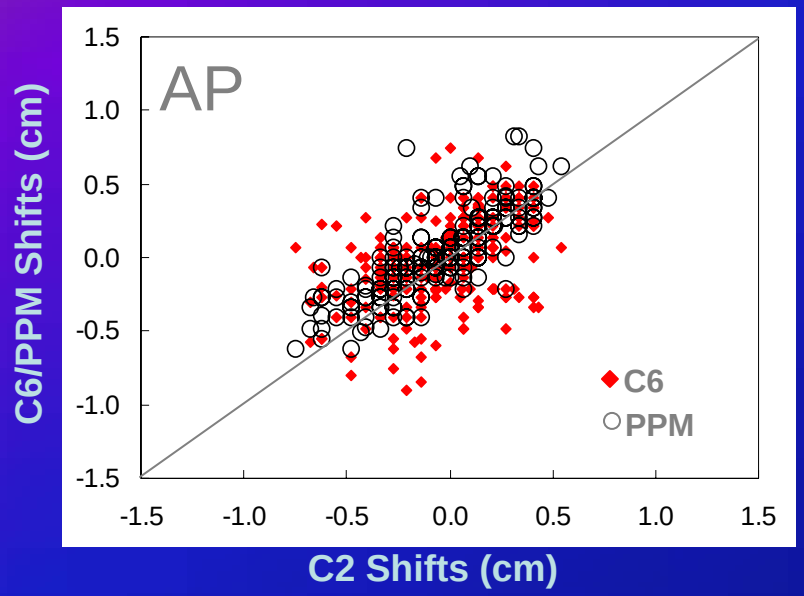


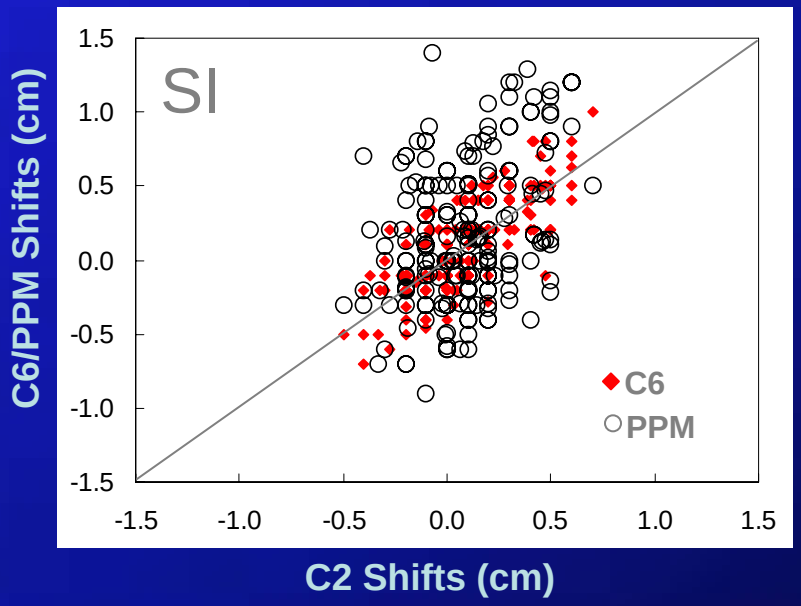
Definition of individual Regions Of Interest (ROIs)

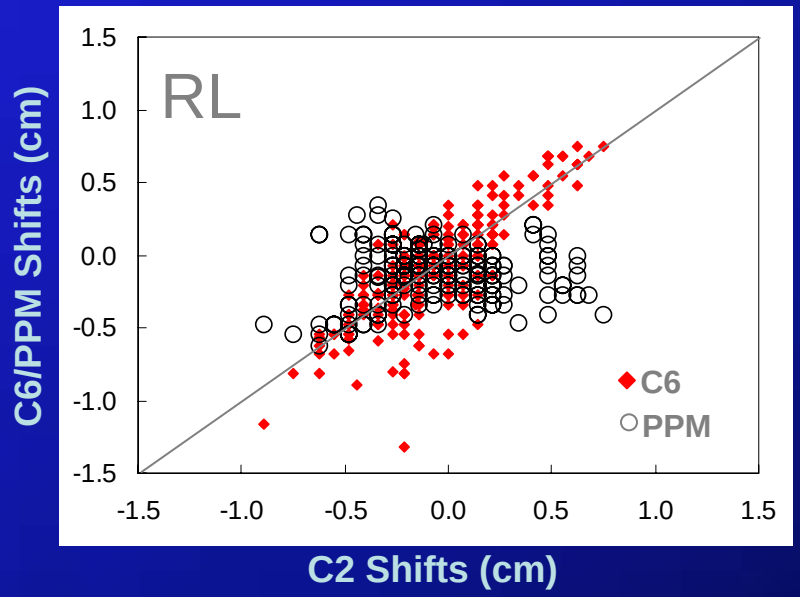


Zhang LF, Garden AS, Lo J, *et al.* Multiple regions-of-interest analysis of setup uncertainties for head-and-neck cancer radiotherapy. *Int J Radiat Oncol Biol Phys* 2006;64:1559-1569.

Correlation of Setup Shifts between C2 and C6/PPM





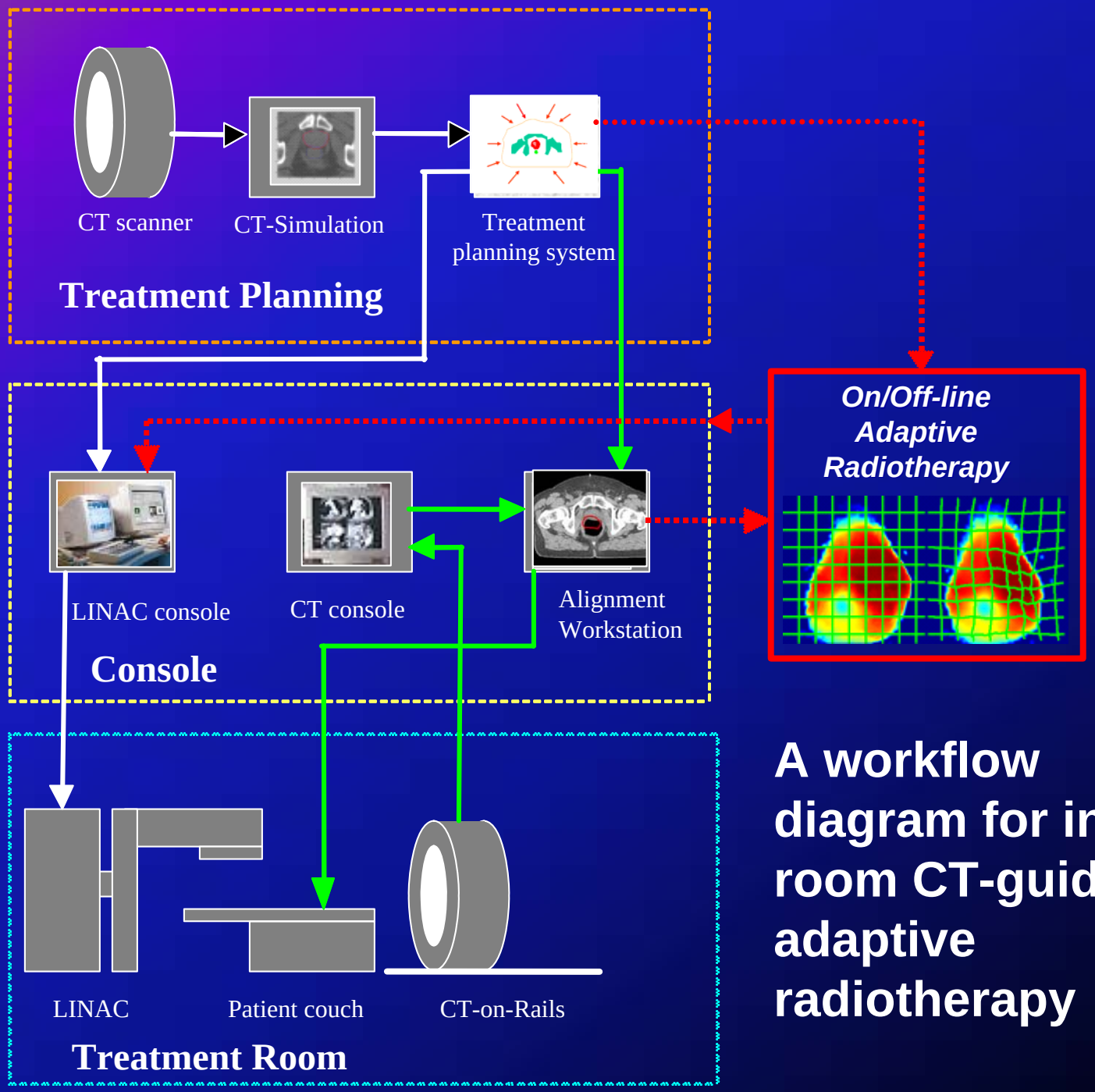


Zhang LF *et al.* Multiple regions-of-interest analysis of setup uncertainties for head-and-neck cancer radiotherapy. *Int J Radiat Oncol Biol Phys* 2006;64:1559-1569.

Workflow

Online vs. Offline

- On-line approach makes treatment interventions based upon data acquired during the current treatment session
  - Speed
    - Simple image guidance: couch shifts
- Off-line approach is to determine treatment interventions from an accumulation of information that may be drawn from previous treatment sessions.
  - Predictable models
  - More comprehensive but infrequent corrections
    - Replanning etc.



A workflow diagram for in-room CT-guided adaptive radiotherapy

Expectations for Online Applications

- Speed
  - Patient is on the treatment couch
  - ~ seconds
  - Rigid-body alignment
  - Image guidance for patient setup
- Accuracy
  - Low alignment error
    - Fighting for every mm
- Robustness
  - High reliability and successfully rate

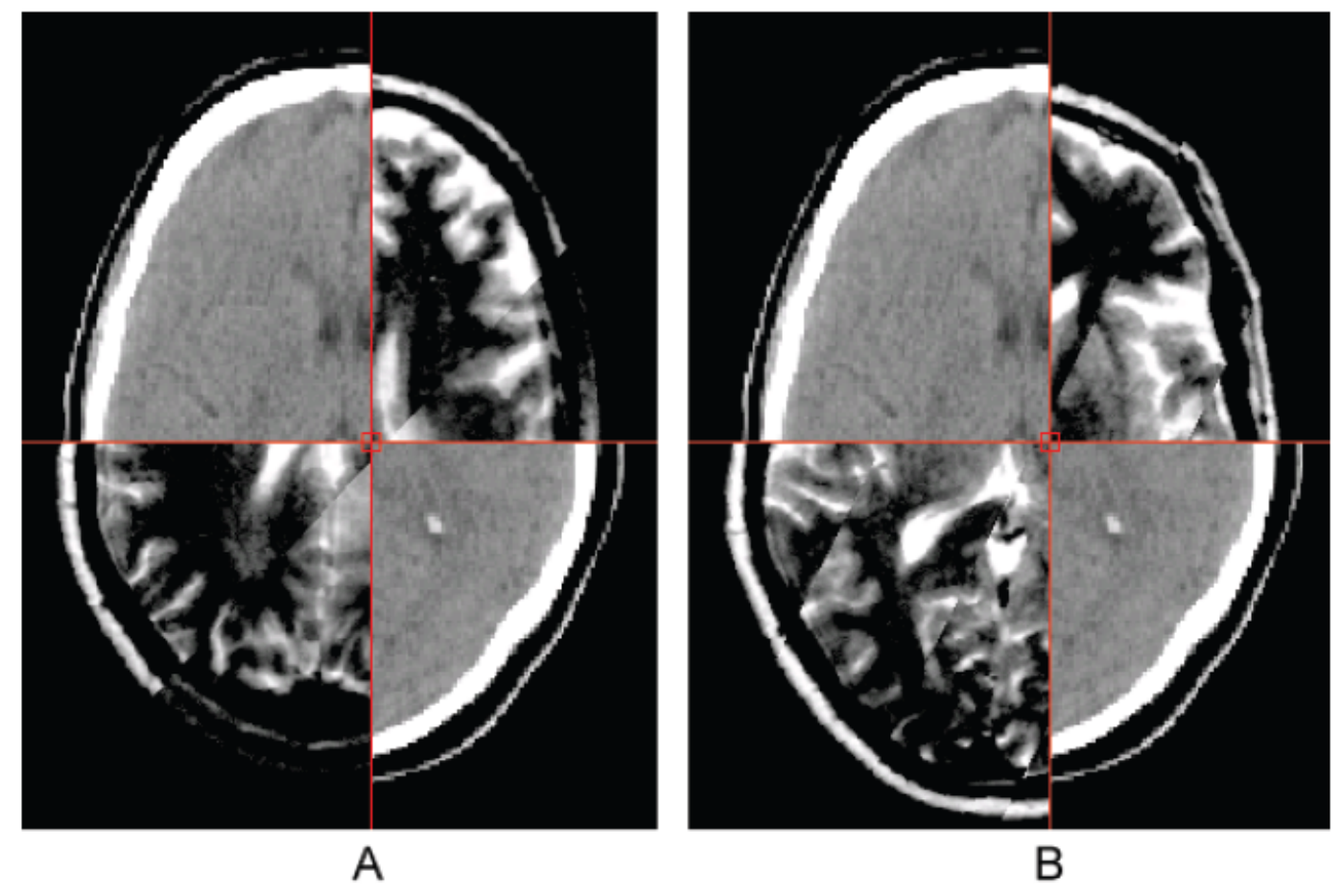
Manual Alignment

- The most reliable and intuitive approach for volume alignment
- Required for confirming the result of automatic alignment
- Subject to inter-observer subjectivity/variations

Methods for Manual Alignment

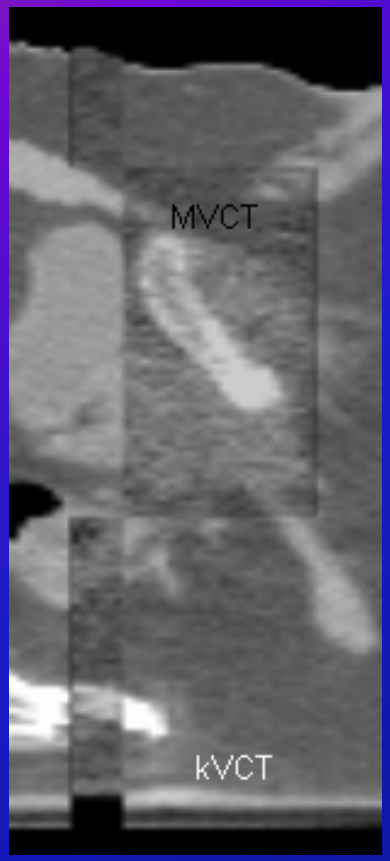
- Image-based
  - Direct comparison of two images
    - Side-by-side
    - Transparent color blending
    - Split view
    - Checkerboard
- Feature-based
  - Features (contours, fiducial points etc.) are extracted from the reference image and overlaid onto the daily image

Split View

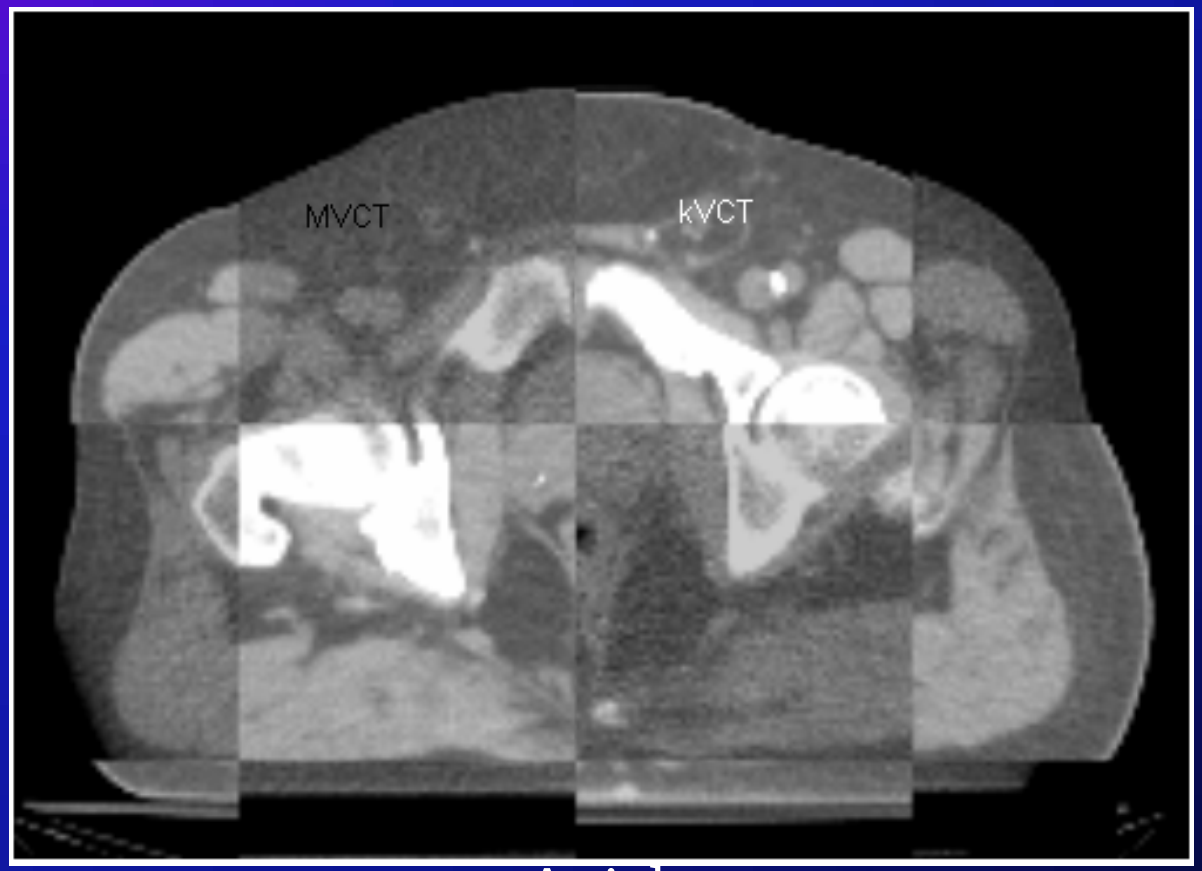


A more accurate alignment

Inaccurate alignment

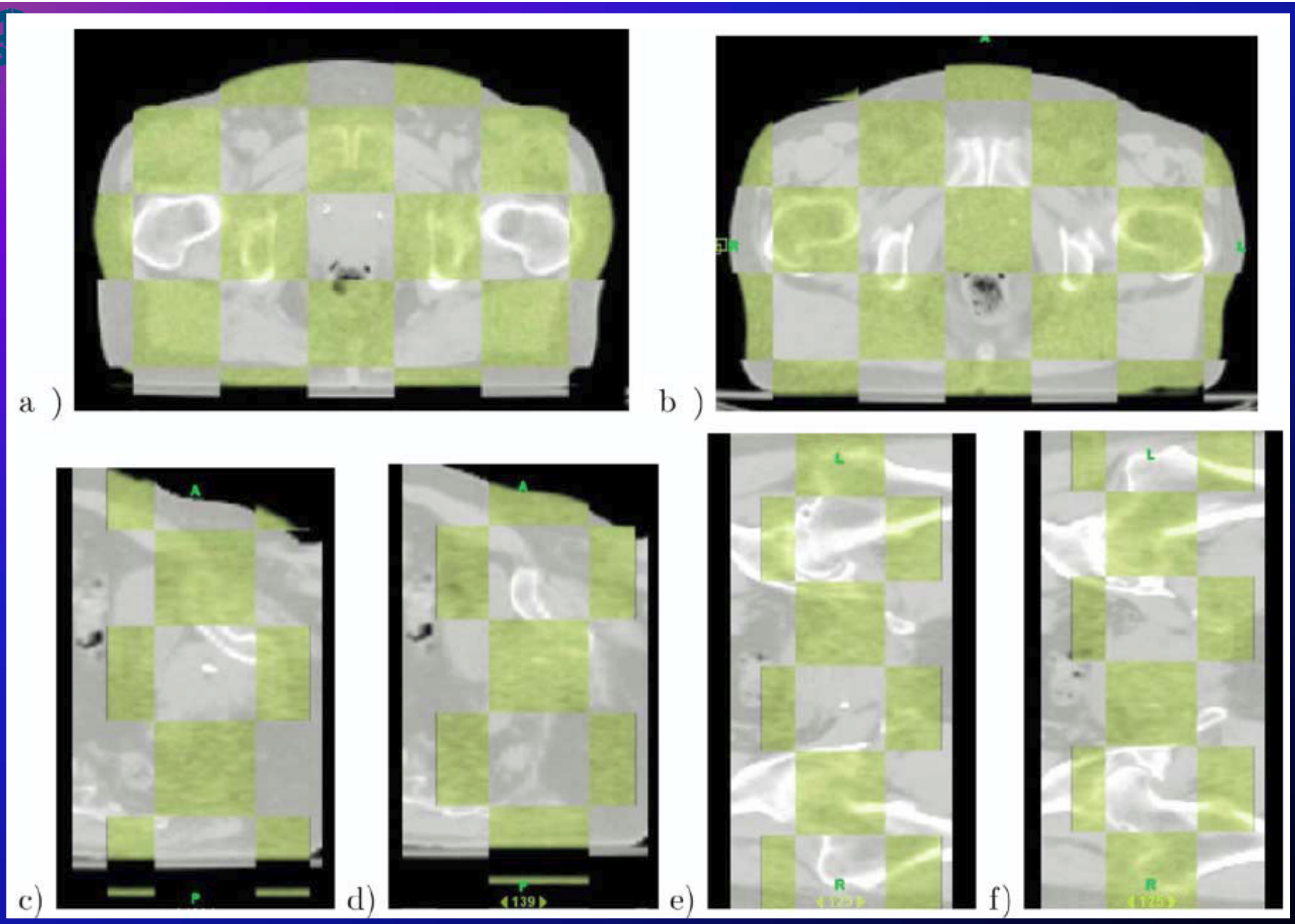


Sagittal

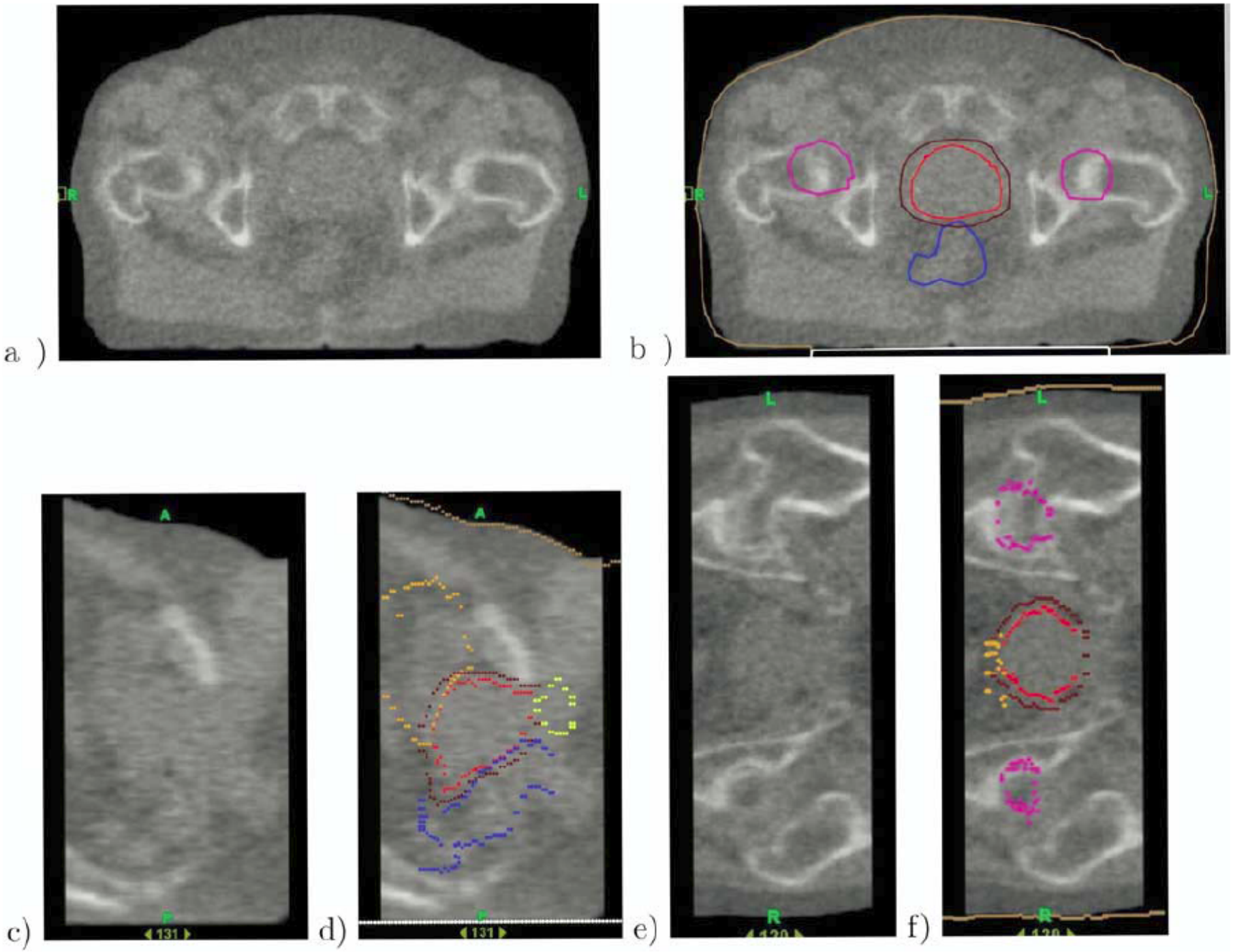


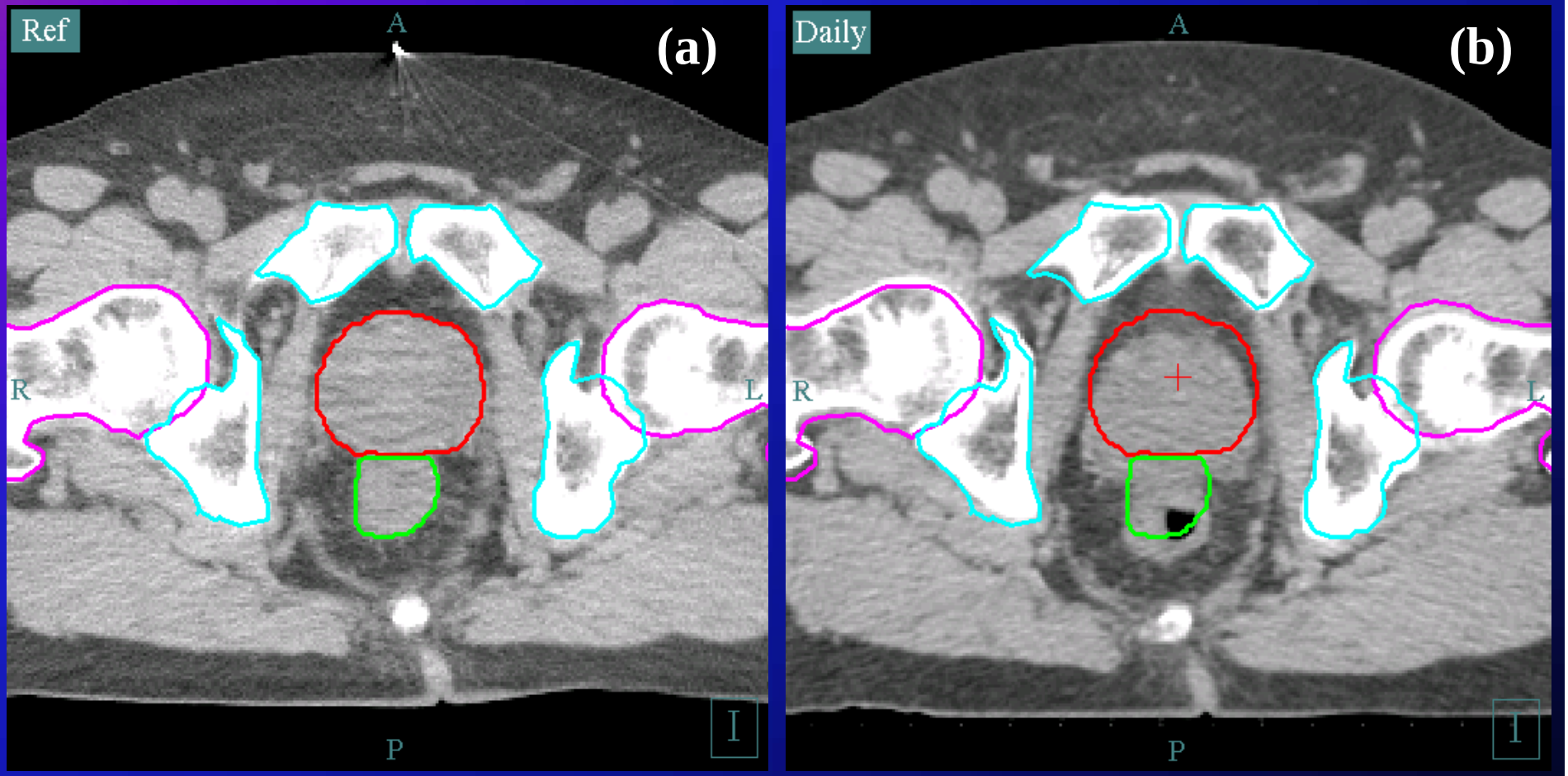
Axial

Figure 1. A checkerboard method is often used for visual evaluation of image registration. In this example, the tomotherapy megavoltage CT image (MVCT) and the conventional kilovoltage planning CT image (kVCT) are shown in each checkerboard window. Image alignment is verified if the anatomy can extend smoothly from one window into another. Picture curtsey of Katja Langen, Ph.D., M.D. Anderson Cancer Center at Orlando, Orlando, FL.

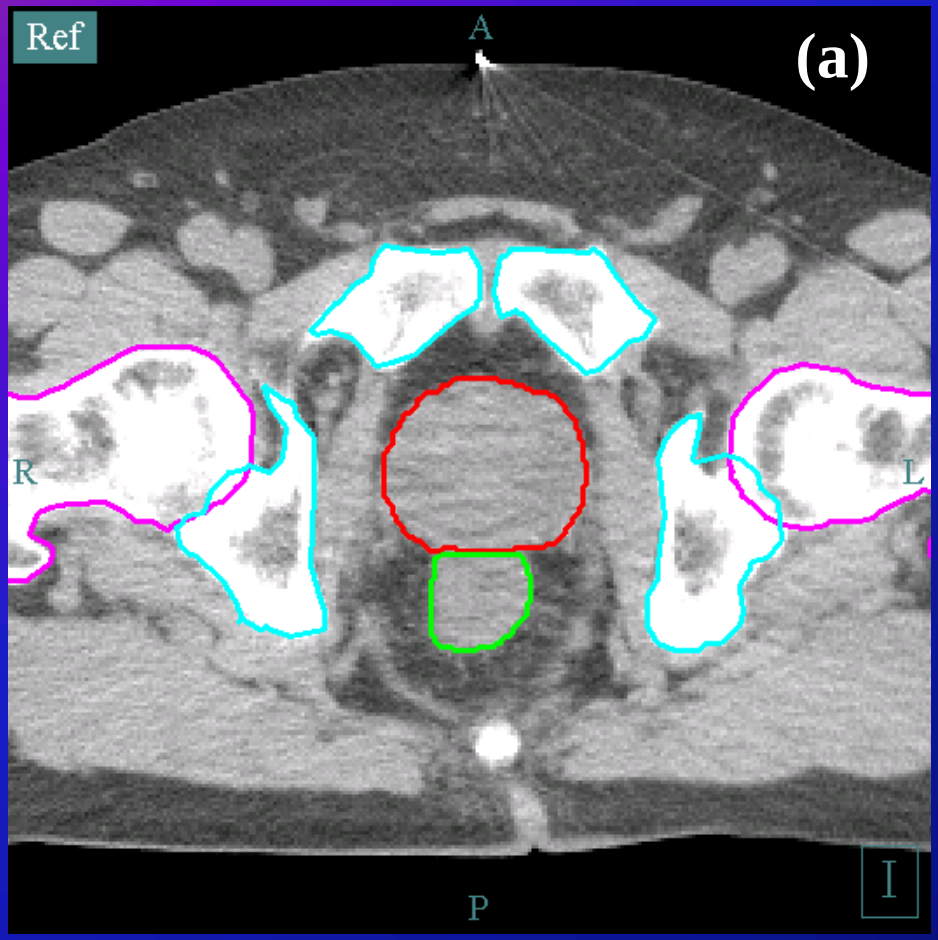


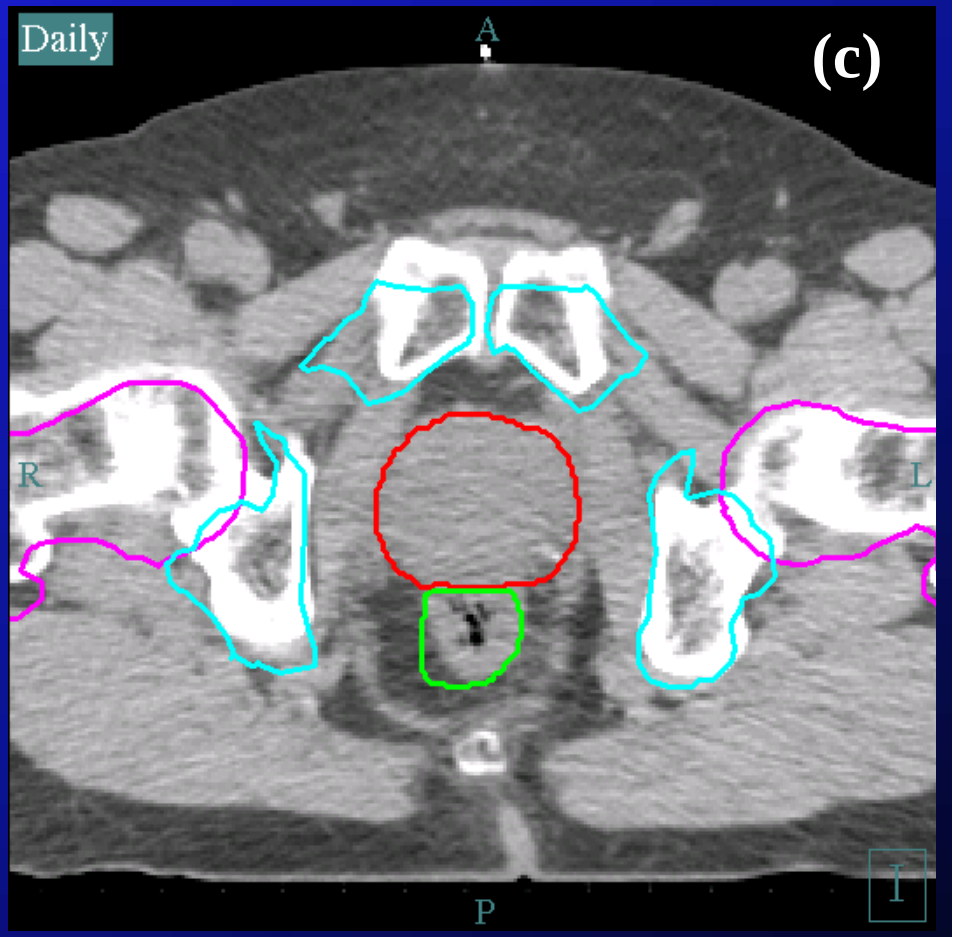
Anatomy-based megavoltage CT (yellow) and kilovoltage CT (gray) registration. The soft-tissue interface between the prostate and its surrounding tissues was used for image registration.


a)
b)
c)
d)
e)
f)
R
L
A
P
131



An example of soft tissue target (prostate) alignment
The reference (planning) CT image is shown in (a); the initial alignment (using skin marks) is shown in (b)





The final aligned image is shown in (c).

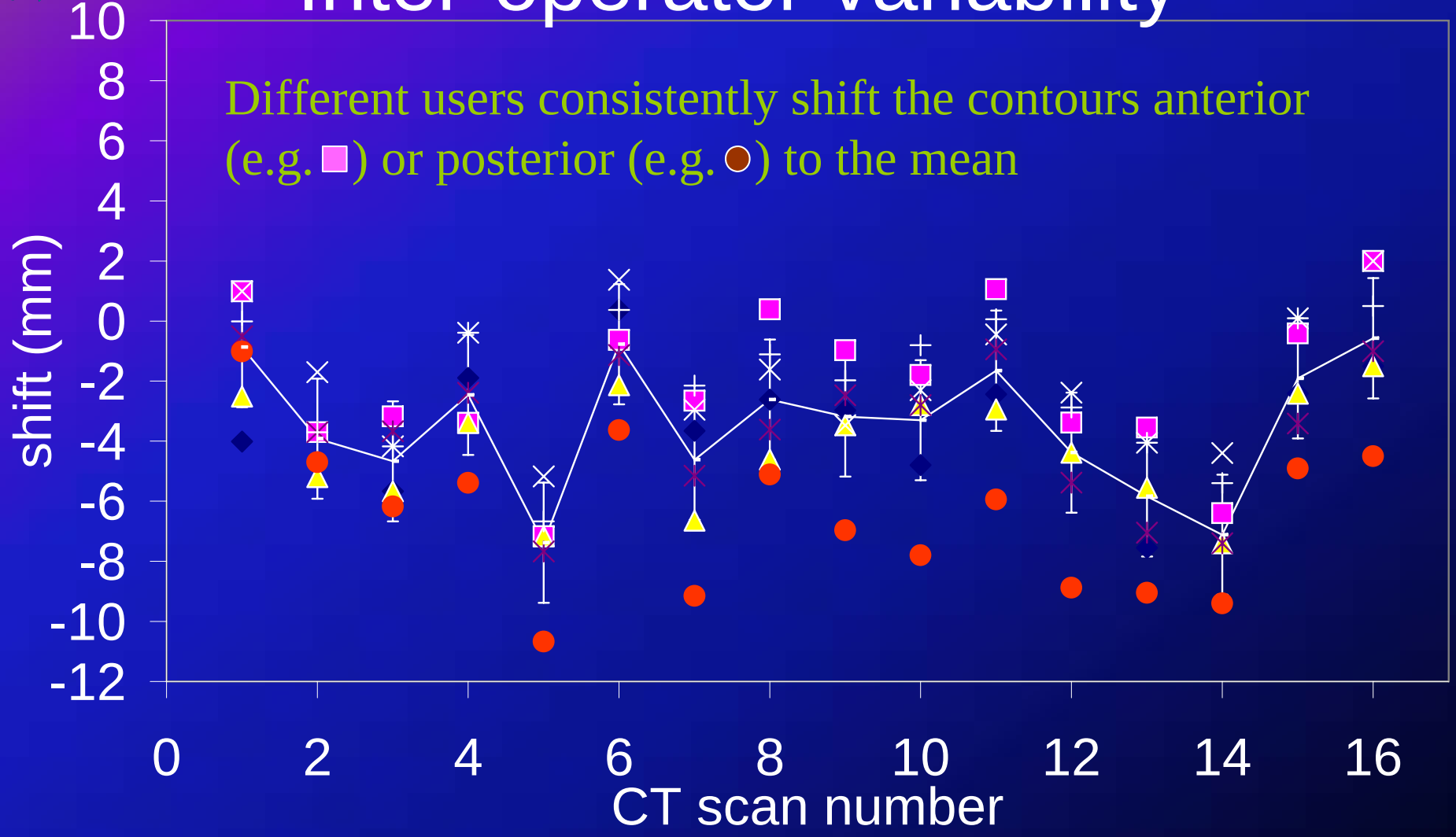
Uncertainties in Manual Alignment

- Differences in Image Interpretation
  - Inter-observer variations
    - Differences in the interpretation of the same anatomy
    - Differences in the interpretation of features extracted from the same anatomy
    - Therapist's alignment may not agree with physician's contour
- Day-to-day variations
  - Organ deformation
    - What is the best compromise?
  - Intra-observer variations
- Techniques
  - The use of other viewing planes (sagittal, coronal, and axial) for 3D alignment

Previous Studies

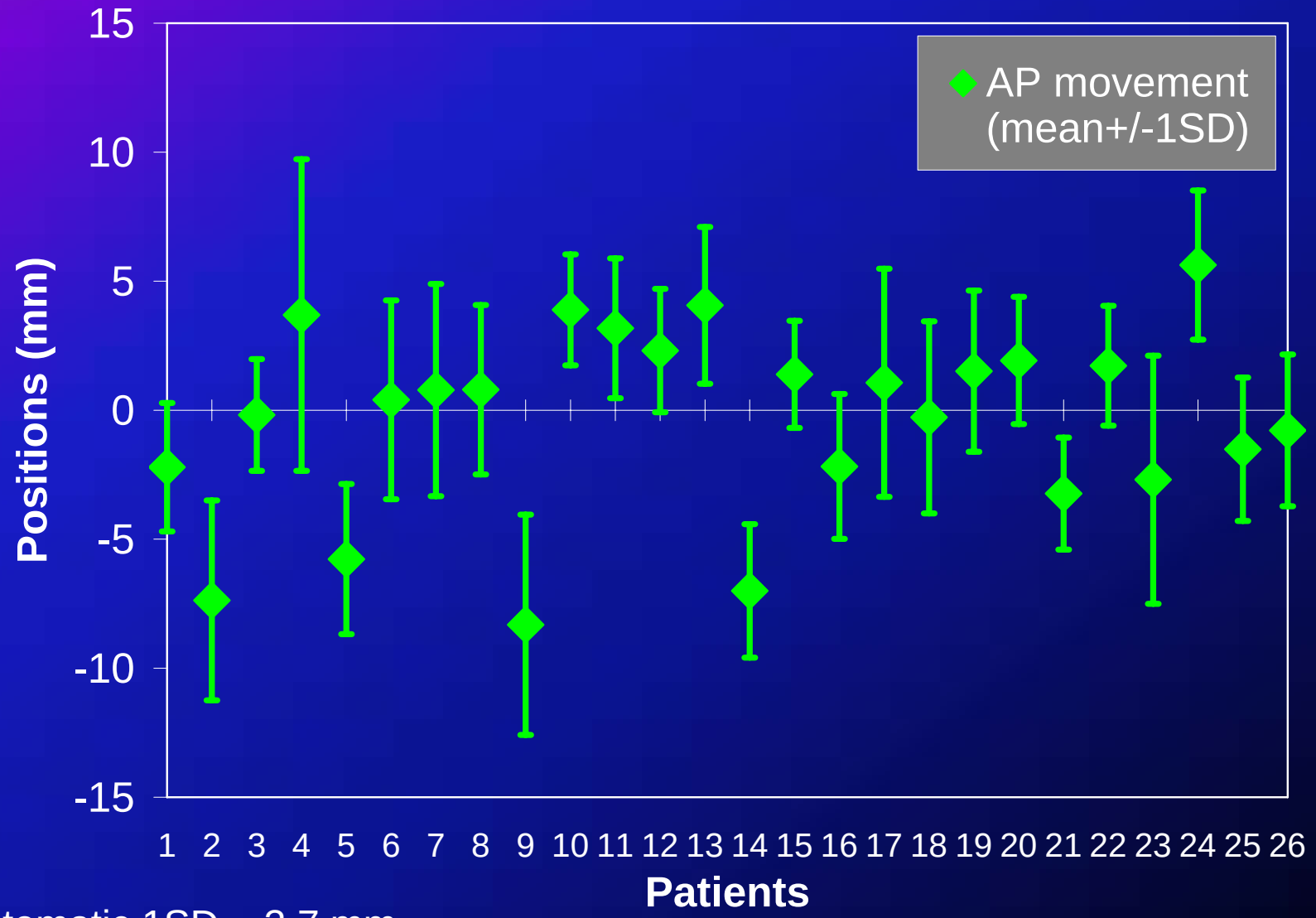
- Court LE, Dong L, Taylor N, et al. Evaluation of a contour-alignment technique for CT-guided prostate radiotherapy: an intra- and interobserver study. *Int J Radiat Oncol Biol Phys 2004;59:412-418.*
  - 28 CTs evaluated by 7 observers
  - Variations 0.8mm (RL), 2.0mm(AP), and 2.2mm(SI)
  - Using a reference CT side-by-side
    - 0.7mm (RL), 1.0mm (AP), and 1.6mm (SI)
- Intra-user variability
  - 0.5mm (RL), 0.7mm (AP), 0.5mm(SI)

Inter-operator variability



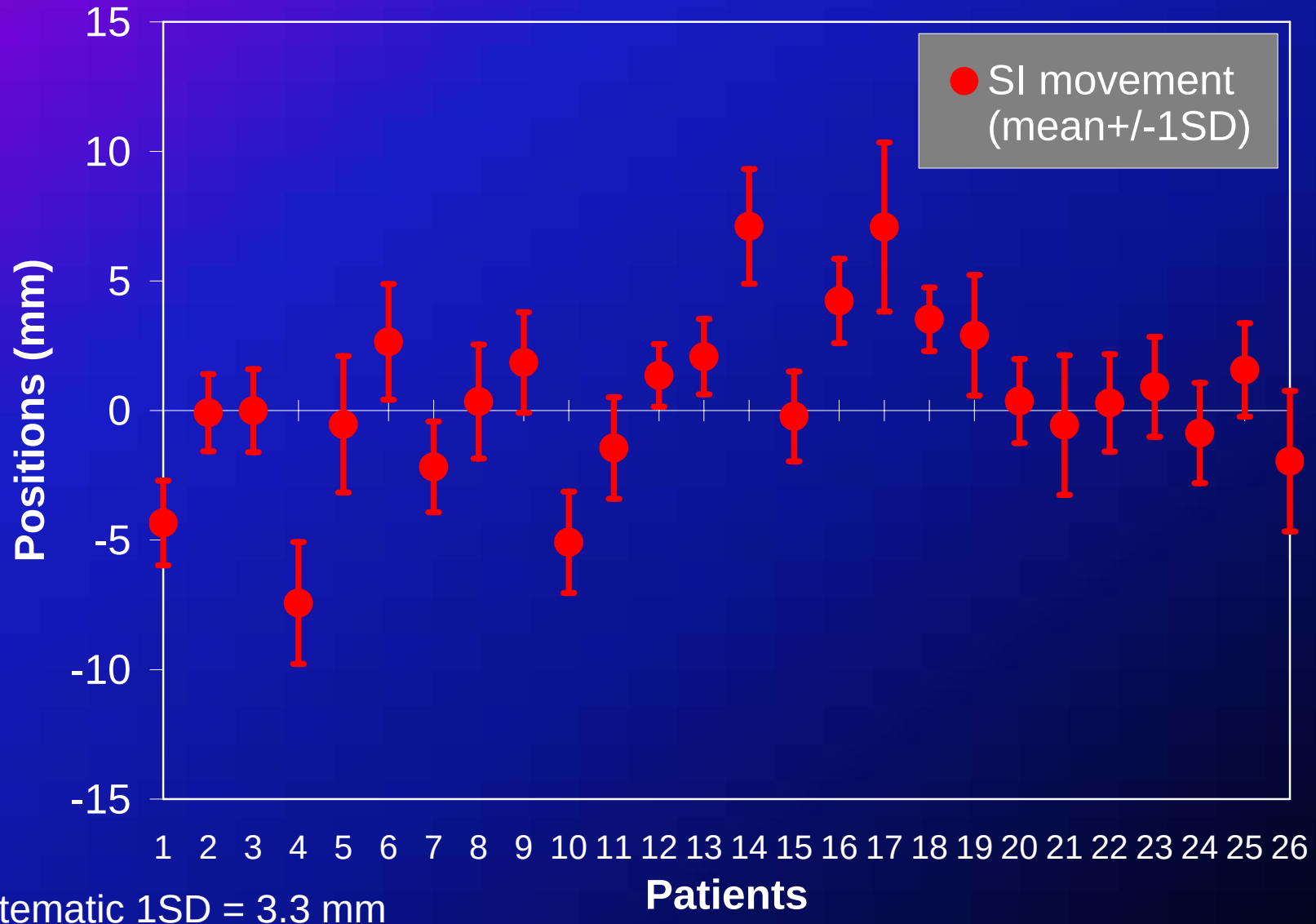
Court LE, Dong L, Taylor N, Ballo M, Kitamura K, Lee AK, O'Daniel J, White RA, Cheung R, Kuban D. Evaluation of a contour-alignment technique for CT-guided prostate radiotherapy: an intra- and interobserver study. *Int J Radiat Oncol Biol Phys* 2004; 59 (2):412-418.

Prostate Position Relative to Skin Marks



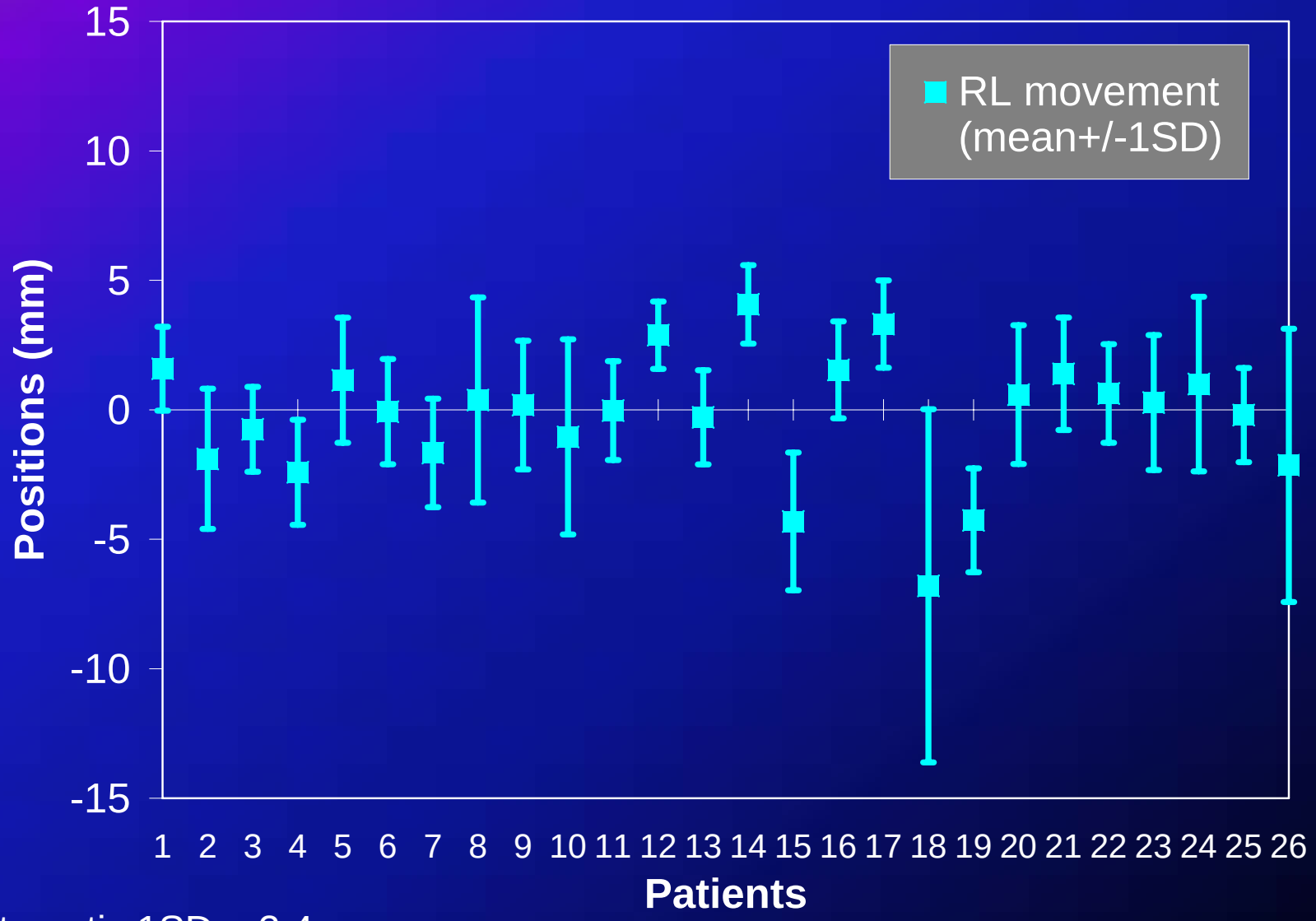
Systematic 1SD = 3.7 mm
Random 1SD = 3.3 mm

Prostate Position Relative to Skin Marks



Systematic 1SD = 3.3 mm
Random 1SD = 2.0 mm

Prostate Position Relative to Skin Marks



Systematic 1SD = 2.4 mm
Random 1SD = 2.8 mm

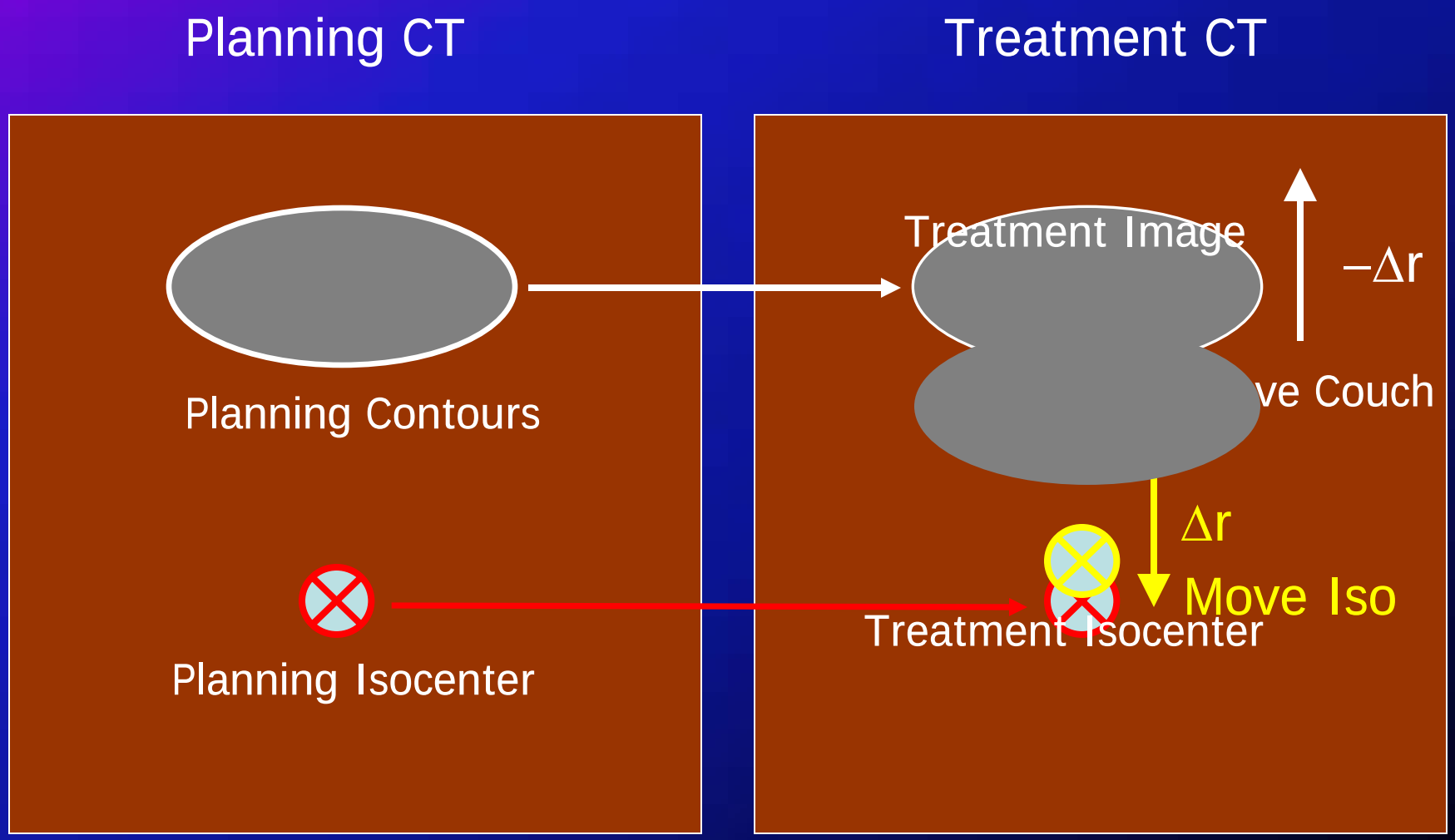
Reducing Inter-observer Variation By Using Direct Image Comparison

- Langen *et al.* Initial experience with megavoltage (MV) CT guidance for daily prostate alignments. *Int J Radiat Oncol Biol Phys* 2005;62:1517-1524.
  - Comparison of image-based and contour-based alignment methods
    - Agreement is better in image-based alignments
    - 3mm accuracy can be achieved in 97% (RL), 52% (AP), and 76% (SI).
  - Fiducial markers (3) are more consistent for alignment

Automatic Alignment

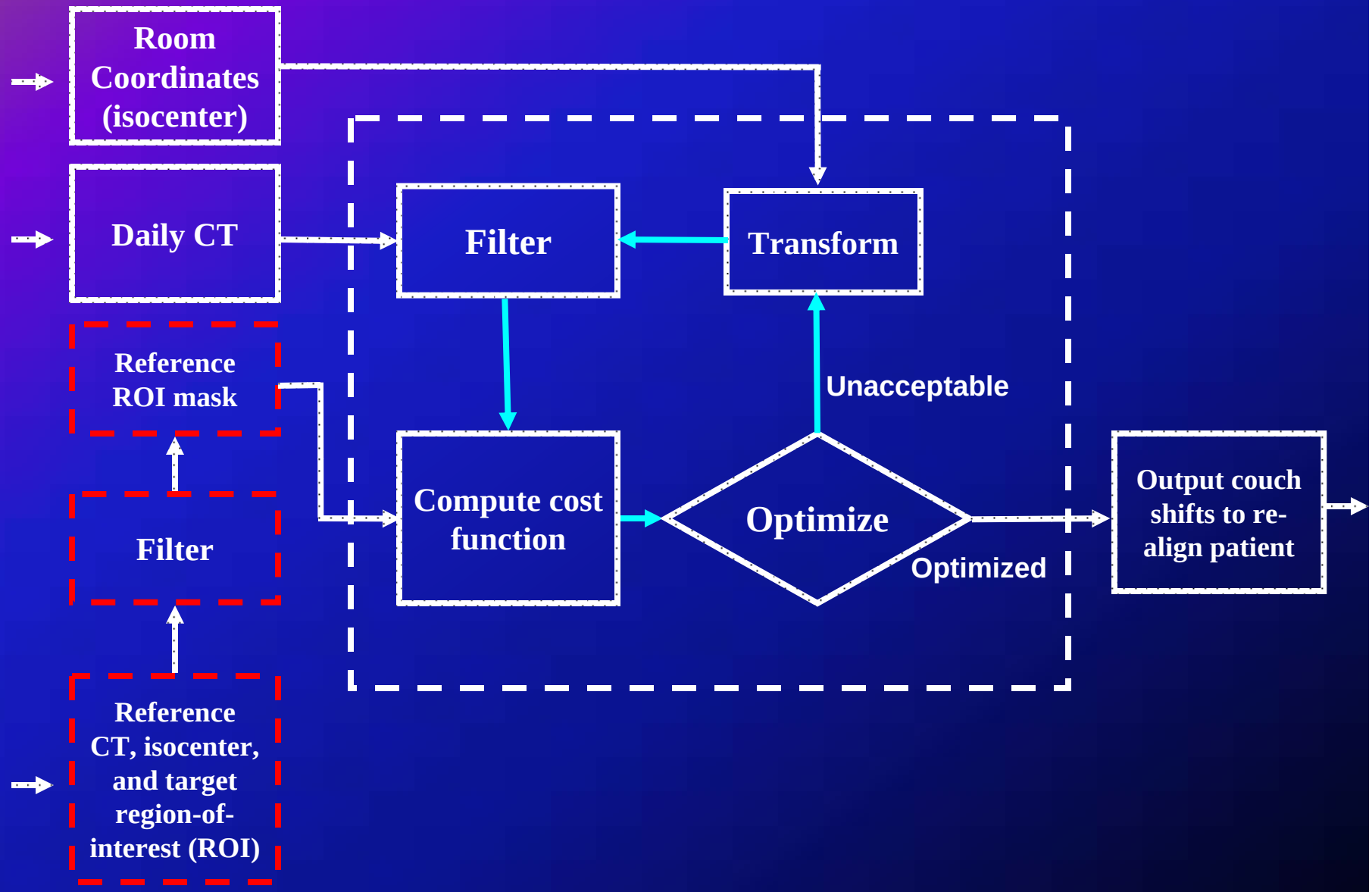
- Direct image-based comparison
  - Soft-tissue target alignment
- More consistent
- Good image quality in volumetric CTs
- Good pixel accuracy or consistency
- 3D representation of an object
- Fast alignment (~ seconds)

Alignment Process



Main Components in An Automated Alignment Process

- Room coordinate system
  - Where is the beam?
  - Isocenter (or reference point)
- Alignment target
  - ROI
    - Treatment target itself: prostate
  - Target surrogates
    - Bony structures: lung cancer
- Cost function



A diagram showing the volumetric CT-to-CT automatic registration process

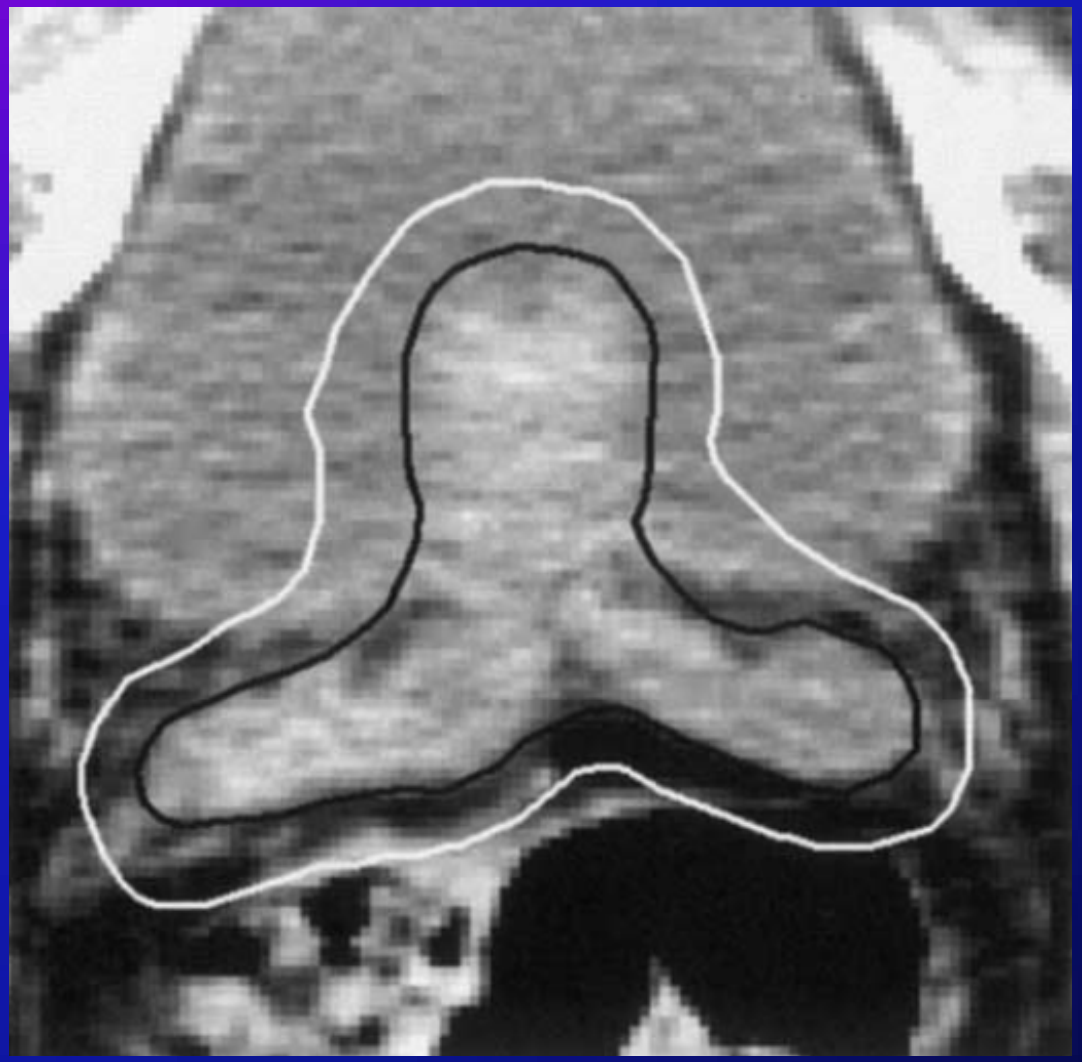
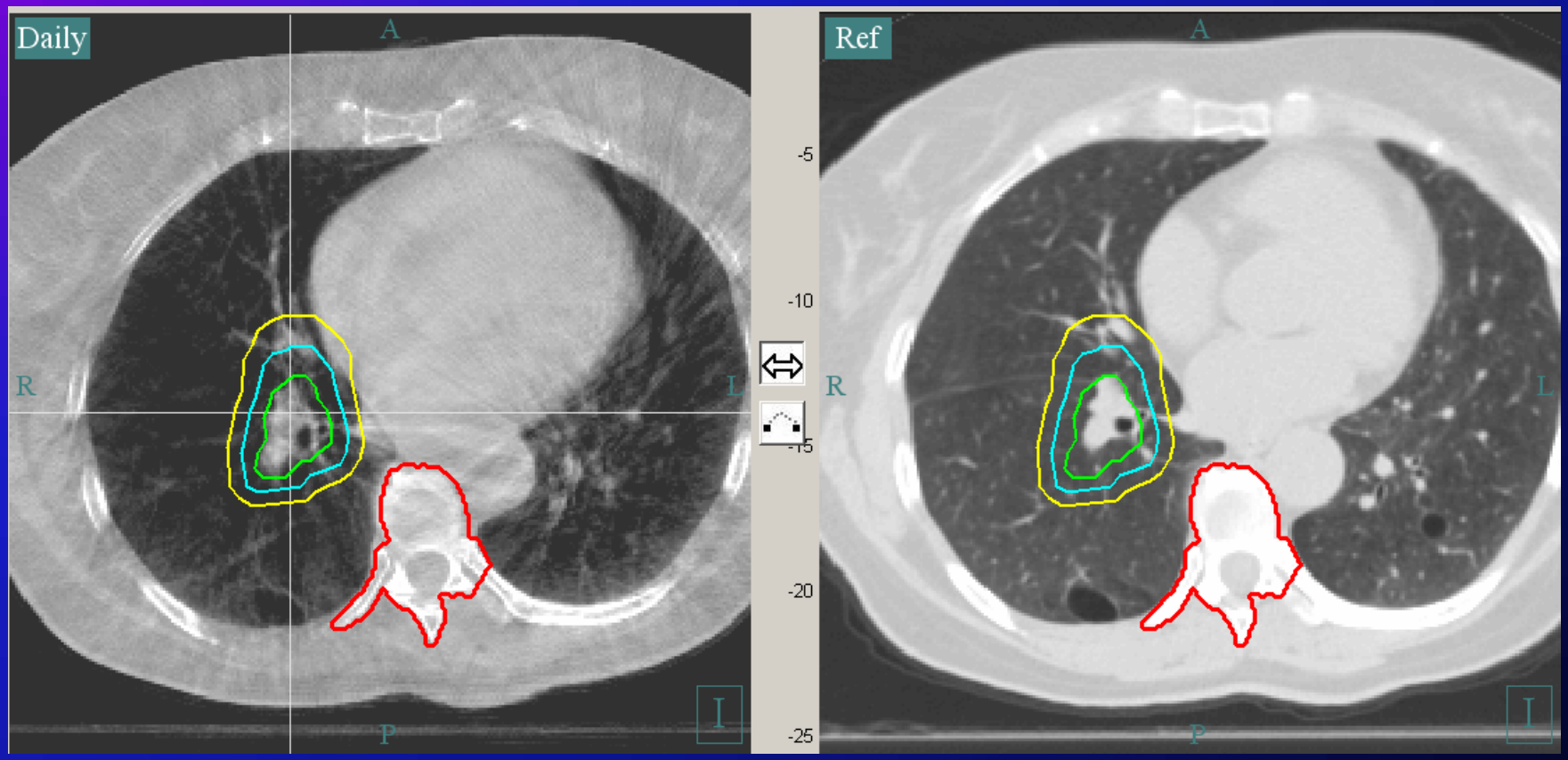


Figure 3. A target ROI can be obtained from the contoured target in the treatment planning CT. The black line represents the delineated contours of the prostate and the seminal vesicles in one CT slice and the gray line represents an additional 5-mm expansion for the alignment ROI. The picture was originally published by Smitsmans et al (2004). "Automatic localization of the prostate for on-line or off-line image-guided radiotherapy." Int. J. Radiat. Oncol. Biol. Phys. 60(2): 623-635.

Example of Alignment Target



Cone-beam CT

Planning CT

Cost Function = Similarity Measure

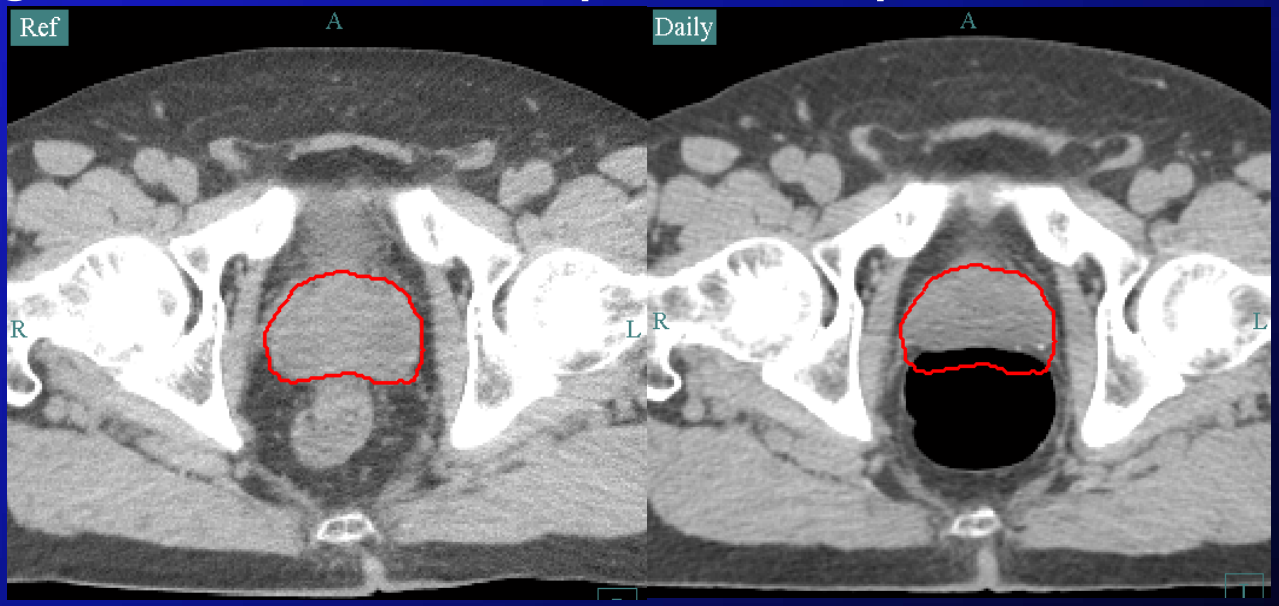
- Feature based
  - Automatic feature extraction:
    - fiducial points, bony patterns etc.
    - The distance between features, such as points,curves,or surfaces of corresponding anatomical structure.
- Intensity based
  - Intensity differences or ratios
  - Cross correlation
  - Mutual information

The Role of Image Filter

- Image filter is a pre-alignment image processing step
  - Image enhancement
    - Window/level adjustment etc.
  - Image processing with prior knowledge
    - Gas removal filter
    - Gas-fill filter
- Main goals for image filter
  - Improve the behavior of the cost function
    - Smooth surface
    - Well-defined minimum
    - Large attraction range

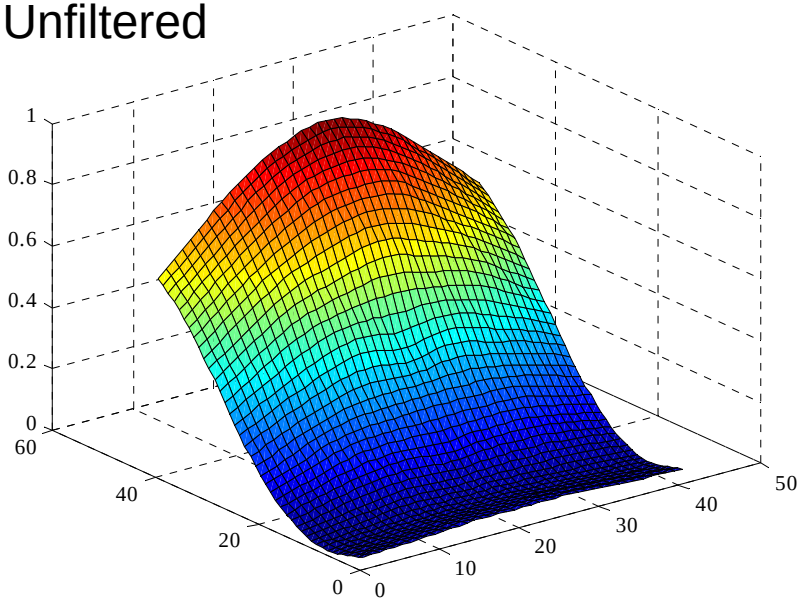
Image Filter For Prostate Alignment

- Gas-removal filter (Court and Dong 2003)
  - Remove pixels corresponding to the area of gas pocket
- Gas-fill filter (Smitsmans et al. 2004)
  - Fill gas with tissue-equivalent pixels

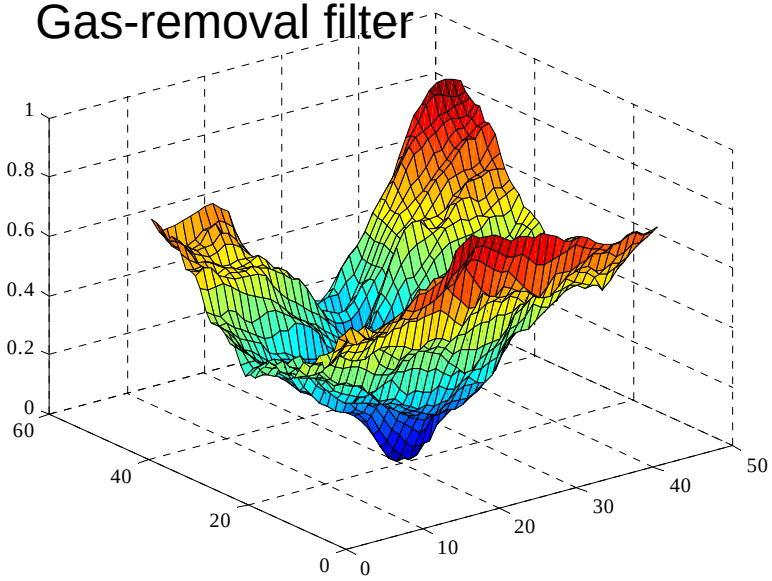


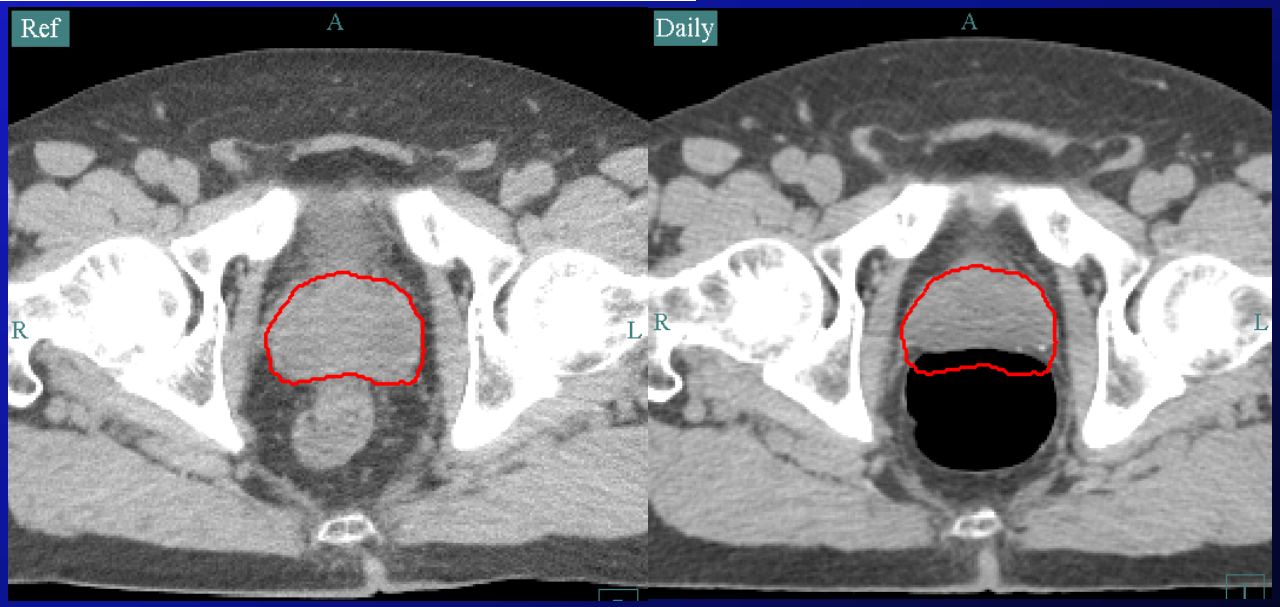
Correlation method

Unfiltered



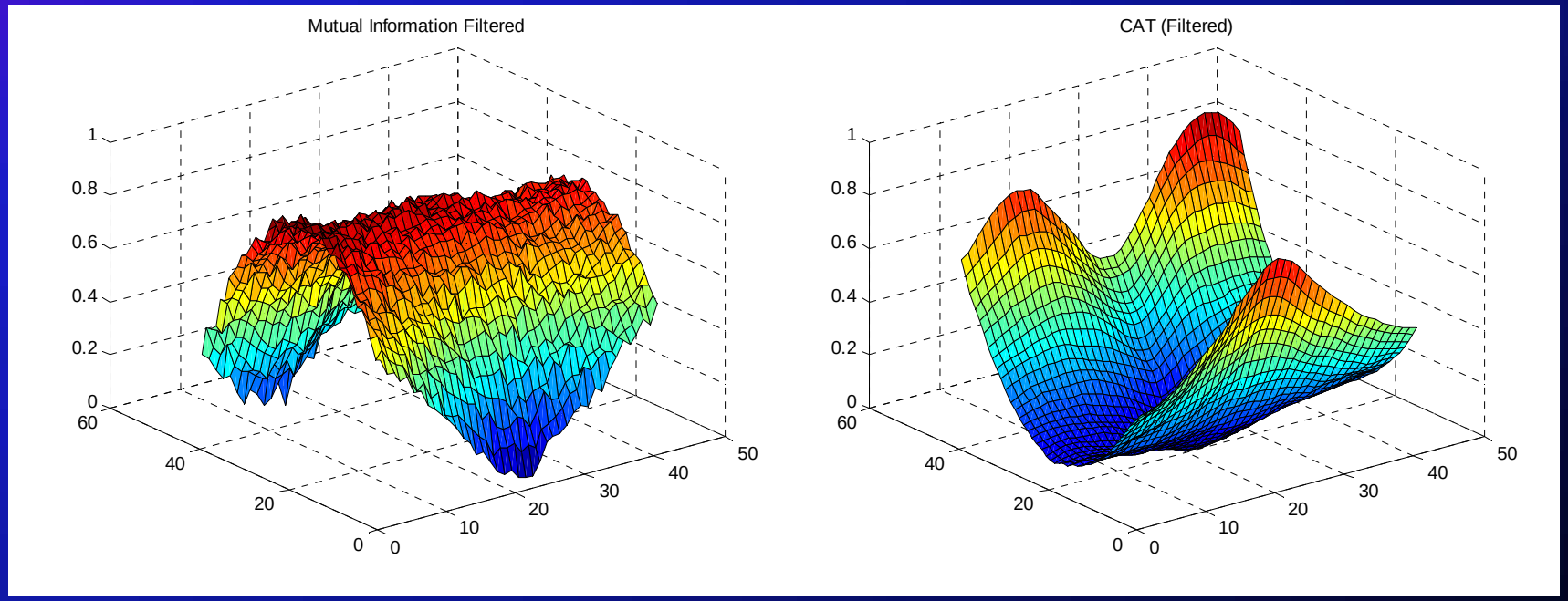
Gas-removal filter





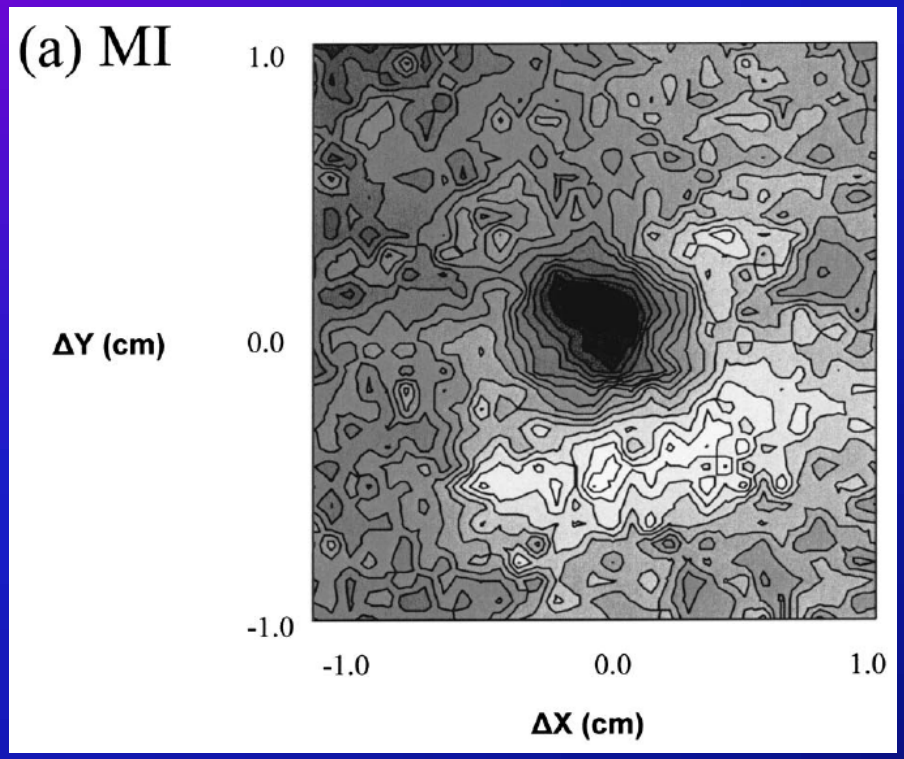
Pat07, CT22

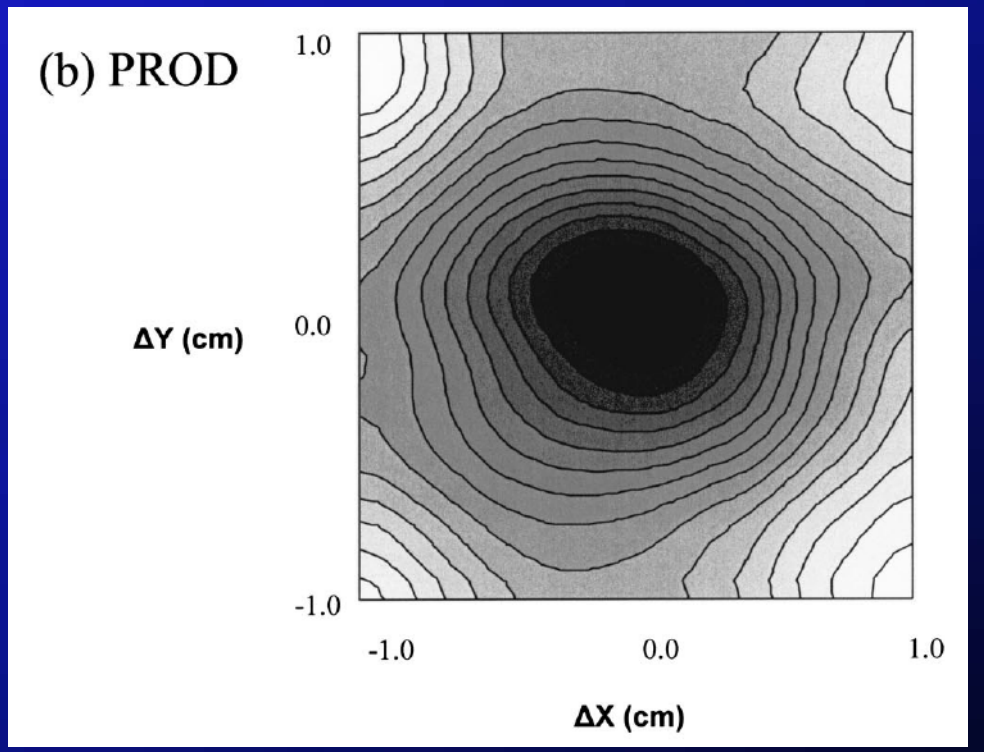
Filtered



Mutual Information

Pixel Intensity Difference

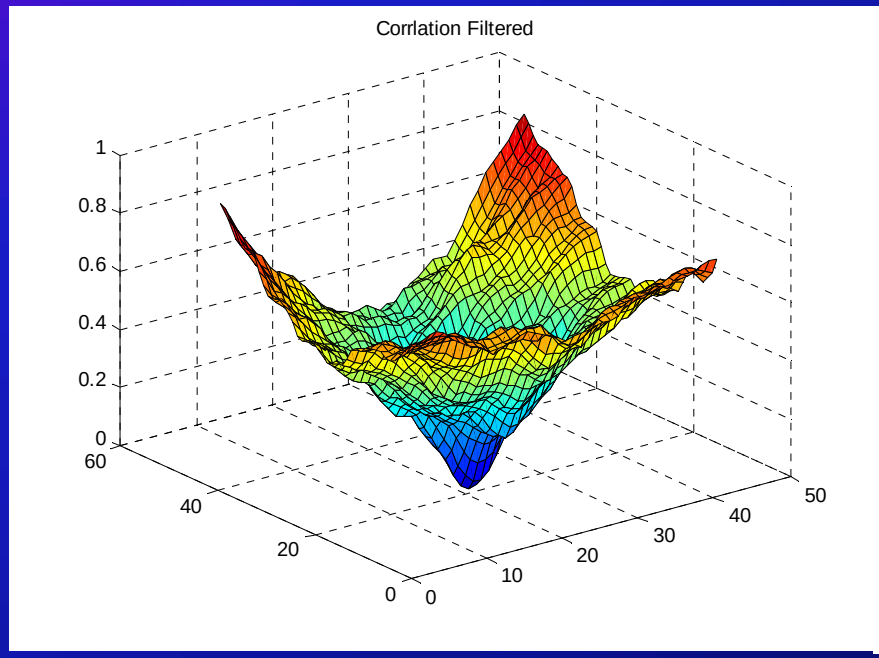


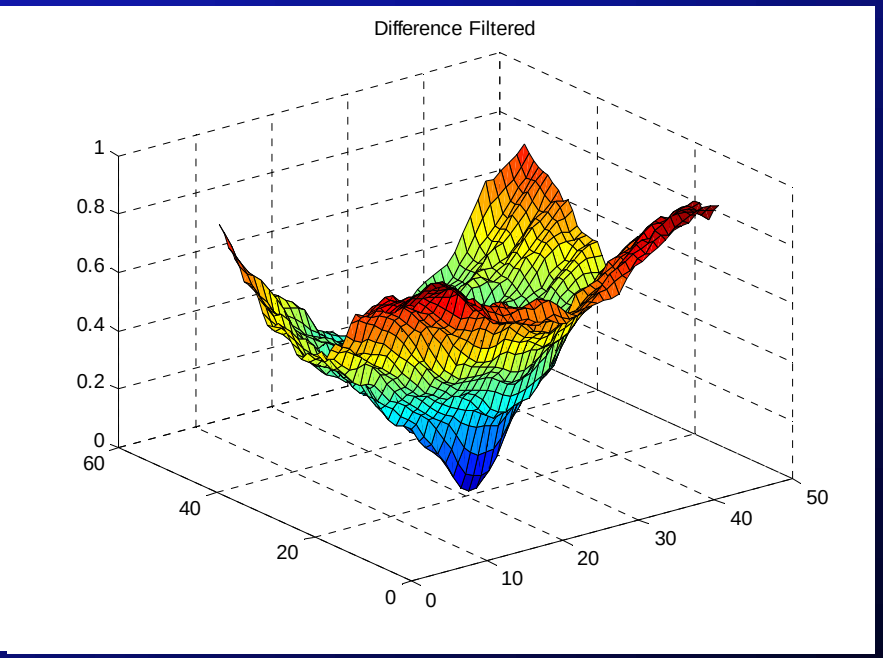


Dekker N, Ploeger LS, van Herk M. Evaluation of cost functions for gray value matching of two-dimensional images in radiotherapy. *Med Phys* 2003;30:778-784.

Pat01, CT23

Filtered

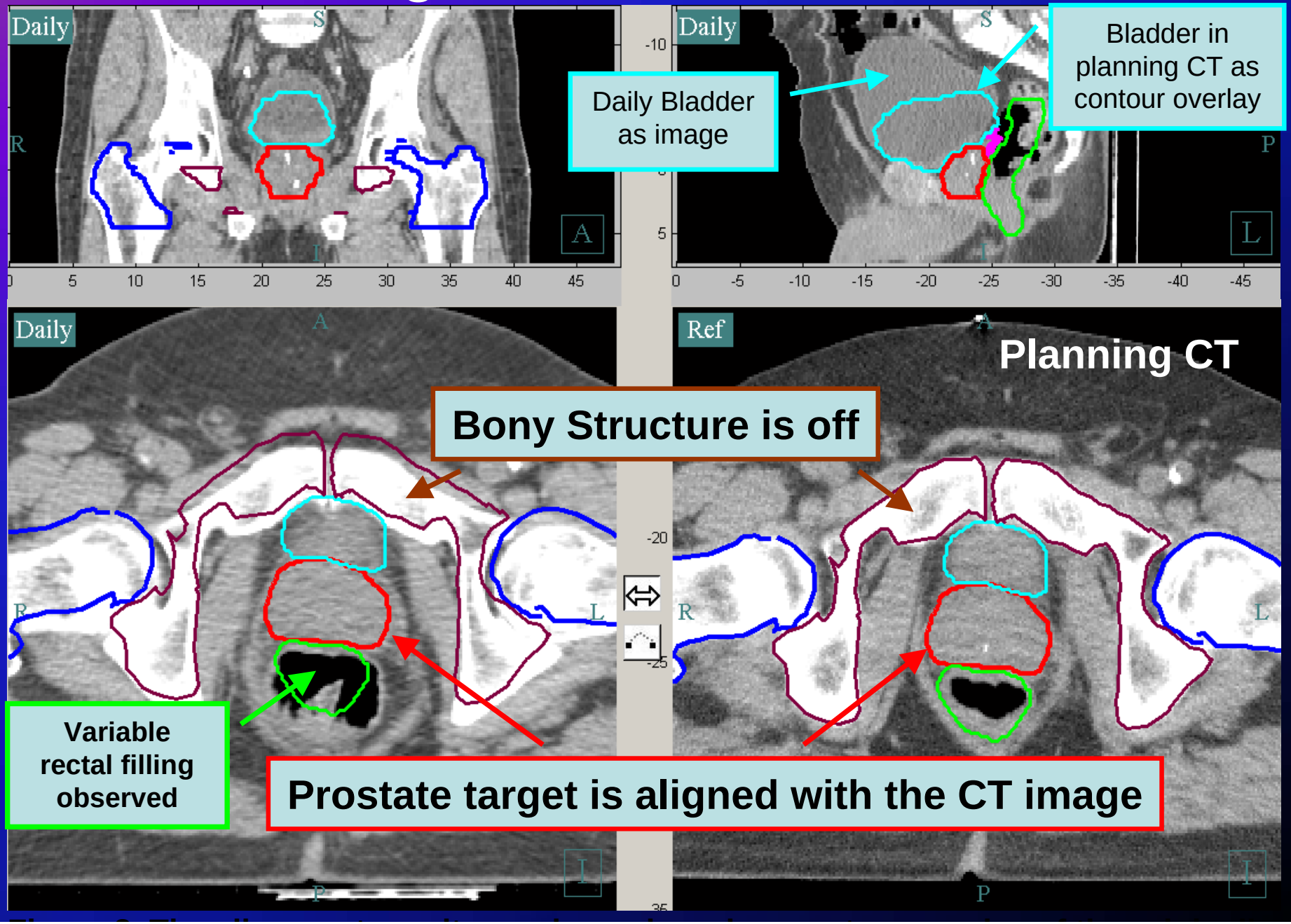




Correlation Method

Pixel Intensity Difference

Alignment Evaluation



Soft-tissue Alignment

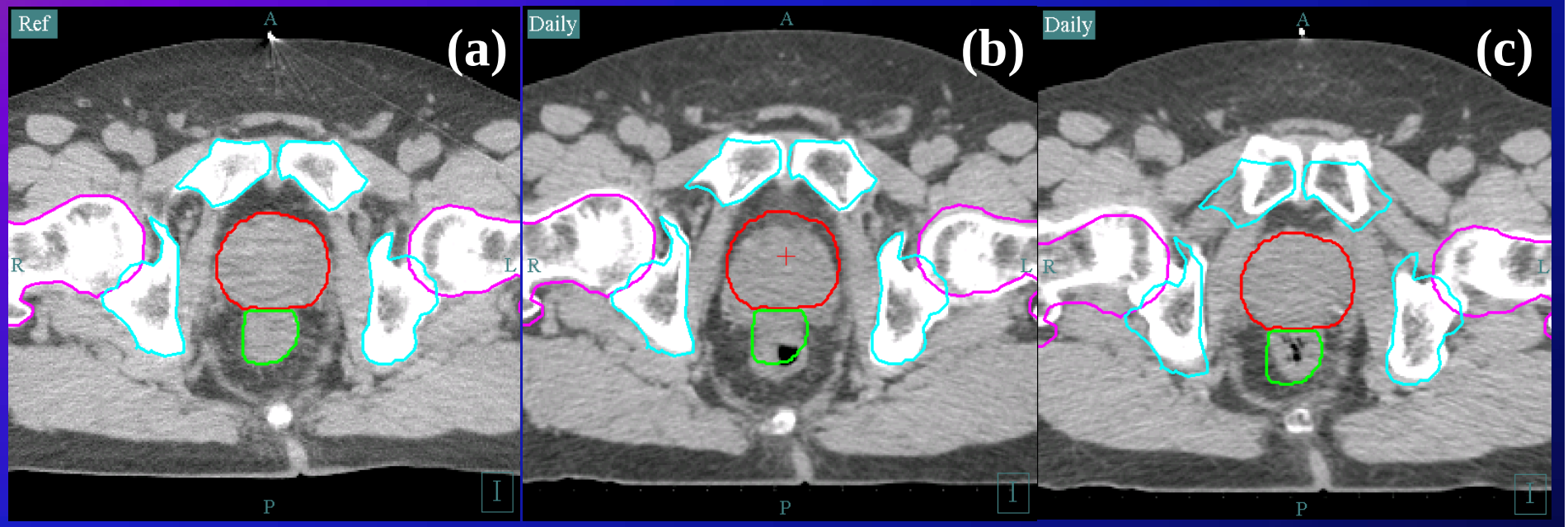
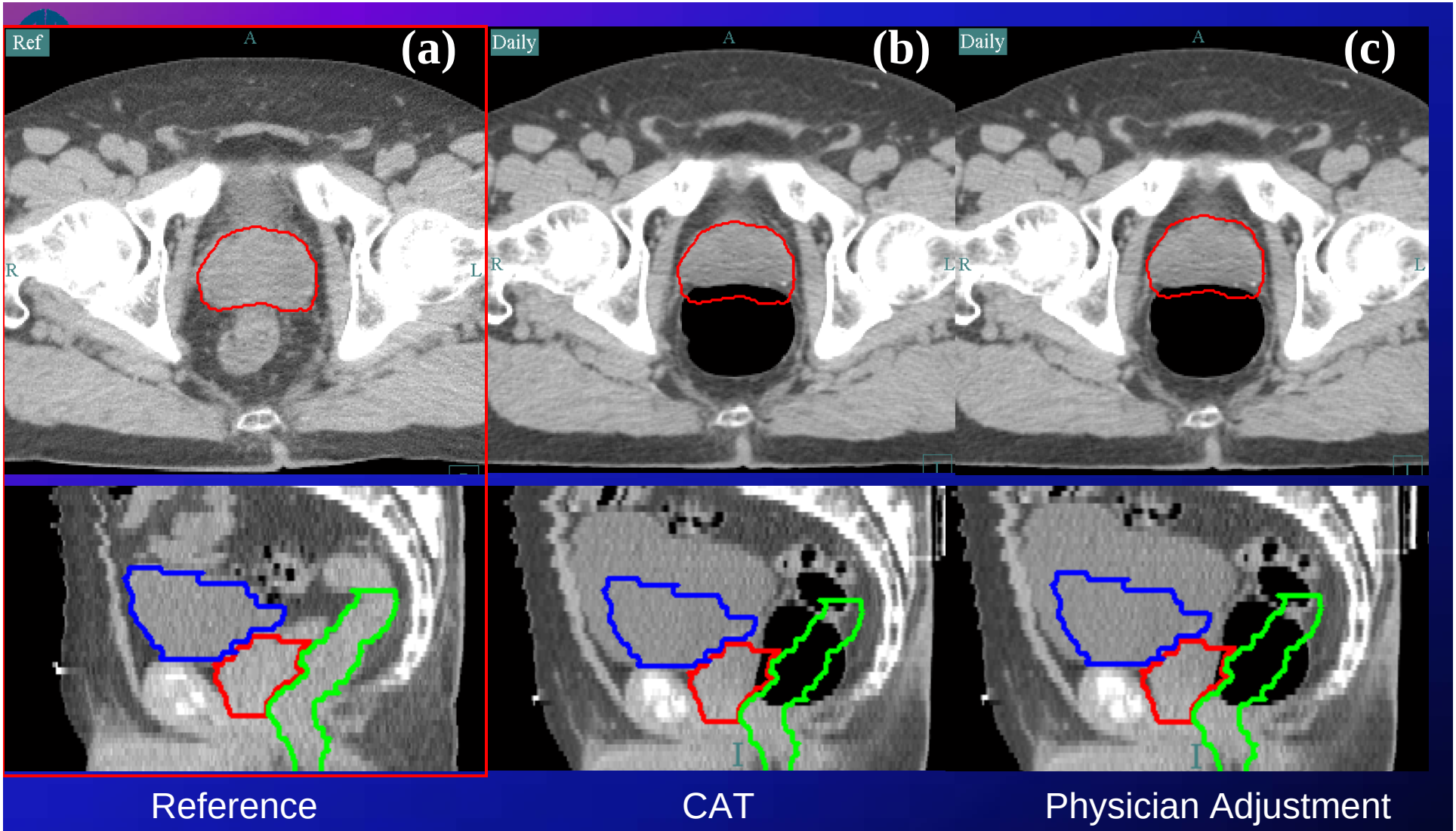


Figure 5. An example of soft tissue target (prostate) alignment using a fully automatic image registration technique. The reference (planning) CT image is shown in (a); the initial alignment (using skin marks) is shown in (b); the final alignment after the automatic image registration is shown in (c). In this example, significant inter-fractional prostate movement exists, which caused severe offset for the bony anatomy after the prostate is aligned in (c).

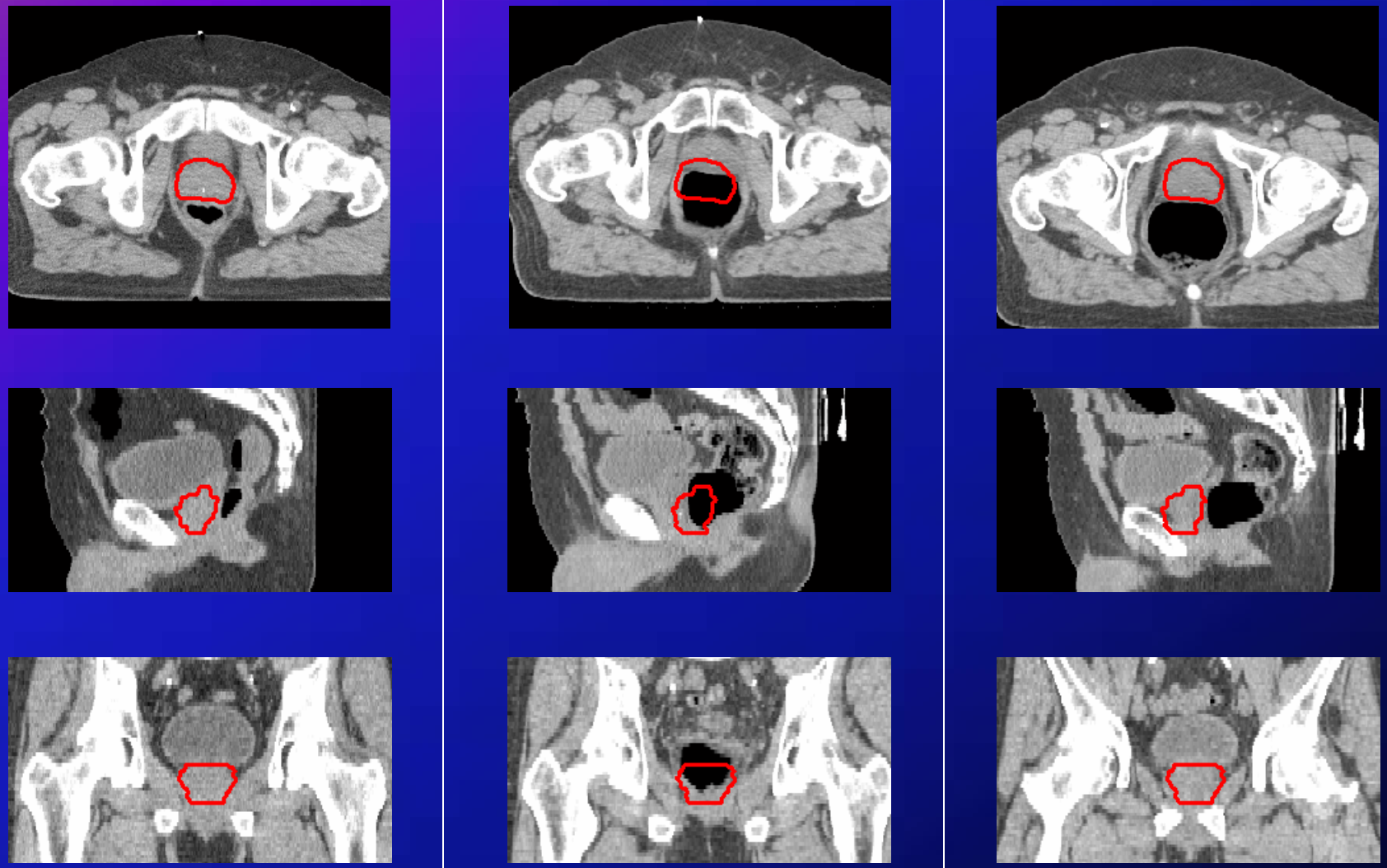


Reference CAT Physician Adjustment

Figure 6. The reference prostate and contour are shown in (a). Due to rectal gas filling, the computer automatic image registration aligned the anterior boundary of the prostate better after the “gas removal” filter in (b). However, a radiation oncologist believes that a better alignment of the prostate-rectum interface is more clinically important. Therefore, he manually adjusted the prostate position to his preference.

Soft Reg

Planning | Daily before alignment | Daily after alignment



Prostate alignment example with large gas filling. Final shifts: posterior: 2.44cm; inferior: 0.8cm; left: 0.84cm.

Results of Soft Tissue Target Localization (366 prostate alignments)

Table 3: Evaluation of CAT automatic soft tissue registration (differences in mm)

	Anterior/Posterior				Superior/Inferior				Right/Left			
	Ave	1SD	%=>3mm	Range	Ave	1SD	%>3mm	Range	Ave	1SD	%>3mm	Range
Pat01	0.0	0.0	0.0%	[0.0 0.0]	0.0	0.0	0.0%	[0.0 0.0]	0.0	0.0	0.0%	[0.0 0.0]
Pat02	0.0	0.0	0.0%	[0.0 0.2]	0.1	0.5	0.0%	[0.0 2.4]	-0.1	0.3	0.0%	[-1.8 0.0]
Pat03	0.0	0.0	0.0%	[0.0 0.0]	0.0	0.0	0.0%	[0.0 0.0]	0.0	0.0	0.0%	[0.0 0.0]
Pat04	-0.3	0.9	4.0%	[-3.6 0.0]	-0.3	1.2	4.0%	[-2.5 3.6]	0.1	0.3	0.0%	[0.0 1.6]
Pat05	-0.1	0.3	0.0%	[-1.2 0.6]	0.0	0.5	0.0%	[-2.0 1.0]	0.0	0.2	0.0%	[-1.0 0.0]
Pat06	0.0	0.0	0.0%	[0.0 0.0]	0.0	0.0	0.0%	[0.0 0.0]	0.0	0.0	0.0%	[0.0 0.0]
Pat07	0.2	0.6	0.0%	[0.0 2.2]	-0.4	1.3	8.6%	[-5.1 0.0]	0.0	0.2	0.0%	[0.0 1.0]
Pat08	0.0	0.0	0.0%	[0.0 0.0]	0.0	0.0	0.0%	[0.0 0.0]	0.0	0.0	0.0%	[0.0 0.0]
Pat09	0.0	0.0	0.0%	[0.0 0.0]	-0.1	0.4	0.0%	[-2.0 0.0]	0.0	0.0	0.0%	[0.0 0.0]
Pat10	0.0	0.0	0.0%	[0.0 0.0]	0.0	0.0	0.0%	[0.0 0.0]	0.0	0.0	0.0%	[0.0 0.0]
Pat11	0.0	0.0	0.0%	[0.0 0.0]	-0.2	0.7	4.0%	[-3.0 0.0]	0.0	0.0	0.0%	[0.0 0.0]
Pat12	0.0	0.0	0.0%	[0.0 0.0]	0.0	0.0	0.0%	[0.0 0.0]	0.0	0.0	0.0%	[0.0 0.0]
Pat13	0.0	0.0	0.0%	[0.0 0.0]	0.0	0.1	0.0%	[-0.4 0.0]	0.0	0.2	0.0%	[-0.9 0.0]
Pat14	0.0	0.2	0.0%	[-1.0 0.0]	-0.9	1.3	16.7%	[-3.0 0.0]	0.0	0.0	0.0%	[0.0 0.0]
Pat15	0.0	0.0	0.0%	[0.0 0.0]	0.0	0.0	0.0%	[0.0 0.0]	0.0	0.0	0.0%	[0.0 0.0]
Total	**0.0**	**0.3**	**0.3%**	**[-3.6 2.2]**	**-0.1**	**0.7**	**2.1%**	**[-5.1 3.6]**	**0.0**	**0.2**	**0.0%**	**[-1.8 1.6]**

Results of Bony Registration (366 pelvic bone alignments)

Table 4: Evaluation of bony alignment using CAT software (difference in mm)

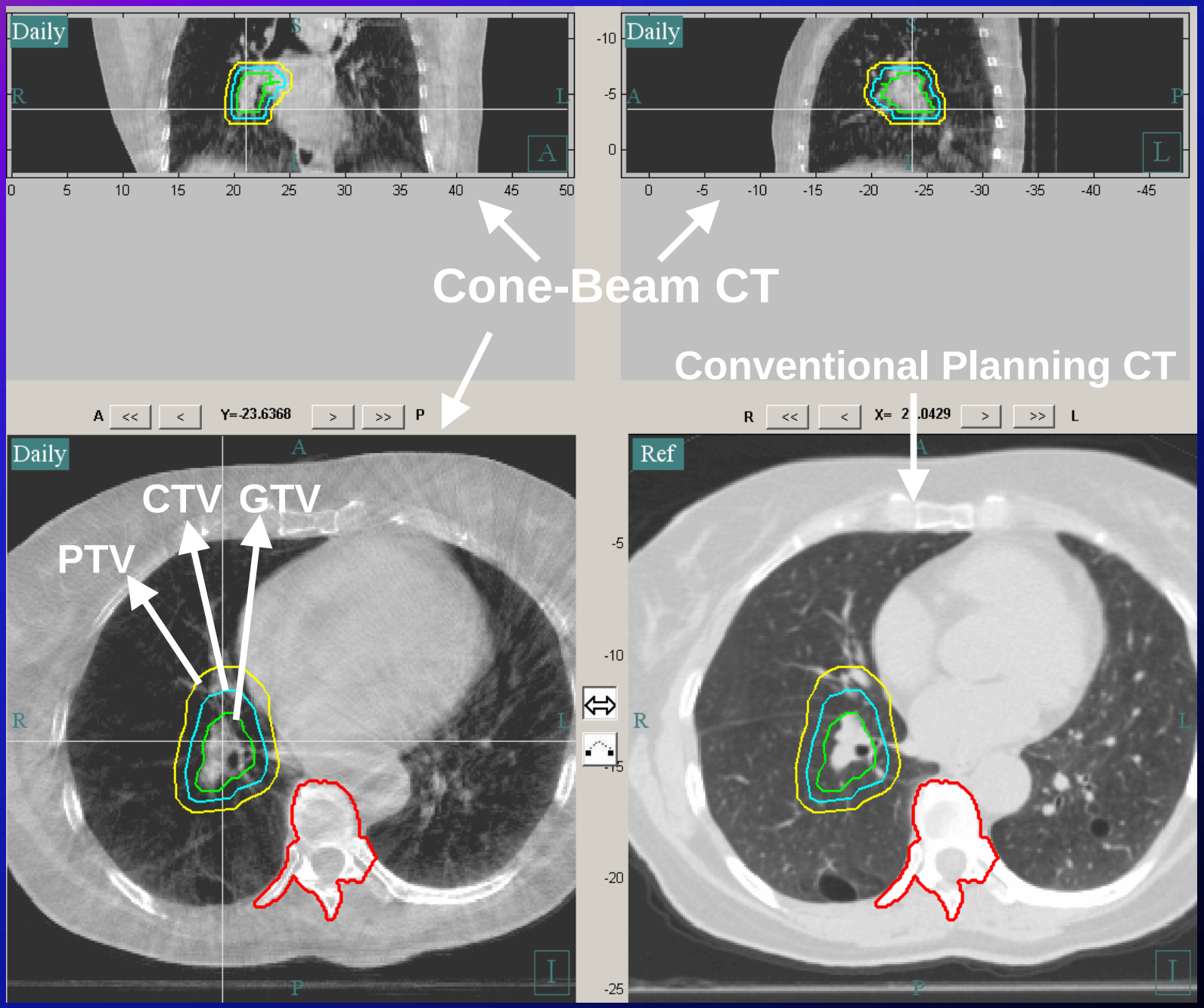
	Anterior/Posterior				Superior/Inferior				Right/Left			
	Mean	1SD	%=>3mm	Range	Mean	1SD	%>3mm	Range	Mean	1SD	%>3mm	Range
Total	0.0	0.1	0.0%	[-1.0 1.0]	-0.3	0.7	1.6%	[-4.0 1.5]	0.0	0.1	0.0%	[-1.8 0.0]

Successful Rate

- Success: defined as <= 3 mm between calculation and experienced human evaluation
  - 97.9% for soft tissue target (prostate)
  - 98.4% for bony registration (pelvic bone)

Smitsmans MHP, De Bois J, Sonke J-J, *et al.* Automatic prostate localization on cone-beam CT scans for high precision image-guided radiotherapy. *Int J Radiat Oncol Biol Phys* 2005;63:975-984.

- 32 patients 332 CBCT alignments
- Importance of image quality
  - Collimated CBCT
    - 65% successful rate to 84%
  - Streaky artifacts due to prostate/rectum motion during CBCT acquisition
    - Alignment error (1SD)
      - 1.0 mm (RL)
      - 2.0-2.4 mm (SI)
      - 1.7-2.3 mm (AP)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Cone-Beam CT
Conventional Planning CT
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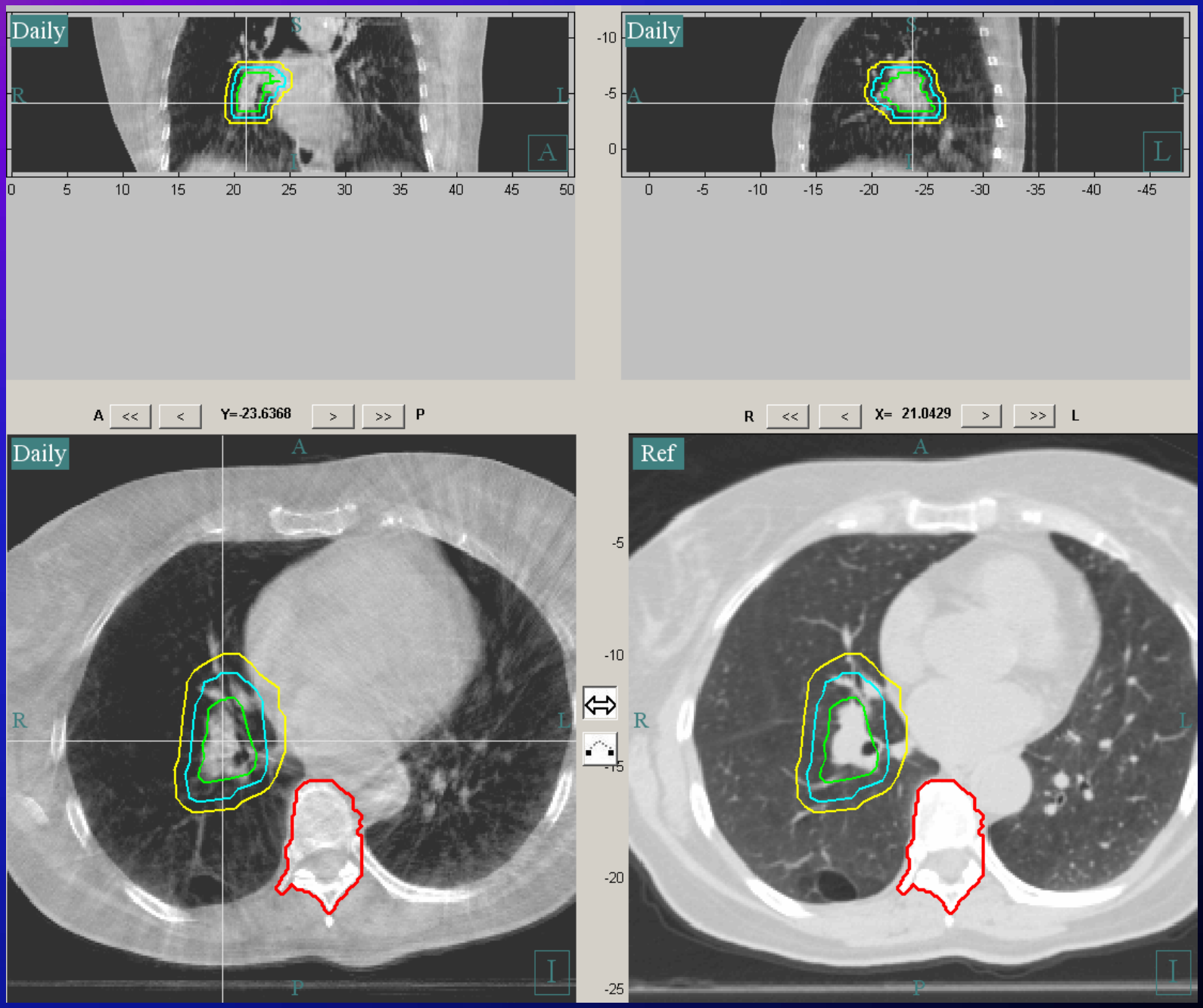
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R << < X= 21.0429 > >> L
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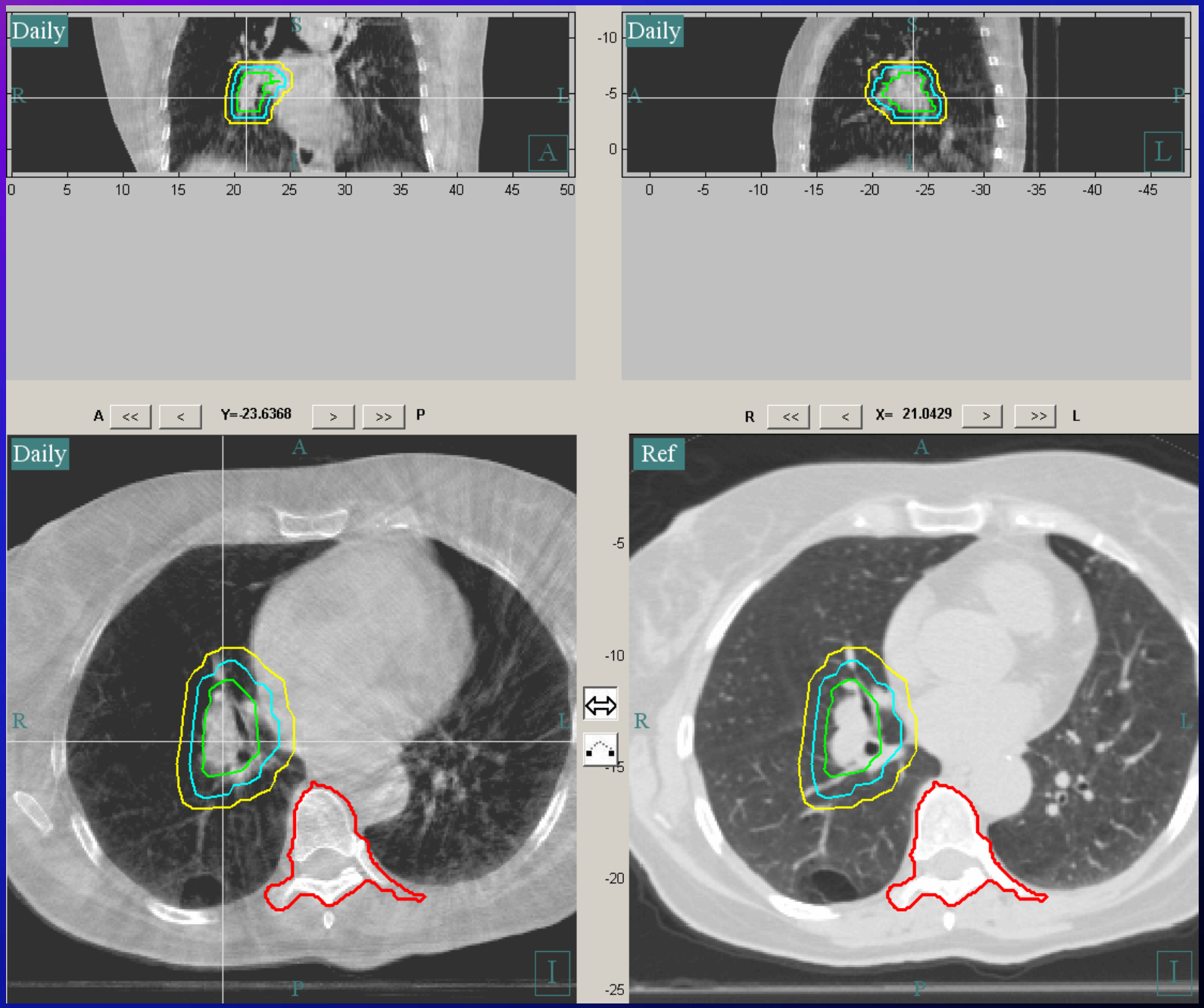
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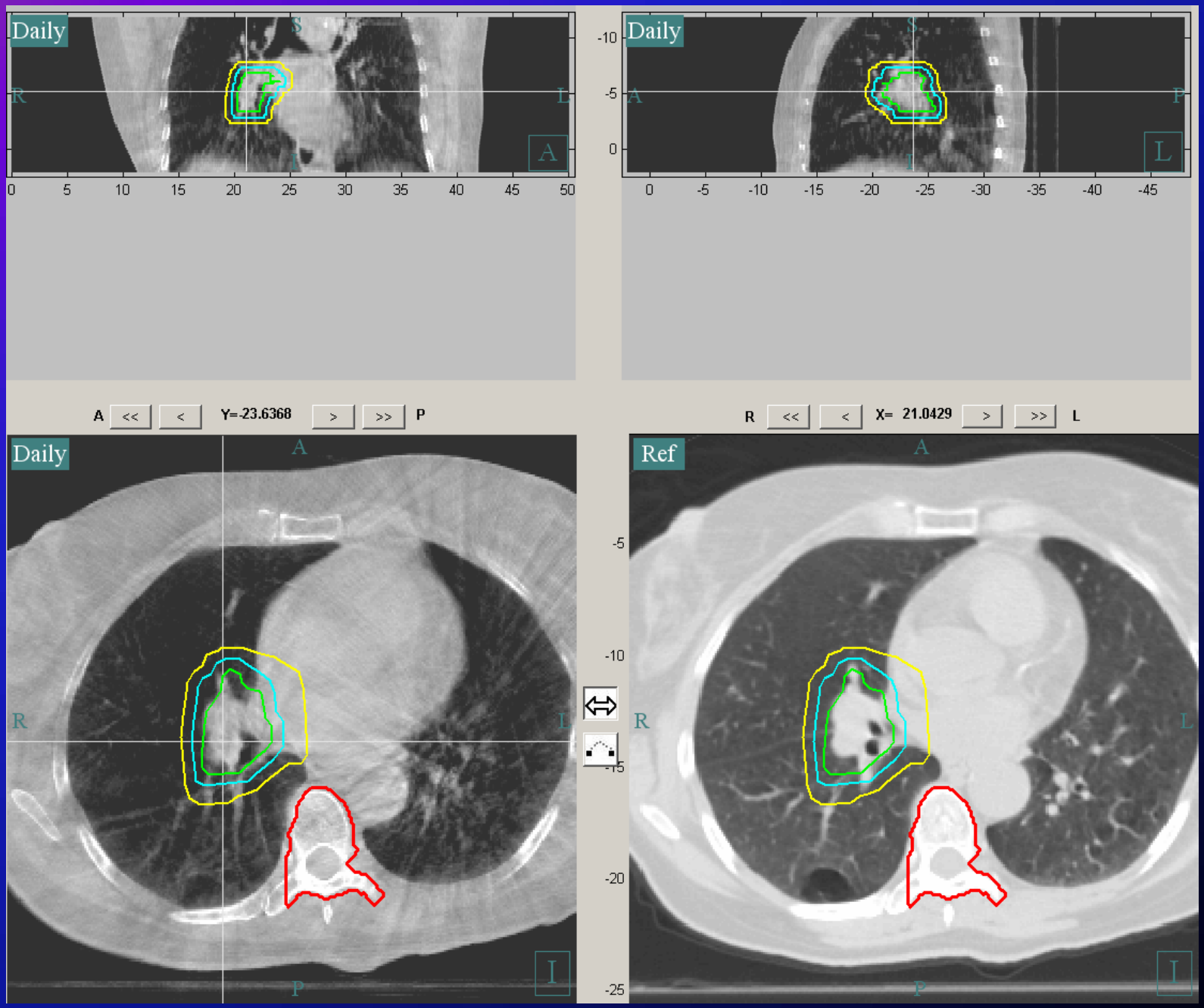
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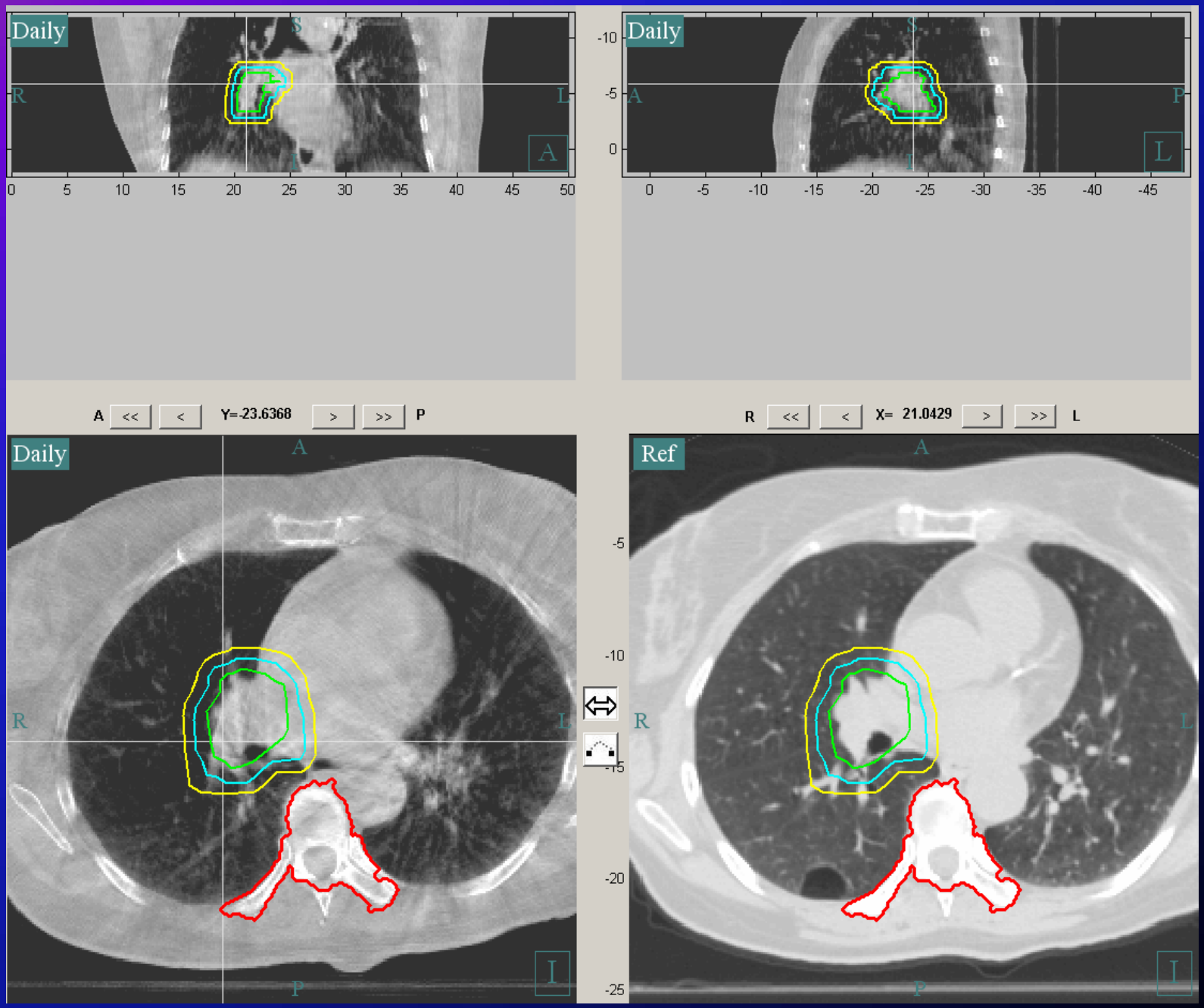
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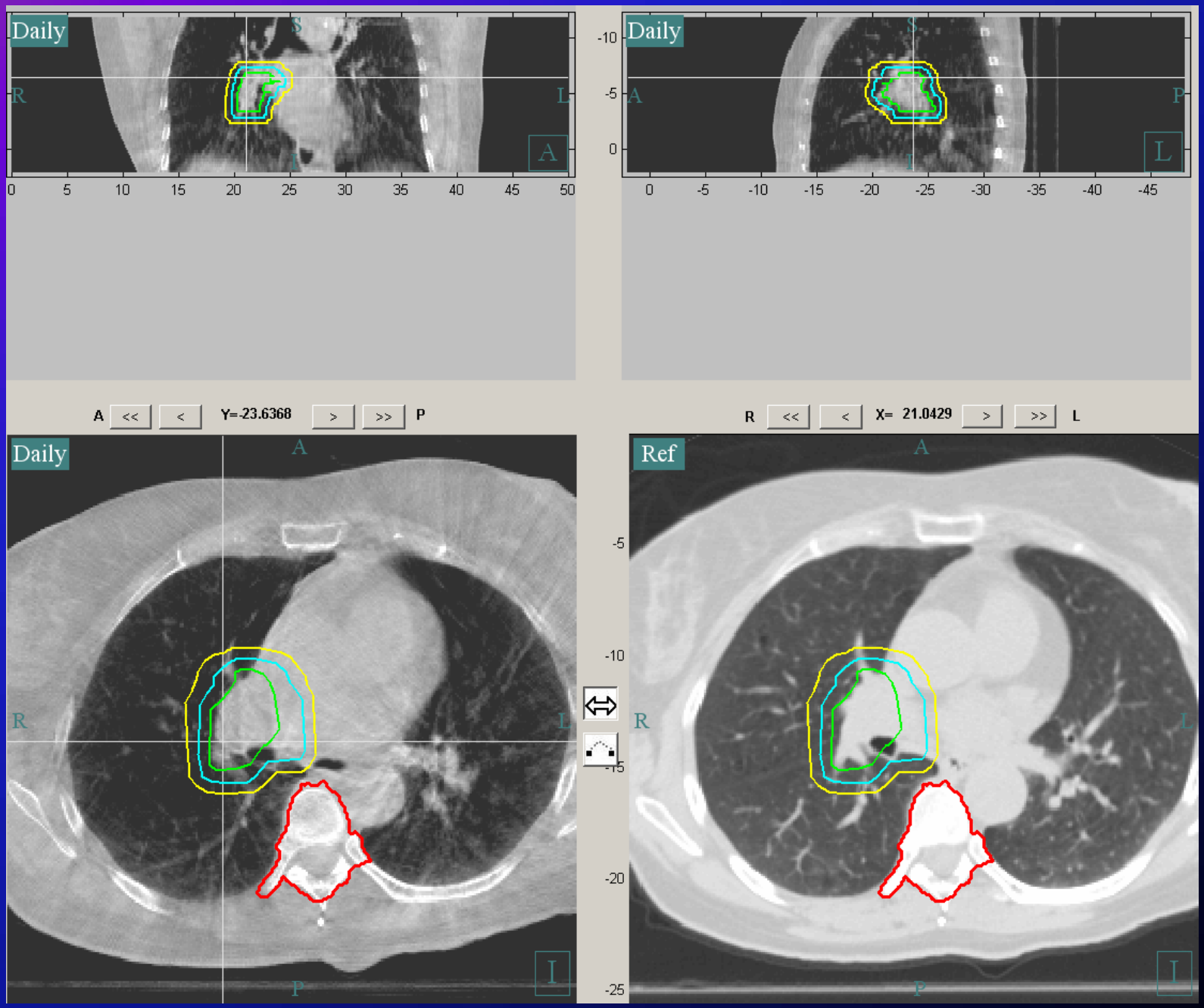
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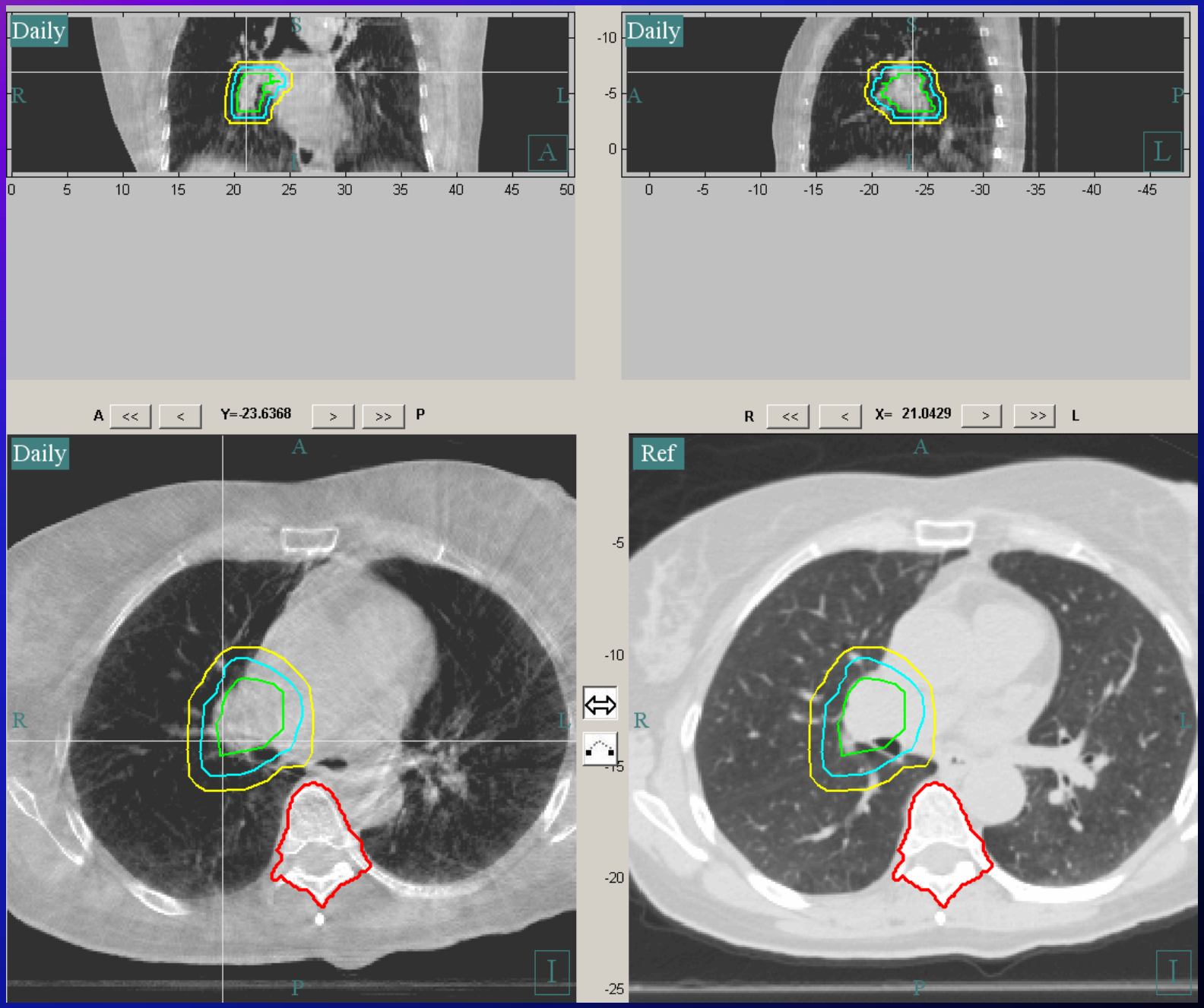
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A << < Y=-23.6368 > >> P
R << < X= 21.0429 > >> L
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-20
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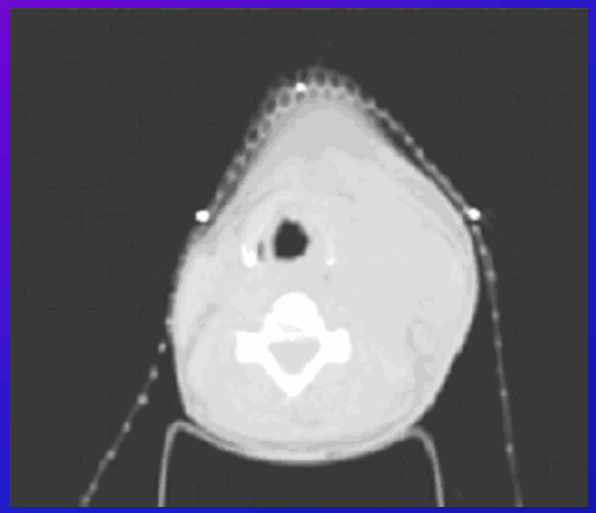
Head & Neck Study

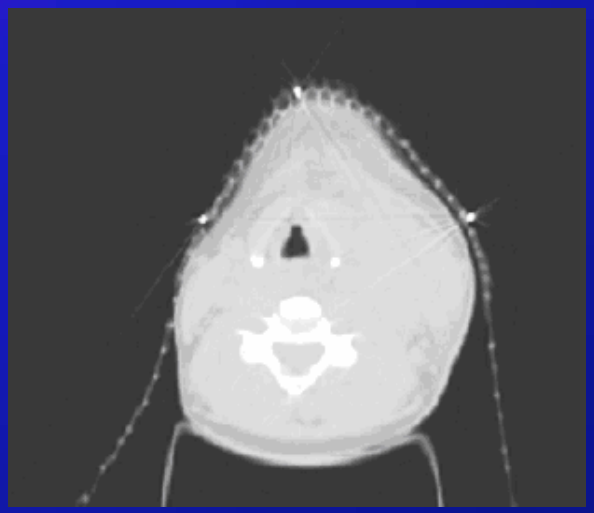
Significant daily setup variation was observed using 3D analysis

An Example

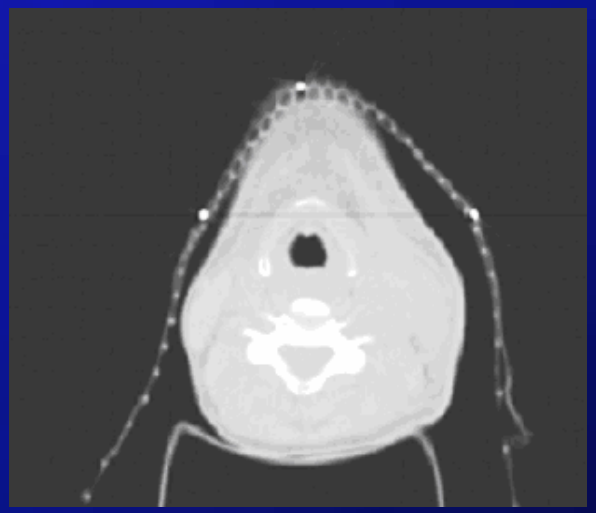
Planning



First Fraction



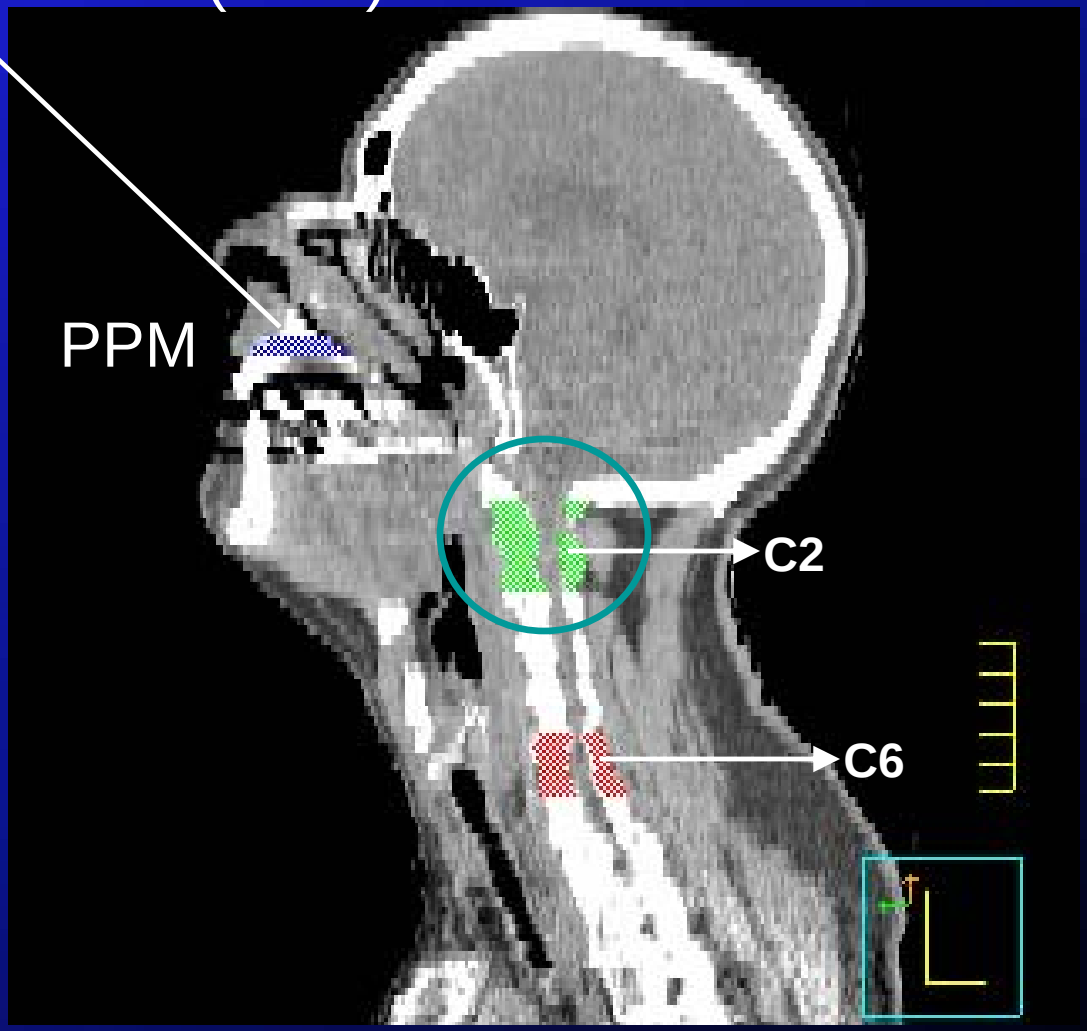
Last Fraction



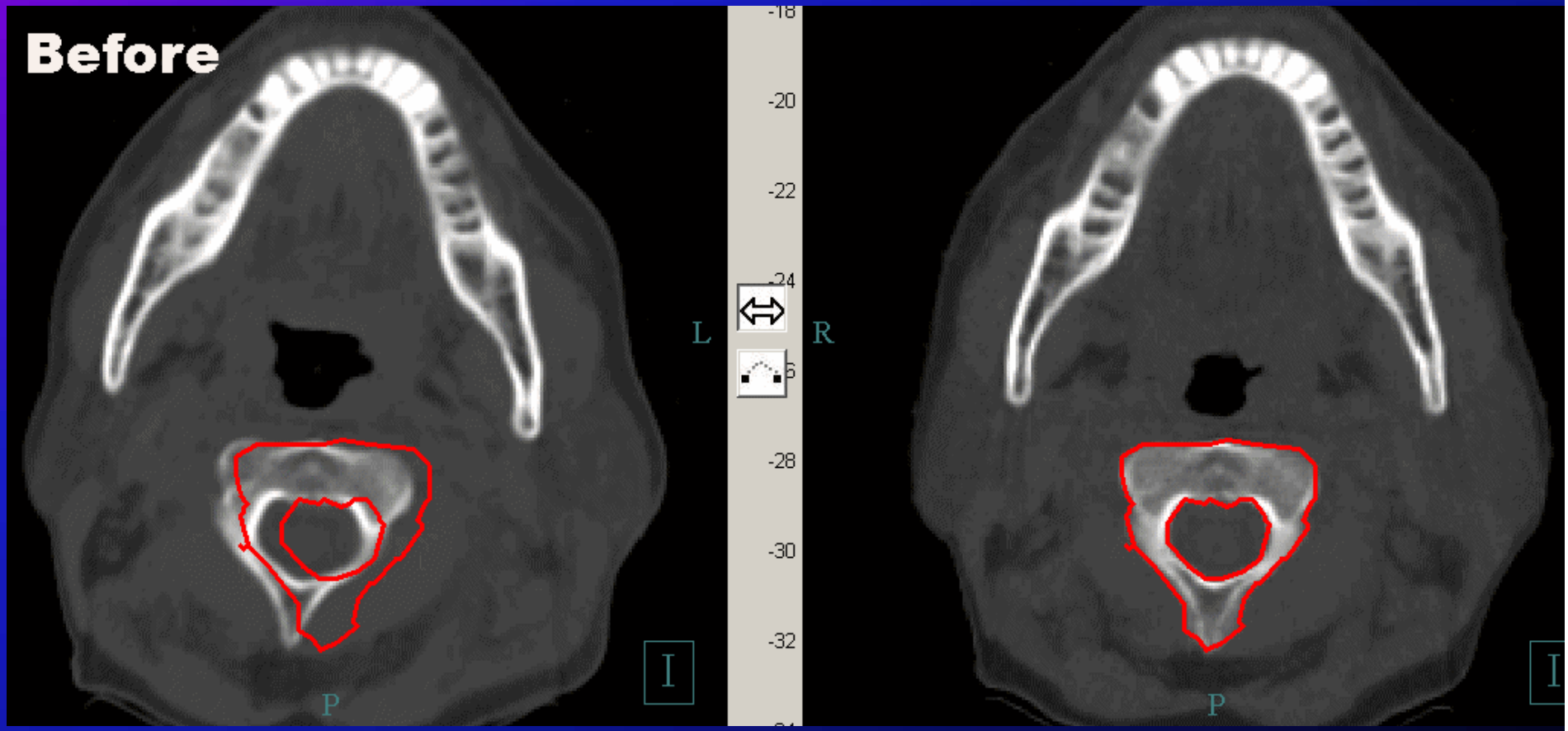
An example of increasing room inside a thermoplastic facemask due to tumor shrinkage as treatment progressing. Near the end of treatment, the lower neck was not centered on the headrest, presumably due to patient's self-adjustment to the relatively "roomier" mask.

Head & Neck Cancers: Best ROI: C2

Palatine Process of Maxilla (PPM)



CT-to-CT Auto-Registration (ROI image-based bony registration)



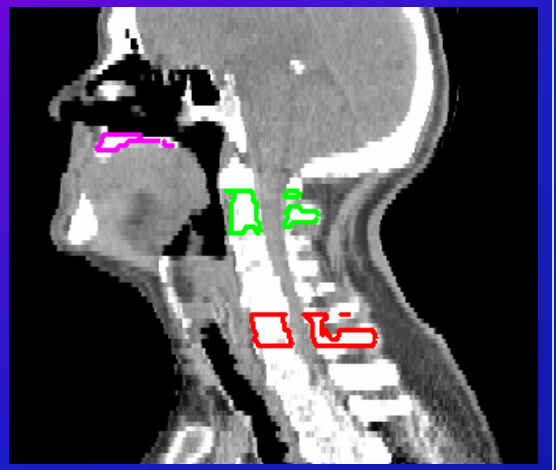
Daily Treatment CT

Planning CT

Zhang L, Dong L, Court L, et al. Validation of CT – Assisted Targeting (CAT) Software for soft tissue and bony target localization. AAPM, 2005.

Result – Margins and Residual Errors

Reference



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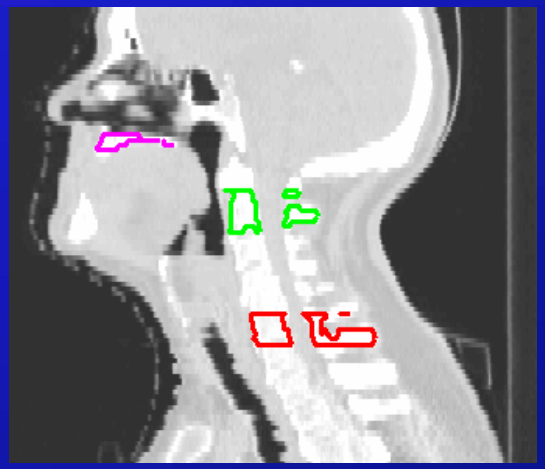
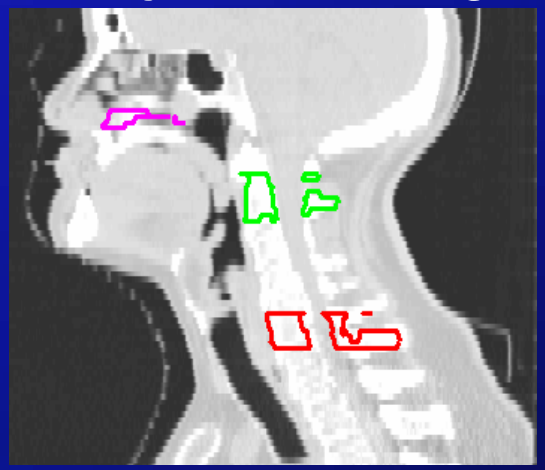
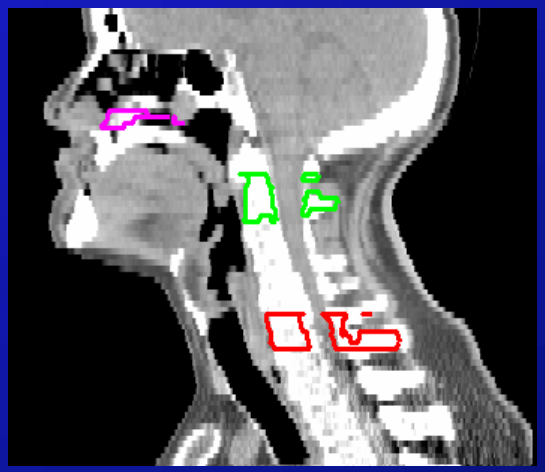


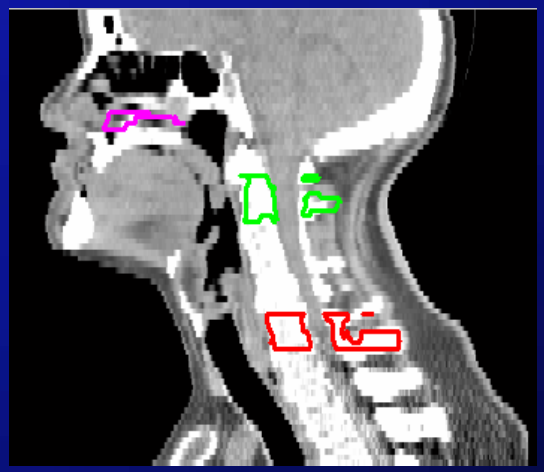
Daily after C2 align



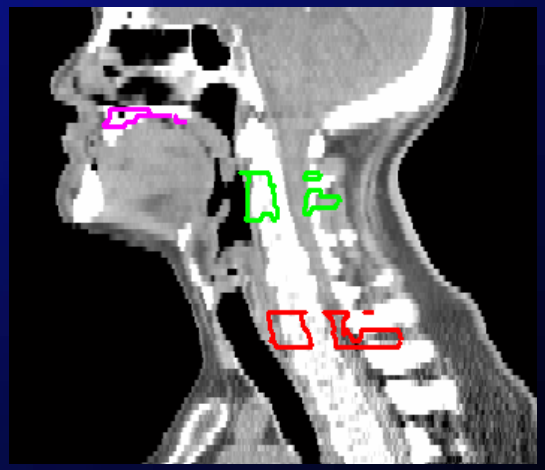
Daily after C2 align



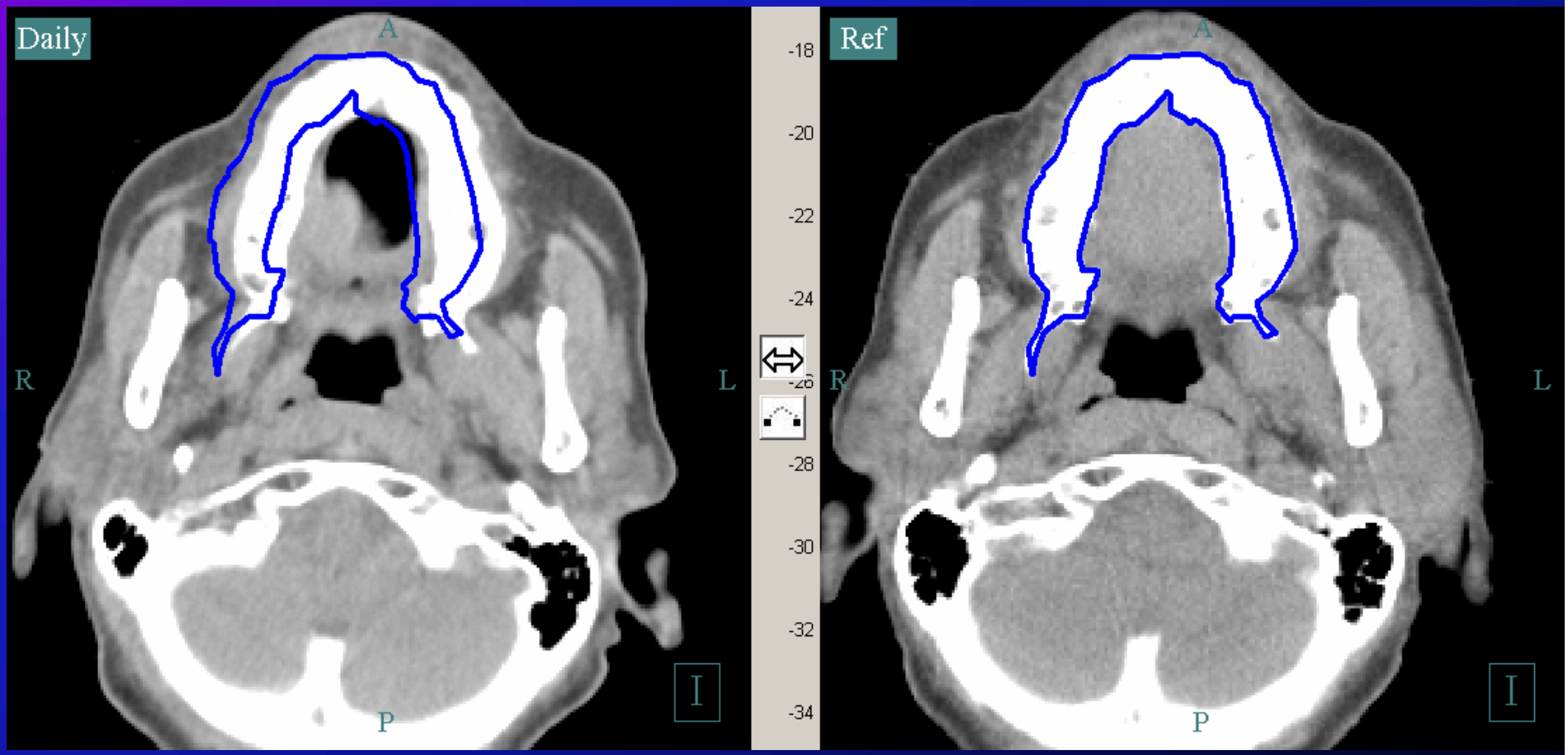
Daily after C6 align



Daily after PPM align



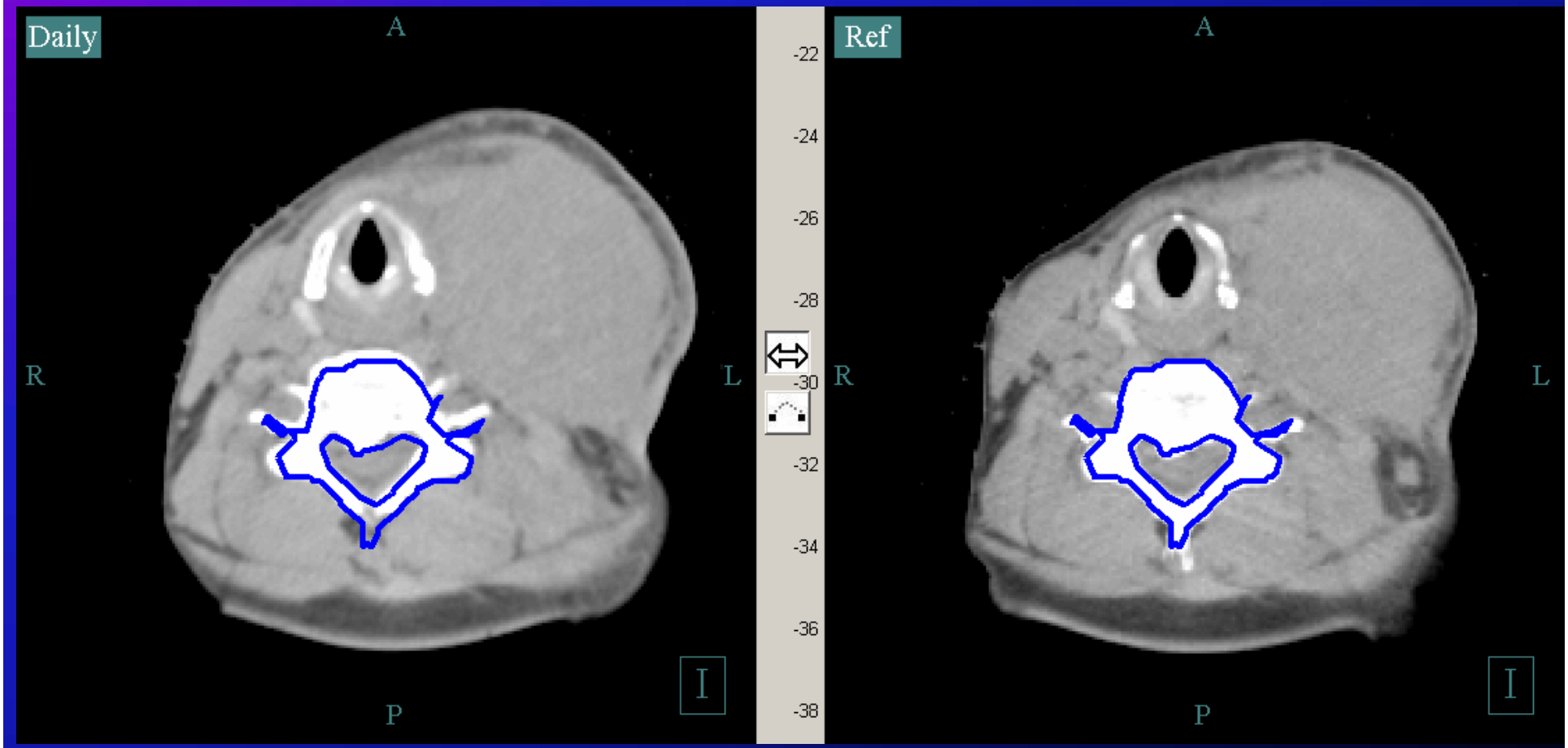
PPM did not match after C2 alignment



Daily Treatment CT

Planning CT

C6 did not match after C2 alignment

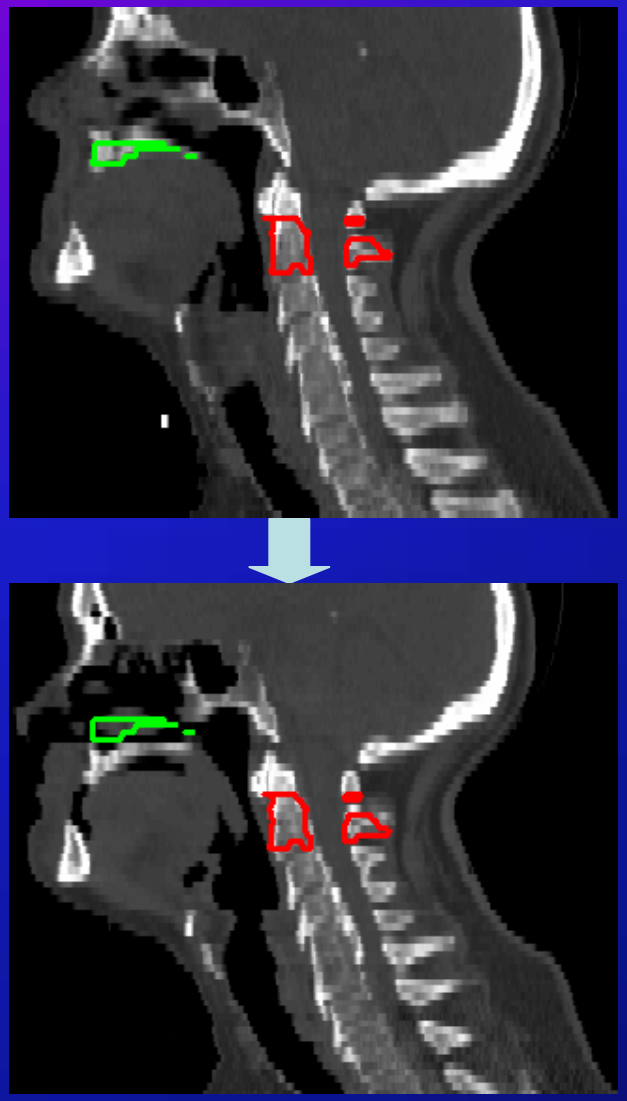


Daily Treatment CT

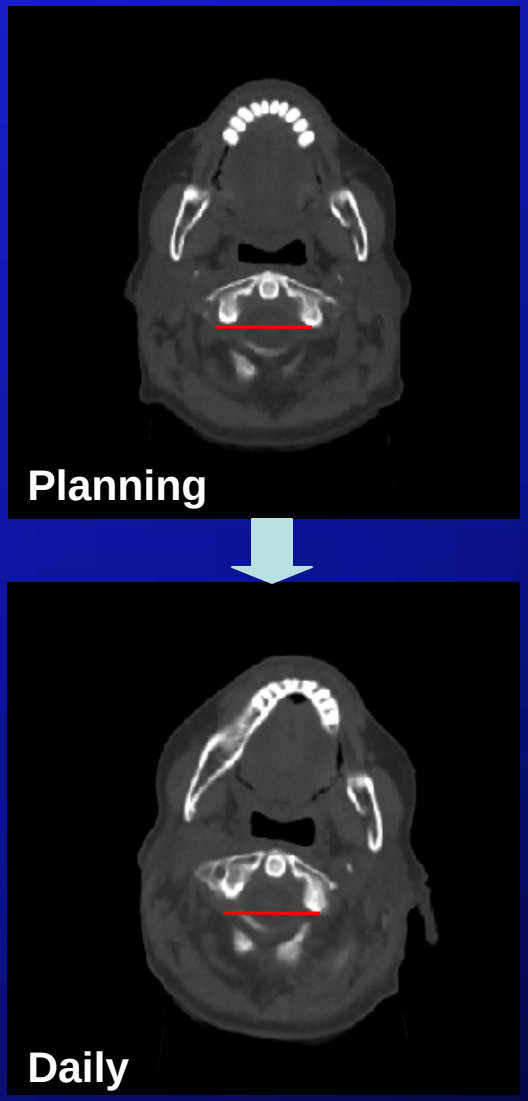
Planning CT

Effect of Rotations

Pitch



Roll Example



Yaw Example

Summary of Head & Neck Study

1. A true 3D analysis of setup uncertainties was performed using CAT software.
2. Relative shifts among multiple ROIs are significant due to non-rigid movements of different bony parts and rotations.
3. A simple couch translation is impossible to correct all shifts in the H & N area, but C2 bony alignment is the best compromise.
4. Positioning mouthpiece is found effective in reducing SI motion for PPM.
5. No significant benefit is found when using S-board for reducing C6 motion (neck immobilization).

Zhang et al. 2006

Other Factors in Volume Alignment

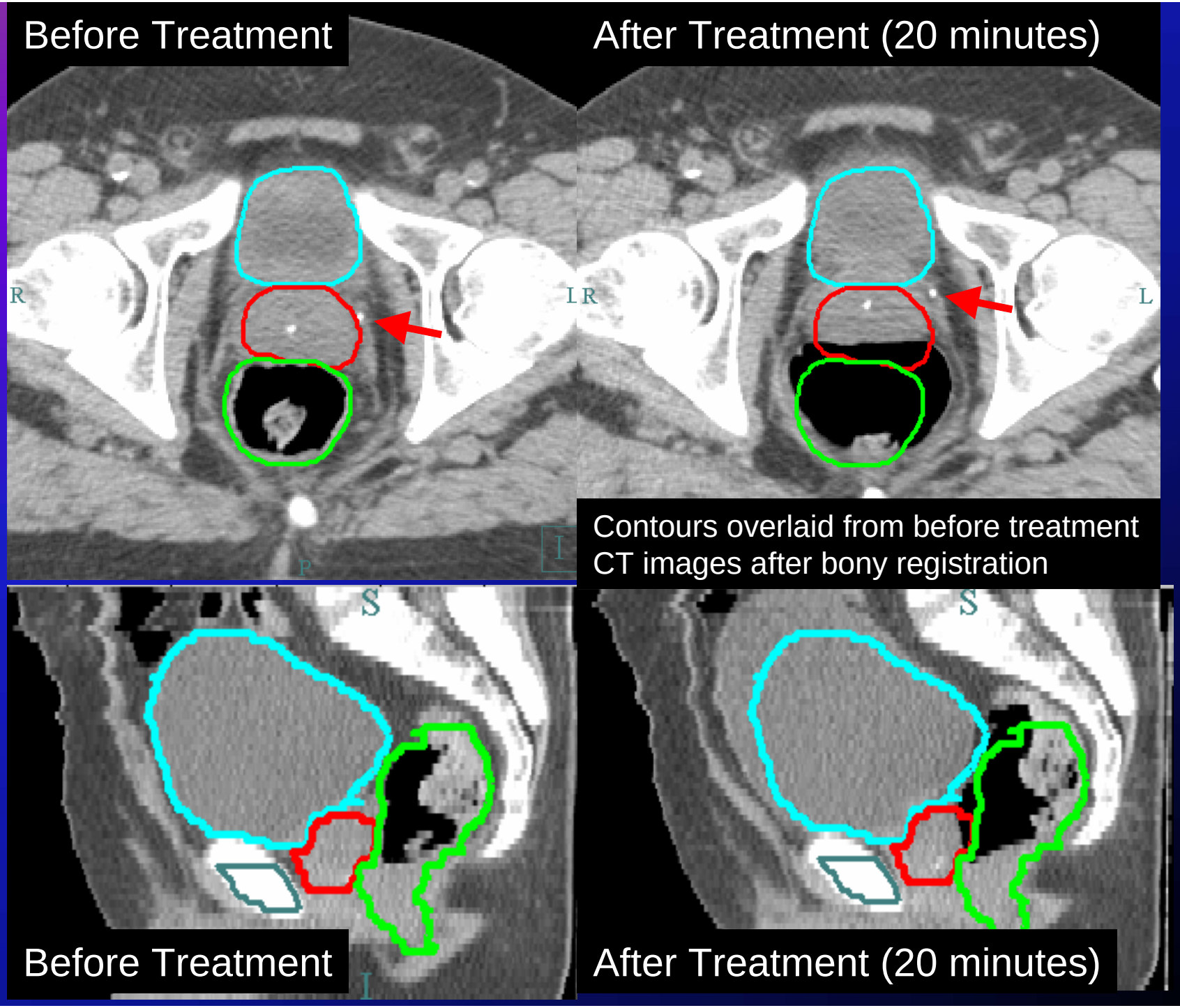
- Correction for rotations
  - Small target
  - Large target
- Deformation
- Intra-fractional organ motion

Anatomic and Dosimetric Analysis of Intra-fractional Motion during an IMRT Treatment Fraction

A Melancon*, R de Crevoisier, L Zhang, J O'Daniel, D Kuban, R Cheung, A Lee, R Mohan, L Dong,

Univ. of Texas M. D. Anderson Cancer Center, Houston, TX

THE UNIVERSITY OF TEXAS
MD ANDERSON
CANCER CENTER
Making Cancer History™

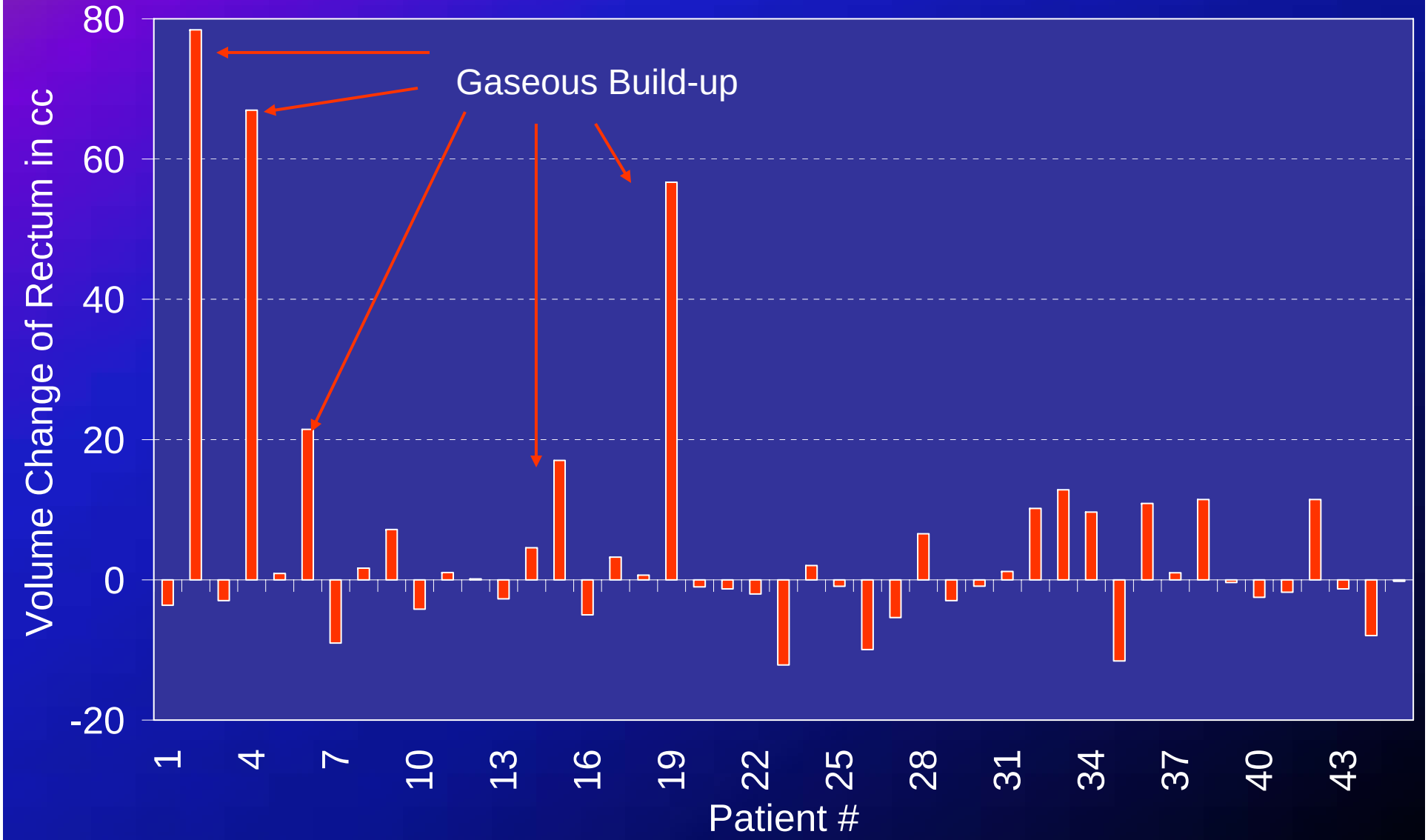

Before Treatment
After Treatment (20 minutes)
R
L
R
L
Contours overlaid from before treatment
CT images after bony registration
S
S
Before Treatment
After Treatment (20 minutes)

Results
Statistics of 45 patients

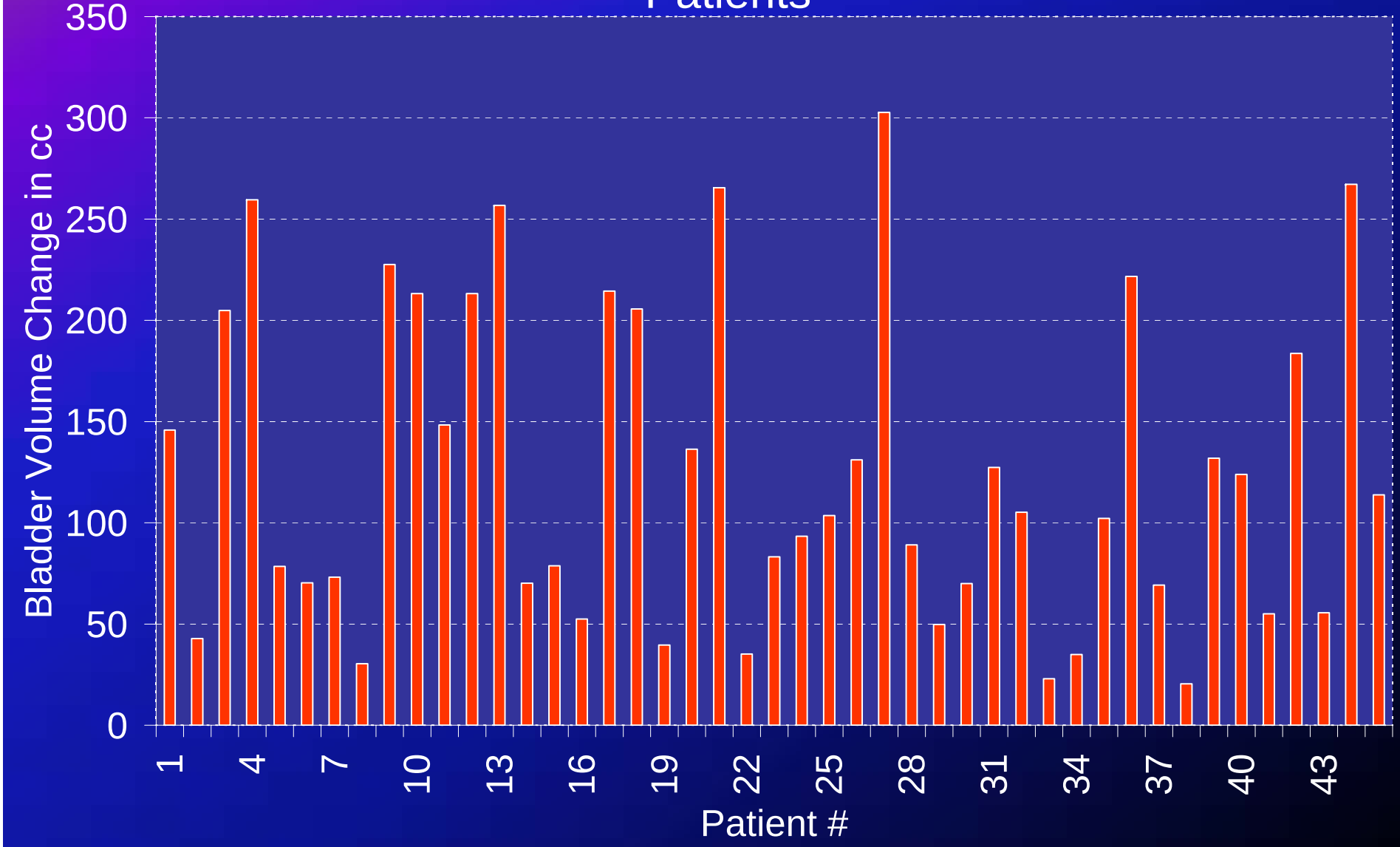
	Mean	SD	Z-test p-value
Fraction Duration (min)	21.4	4.25	N/A
Rectal Volume Change (cc)	5.50	18.32	0.02
Bladder Volume Change	124.9	78.87	0.00
Anterior Prostate Displacement (cm)	0.13	0.29	0.00
Anterior SV Displacement	0.12	0.41	0.03
Inferior Prostate Displacement	-0.07	0.26	0.04
Inferior SV Displacement	-0.15	0.29	0.00

- All measurements significantly different from zero with one-sided z test

Volume Change of the Rectum for 45 patients



Change in Bladder Volume During One Fraction for 45 Patients



Residual Error

- Do you reduce margins (to zero) for online CT-guided treatment?
  - Suggest 3-mm margin minimum for prostate target alignment

Summary of Learning Objectives:

- Learn about the rationales and procedures for in-room CT-guided radiotherapy.
- Suggest the design of computer-aided image processing algorithms.
- Demonstrate workflow and clinical applications.