In-room CT Imaging: Conventional CT

Lei Dong, Ph.D.
University of Texas M. D. Anderson Cancer Center
Houston, Texas

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- Laurence Court, Ph.D.
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Outline

- History of in-room (conventional) CT for radiotherapy applications
- Workflow
- Mechanical precision and imaging dose
- QA
- Applications

Why CT?

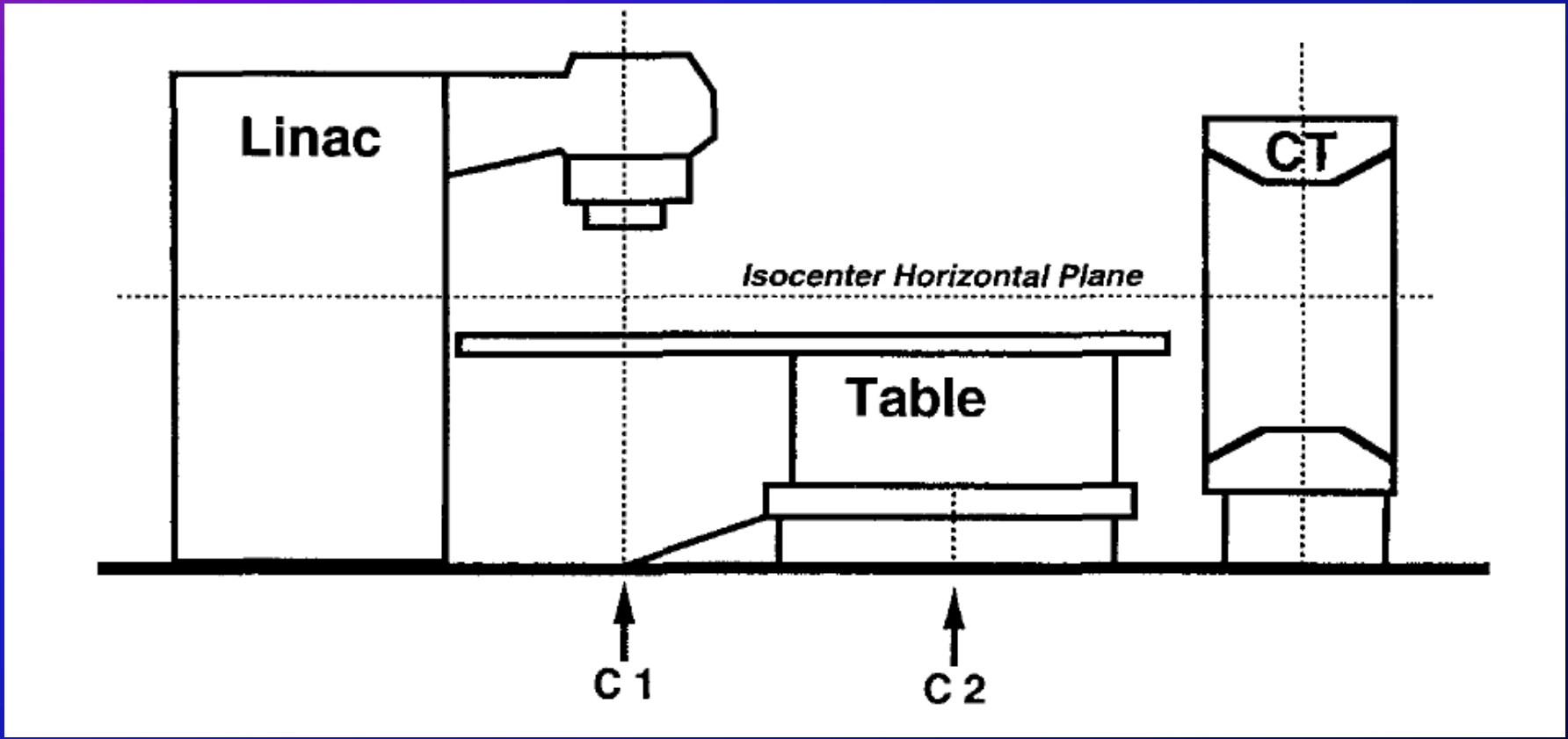
- 3D definition of anatomy (volumetric imaging) in treatment room
- CT for dose calculation (planning or treatment evaluation)
- Mature technology (with minor modifications for radiation therapy applications)
- CT images are widely accepted and familiar by radiation oncologists to determine target volumes and critical organs
- No direct contact with patient
- Single modality when compared with the planning CT.

In-room CT imaging for treatment guidance

- Uematsu et al. (1996), National Defense Medical College, Saitama, Japan.
  - Toshiba CT scanner, motorized couch.
  - Frameless, fractionated SRS/SRT

A DUAL COMPUTED TOMOGRAPHY LINEAR ACCELERATOR UNIT FOR STEREOTACTIC RADIATION THERAPY: A NEW APPROACH WITHOUT CRANIALLY FIXATED STEREOTACTIC FRAMES

MINORU UEMATSU, M.D., TOSHIHARU FUKUI, R.T.T., AKIRA SHIODA, R.T.T., HIDEYUKI TOKUMITSU, R.T.T., KENJI TAKAI, M.D., TADAHARU KOJIMA, B.S., YOSHIKO ASAI, B.S. AND SHOICHI KUSANO, M.D.



A diagram of a CT-LINAC combination system inside a radiotherapy treatment room. The table has two rotation axes; C1 is for isocentric couch rotation and C2 is for rotation between the CT and the LINAC. The gantry is coaxial to both the CT and the LINAC. Figure from Uematsu et al. 1996.

Int. J. Radiation Oncology Biol. Phys., Vol. 35, No. 3, pp. 587-592, 1996

Isocenter Verification

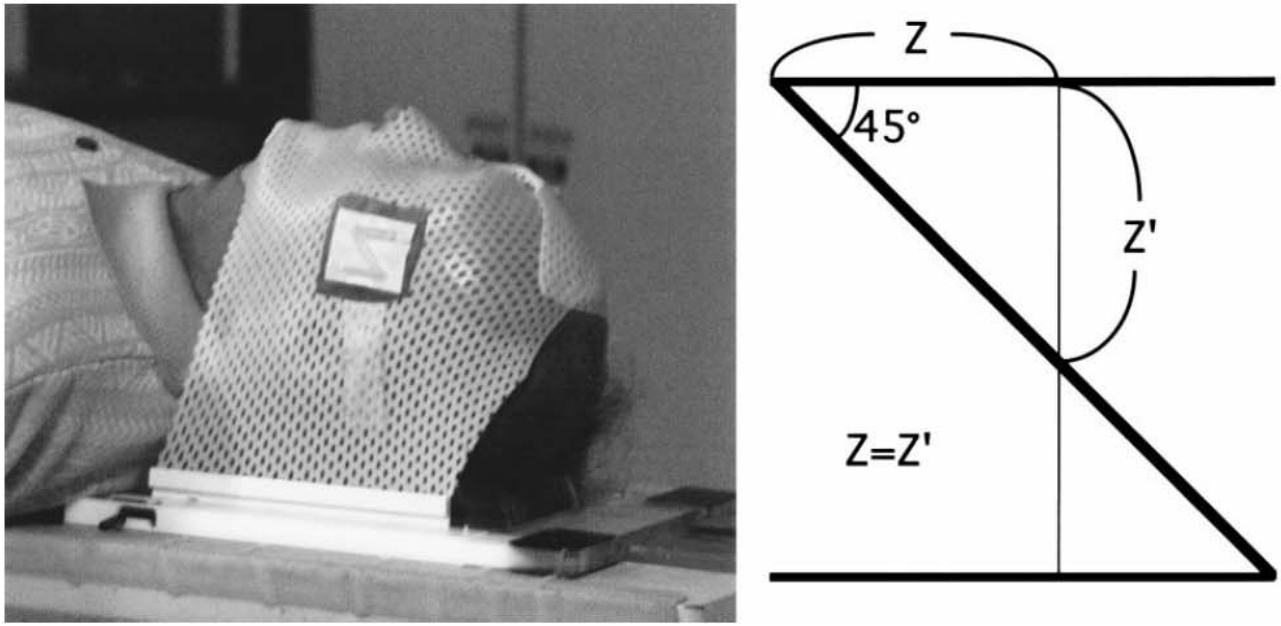


Fig. 1. The Z-marker (Mark-It) is attached to the patient. The distance Z′, which can be measured with CT images, is the same as Z in the cranio–cauda axis.

Uematsu M, Shioda A, Tahara K, et al. Daily positioning accuracy of frameless stereotactic radiation therapy with a fusion of computed tomography and linear accelerator (focal) unit: Evaluation of z-axis with a z-marker. Radiotherapy and Oncology 1999;50:337-339.

Simulator + CT + Linac

Intrafractional tumor position stability during computed tomography (CT)-guided frameless stereotactic radiation therapy for lung or liver cancers with a fusion of CT and linear accelerator (FOCAL) unit.

Uematsu M, Shioda A, Suda A, Tahara K, Kojima T, Hama Y, Kono M, Wong JR, Fukui T, Kusano S

Int J Radiat Oncol Biol Phys 2000; 48 (2):443-448.

Uematsu et al, *Int J Radiat Oncol Biol Phys* 2000; 48 (2):443-448.

INTRAFRACTIONAL TUMOR POSITION STABILITY DURING COMPUTED TOMOGRAPHY (CT)-GUIDED FRAMELESS STEREOTACTIC RADIATION THERAPY FOR LUNG OR LIVER CANCERS WITH A FUSION OF CT AND LINEAR ACCELERATOR (FOCAL) UNIT

Minoru Uematsu, M.D.,* Akira Shioda, R.T.T.,* Atsushi Suda, R.T.T.,* Kazuhiko Tahara, R.T.T.,* Tadaharu Kojima, B.S.,* Yukihiro Hama, M.D.,* Masashi Kono, M.D.,* James R. Wong, M.D.,† Toshiharu Fukui, R.T.T.,* and Shoichi Kusano, M.D.*

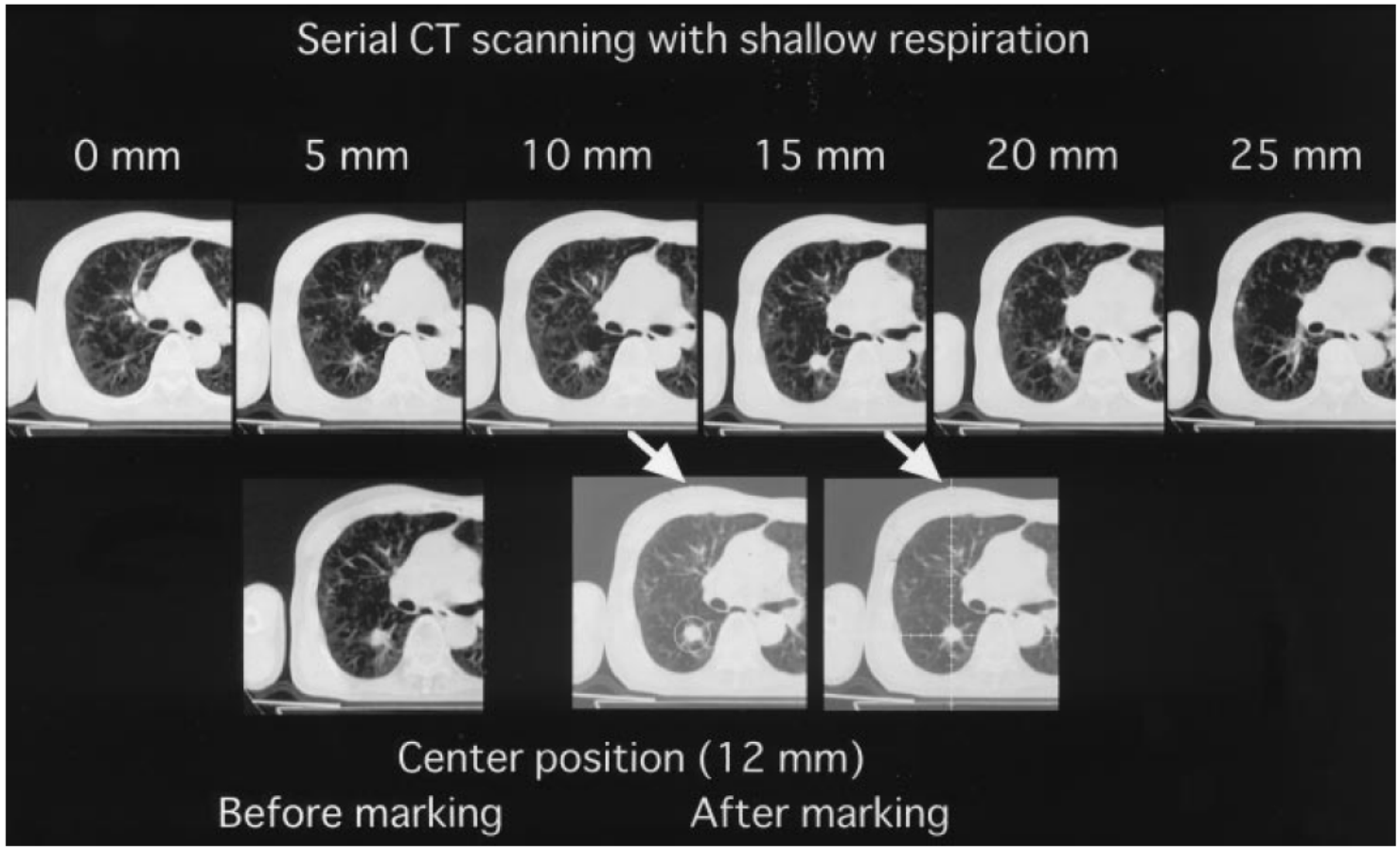


Fig. 4. (upper) The serial CT images are obtained with reduced respiration. (lower) The center position is visually confirmed, and then marked with tiny metallic markers. The circle in the lower center image is planned 80% isodose line.

Uematsu *et al.* Computed tomography-guided frameless stereotactic radiotherapy for stage I non-small cell lung cancer: a 5-year experience. *Int J Radiat Oncol Biol Phys* 2001;51:666-670.

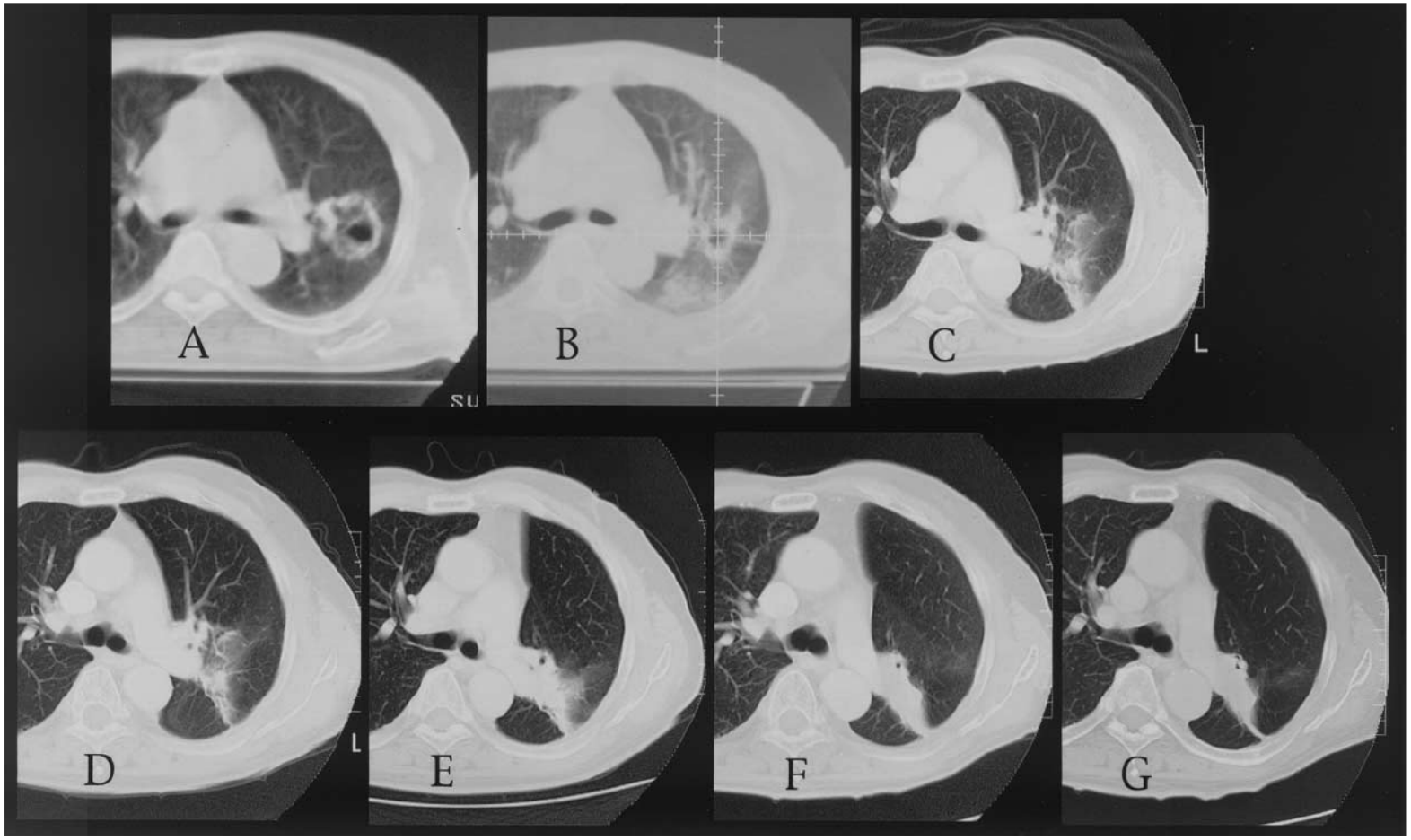


Fig. 2. T2N0M0 squamous cell carcinoma of the lung. (A) A 4.5-cm tumor with the cavity seen on the positioning CT. To reduce the risk of marginal recurrence, conventional RT of 50 Gy in 25 fractions during 5 weeks was initially given. (B) After RT, shrunken tumor (<3 cm) and radiation-induced interstitial changes were seen. SRT of 40 Gy in 8 fractions during 2 weeks was given at the 80% isodose line of 3.5 cm in diameter. (C) Three months after SRT, the tumor was not clear but localized radiation-induced fibrotic changes were apparent. (D) Six months after SRT, the volume of the radiation fibroses was reduced. (E) Nine months after SRT, the volume of the radiation fibroses had reduced further but localized atelectasis was seen. (F) Twenty-five months after SRT, the atelectasis was localized. (G) Fifty-five months after SRT, the volume of the atelectasis was somewhat smaller.

Figure 5. A conventional AcQSim CT scanner (Philips Medical Systems) was installed in a treatment room at the Memorial Sloan-Kettering Cancer Center, New York. A sliding couch top was used to transport the patient from the CT scanner table to the therapy treatment table. The therapy table was rotated to connect with the CT table. Picture is from Hua et al. 2003.

Int. J. Radiation Oncology Biol. Phys., Vol. 55, No. 3, pp. 811–824, 2003

A NEW IRRADIATION UNIT CONSTRUCTED OF SELF-MOVING GANTRY-CT AND LINAC

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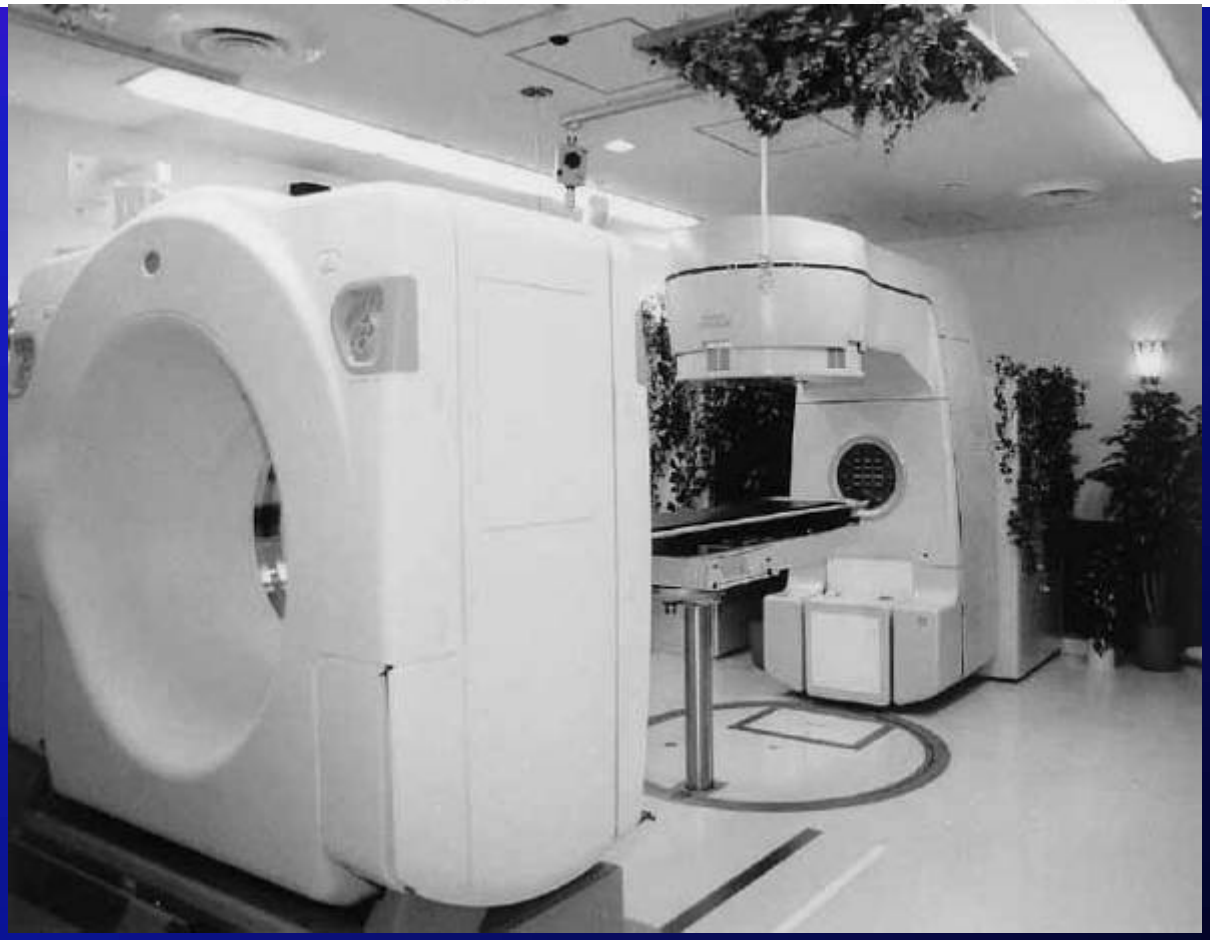
*Department of Radiation Oncology, University of Yamanashi, School of Medicine, Yamanashi, Japan; †Department of Radiology, Division of Radiation Oncology, National Defense Medical College, Tokorozawa, Japan



Int. J. Radiation Oncology Biol. Phys., Vol. 55, No. 2, pp. 428–435, 2003

Figure 2. The Siemens Primatom™ CT-on-rails system, which contains a Primus™ linear accelerator and a Somatom™ sliding-gantry CT scanner (CT-on-Rails). The left picture was the first Primatom unit installed at the Morristown Memorial Hospital, New Jersey. Picture curtsey of Lisa Grimm, Ph.D. The right picture shows a recent model of the unit installed at the Fox Chase Cancer Center, Philadelphia, PA. Picture curtsey of Charlie Ma, Ph.D.

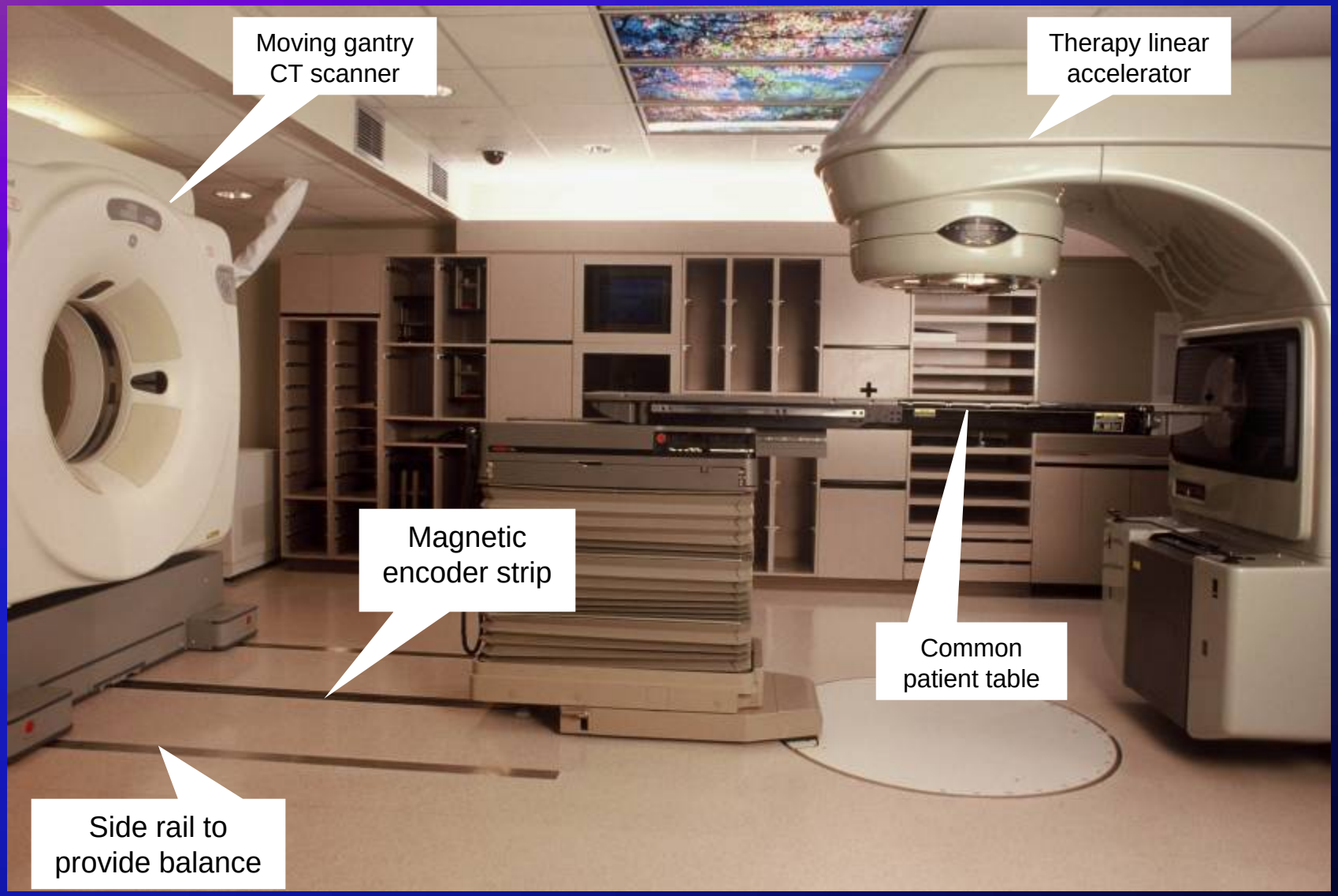


Figure 4. A CT-on-Rails system combining a GE Smart Gantry CT scanner and a Varian 2100EX linear accelerator was installed at the M.D. Anderson Cancer Center. After rotating the couch 180 degrees, a patient can receive a CT scan while in the immobilized treatment position just prior to the start of radiation treatment.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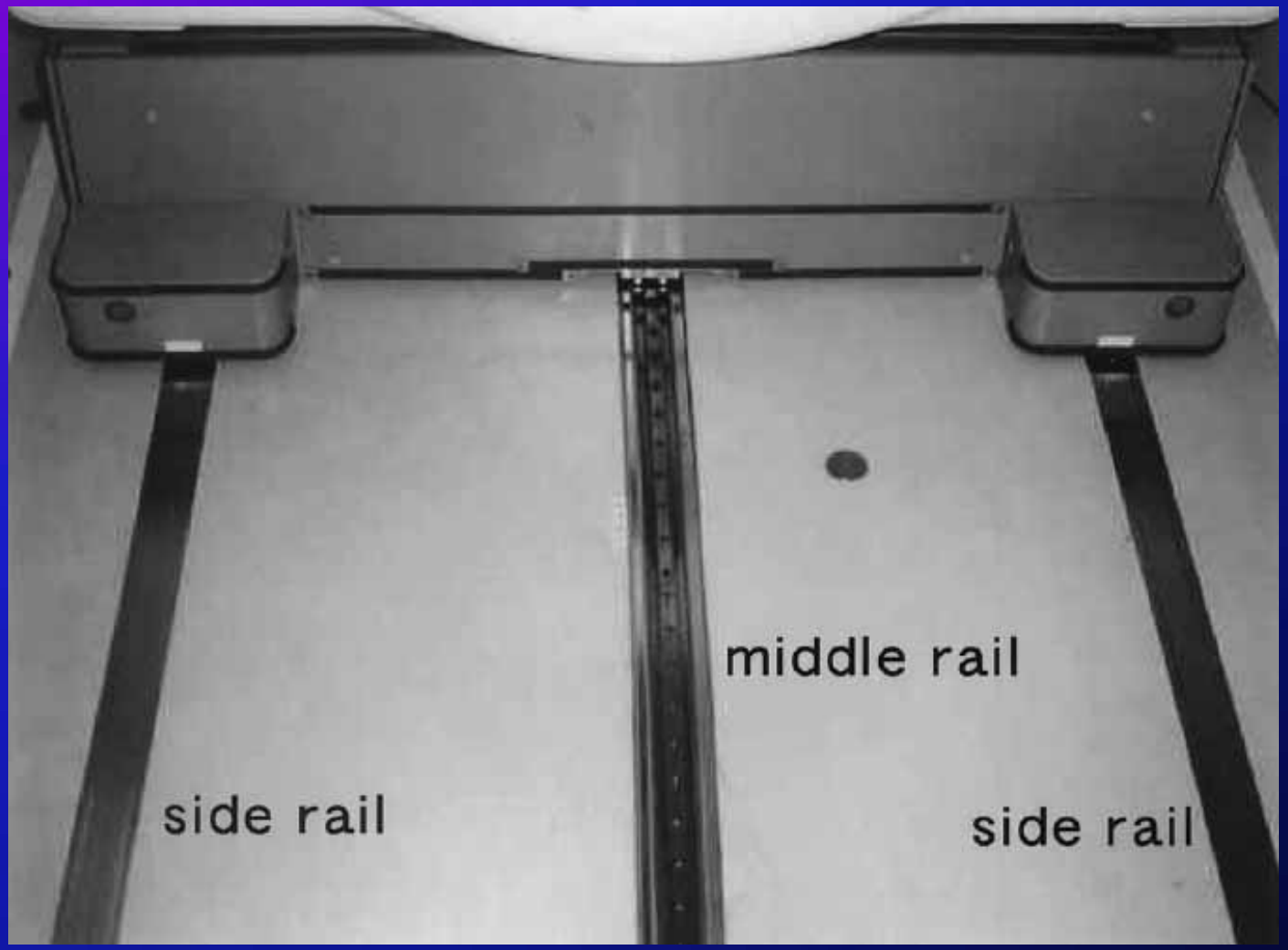
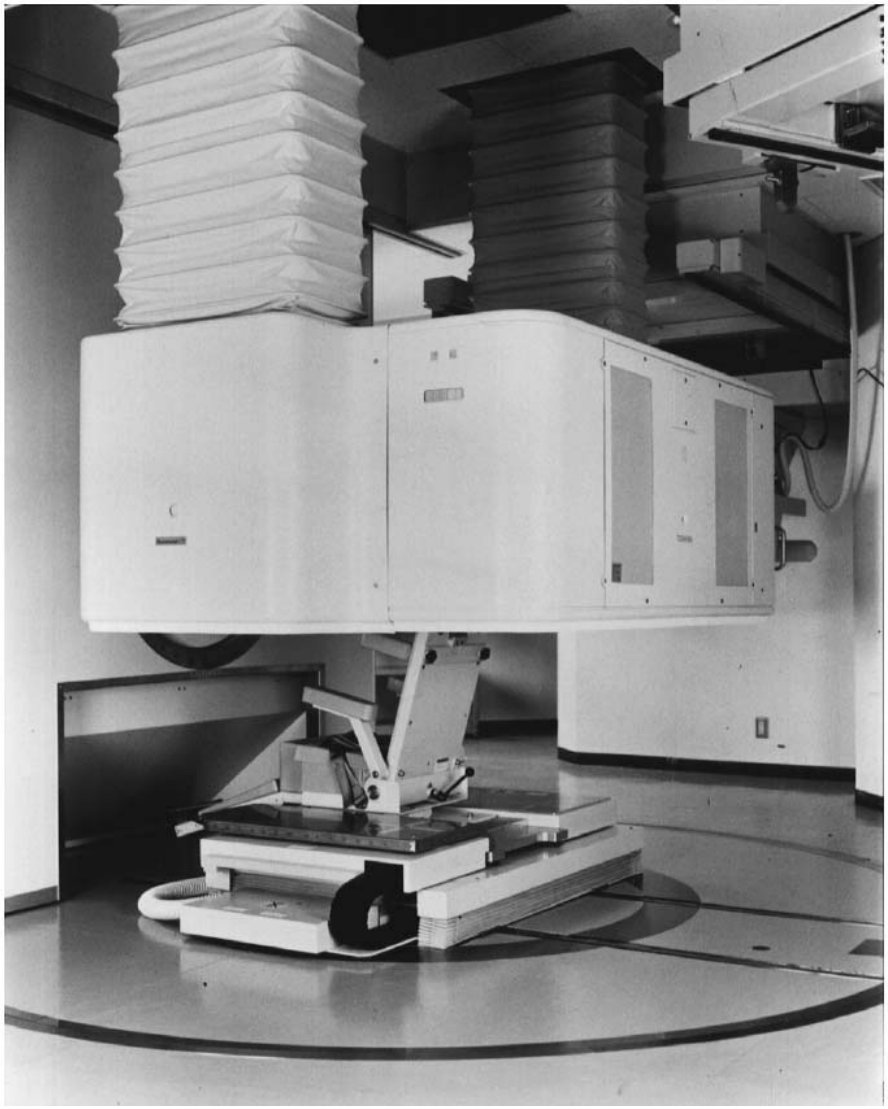


Figure 3. In the GE Smart Gantry ™ CT-on-Rails system, two side rails keep the gantry horizontal when scanning. One middle rail keeps the gantry moving straight along the axis of the scanning. Picture is from Kuriyama et al. 2003.



A horizontal CT system dedicated to heavy-ion beam treatment

Tadashi Kamada[a,*], Hirohiko Tsujii[a], Jun-Etsu Mizoe[a], Yoshisuke Matsuoka[a], Hiroshi Tsuji[a], Yasuhiro Osaka[a], Shinichi Minohara[b], Nobuyuki Miyahara[b], Masahiro Endo[b], Tatsuaki Kanai[b]

[a]*Division of Radiation Medicine, Research Center of Charged Particle Therapy, National Institute of Radiological Sciences, Chiba 261, Japan*
[b]*Division of Accelerator Physics and Engineering, Research Center of Charged Particle Therapy, National Institute of Radiological Sciences, Chiba 261, Japan*

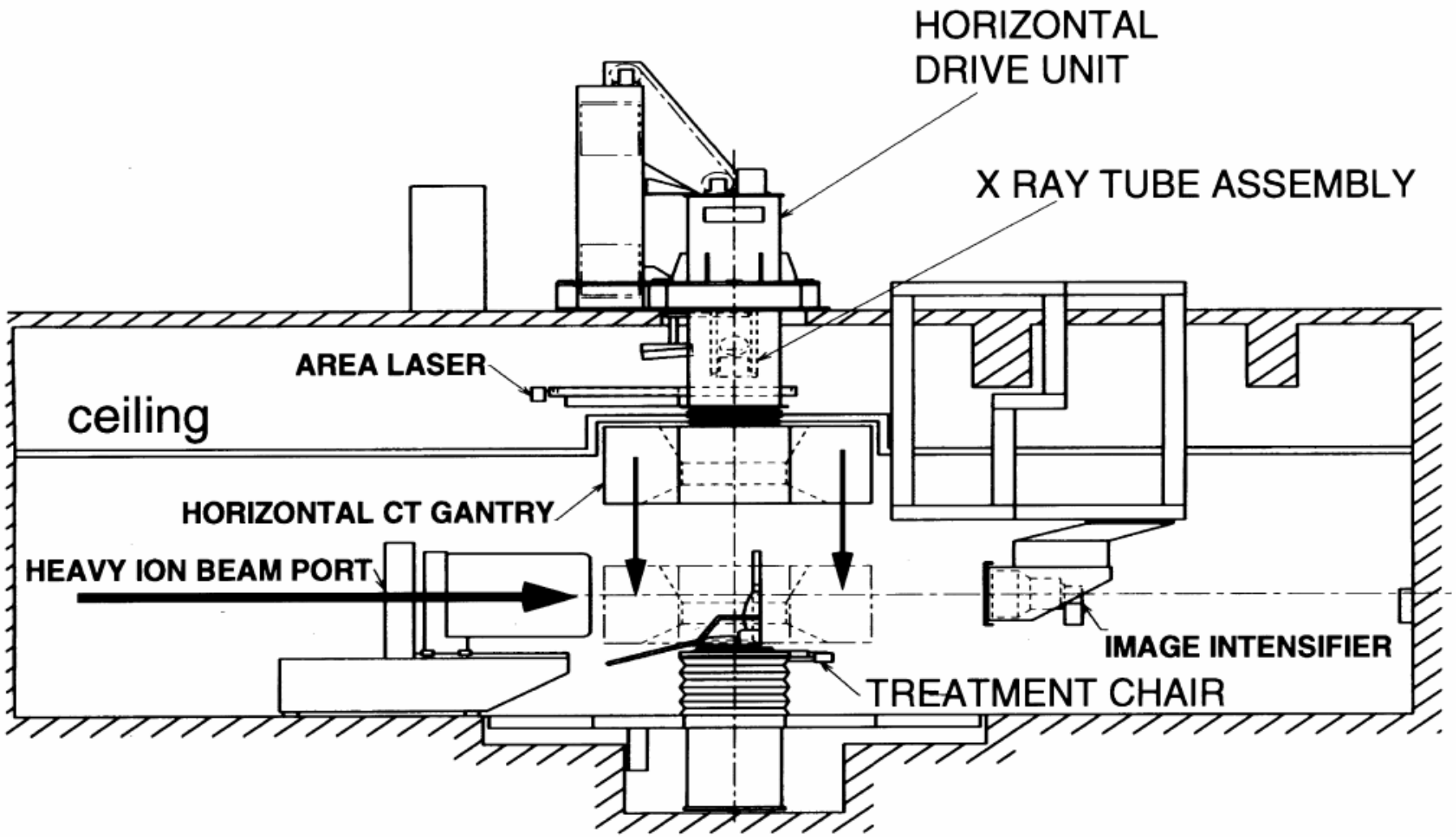


Fig. 1. Layout of the horizontal CT system.

Patient Transportation System

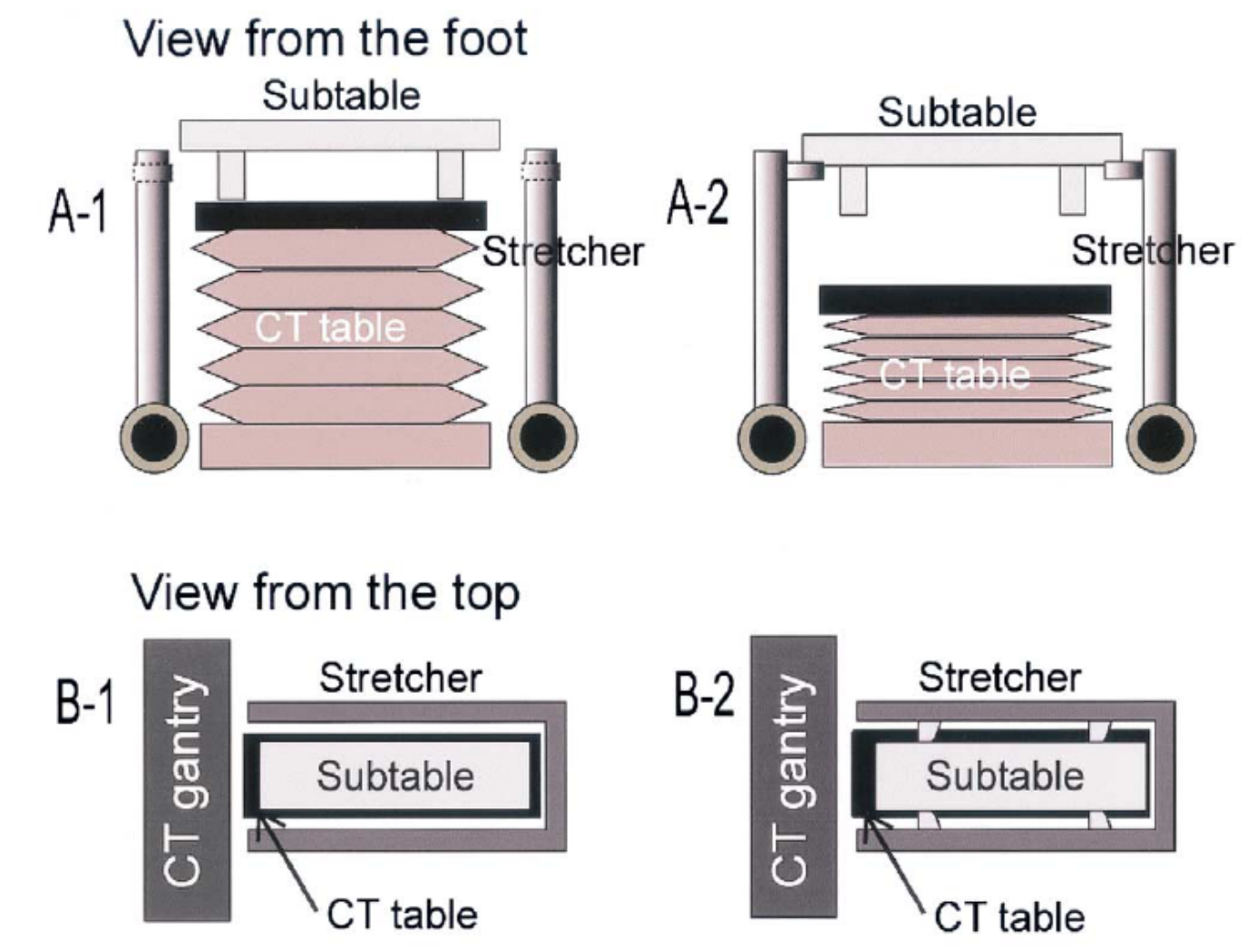
A NOVEL SUPPORT SYSTEM FOR PATIENT IMMOBILIZATION AND TRANSPORTATION FOR DAILY COMPUTED TOMOGRAPHIC LOCALIZATION OF TARGET PRIOR TO RADIATION THERAPY

Kenji Nemoto, M.D., Ph.D.,* Kazumasa Seiji, M.D., Ph.D.,† Kazuya Sasaki, R.T.T.,† Nobutaka Kasamatsu, R.T.T.,† Toshie Fujishima, R.T.T.,† Yoshihiro Ogawa, M.D., Ph.D.,* Hisanori Ariga, M.D., Ph.D.,* Ken Takeda, M.D., Ph.D.,* Tokihisa Kimura, M.D., Ph.D.,‡ and Shogo Yamada, M.D., Ph.D.*

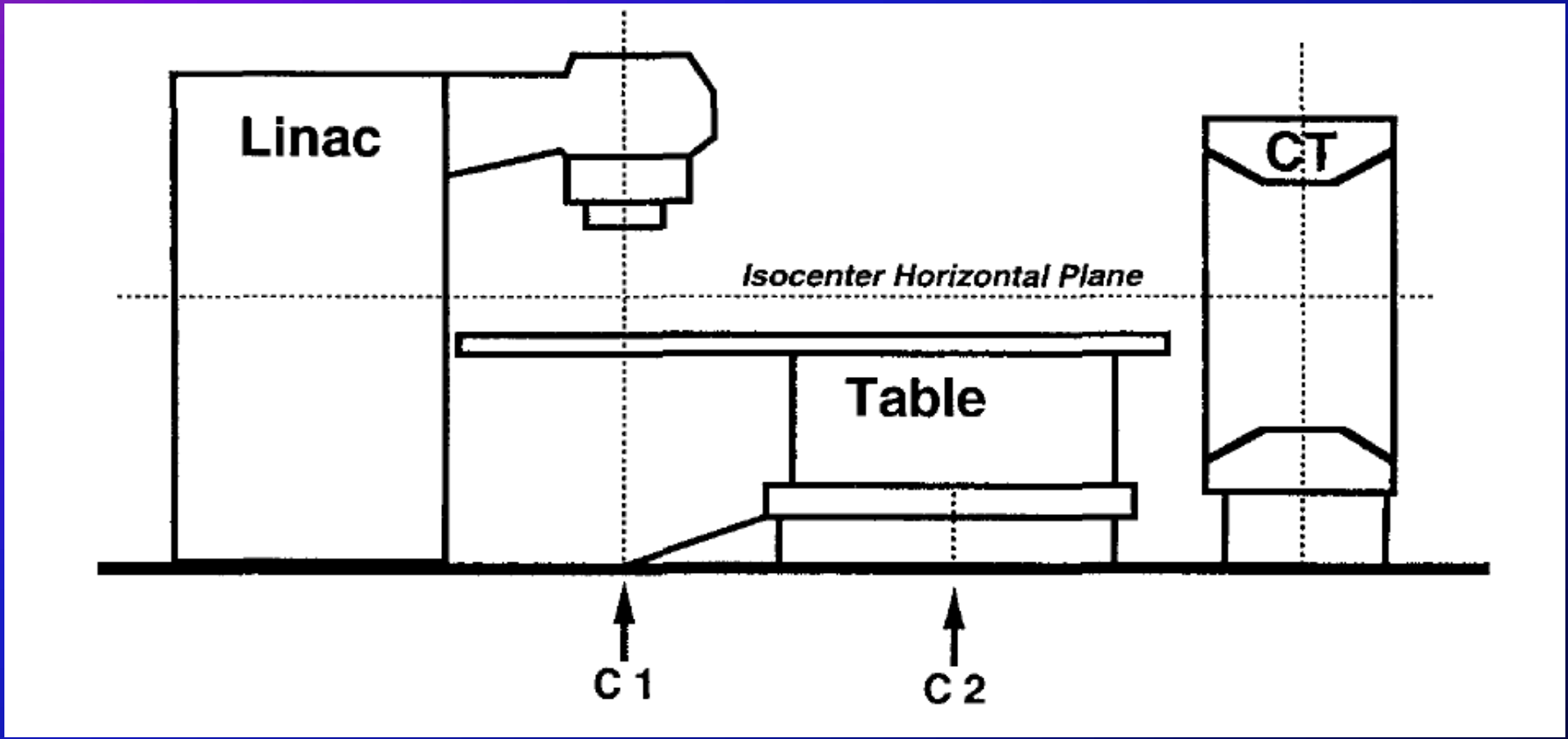
*Department of Radiation Oncology, Tohoku University School of Medicine, Sendai, Miyagi, Japan; Departments of †Radiology and ‡Endocrinology and Metabolism, Furukawa City Hospital, Furukawa, Miyagi, Japan

Int. J. Radiation Oncology Biol. Phys., Vol. 55, No. 4, pp. 1102–1108, 2003

Patient Transportation System



Workflow



A diagram of a CT-LINAC combination system inside a radiotherapy treatment room. The table has two rotation axes; C1 is for isocentric couch rotation and C2 is for rotation between the CT and the LINAC. The gantry is coaxial to both the CT and the LINAC. Figure from Uematsu et al. 1996.

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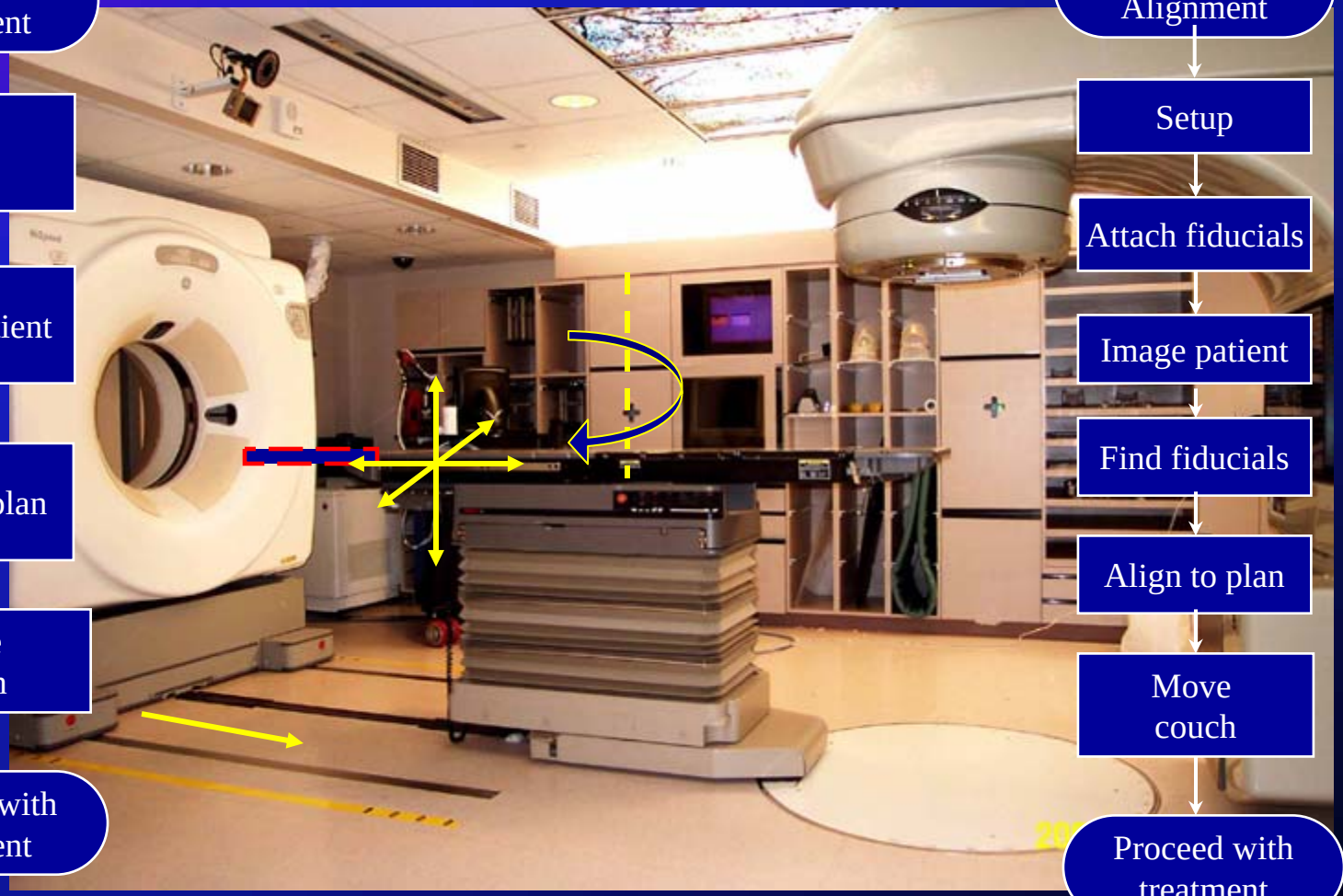
Example of workflow

1. CT scanning of the target with 2 mm slice spacing
2. Selecting the center of the target,
3. Placing two tiny radio-opaque markers on the surface of the patient or the immobilization device to mark the isocenter,
4. Re-CT scanning to verify marker positions relative to the target
5. Aligning markers with linac's treatment beams.

CT-on-Rails at MDACC



Start Alignment → Setup → Image patient → Align to plan → Move couch → Proceed with treatment

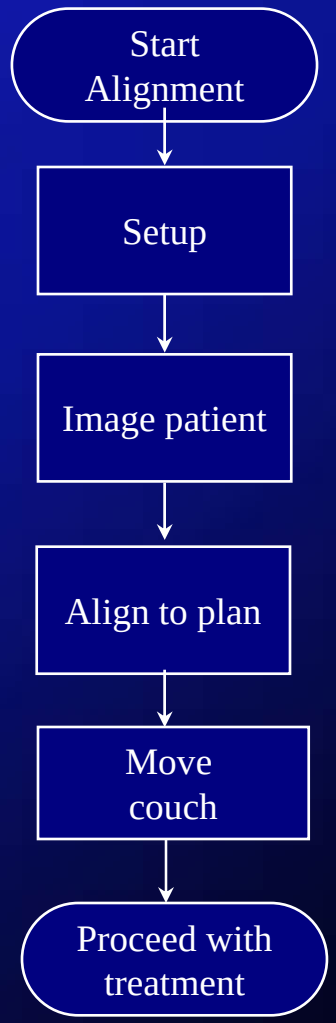
Start Alignment → Setup → Attach fiducials → Image patient → Find fiducials → Align to plan → Move couch → Proceed with treatment

Common Iso Method

Daily Iso Method

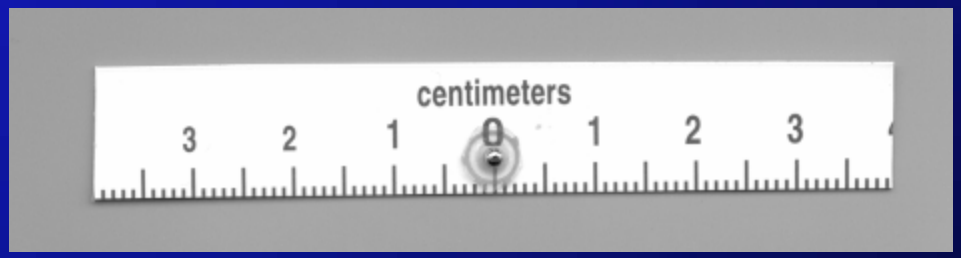
Common isocenter method

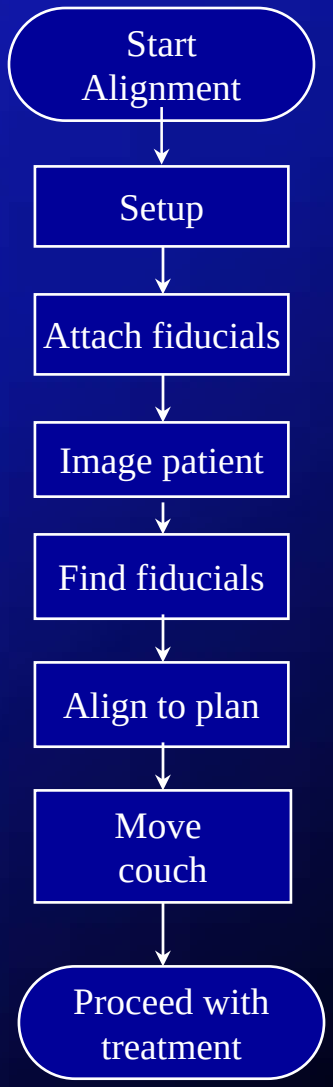
- Relies heavily on mechanical integrity of the system
- Assume isocenter is fixed
- Shift using couch digital readout



Daily isocenter method

- Reduced reliance on system's mechanical integrity
- Assume isocenter varies daily
- Removes uncertainties in couch position
- Fiducials to define isocenter
- Shift patient using lasers





Mechanical Precision

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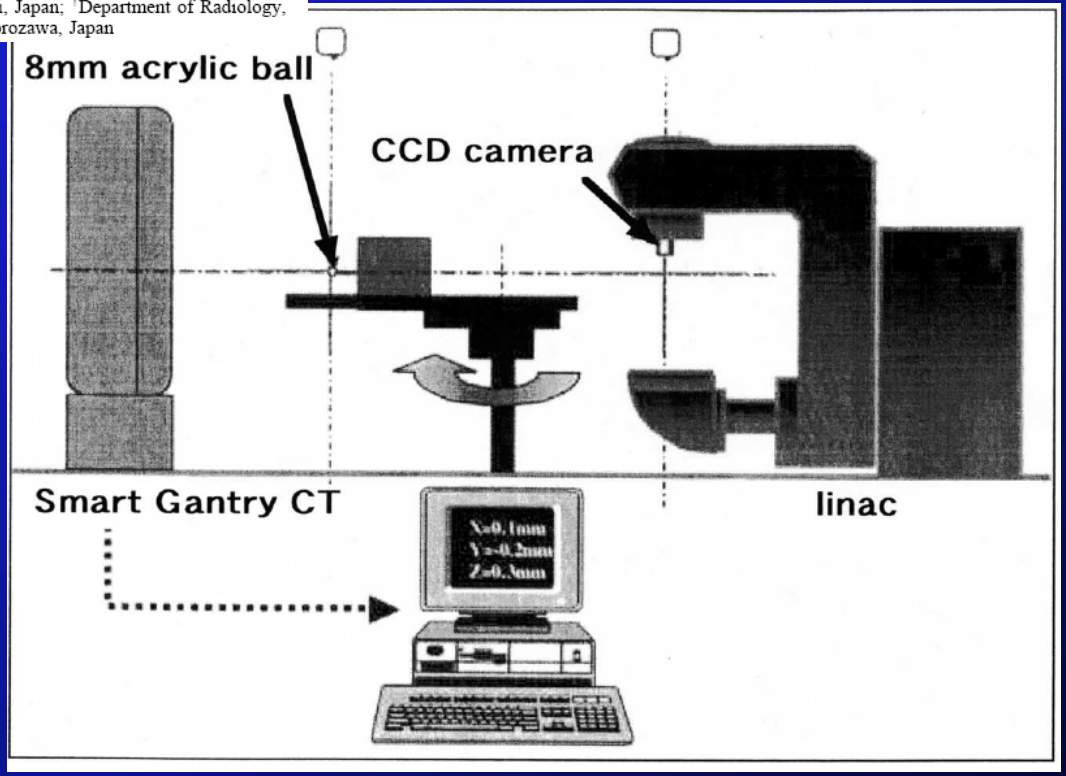

Table 1. Rotational accuracy of the common treatment couch

Direction	Difference from center of the ball (mm)*
Lateral (right-left)	0.20 ± 0.32
Longitudinal (cranial-caudal)	0.18 ± 0.13
Vertical (anterior-posterior)	0.39 ± 0.10

* Difference is shown in mean ± SD.

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Uncertainties in Various Steps

- the patient couch position on the linac side after a rotation
- the patient couch position on the CT side after a rotation
- the precision of the couch position as indicated by its digital readout
- the difference in couch sag between the CT and linac positions
- the geometric accuracy of the reconstructed CT images
- the identification of fiducial markers from CT images (if necessary)
- the alignment with setup lasers
- the alignment of the planning contours with the anatomy in the CT image (under ideal conditions without organ deformation).

Individual uncertainties (in 1-SD)

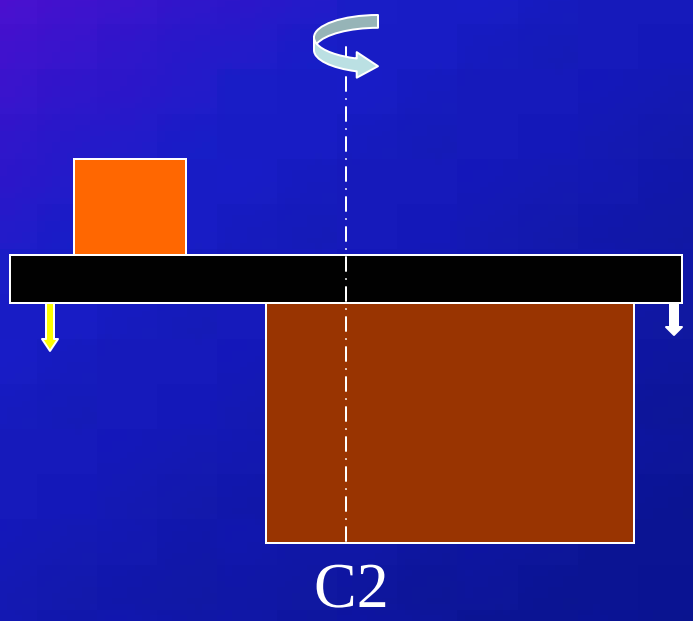
Source of uncertainty	Uncertainty, mm		
	Longitudinal	Lateral	Vertical
Align scale with laser	0.2	0.2	0.2
Couch position at LINAC side	negligible	negligible	negligible
Couch position at CT side	negligible	0.5	negligible
Couch digital readout	0.3	0.3	0.3
CT coordinates	negligible	negligible	negligible
Identification of fiducial coordinates	0.2	0.1	0.1
Alignment of contours with structures	0.4	0.3	0.3
Variation in couch sag differences	negligible	negligible	0.2

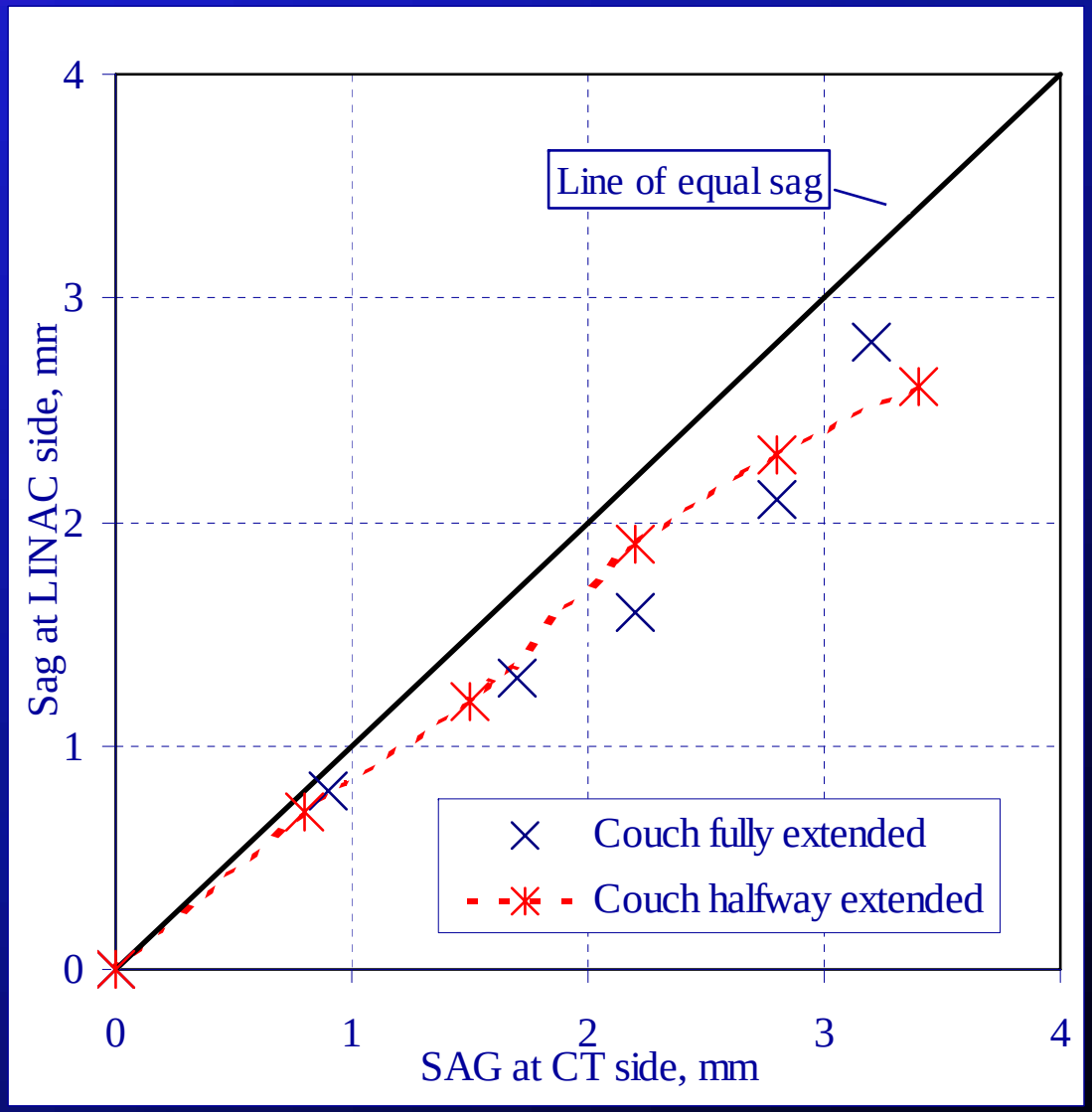
- Only two uncertainties larger than 0.3mm

Court L, Rosen I, Mohan R and Dong L 2003 Evaluation of mechanical precision and alignment uncertainties for an integrated CT/LINAC system *Medical Physics,* **30,** 1198-210.

Figure 6. Measurements of couch sag for various weight loads after an 180-degree couch rotation in a CT-linac system. Ideally, the amount of sag should be equal after a couch rotation to maintain spatial symmetry between the linac and CT coordinates.

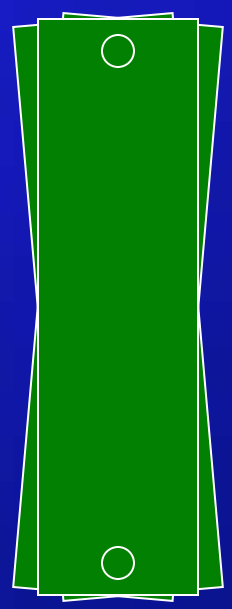
Effect of couch sag after a couch rotation





Uncertainty in Couch Rotation

CT



Linac

Uncertainty: 0.5mm

Precision for the two methods

$$\sigma_{total}^2 = \sigma_{I_{CT}}^2 + \sigma_{I_{plan}}^2 + \sigma_{shift}^2$$

Common isocenter method

$$\sigma_{total}^2 = \left(\sigma_{couch}^2 + \sigma_{CT}^2\right) + \sigma_{contour}^2 + \sigma_{coordinates}^2$$

Daily isocenter method

$$\sigma_{total}^2 = \sigma_{bb}^2 + \sigma_{contour}^2 + \sigma_{L}^2$$

$$\left(\sigma_{couch}^2 = \sigma_{coordinates}^2 + \sigma_{couch,CT}^2 + \sigma_{couch,LINAC}^2 + \sigma_{sag}^2\right)$$

Predicted uncertainty

	Uncertainty (mm)		
Setup protocol	**Longitudinal**	**Lateral**	**Vertical**
Daily isocenter	0.5	0.4	0.4
Common isocenter	0.6	0.7	0.6 (0.5 without sag)

Radiation Dose from CT Imaging

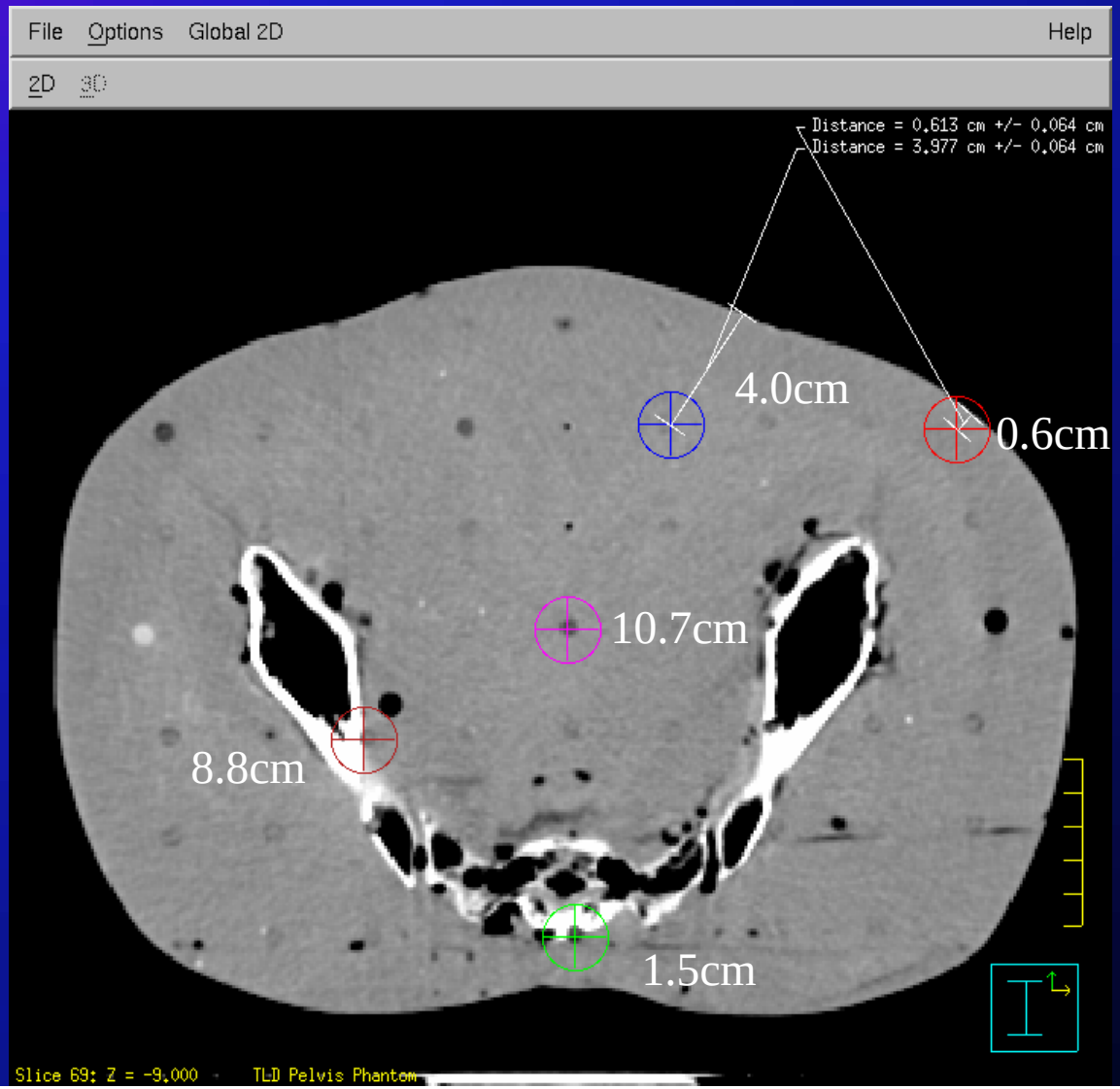
Where is the concern?

- CT-guided treatments
  - Multiple, repeated imaging
    - 42 fractions for prostate treatments
  - Low CT dose becomes a concern

Objectives

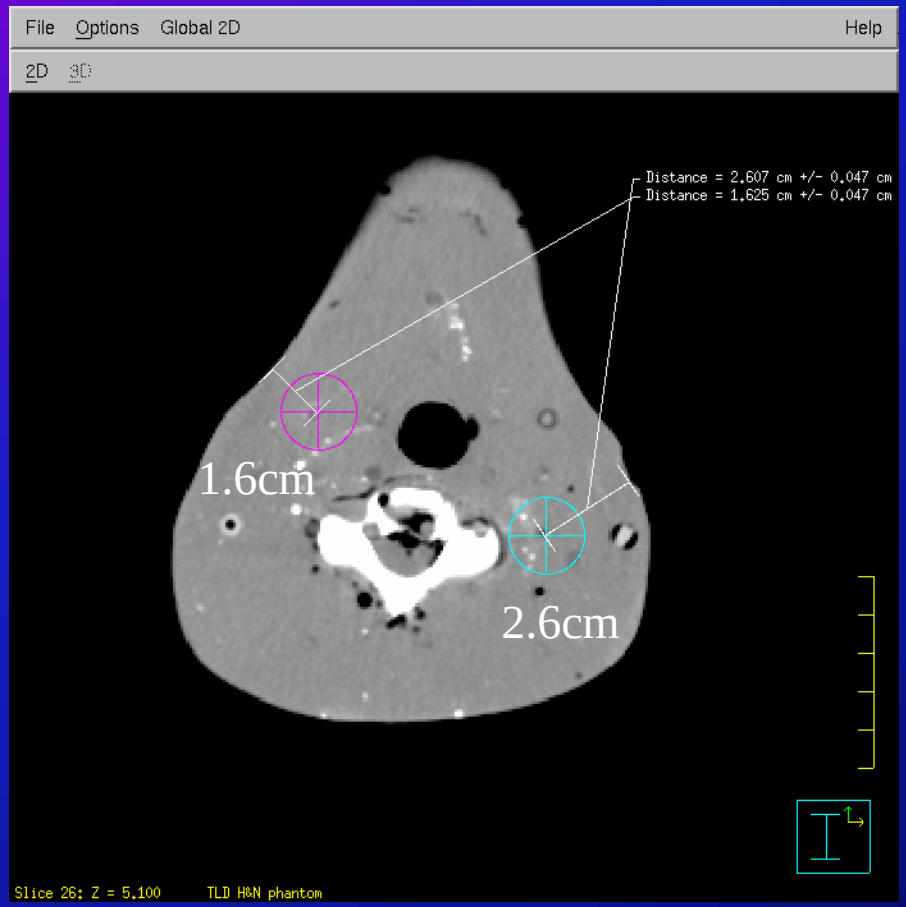
- Measure the typical daily CT dose from in-room CT-guided radiotherapy
  - abdomen/pelvis
  - head & neck
  - thoracic
- Compare with current practice using weekly portal films or EPIDs

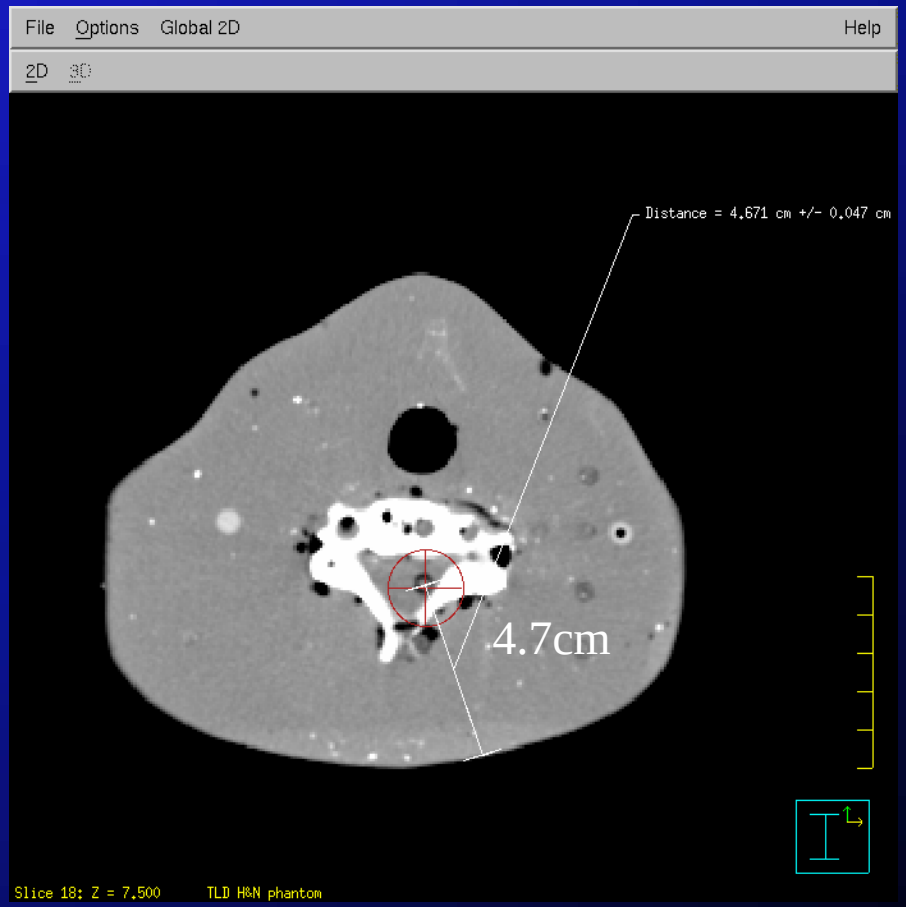
TLD in Pelvis Phantom



TLD in Head & Neck Phantom

TLD in Head & Neck Phantom





Scanning Protocol

Head & Neck

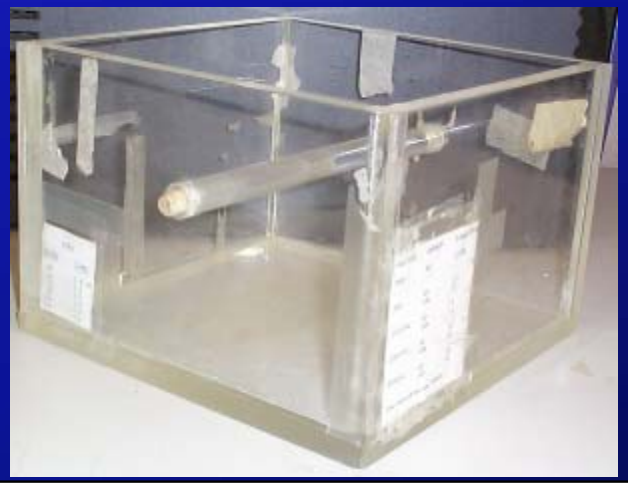
- Scout: 120kV, 20mA
- Helical Scan
  - 3mm thickness
  - 1.0 pitch
  - 120kV, 110mA

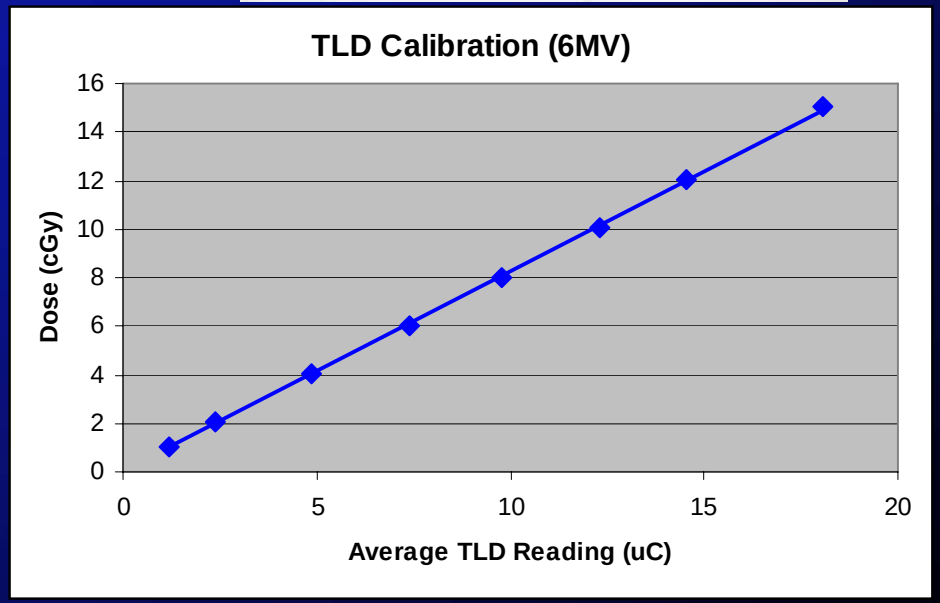
Prostate

- Scout: 120kV, 80mA
- Helical Scan
  - 3mm thickness
  - 1.5 pitch
  - 120kV, 200mA

TLD Calibration

- TLD Calibration Water Tank
  - tube holds TLD at isocenter
  - fill with water to place TLD at desired depth
- 6MV photons
- depth = d_{max} (1.5cm)





$$\text{Dose(cGy)} = 0.8259 * \text{TLD(uC)}$$

Energy-Dependence of LiF TLD

- Budd et al showed that the over-response of LiF TLD at low energies below 150 keV.
- We estimated conservatively that the mean energy of our CT-on-rails scanner was 50 keV.
- Therefore, all dose measurements were divided by a correction factor of 1.25.*

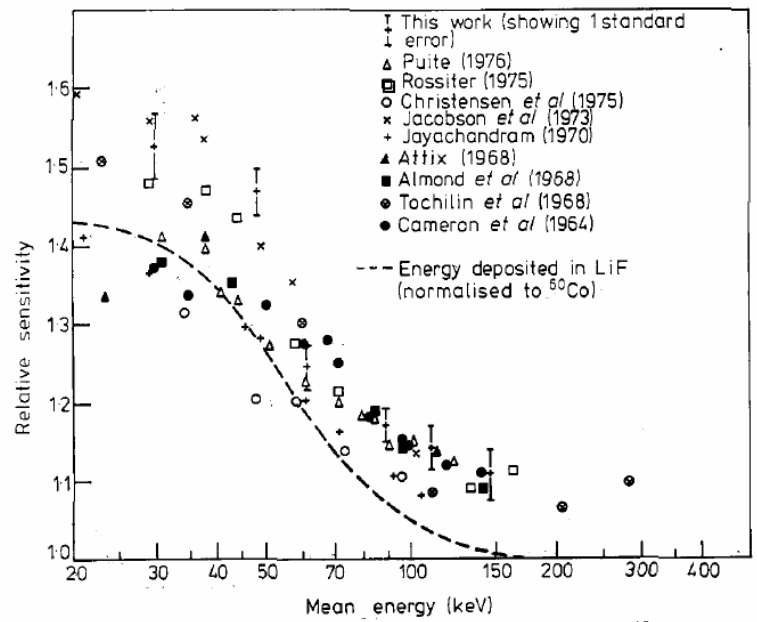


Fig. 2. Response of LiF measured at 240 °c. Sensitivity is expressed as counts per rad in water at a given energy divided by counts per rad in water for ^{60}Co.

*Budd T, Marshall M, People L, et al. The low- and high-temperature response of LiF dosemeters to x-rays. Phys. Med. Biol. 1979: 24; 71-80.

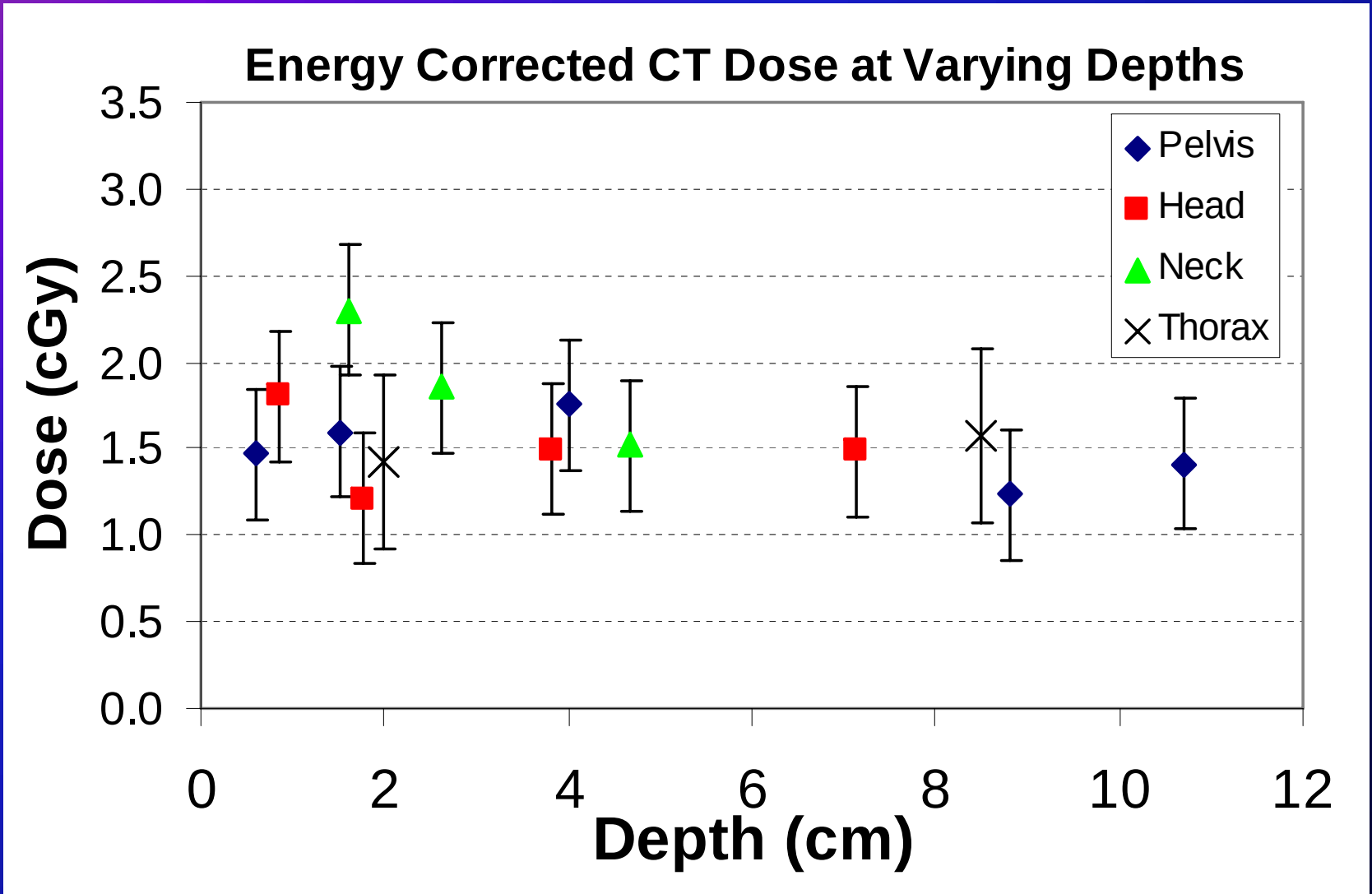


Figure 7. The depth- and site-dependence of CT imaging dose for typical exposures. The measurements were performed in phantom using TLDs. The error bars represent one standard deviation of multiple TLD measurements.

Dose from Portal Films

- One film = 6 - 8 MU
- Two orthogonal films each week, 8 weeks of treatment, assuming no repeat films.
  - 96 - 128 MU ~ 100 cGy
- Typical prescription for prostate = 7560 cGy
- Typical prescription for head&neck = 7000 cGy
  - ~ 1.3% of prescription dose for prostate
  - ~ 1.4% for prescription dose for head&neck

CT dose

~2 cGy x 42 = ~84 cGy

Quality Assurance

For in-room CT imaging

QA for CT Scanner

- AAPM Task Group #2 “Specification and acceptance testing of computed tomography scanners” (Lin et al. 1993)
- Task Group #66 “Quality assurance for computed-tomography simulators and the computed-tomography-simulation process”.(Mutic et al. 2003)
  - In-room CT is very similar to the function of a CT simulator.

Spatial integrity

- The mechanical precision of the CT scanner should be able to determine a patient's position on a shared treatment couch to within 1 mm relative to the treatment beam.
- Any vibration or miscalibration of the CT gantry moving on rails could result in either poor image quality or spatially displaced objects. It is recommended that a long, straight, and leveled object should be scanned along the gantry movement direction to determine any jittering or spatial non-linearity issues.

Low Contrast resolution

- The contrast resolution is defined as the CT scanner's ability to distinguish relatively large objects which differ only slightly in density from background.
- For the moving-gantry CT scanner, the low contrast resolution is worse than conventional couch-moving CT scanners.
  - 1.5% contrast level at 3 mm object
  - 0.3% for conventional (couch-moving) CT

Positioning laser systems

- Two laser positioning systems are usually installed:
  - Linac laser system for patient setup
  - CT laser for position verifications
- Lasers are temporary in-room reference

Safety Interlocks

- X-ray On interlock
- Interlock for couch center position
- Interlock for couch height
- Collision interlocks
- Park position

Comparison with weekly portal filming

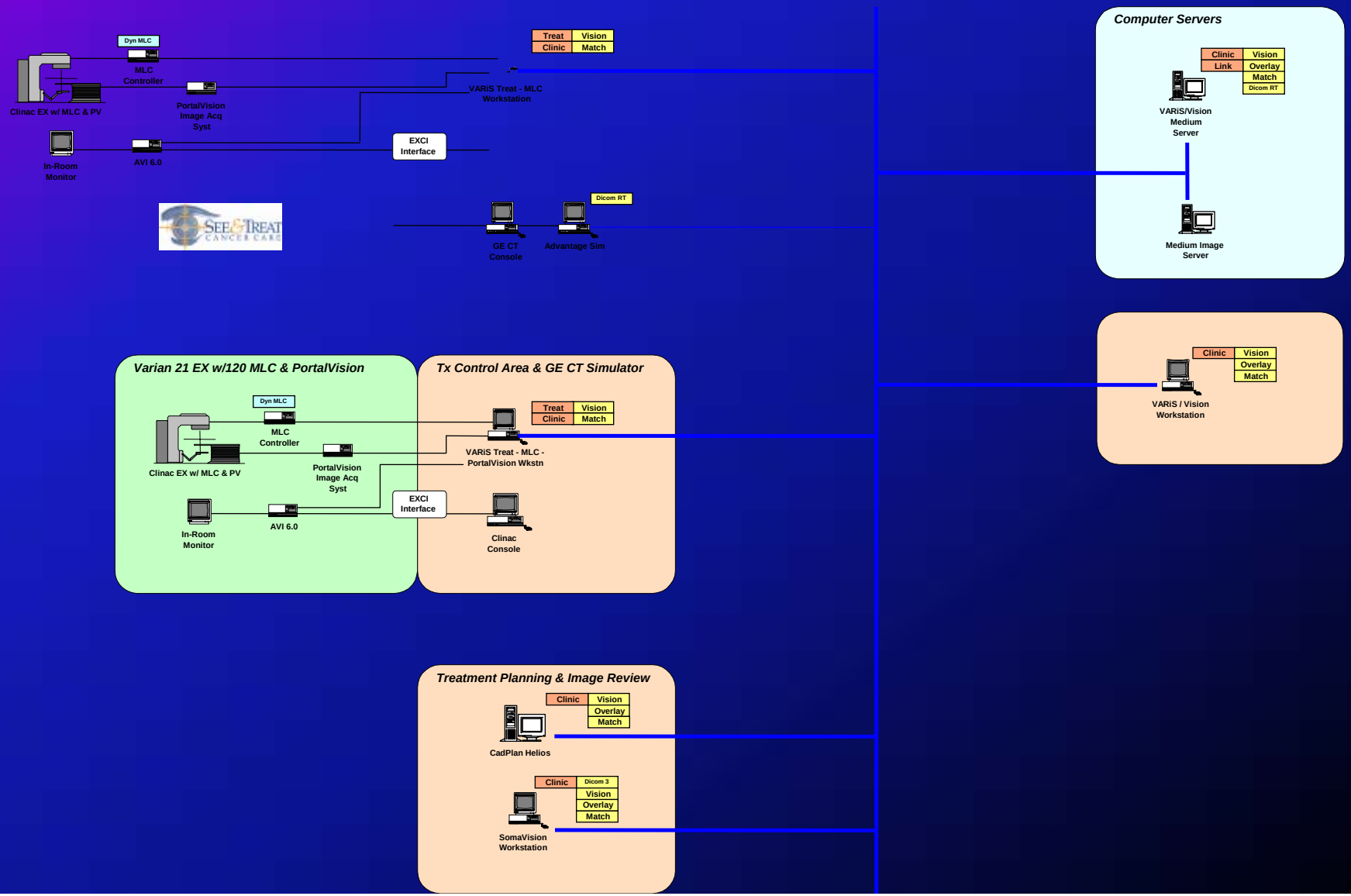
- Portal Films (2 orthogonal films, once/week)
  ~100 cGy (1.3 – 1.4 % of prescription dose)
  * This is conservative because the portal dose from repeat films were not included.
- Daily CT, assuming ~2 cGy per scan, 42 fractions
  ~84 cGy (1.1 – 1.2 % of prescription dose)

Therefore, if daily CT replaces portal films, the imaging dose for patient alignment is comparable.

CT scanning protocols

- Site-dependent and application dependent
  - mA
  - Slice spacing
  - Slice thickness
  - Pitch
  - Scan field-of-view
  - Scan length

Connectivity



General Recommendations

- Daily tests
  - CT number reproducibility and uniformity test
  - High contrast resolution (visual inspection)
- Monthly tests
  - Repeat daily tests
  - Alignment test using a phantom
- Annual tests
  - CT scanner annual calibration/tests
    - CT number accuracy
    - Spatial integrity
    - Image quality
    - Imaging dose
    - Interlock systems
    - Application specific tests

In-room CT-guided Applications

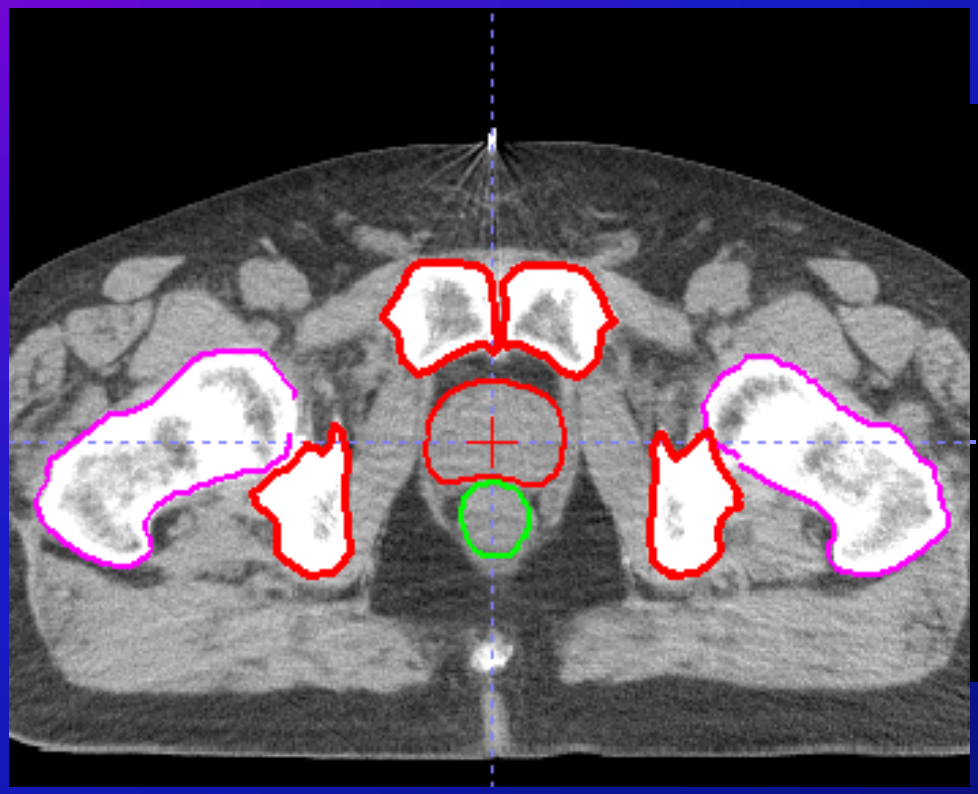
CT-guided RT

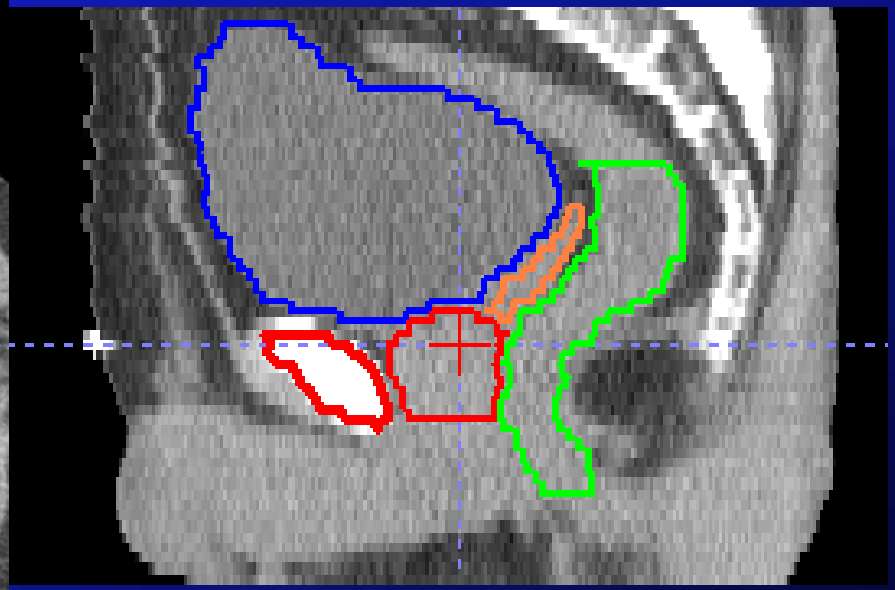
- Reposition patient based on pre-treatment CT images
  - Rigid-body movement (translation)
  - Rotation: rare
- Replan
  - Mid-course correction
  - Image-guided adaptive radiotherapy
- Single treatment
  - SRS/SRT
  - Palliative treatments

Prostate

- 1. Hua CH, Lovelock DM, Mageras GS*, et al.* Development of a semi-automatic alignment tool for accelerated localization of the prostate. *Int J Radiat Oncol Biol Phys* 2003;55:811-824.
- 2. Court LE, Dong L. Automatic registration of the prostate for computed-tomography-guided radiotherapy. *Med Phys* 2003;30:2750-2757.
- 3. Paskalev K, Ma CM, Jacob R*, et al.* Daily target localization for prostate patients based on 3D image correlation. *Phys Med Biol* 2004;49:931-939.
- 4. Fung AYC, Enke CA, Ayyangar KM*, et al.* Prostate motion and isocenter adjustment from ultrasound-based localization during delivery of radiation therapy. *International Journal of Radiation Oncology Biology Physics* 2005;61:984-992.
- 5. Wong JR, Grimm L, Oren R*, et al.* Image-guided radiotherapy for prostate cancer by CT-linear accelerator combination: Prostate movements and dosimetric considerations. *International Journal of Radiation Oncology Biology Physics* 2005;61:561-569.

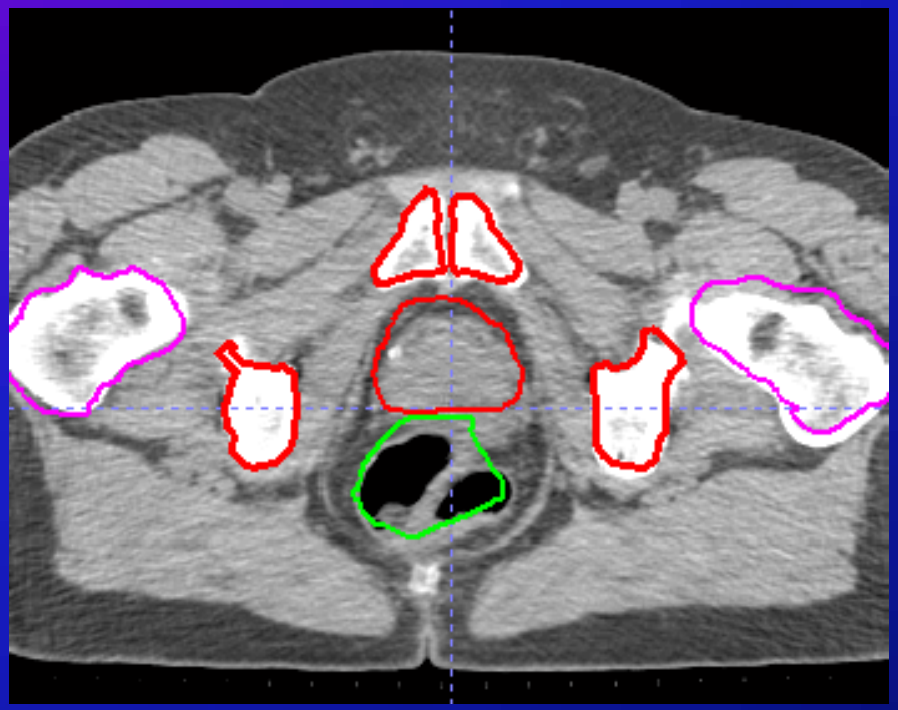
Example of setup error and organ variation during the course of prostate radiotherapy



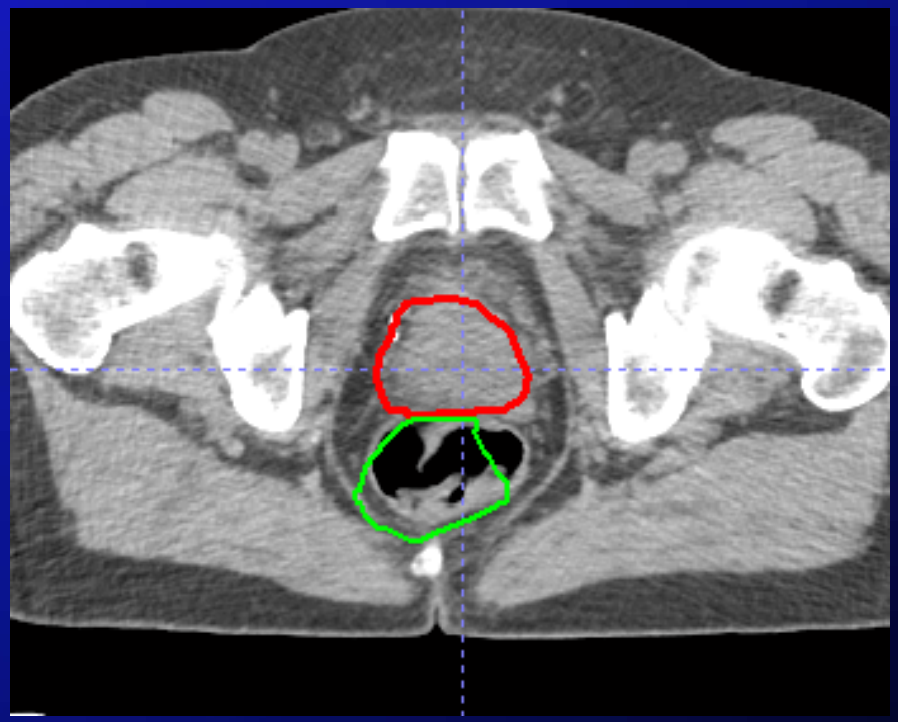


- Contours from treatment planning CT are overlaid as reference
- Patient aligned with BBs

Comparison of Bony and Direct Target Localization



Bony Registration



Direct Target Localization

"freezing" the prostate!

Para-spinal Lesion

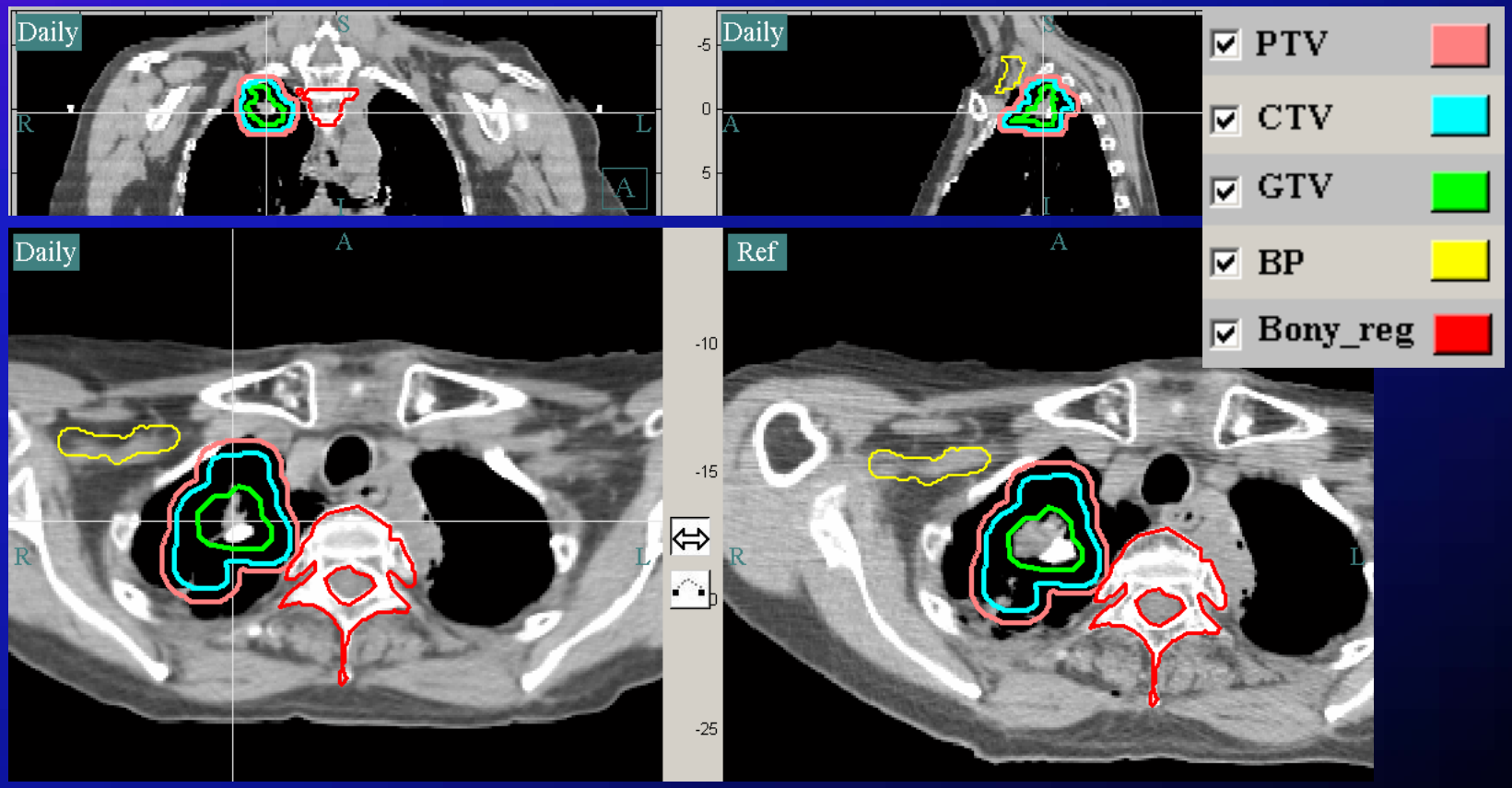
- 1. Yenice KM, Lovelock DM, Hunt MA, *et al.* CT image-guided intensity-modulated therapy for paraspinal tumors using stereotactic immobilization. *Int J Radiat Oncol Biol Phys* 2003;55:583-593.
- 2. Shiu AS, Ye J-S, Lii M, *et al.* Near simultaneous computed tomography image-guided stereotactic spinal radiotherapy: An emerging paradigm for achieving true stereotaxy. *International Journal of Radiation Oncology Biology Physics* 2003;57:605-613.

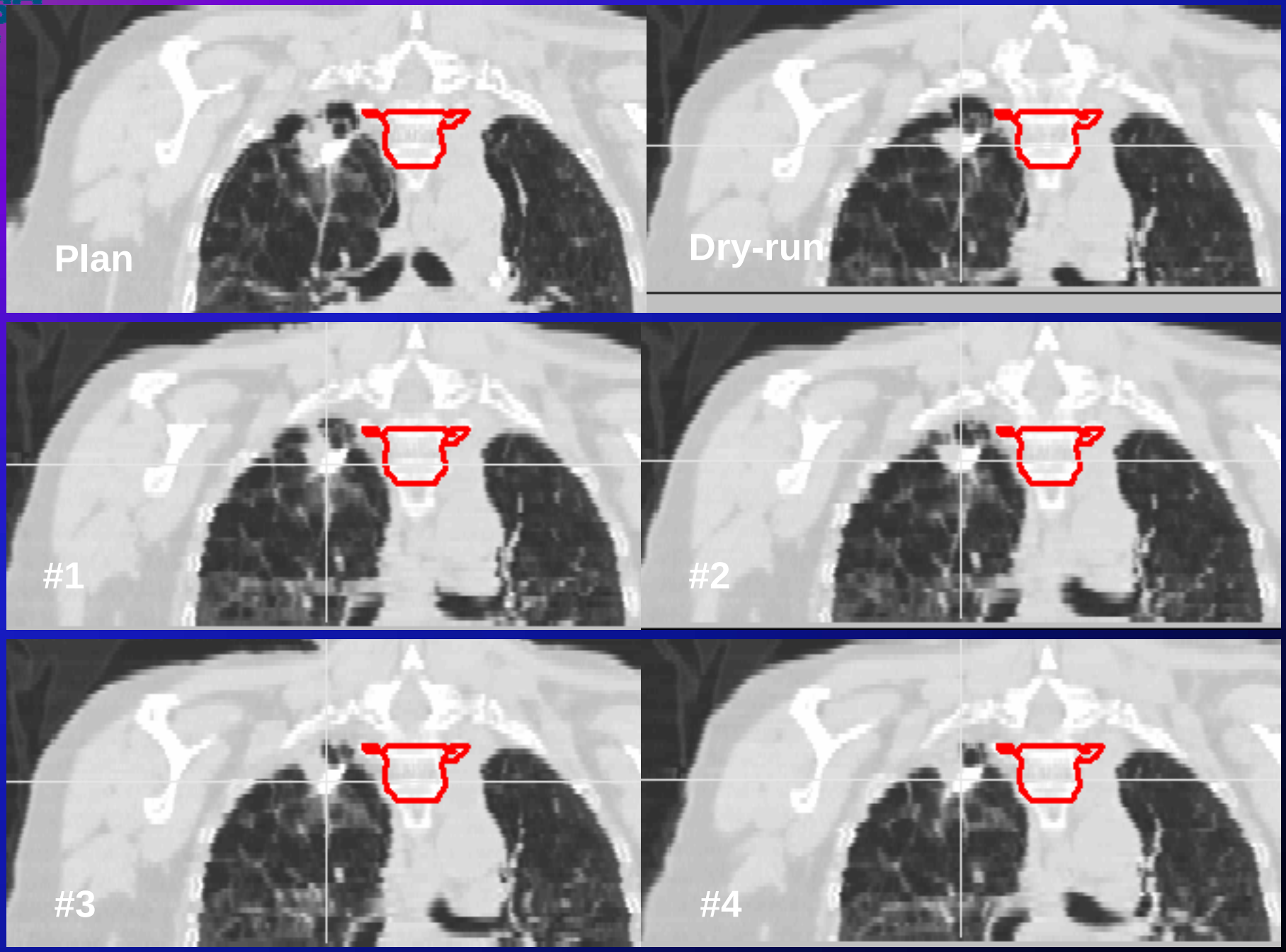
Lung Cancers

- 1. Uematsu M, Fukui T, Shioda A*, et al.* A dual computed tomography linear accelerator unit for stereotactic radiation therapy: a new approach without cranially fixated stereotactic frames. *Int J Radiat Oncol Biol Phys* 1996;35:587-592.
- 2. Uematsu M, Shioda A, Tahara K*, et al.* Focal, high dose, and fractionated modified stereotactic radiation therapy for lung carcinoma patients: A preliminary experience. *Cancer* 1998;82:1062-1070.
- 3. Uematsu M. CT-guided stereotactic radiotherapy for early stage lung cancer. *Nippon rinsho Japanese journal of clinical medicine* 2002;60 Suppl 5:408-410.
- 4. Uematsu M. Stereotactic radiation therapy for non small cell lung cancer. *Nippon Geka Gakkai zasshi* 2002;103:256-257.

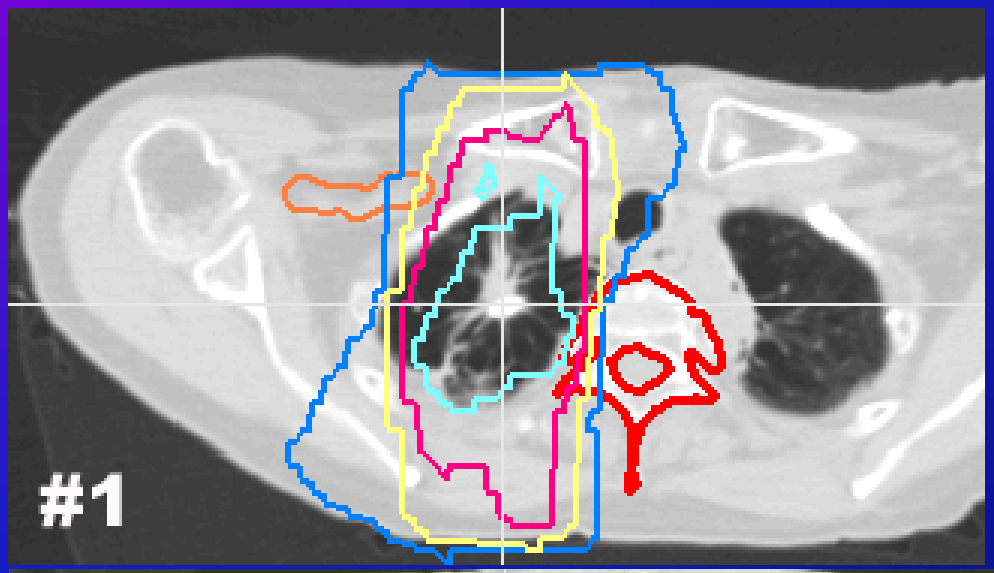
CT-Assisted Targeting (CAT)

- Using daily CT to align to the target of the day
- Planning CT used as a reference
- Auto-registration (with manual adjustment if necessary)
- Overlay of target structure for alignment confirmation



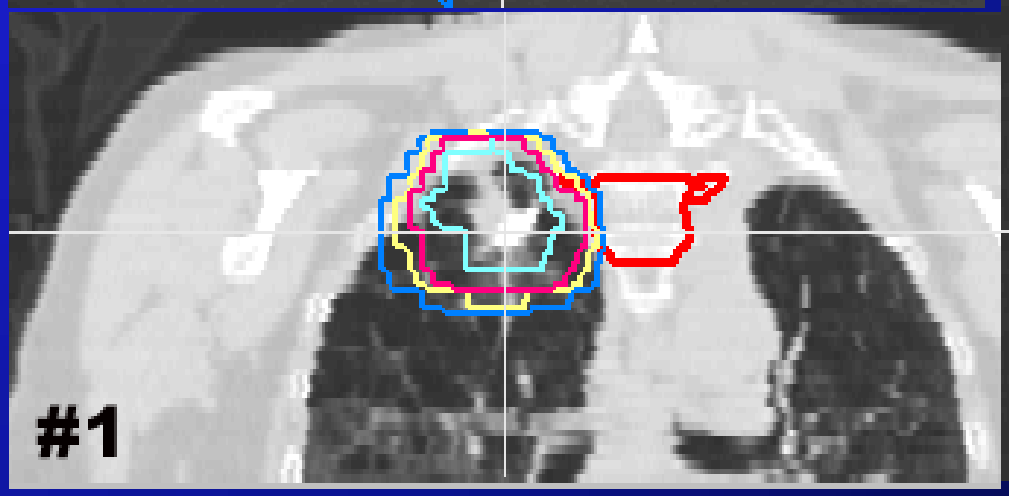

Plan
Dry-run
#1
#2
#3
#4

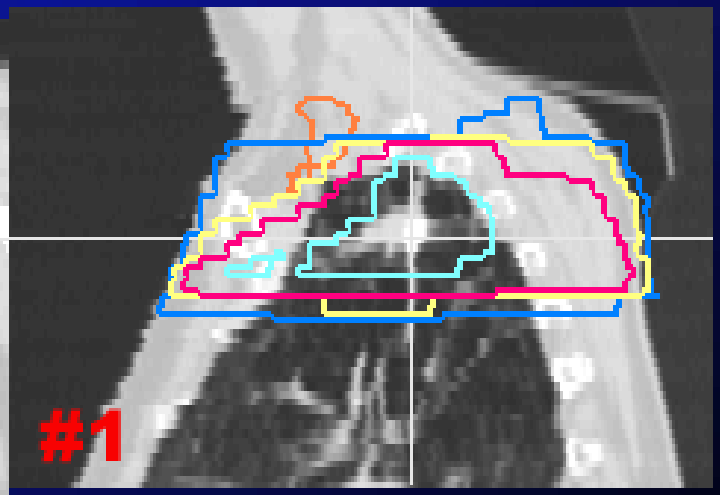
Dose Overlay (animation)



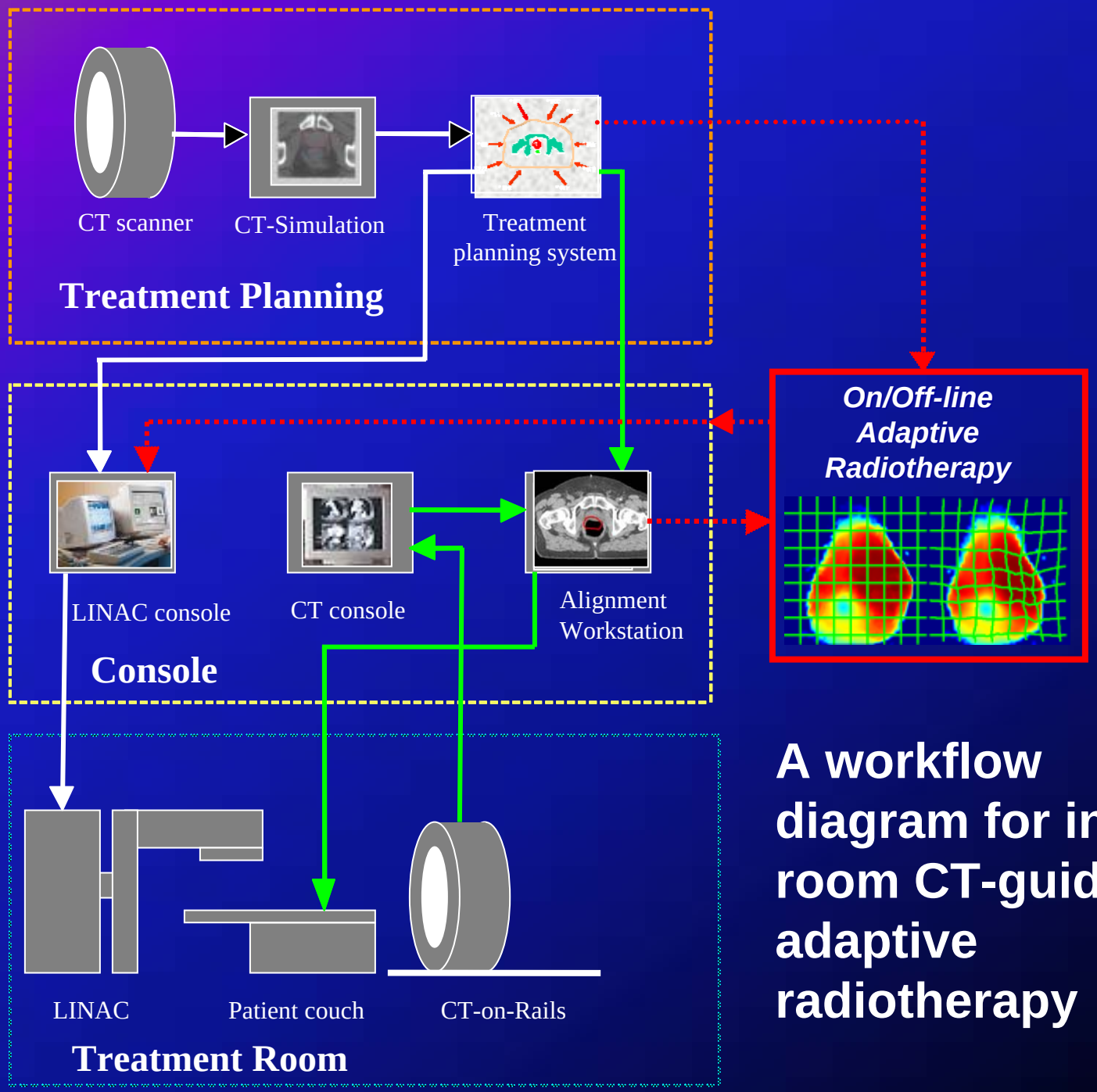
Prescription:
10 Gy x 3 fxs with IMRT
10 Gy x 1 boost AP/PA

---- 40 Gy
---- 30 Gy
---- 20 Gy
---- 10 Gy



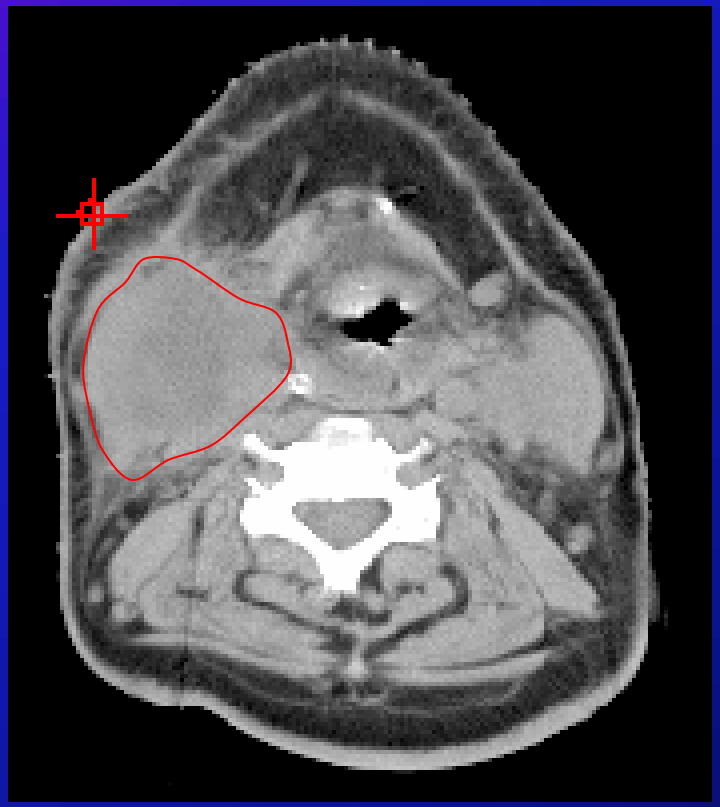


CT-guided Adaptive Radiotherapy

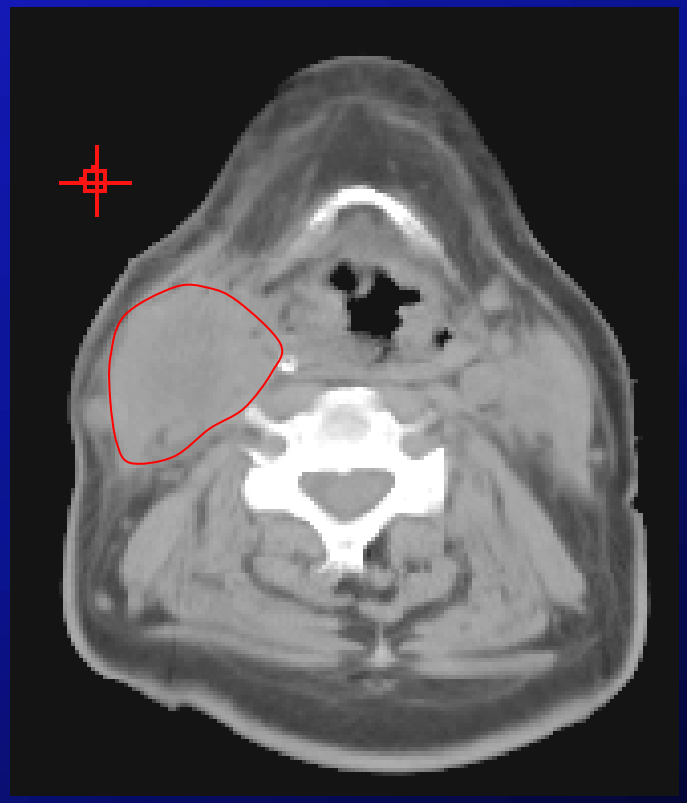


A workflow diagram for in-room CT-guided adaptive radiotherapy

HN Case (three weeks later)



CT on 3/8/02
1st Tx on 3/19/02



CT on 4/3/02

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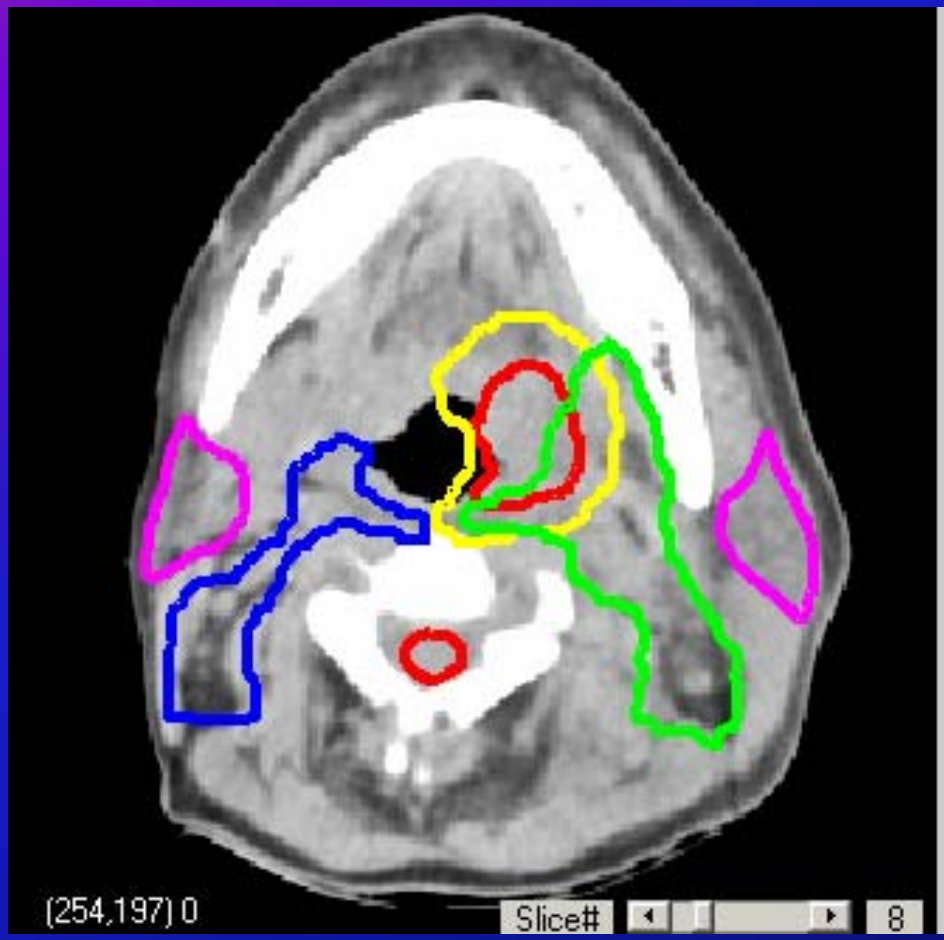
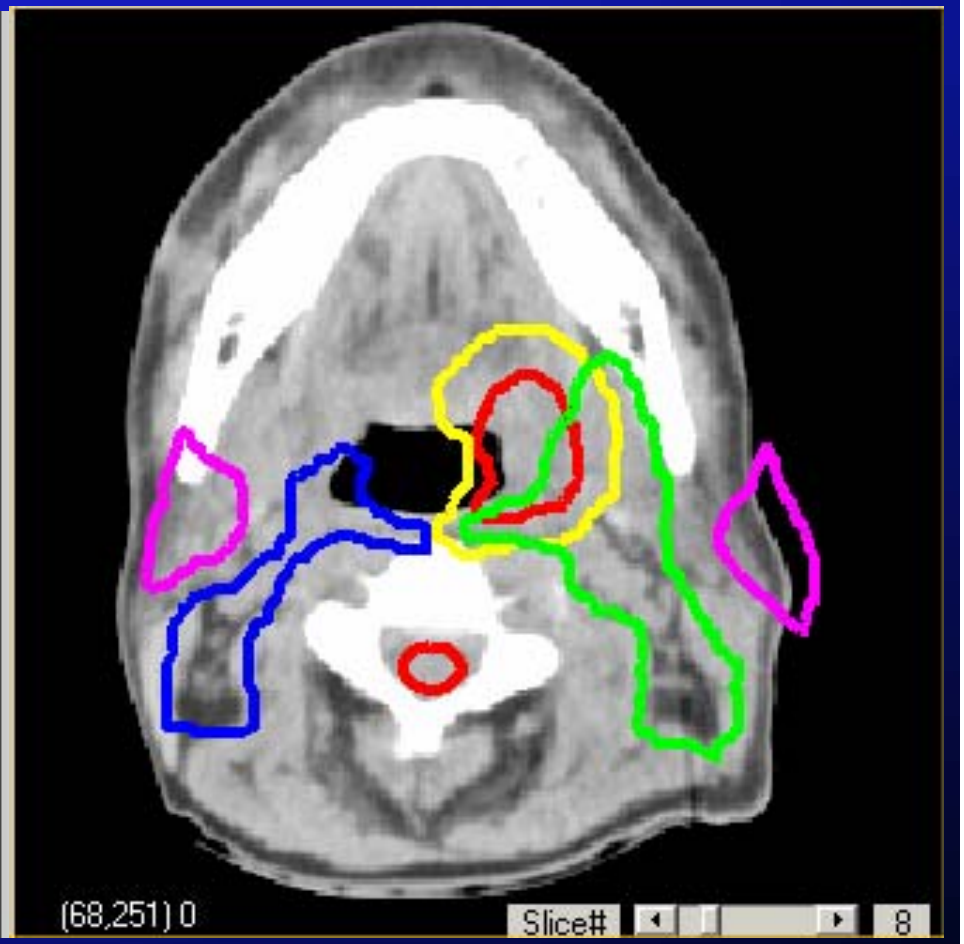
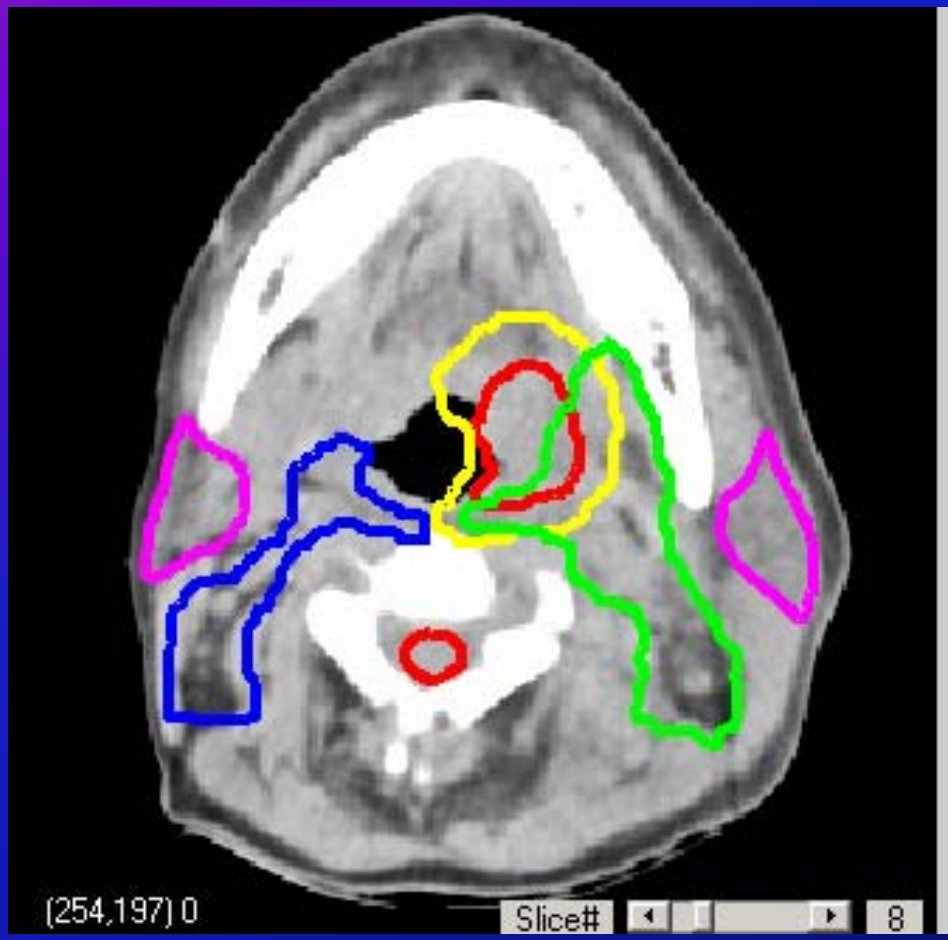
Planning CT with manually-drawn contours



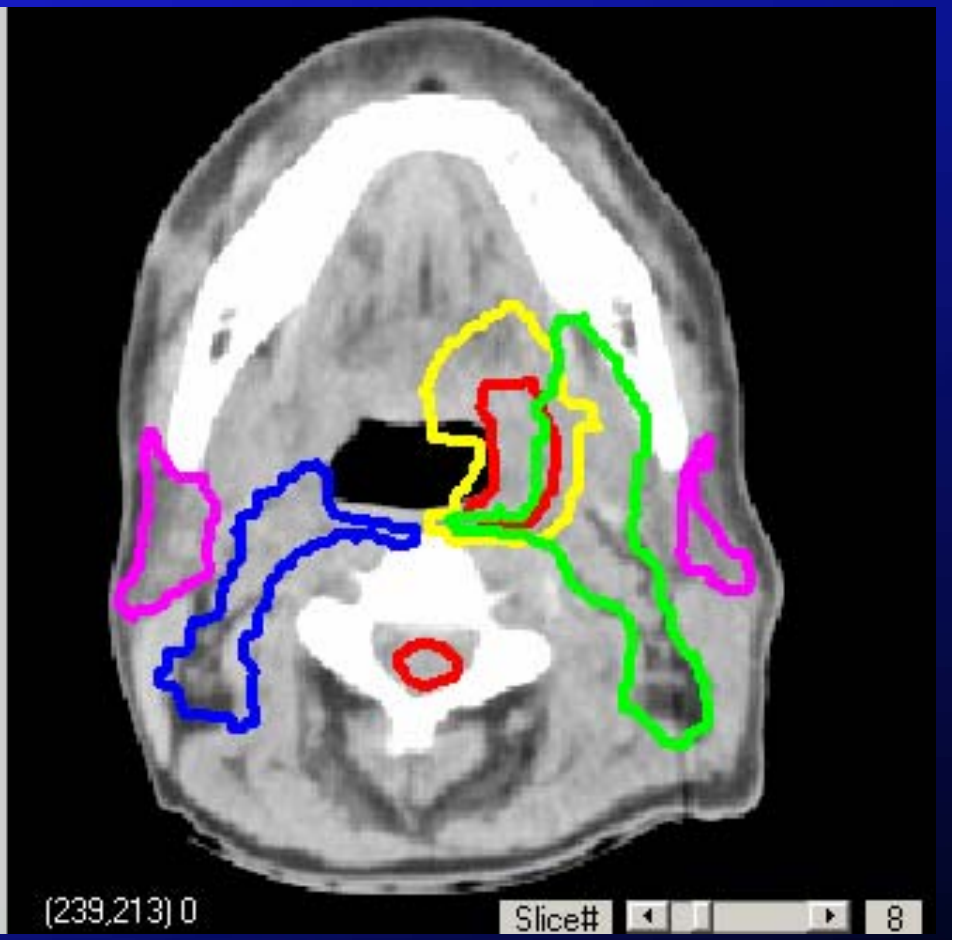
Daily CT with manually-drawn contours overlaid



Planning CT with manually-drawn contours

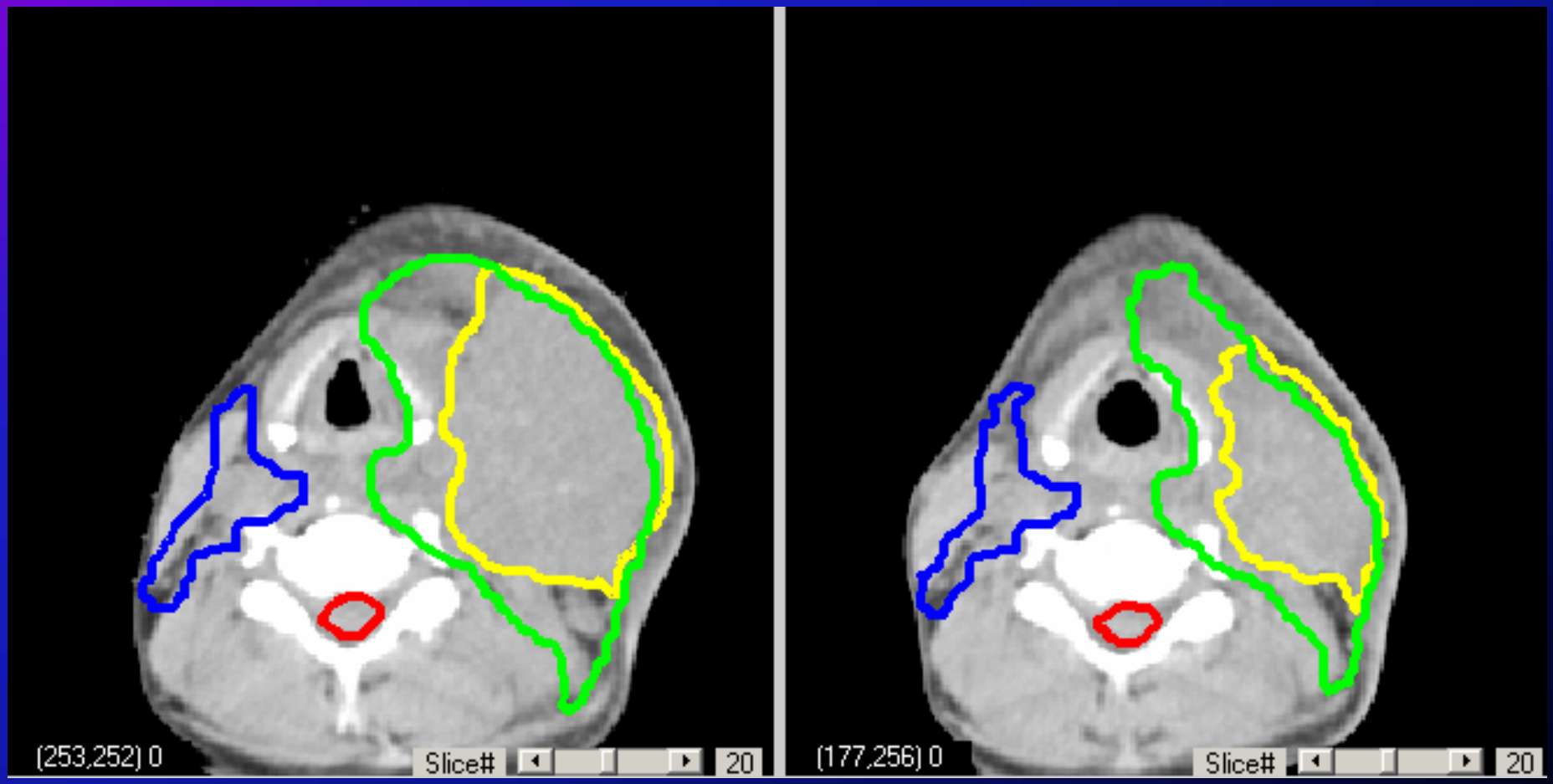


Daily CT with auto-delineated original contours



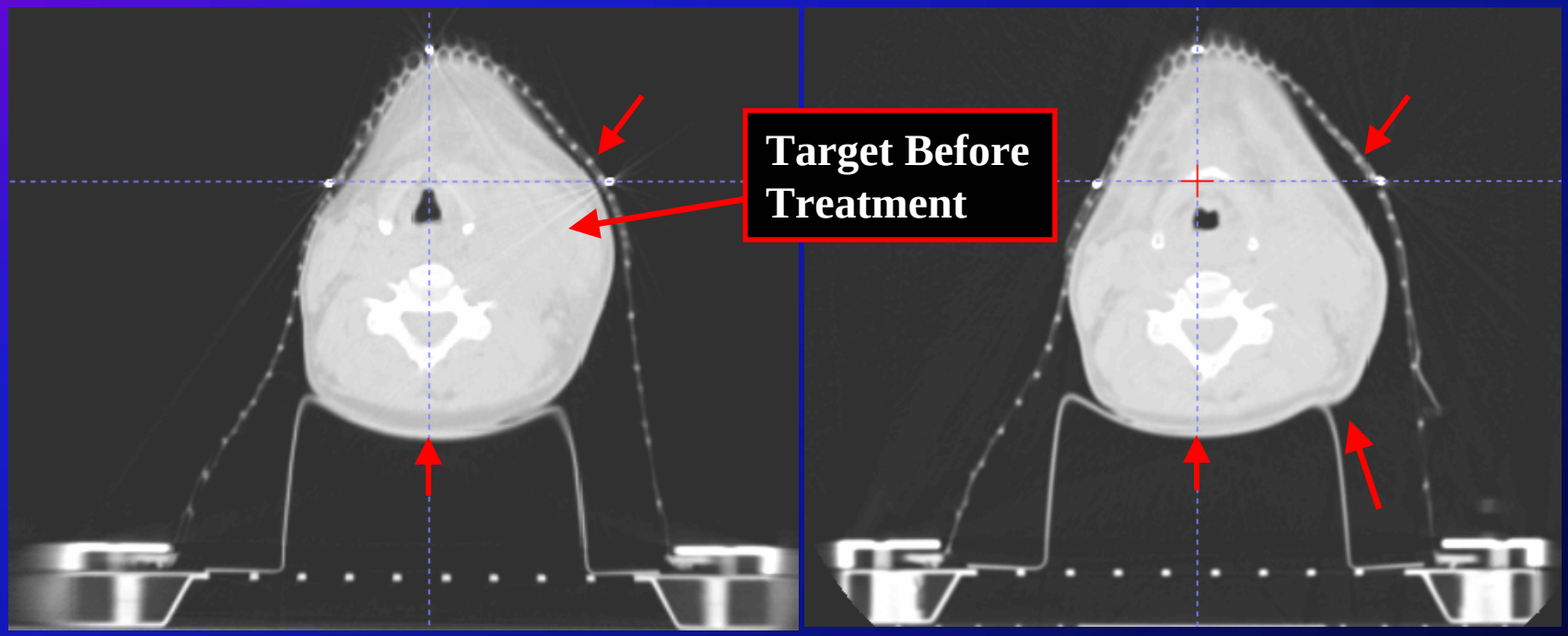
Planning CT with manually-drawn contours

Daily CT with auto-delineated original contours

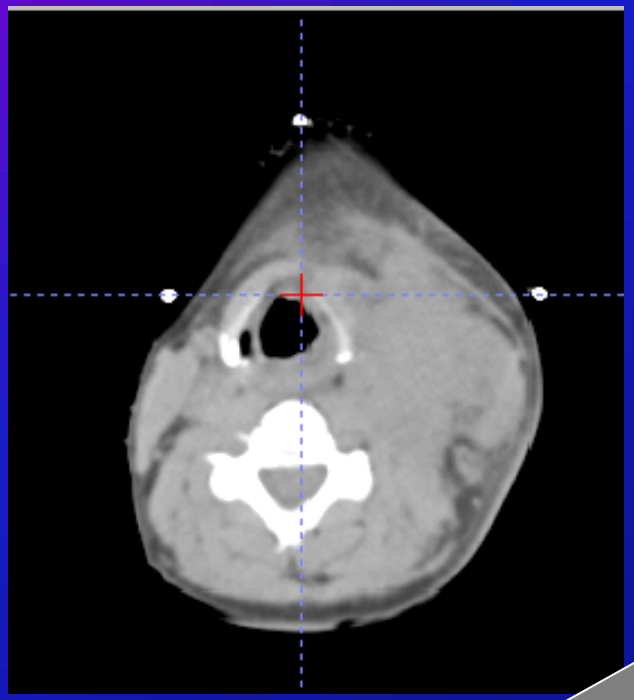


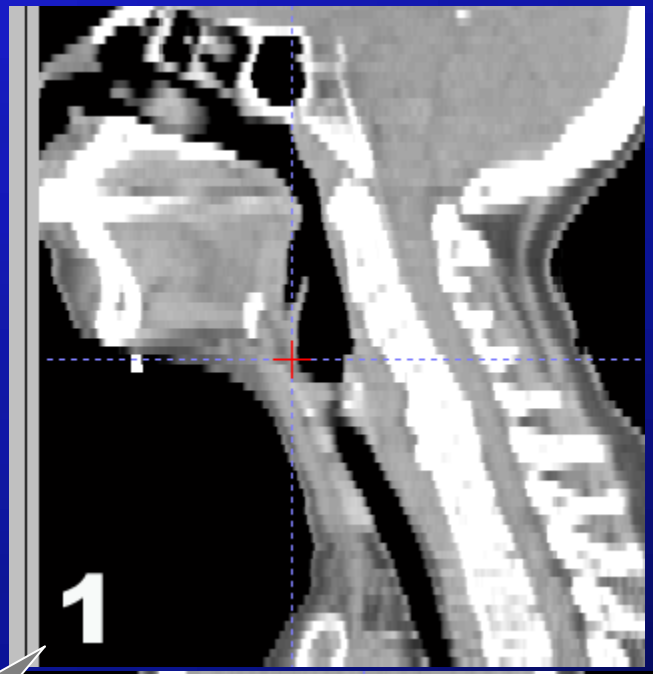
Planning CT

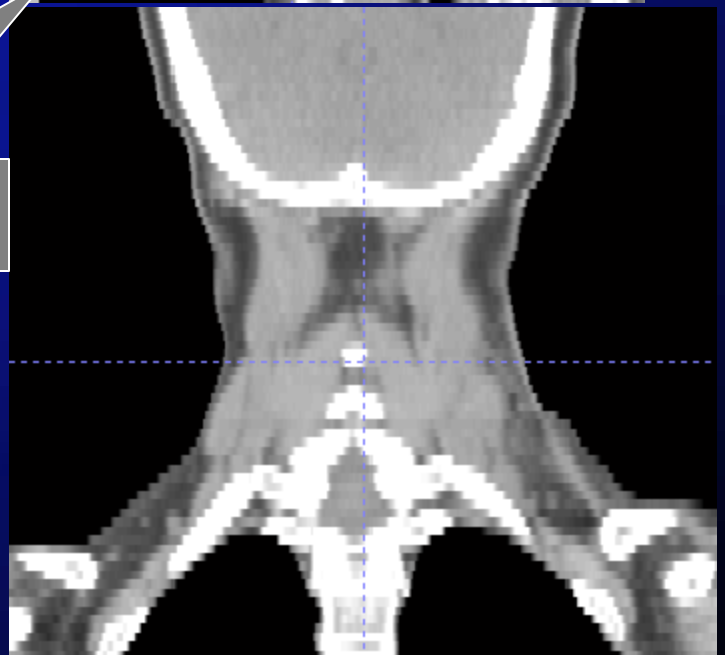
Daily CT



Setup Uncertainties In Head & Neck Treatment







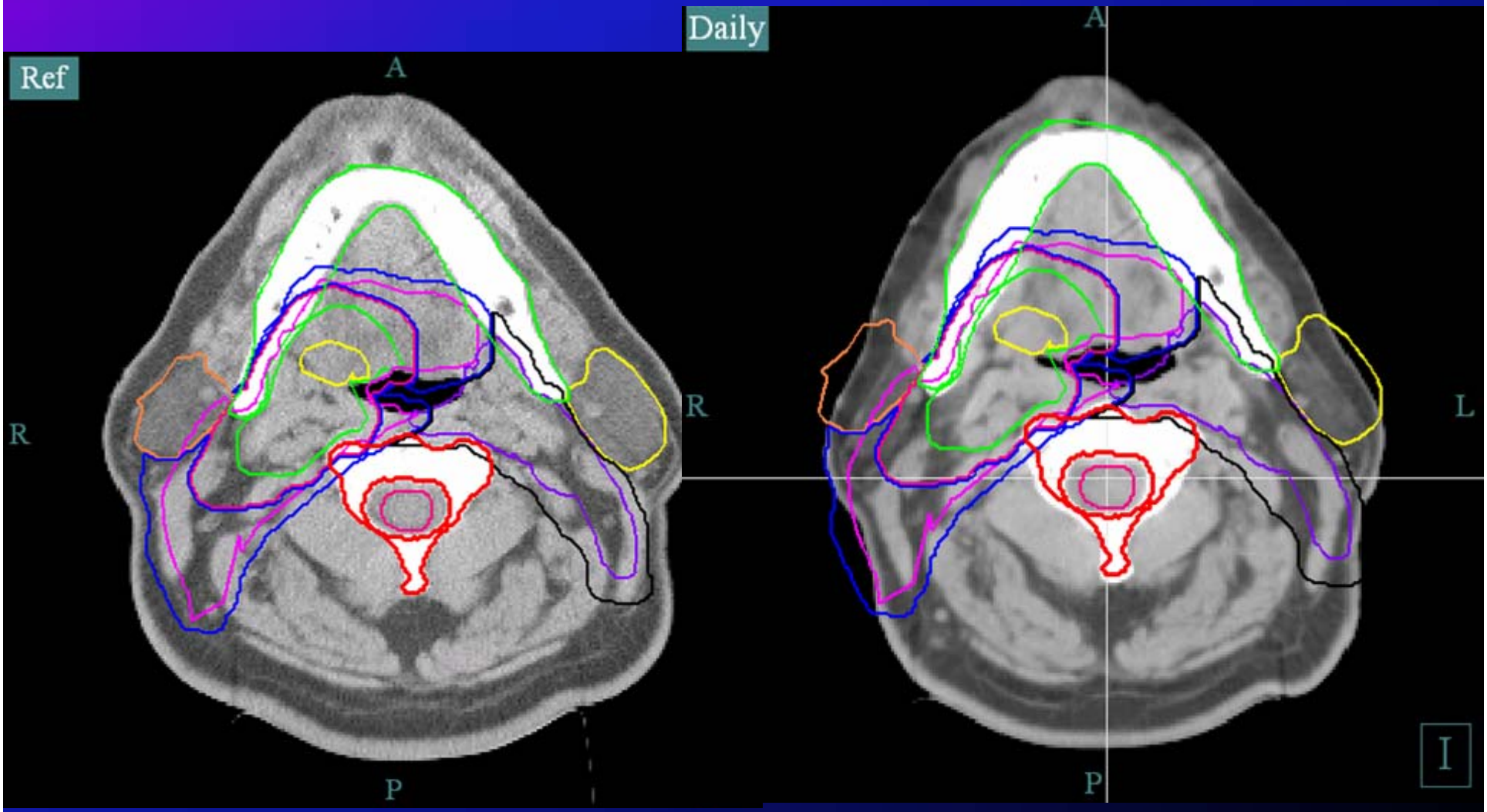
Elapsed Treatment Days

19 Treatment CT scans acquired during the course of head & neck radiotherapy

Movie Clip: Head & Neck Case

Planning CT

Repeat CT
After bony registration



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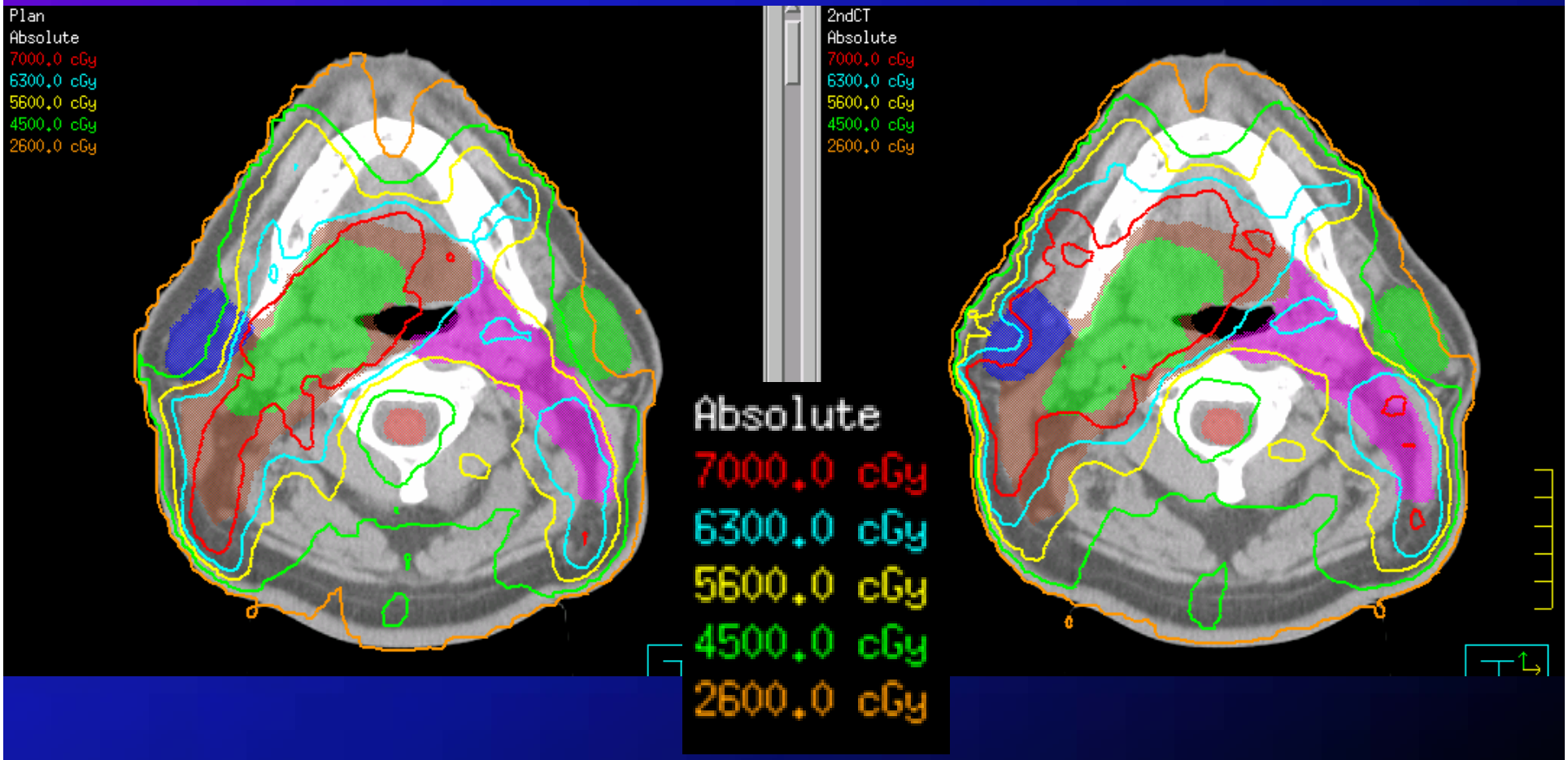
Dosimetric Impact of Anatomy Variation



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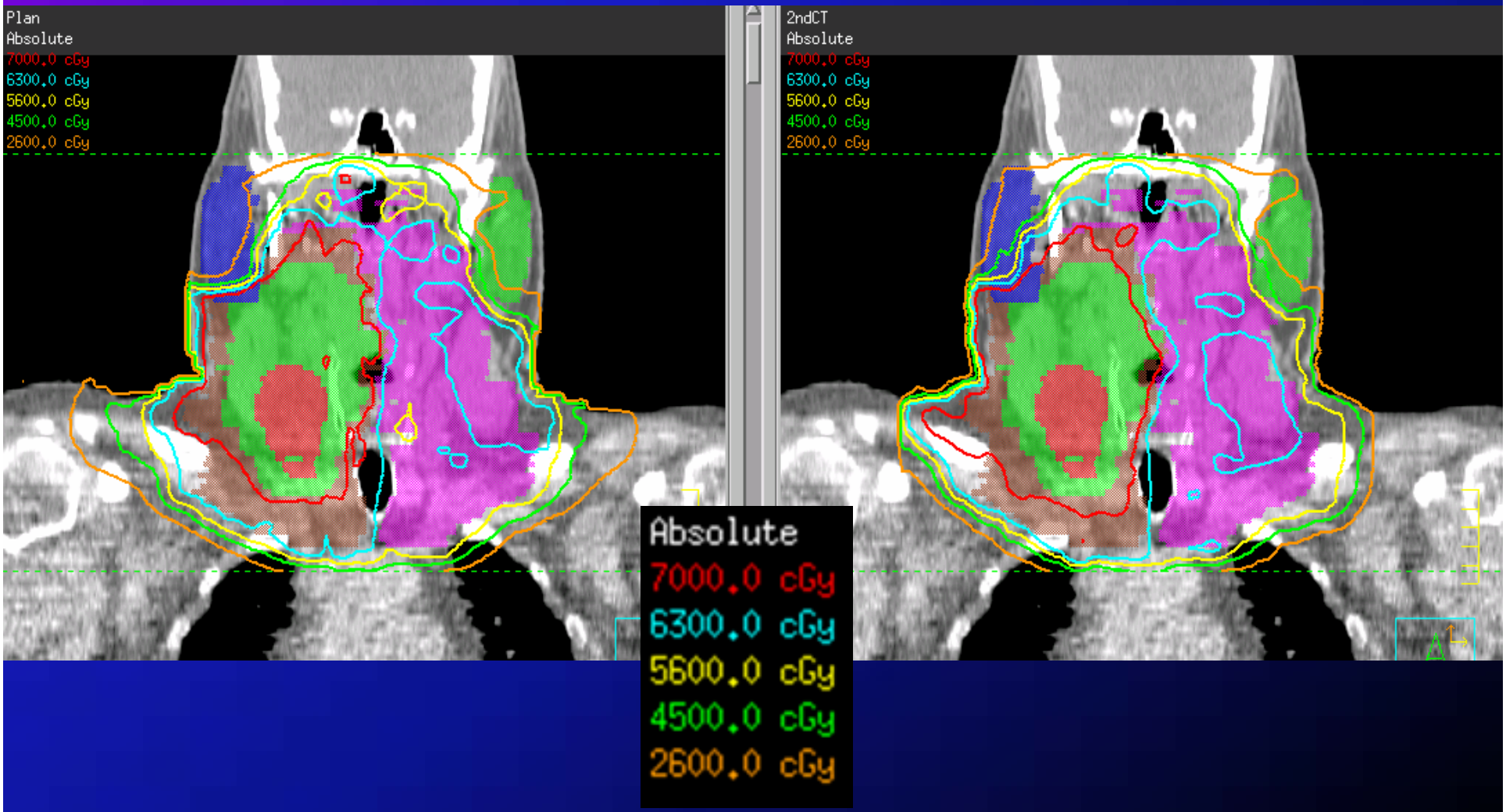
Dosimetric Impact of Anatomy Variation



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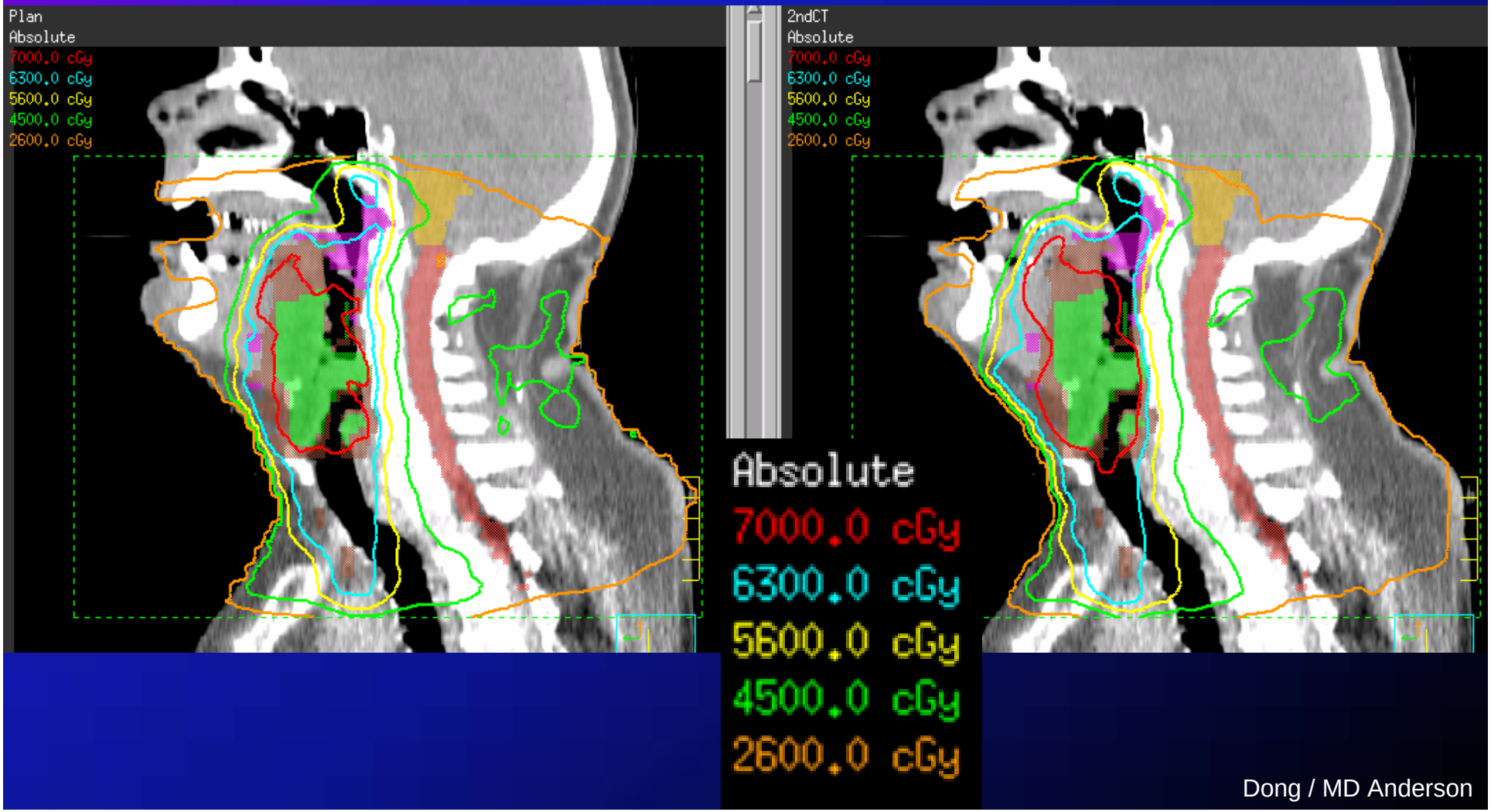
Dosimetric Impact of Anatomy Variation



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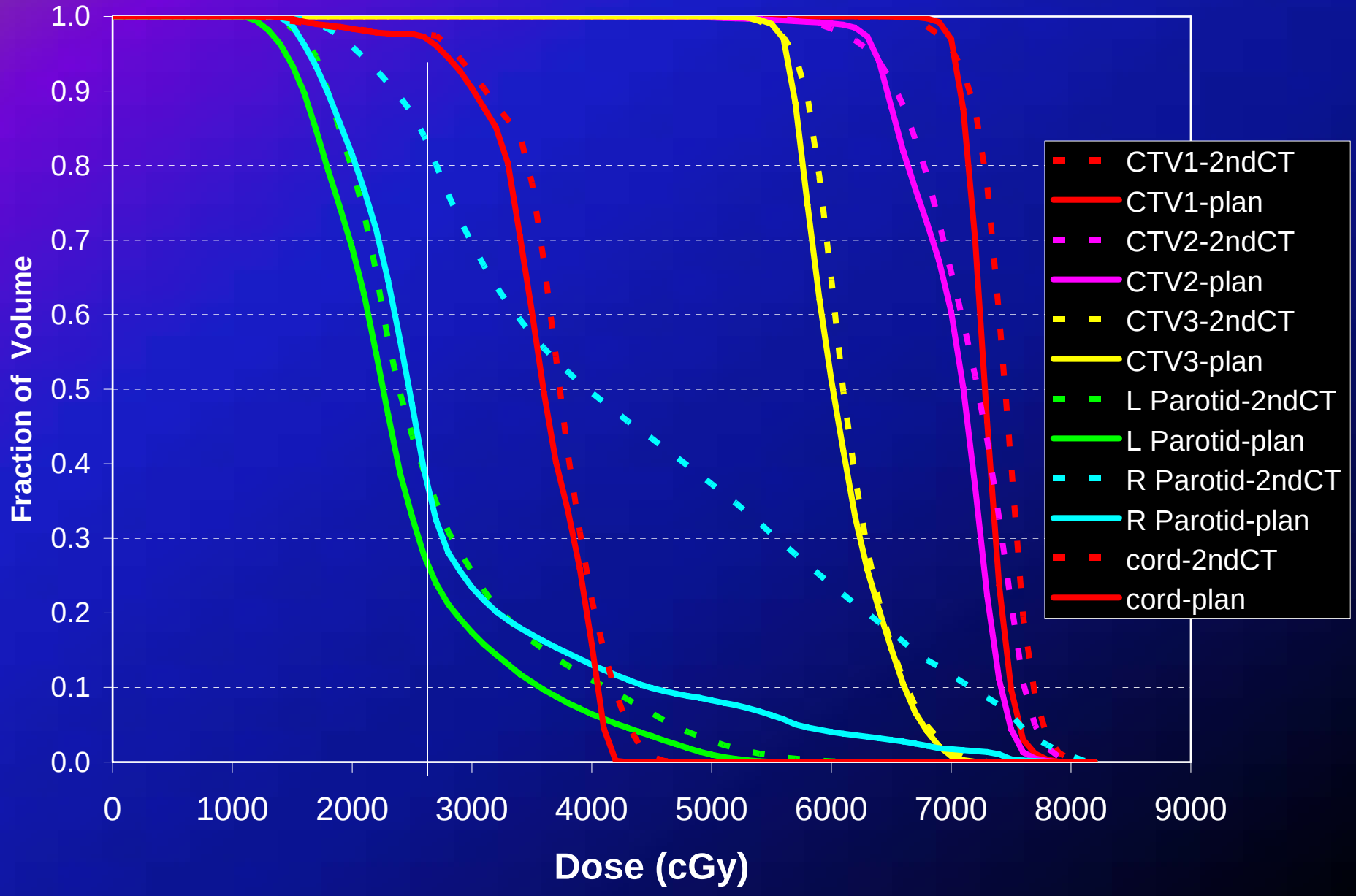
Comparison of DVHs



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Summary and Discussion

- In-room CT imaging extends “CT simulation” just prior to each treatment
- Mature technology for in-room IGRT
- 3D definition of anatomy
  - Familiar by physicians
- Dose calculation
  - Replanning
  - Online “Plan & Treat”
- Image Guidance
  - Setup correction
  - Treatment monitoring
- Learning