Cone Beam CT guided Radiotherapy

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Elekta Synergy Research Group

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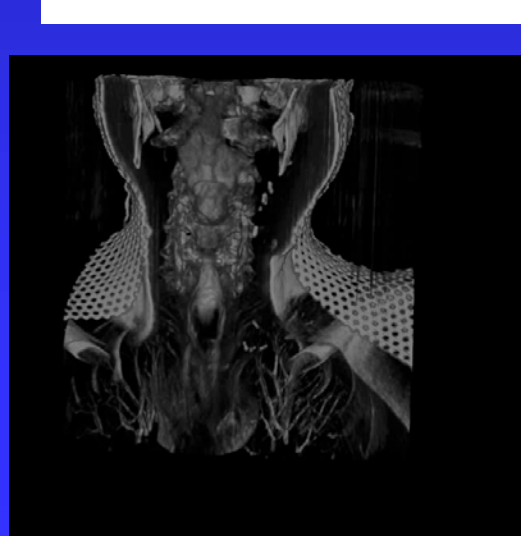
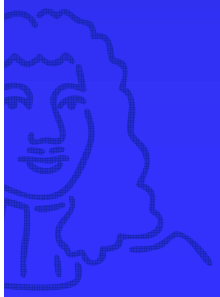


Contents

- Introduction
- CBCT Acquisition & Reconstruction
- CBCT image quality
- Clinical Implementation & Protocols



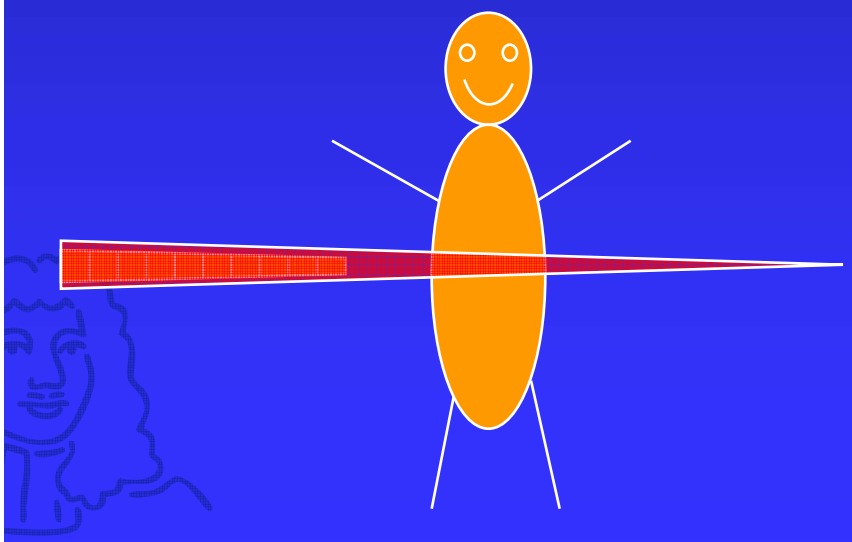
CT Acquisition

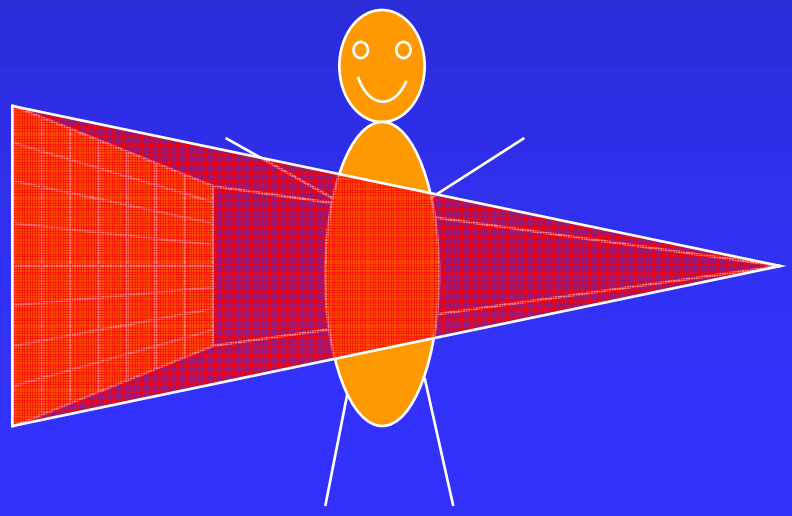
Conventional CT

- ‘Fan’ beam
- 1D detector
- 1 rotation = 1 slice

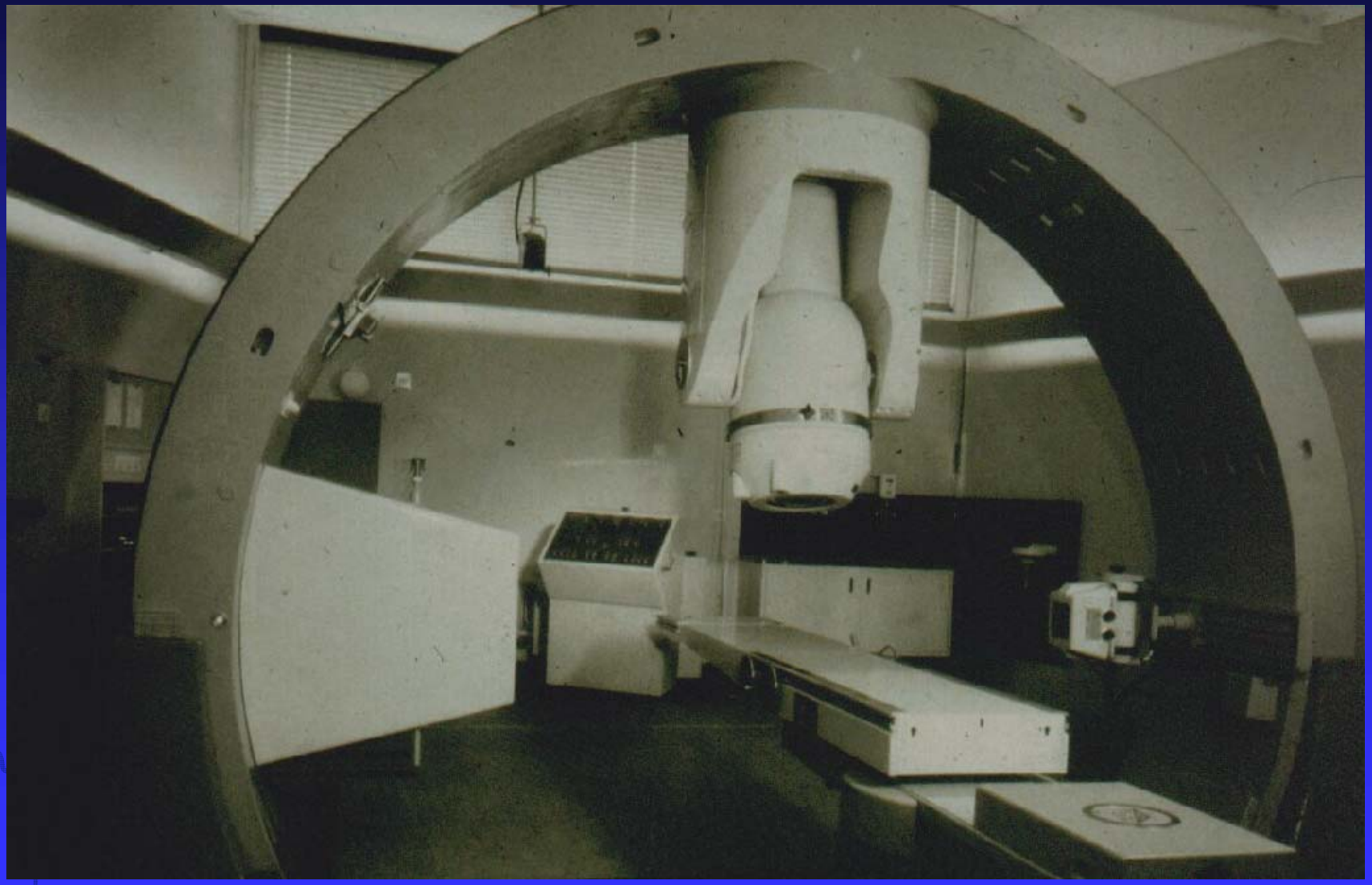
Cone-beam CT

- ‘Cone’ beam
- 2D detector
- 1 rotation = volume (many slices)



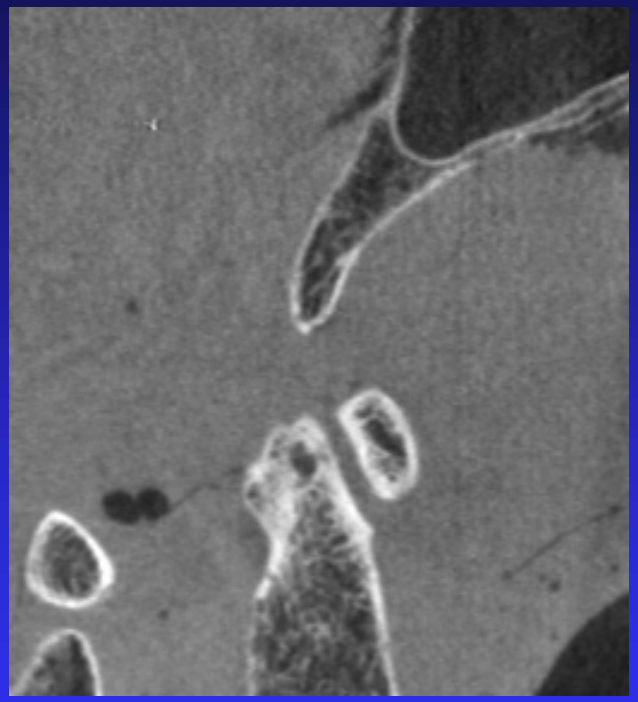


kV image guidance: not a new idea !



First isocentric Co-60 machine in Netherlands at NKI (1960)

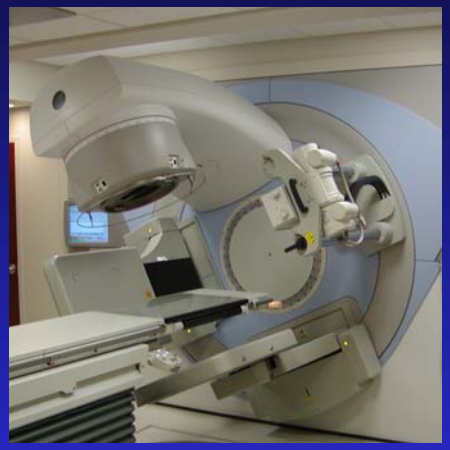
First Prototype CBCT Guided Linac



6.5 cm

D. Jaffray et al. Int J. Radiat. Oncol. Biol. Phys. 2002

Available Cone Beam Systems

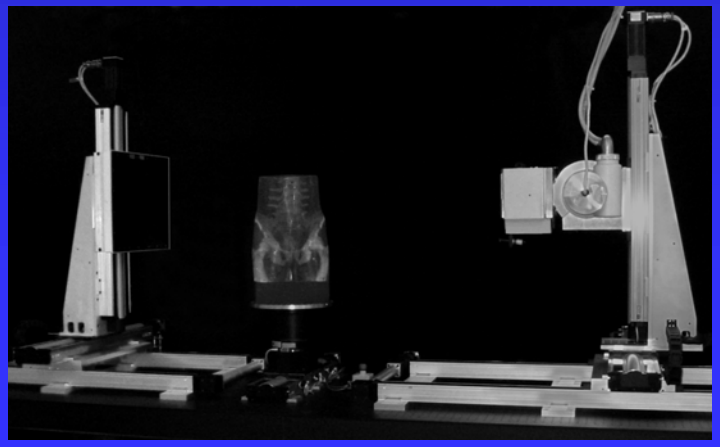


Elekta Synergy™

Siemens Artiste™

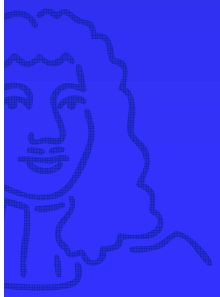
Varian Trilogy™

Bench Top



C-arms

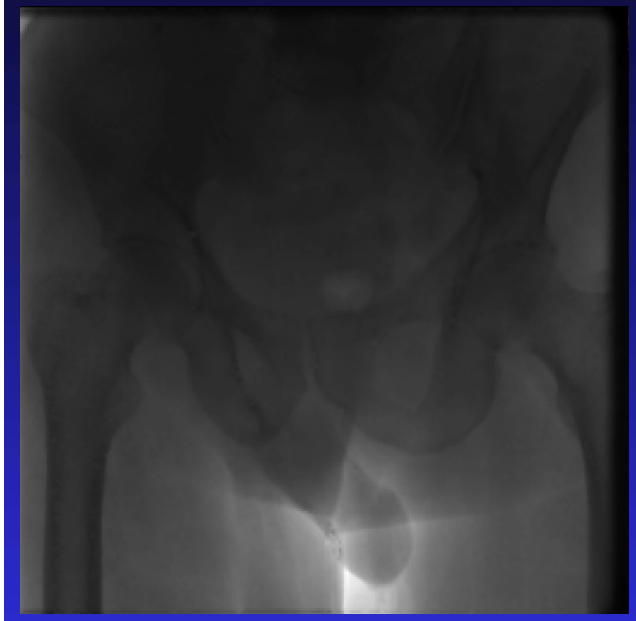
Acquisition and Reconstruction

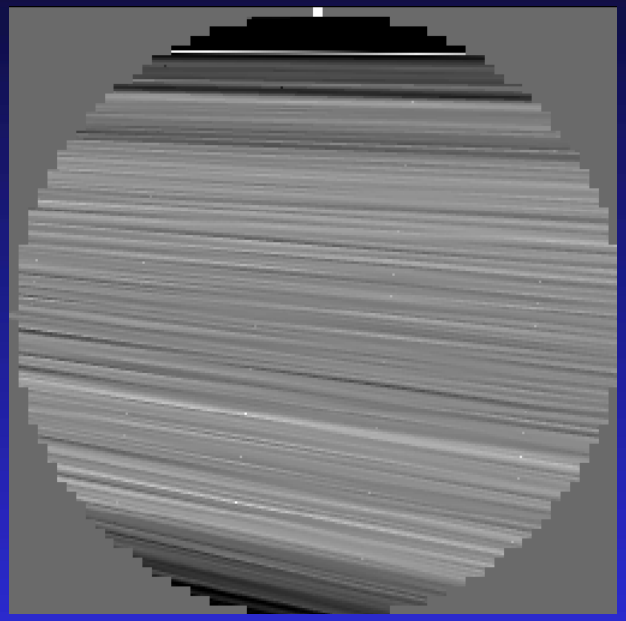


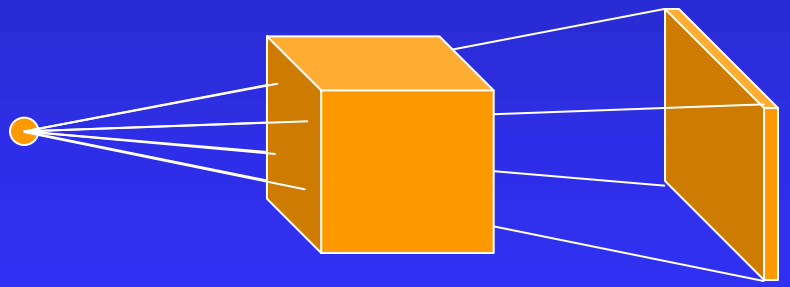
Elekta Synergy Research system at NKI

Frame Rate: 5.4 fps; Acquisition Time: 1 - 2 min

Cone beam reconstruction



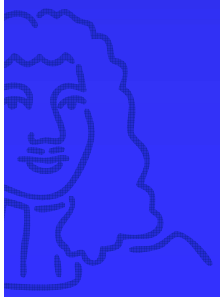




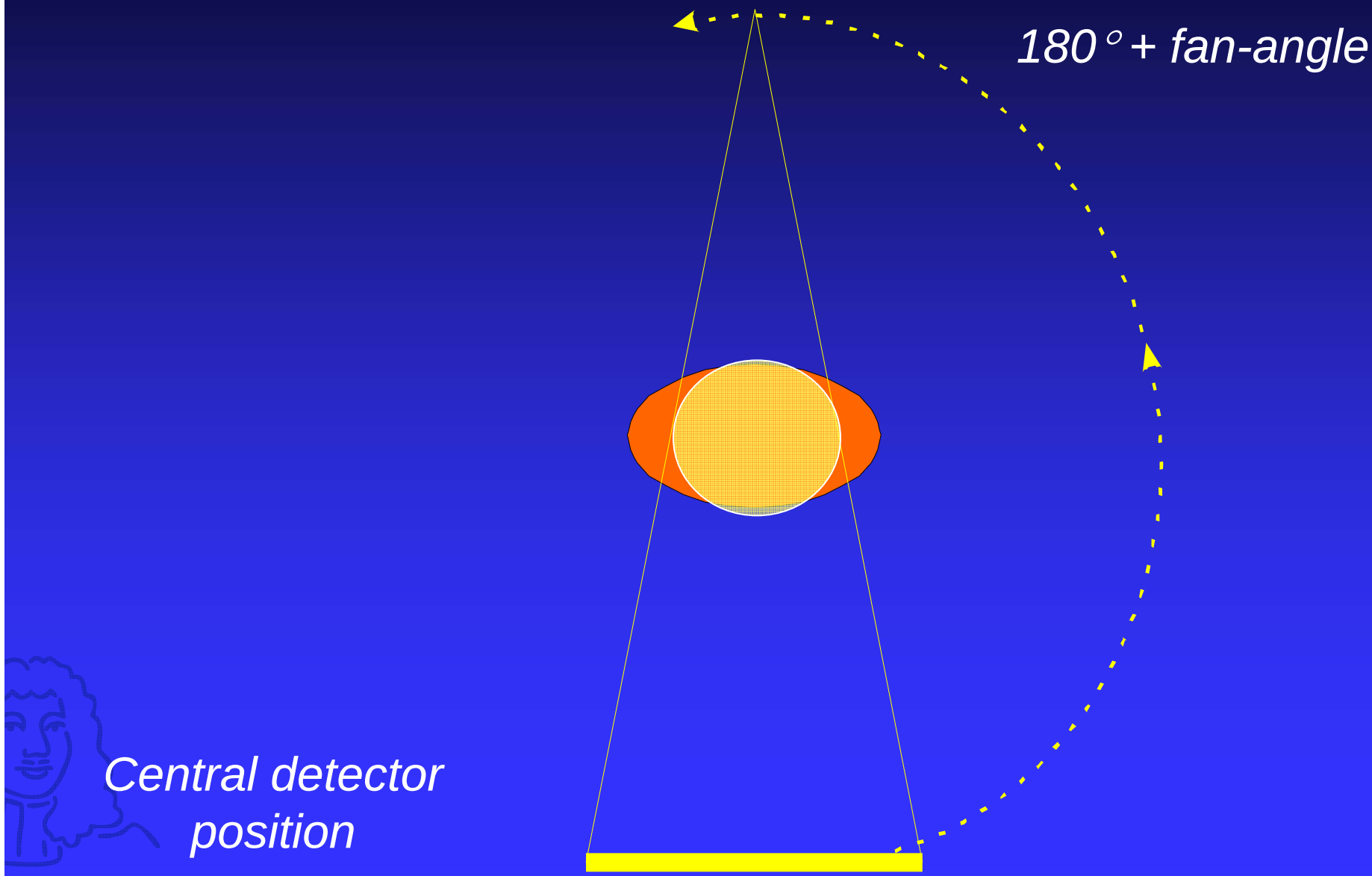
$$V(x,y,z) = \int_0^{2\pi} W_2 \cdot \left(\left(W_1 \cdot p\left(\beta, a(x,y,z,\beta), b(x,y,z,\beta)\right)\right) * g(a) \right) d\beta$$

$dim_x * dim_y * dim_z * N_{proj}$ computations: $5 * 10^9$ for 256^3

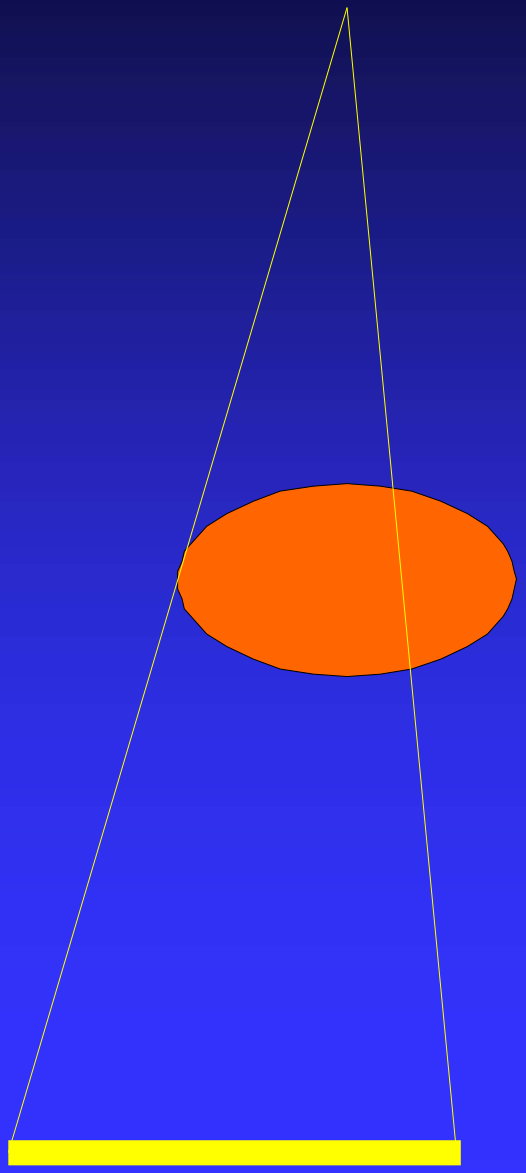
Imaging Field of View



Field of View

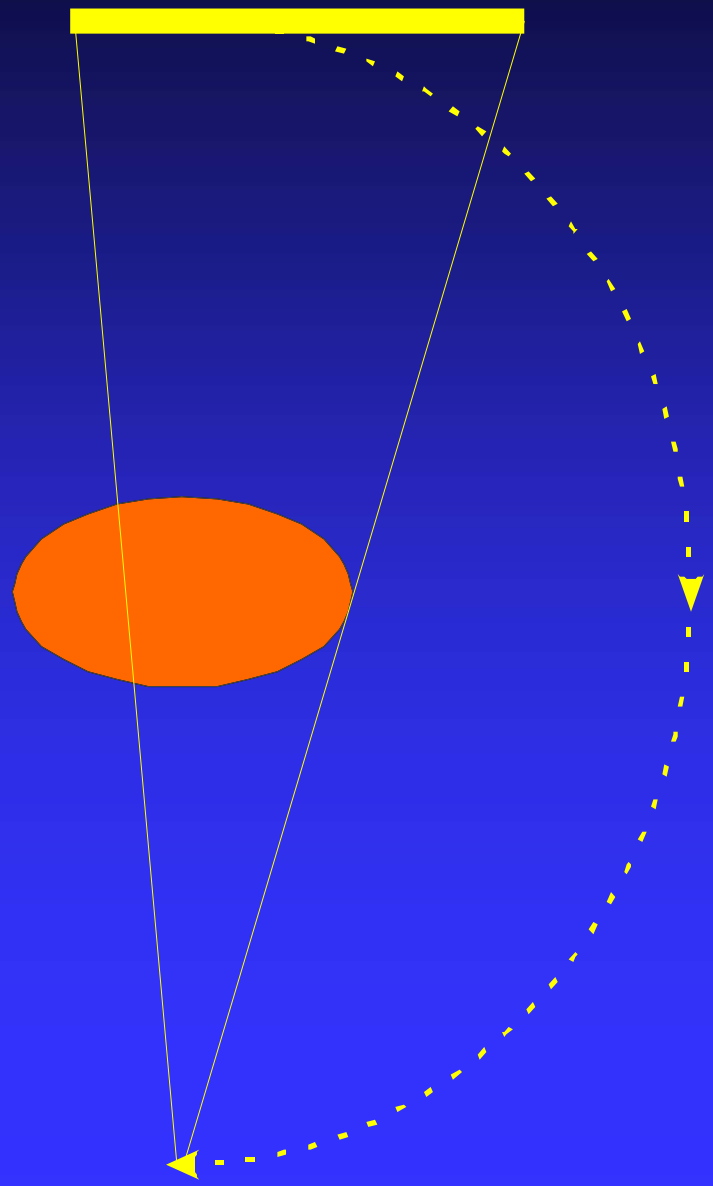


Field of View: Offset Detector



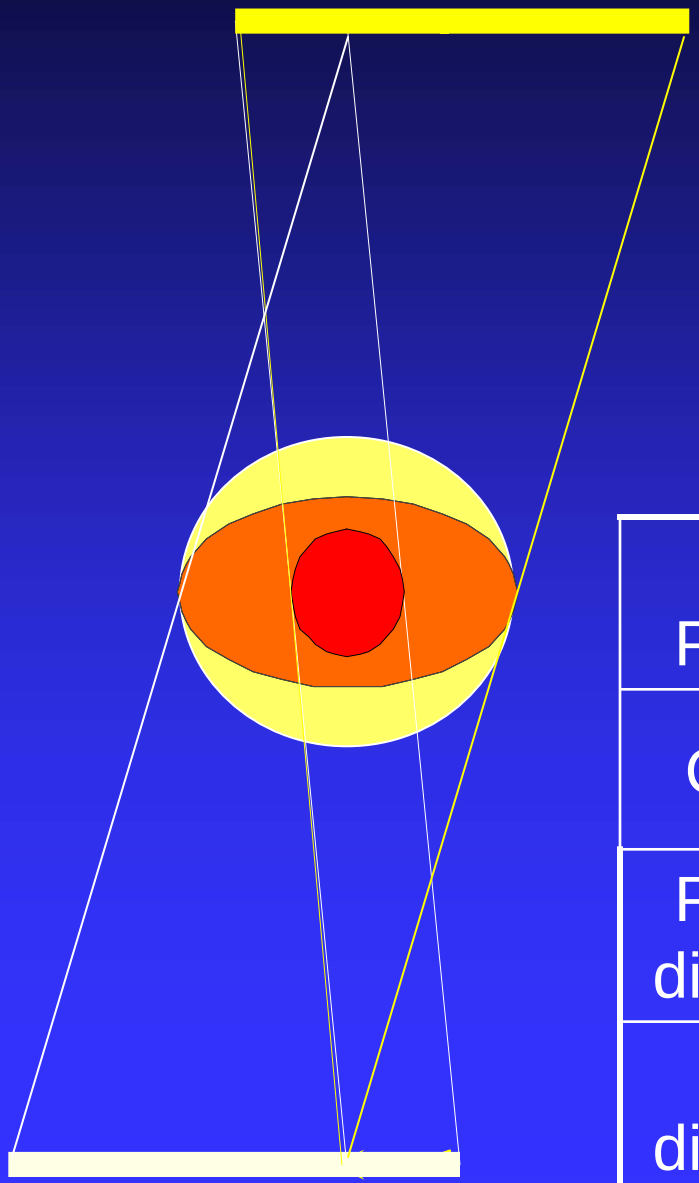
Partially displaced detector position

Offset Detector



Partially displaced detector position

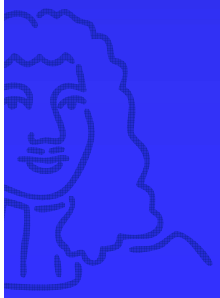
Offset Detector



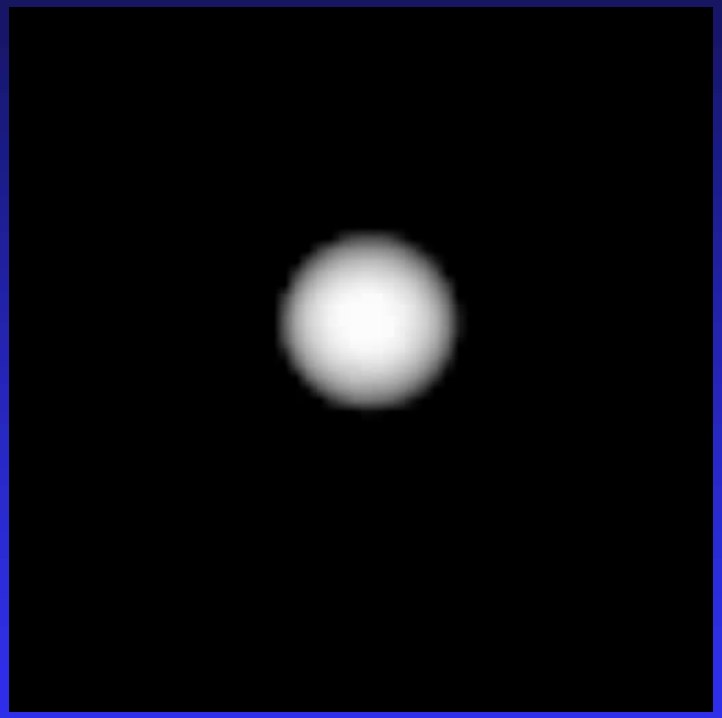
Partially displaced detector position

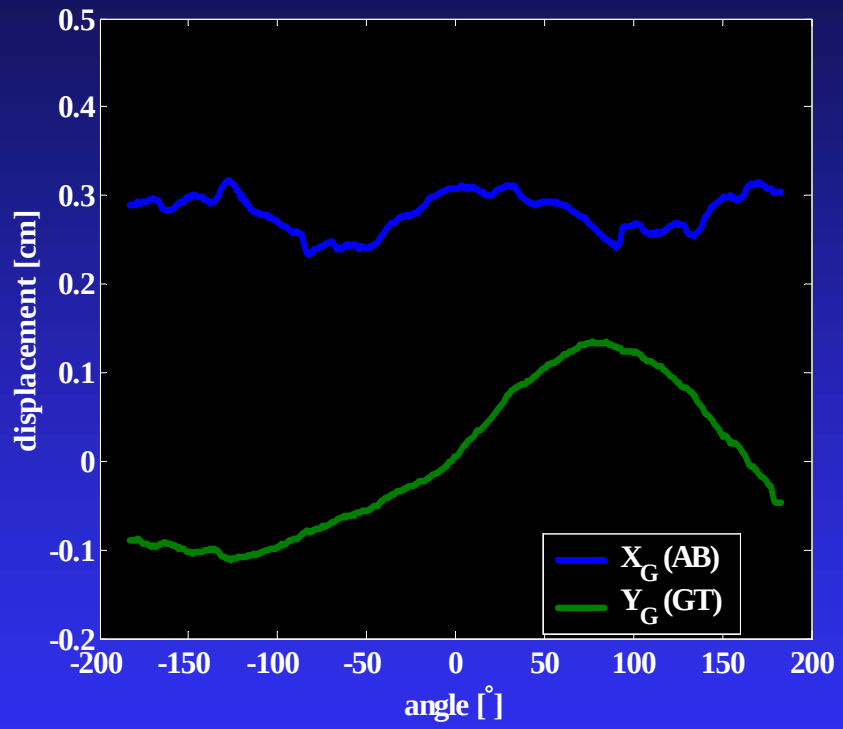
Panel Position	FOV
Central	25 cm
Partially displaced	40 cm
Fully displaced	50 cm

Geometric Calibration and QA



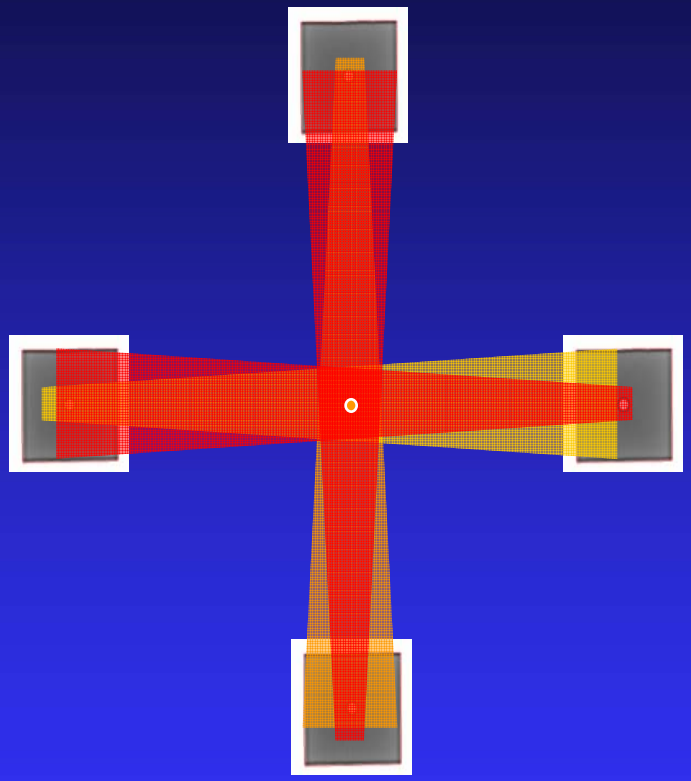
Geometry: Flex calibration

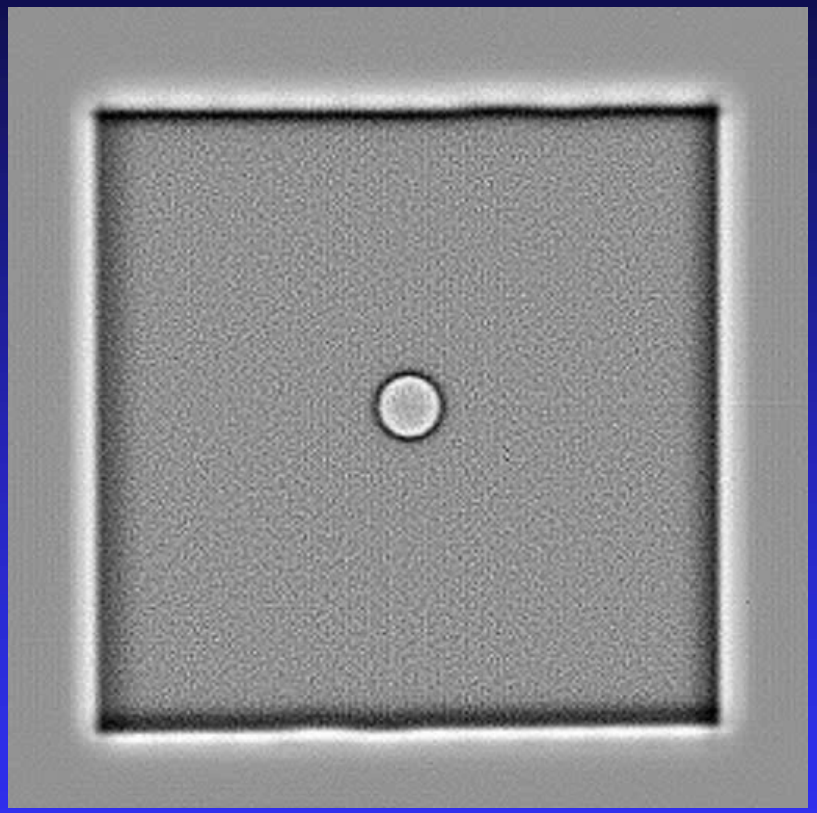




- Calculate center of ball bearing for all gantry angles
- Generate Lookup table for U & V displacements
- Lookup table includes Set-up error BB

Geometry: kV to MV Isoc Calibration



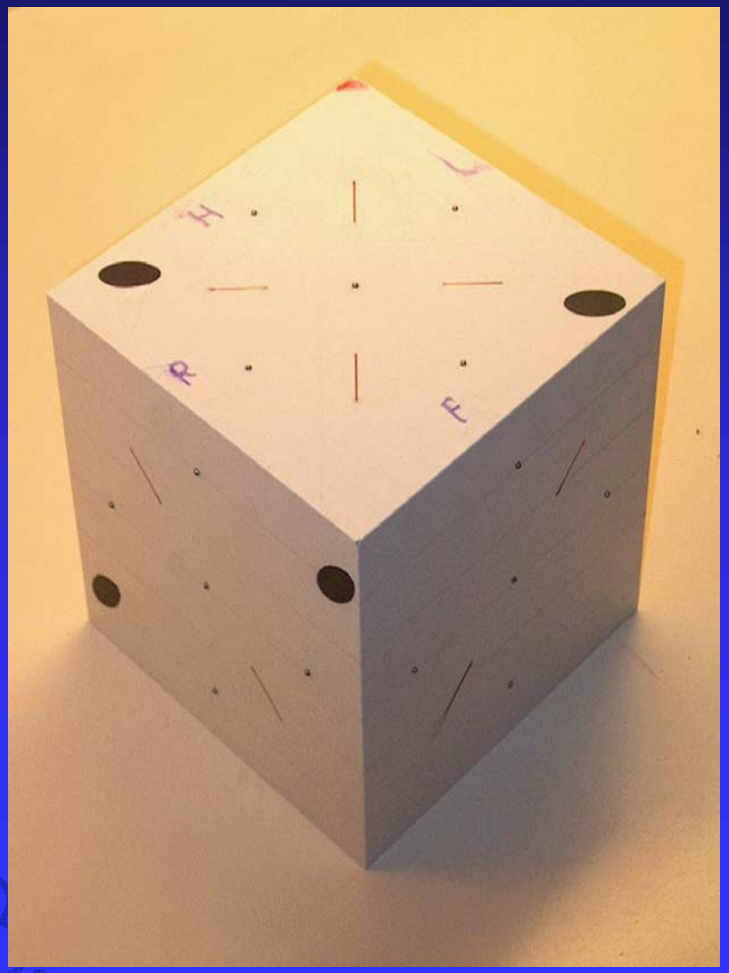


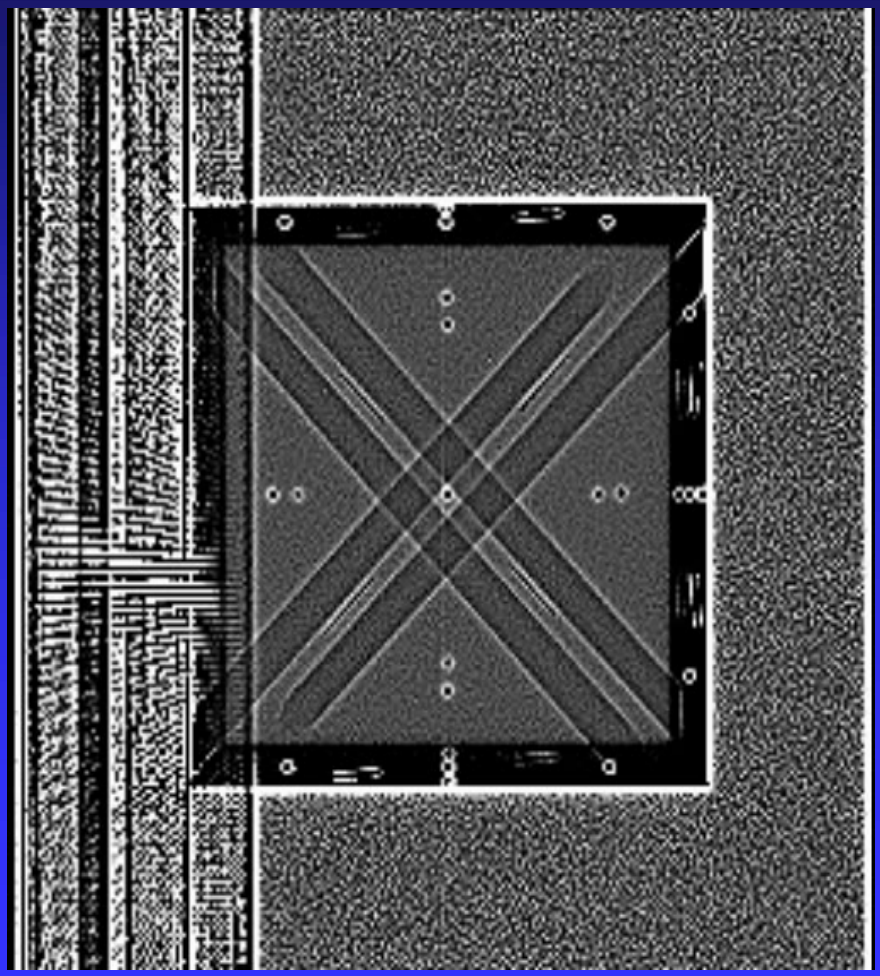
Gantry& Collimator Angle: -180, -90, 0, 90, 180

Determine COG field edge & BB

Calculate mean setup error

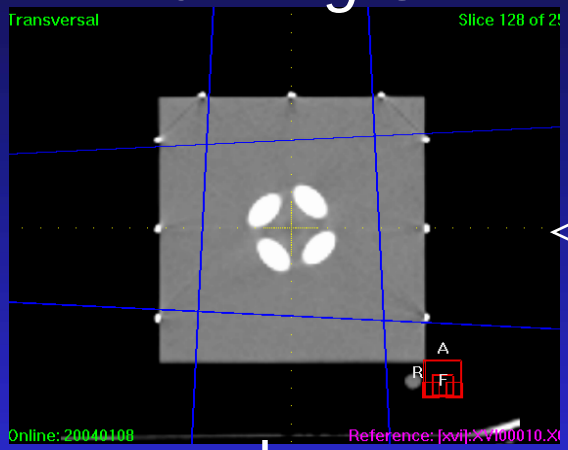
QA Phantom



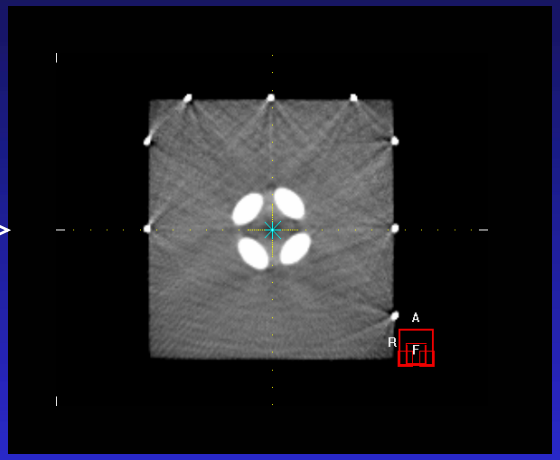


QA Geometrical Accuracy

Planning CT

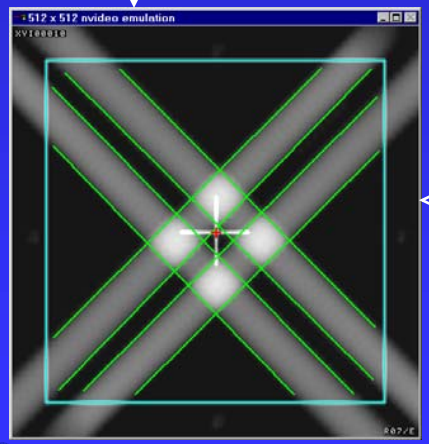


CBCT CT



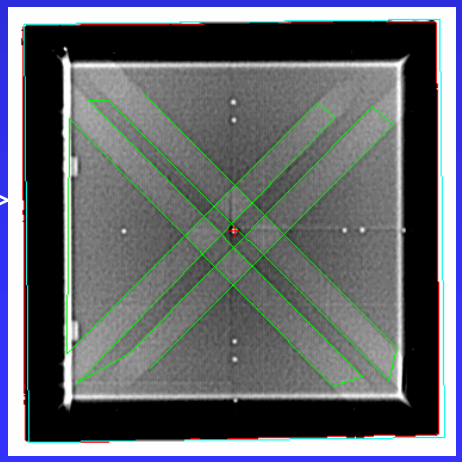
Match 3D

same ?



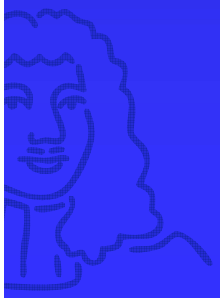
DRR

Match 2x 2D



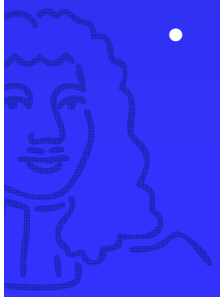
EPI

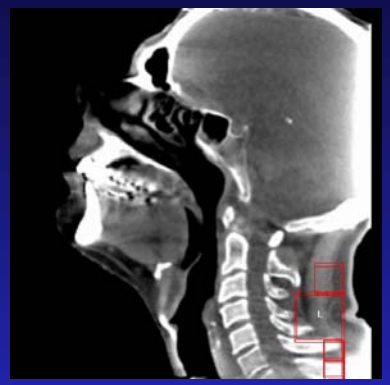
3D Imaging Performance and Artifacts

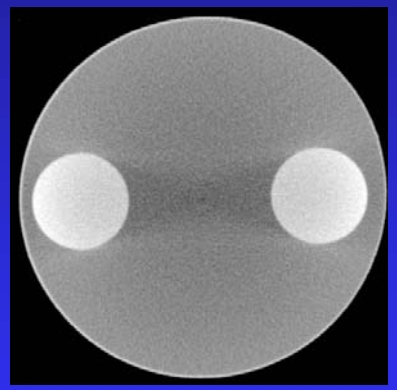


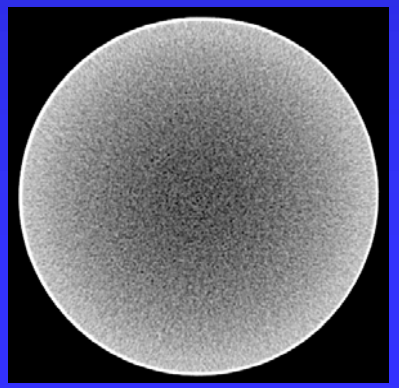
Sources of cupping and streaks

- Missing data (truncation)
  - Detector field of view 25 cm
- Scattered radiation
  - Extra signal not from local anatomy
  - Adds noise !
- Beam hardening
  - Attenuation of patient smaller than expected
- Ghosting
  - High exposure signal gives residual extra signal later

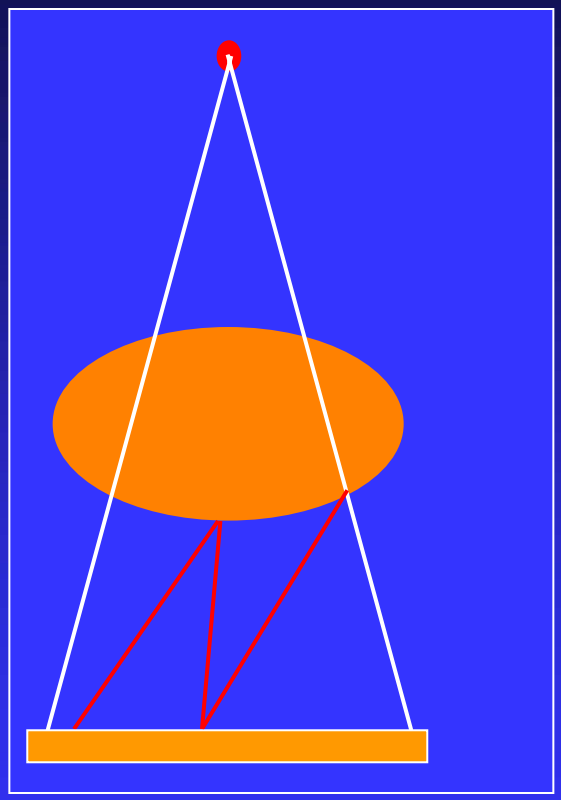




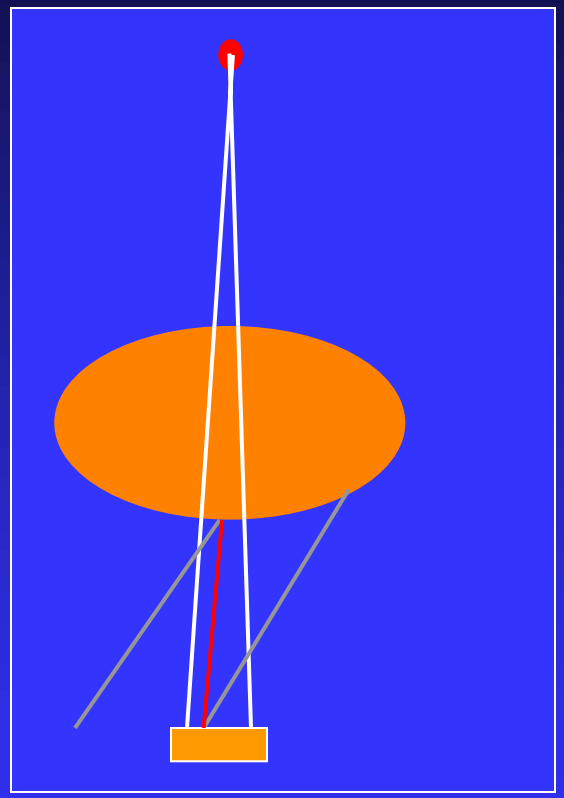




Scatter & Imaging Geometry



Cone Beam CT



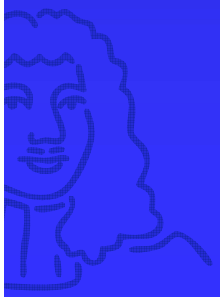
Fan Beam CT

Scatter-to-primary ratio (SPR) in excess of 300% occur in lateral pelvic projection data occur for CBCT geometry

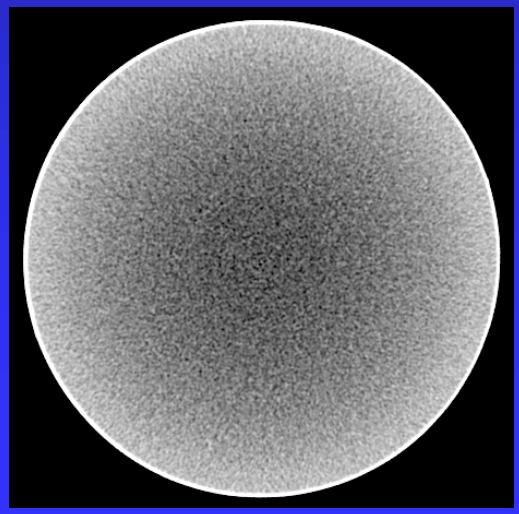
Strategies for Scatter Management

- Select
  - Minimize FOV_{cc} to minimize SPR
  - Optimize Air gap $\rightarrow$ 0.5 – 0.6 m
  - Compensators (e.g. BowTie filters)
- Reject
  - Anti-scatter grid

    $\rightarrow$ Siewerdsen et al. Med.Phys. Dec2004
- Correct
  - Scatter correction algorithm

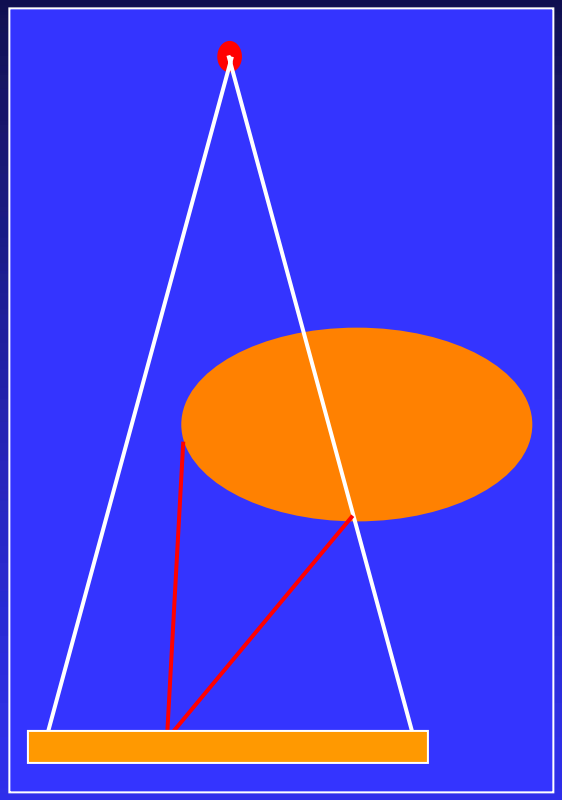


Courtesy Jaffrey Siewerdsen

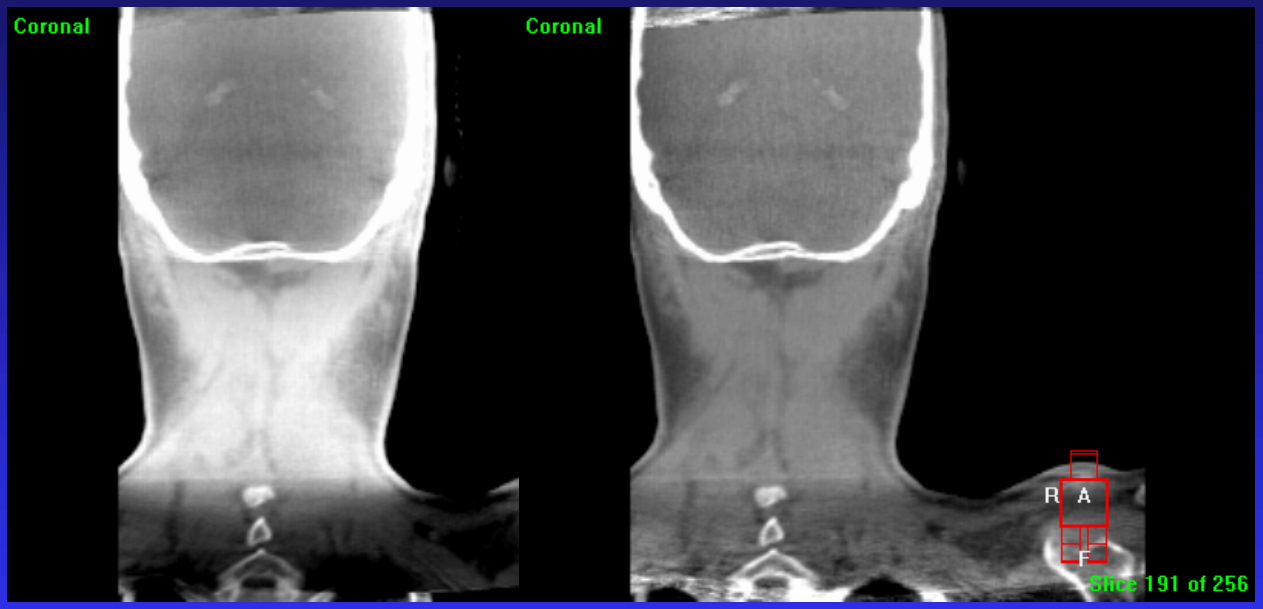


Shading

Scatter correction algorithm



Assumption: scatter uniform and proportional to average image intensity where there is patient in the beam

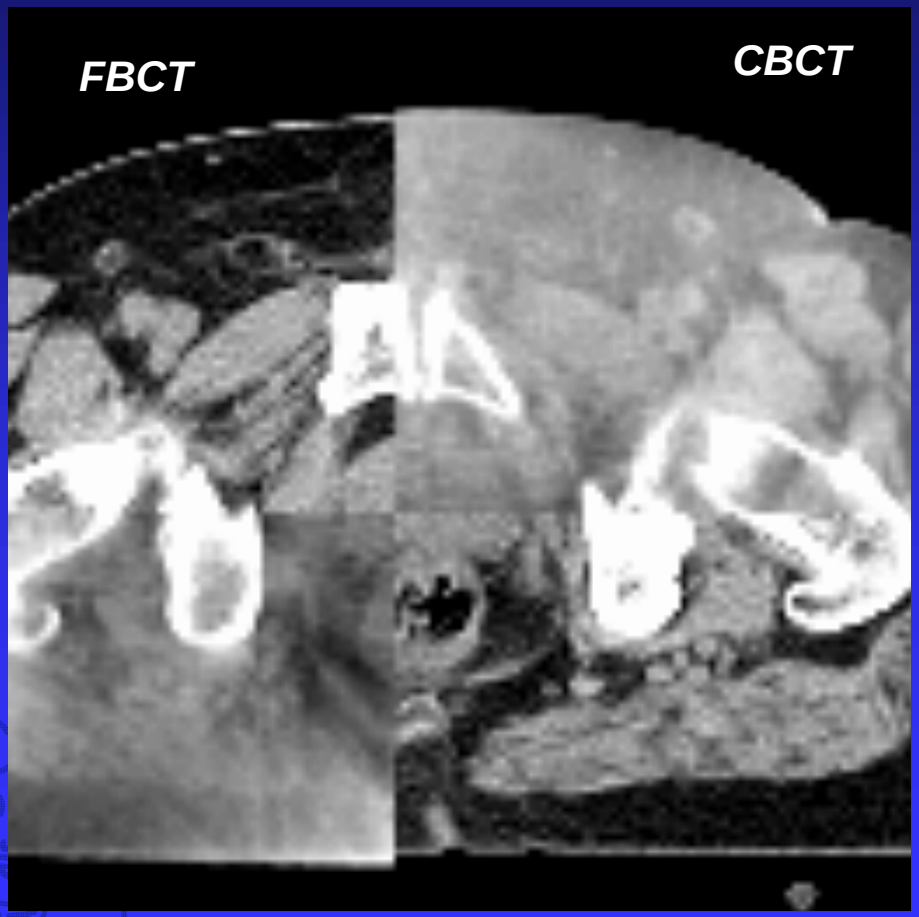


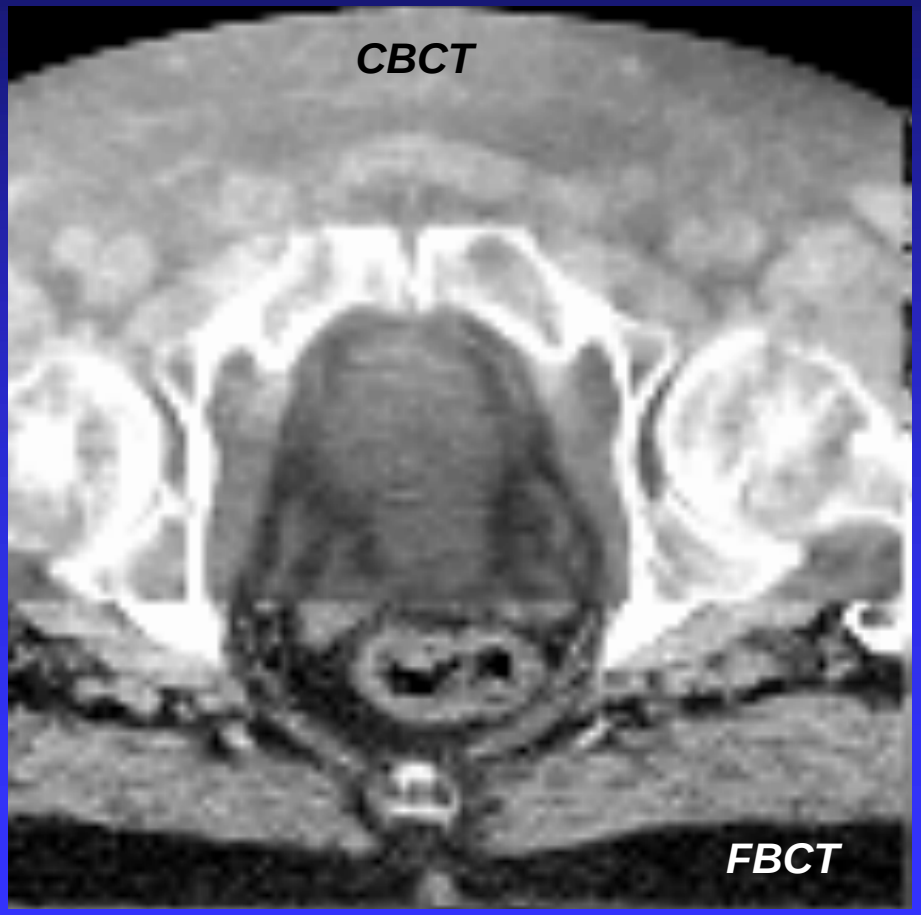
Without correction

With correction

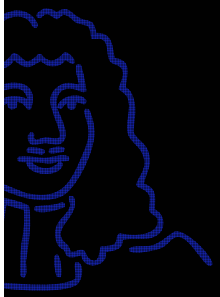
Boellaard et al. Two-dimensional exit dosimetry using a liquid-filled electronic portal imaging device and a convolution model *Radiother. Oncol.* **44** 149-157, 1997

CBCT versus Fan Beam CT

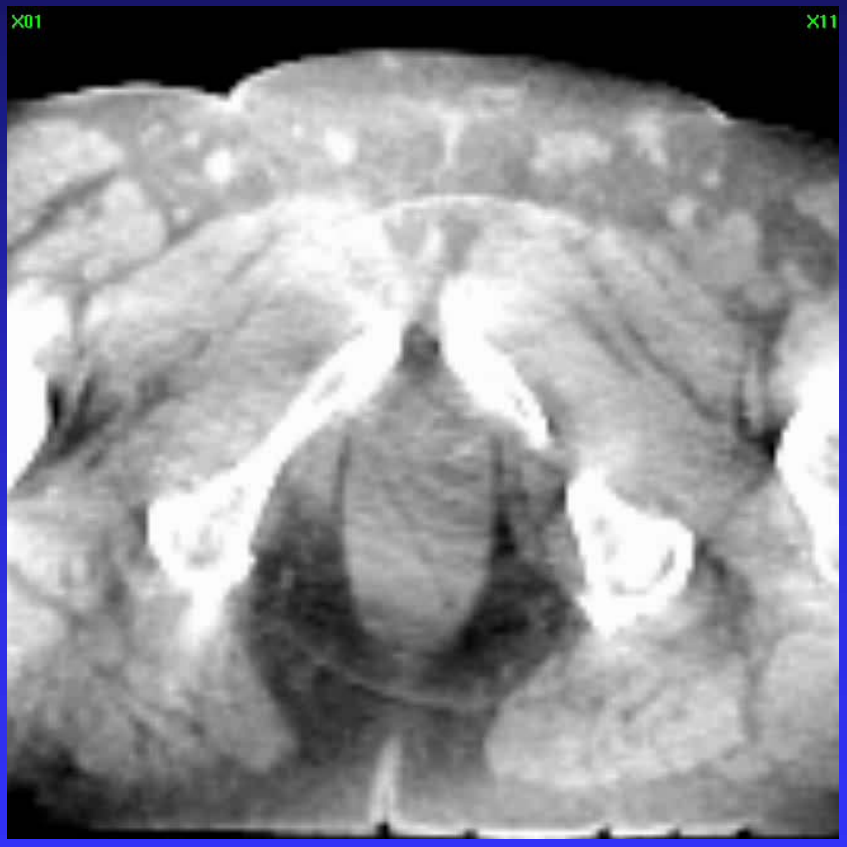




Motion



Moving Gas



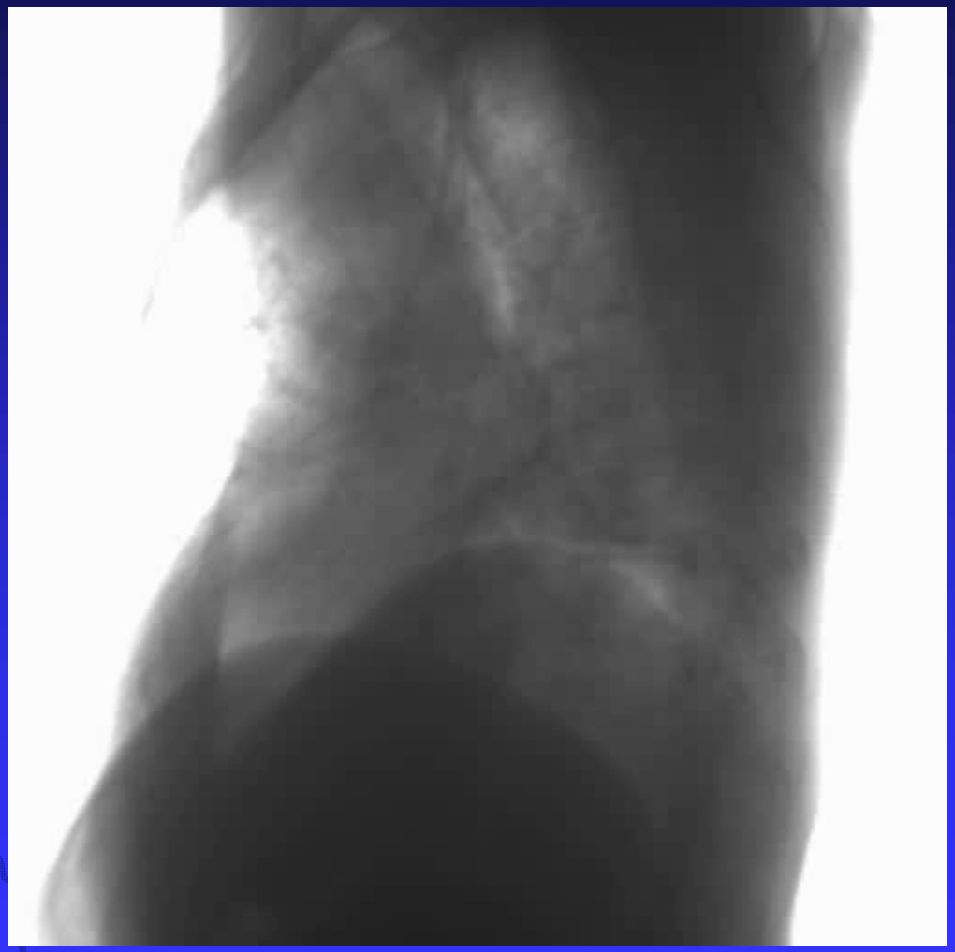
Smitsmans et al. Med Phys. 2005

Image quality

- Diet, given by a dietician based on the patients own insight, starting 7 days before treatment

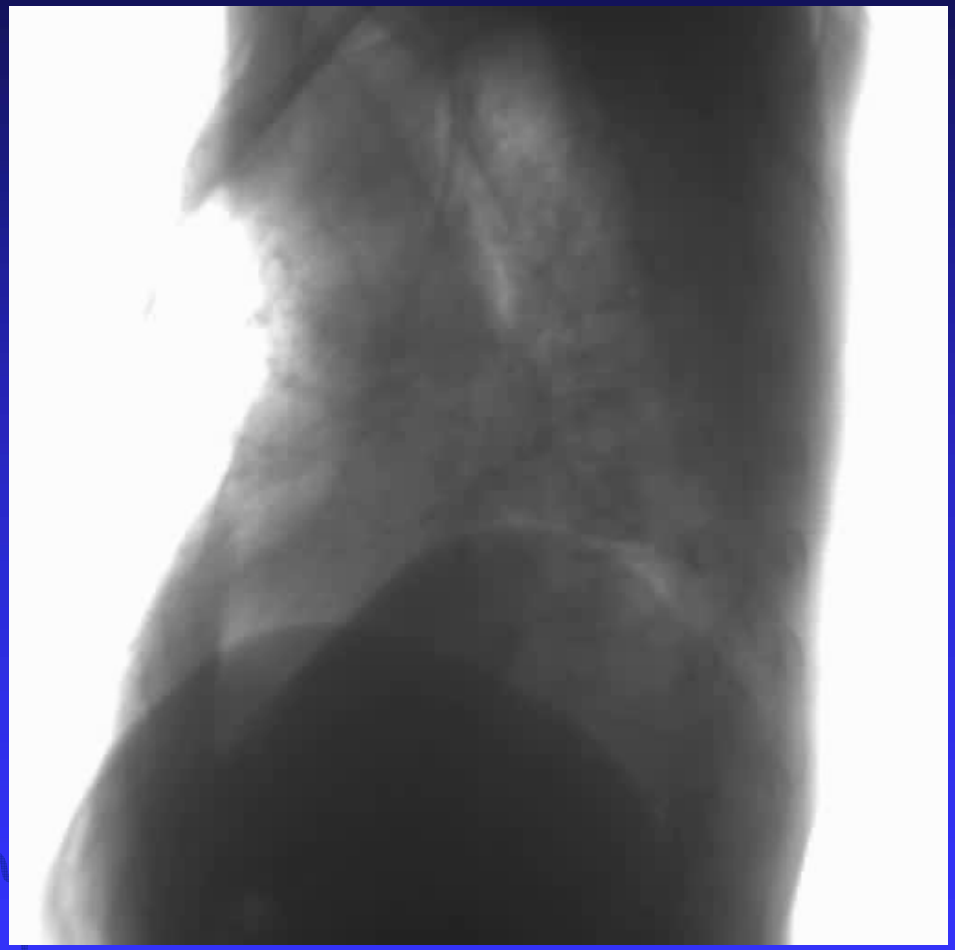
- Mild laxatives: Magnesium-oxide tablets (1 gram) 2 nights before CT scan and during treatments
- No scans/treatments before 10 am

CBCT

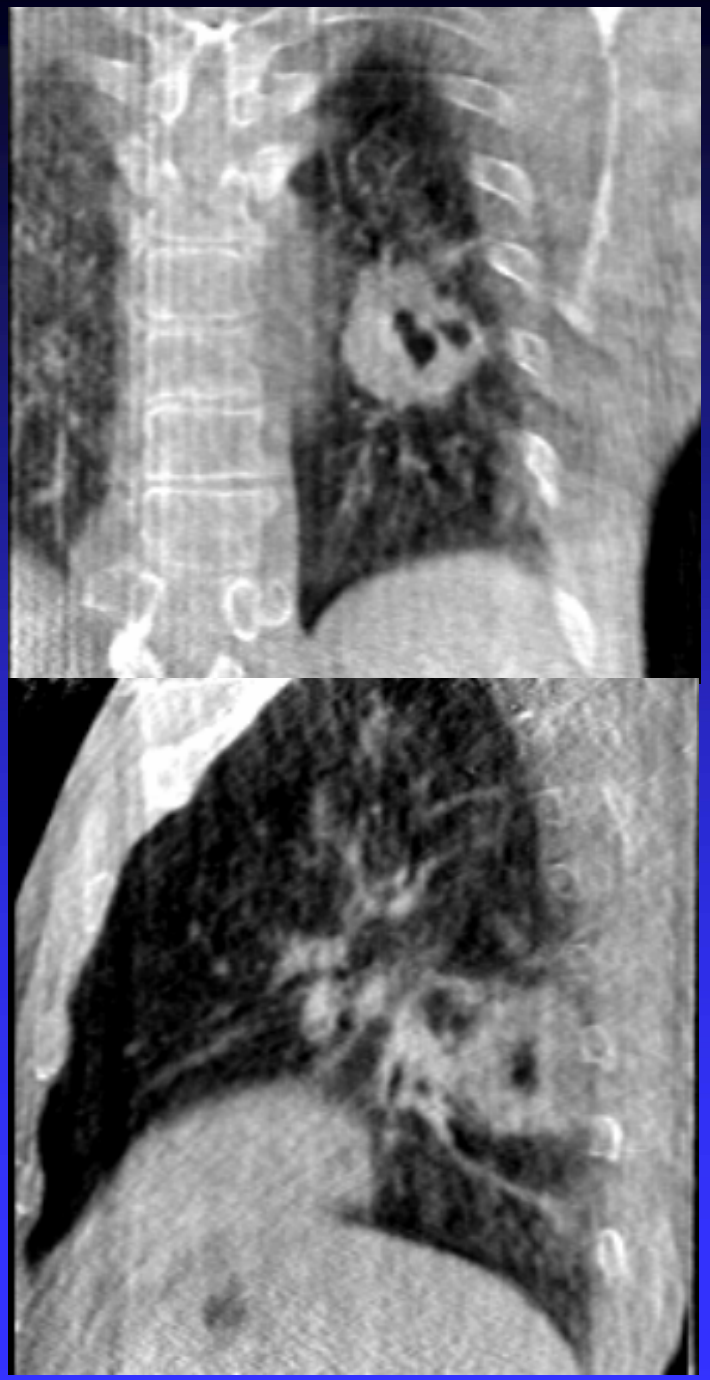


Moving structures are blurred over their trajectory

4D CBCT



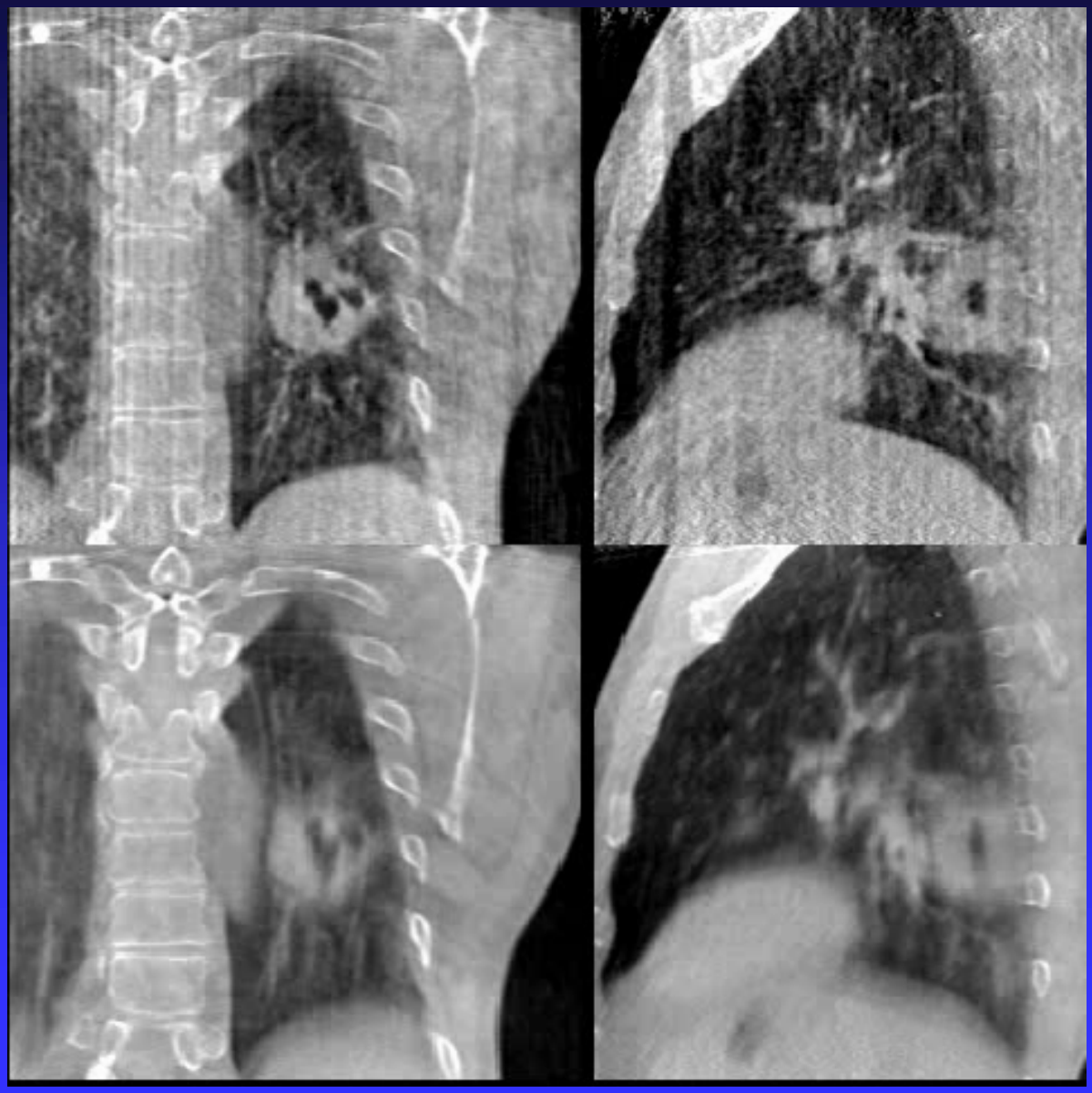
Retrospective sorting of the projections before reconstruction yields 4D data



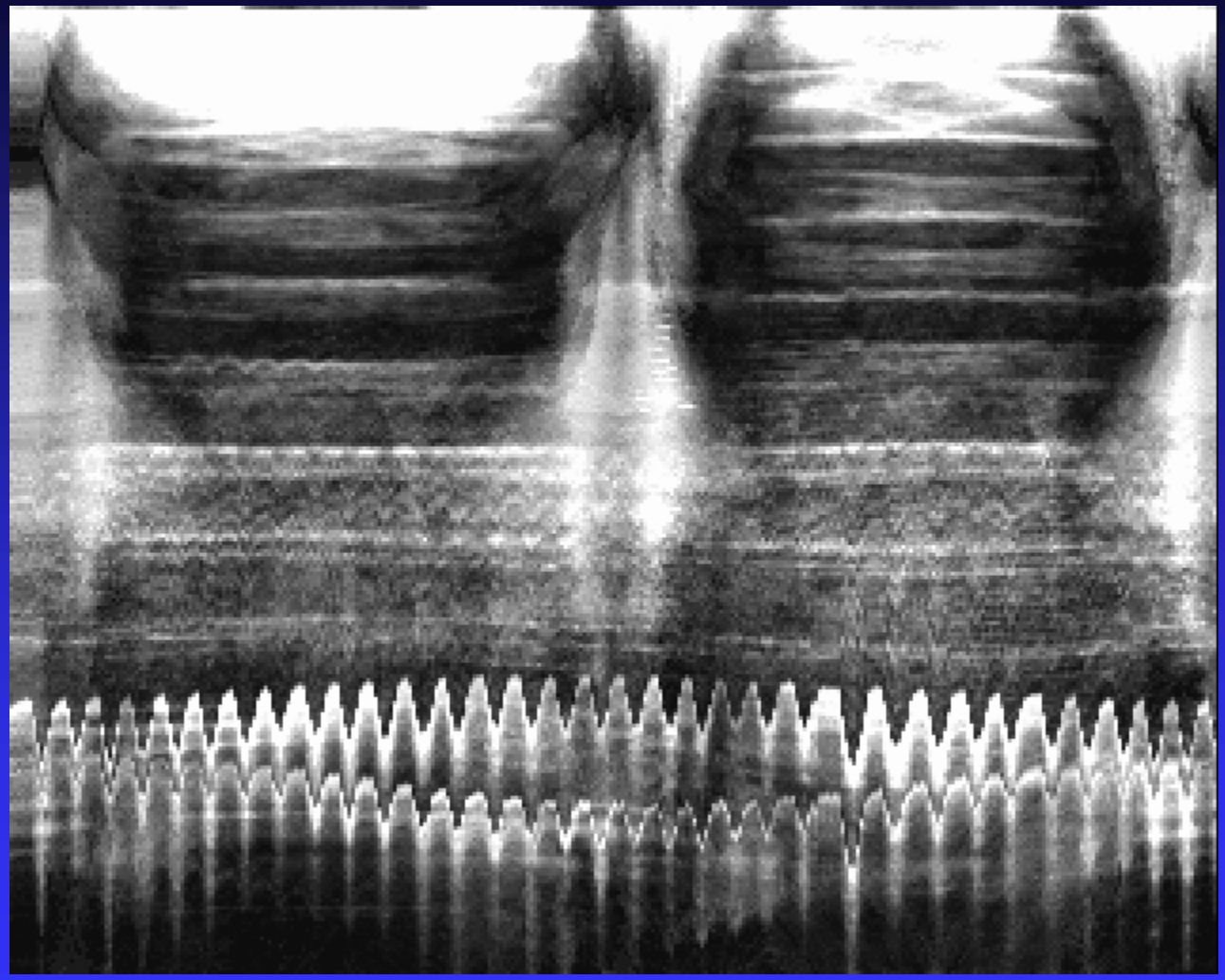
3D versus 4D CBCT

- 4D Data set
- 8 x 84 projections

- 3D Data set
- 670 projections



The ‘Amsterdam Shroud’ (Lambert Zijp)

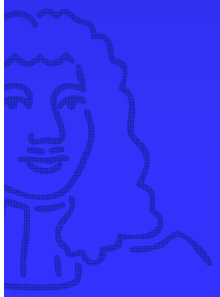


CC position

X-ray image #

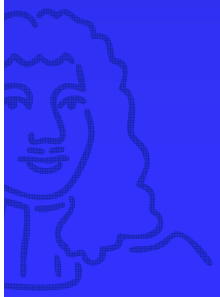
Breathing Signal automatically extracted from projection data

Clinical Implementation



Clinical Implementation CBCT @ NKI-AvL

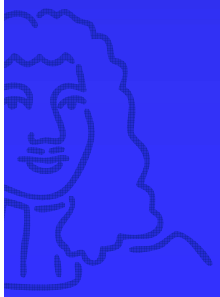
- First clinical images on July 9th, 2003
- Special team of 4 radiotherapy technicians
- Normal patient program during the morning
- Patients with extra CBCT in the afternoon
- Close cooperation with the physicists



Clinical Implementation CBCT @ NKI-AvL

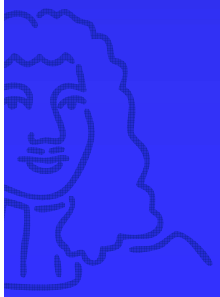
8 months of validation and improvement of image quality (waiting for CE marking for intervention):

- Over 150 scans made to compare with EPID:
  - prostate, head & neck, lung, bladder, sarcoma, stomach and breast patient
- Different scan protocols were tested
  - Position of the detector
  - Variation in kV and mA
  - Variation in number of frames, by reducing gantry rotation speed



Current situation @ NKI - AvL

- Patient set-up is monitored with CBCT for most of our patient groups, using a decision protocol based on bony anatomy match
- Radiotherapy technicians perform the acquisition, registration and evaluation (bony anatomy)
- Soft-tissue registrations performed by dedicated radiotherapy technicians in close cooperation with physicists and physicians

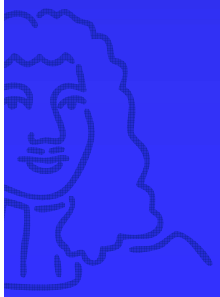


Current situation (AvL)

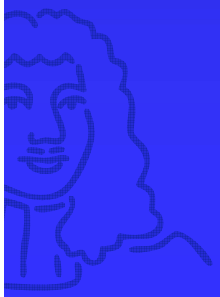
June 2006

We have acquired:

- > 6500 CBCT scans
- On 3 Synergy systems
- > 700 patients



Archiving



Scenario I

- Online Protocol
  → 30 scans per day per machine
- Storing projections at high resolution (1024^2)
  → 650 * 2 MB per image
- Storing high resolution scans (0.5 mm voxel size)
  → 256 – 625 MB per scan

- ~225 GB per machine per week

Scenario II

- Offline Protocol
  → 10 scans per day per machine
- Storing projections at medium resolution (1024^2)
  → 650 * 0.5 MB per image
- Storing medium resolution scans (1 mm voxel size)
  → 32 MB per scan

- ~17 GB per machine per week

Scenario III

- Offline Protocol
  $\rightarrow$ 10 scans per day per machine
- Storing no projections

- Storing medium resolution scans (1 mm voxel size)
  $\rightarrow$ 32 MB per scan

- ~1.5 GB per machine per week

Set-up Error
Bony Anatomy
Registration

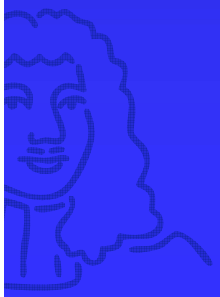
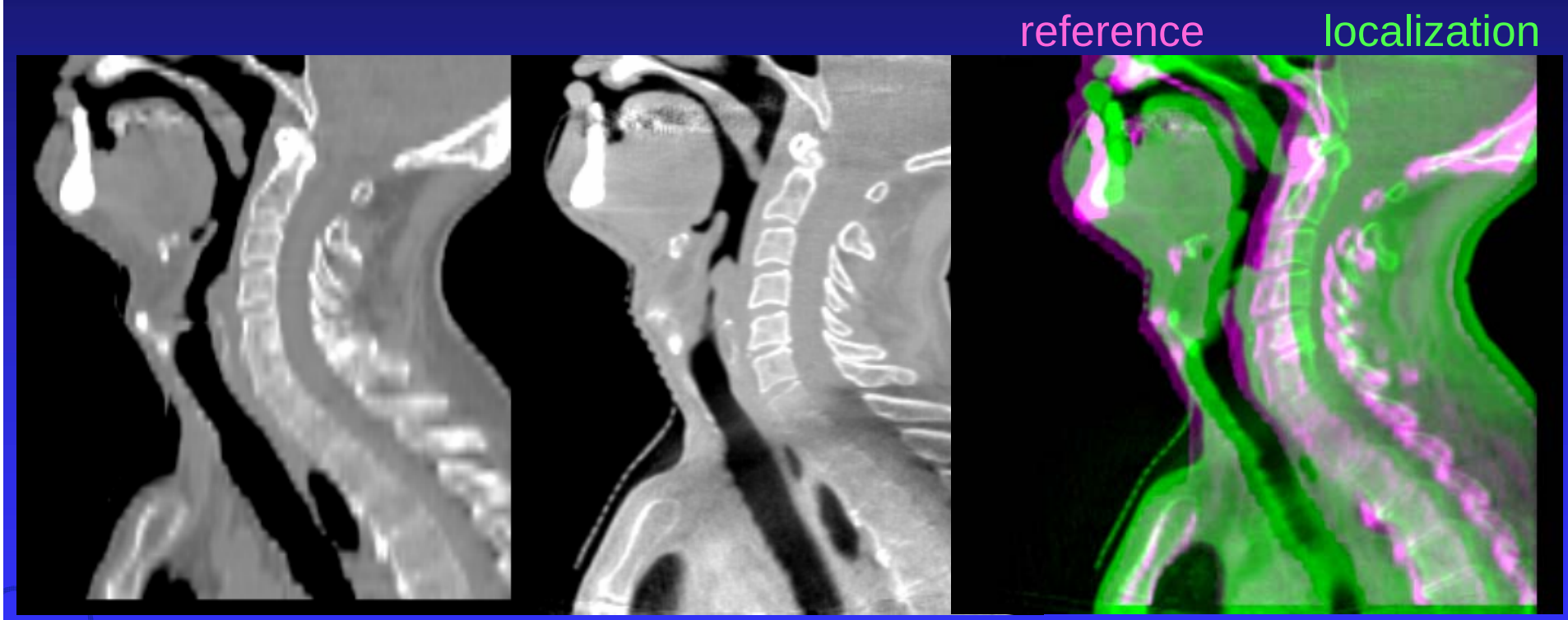


Image analysis: comparison with reference image



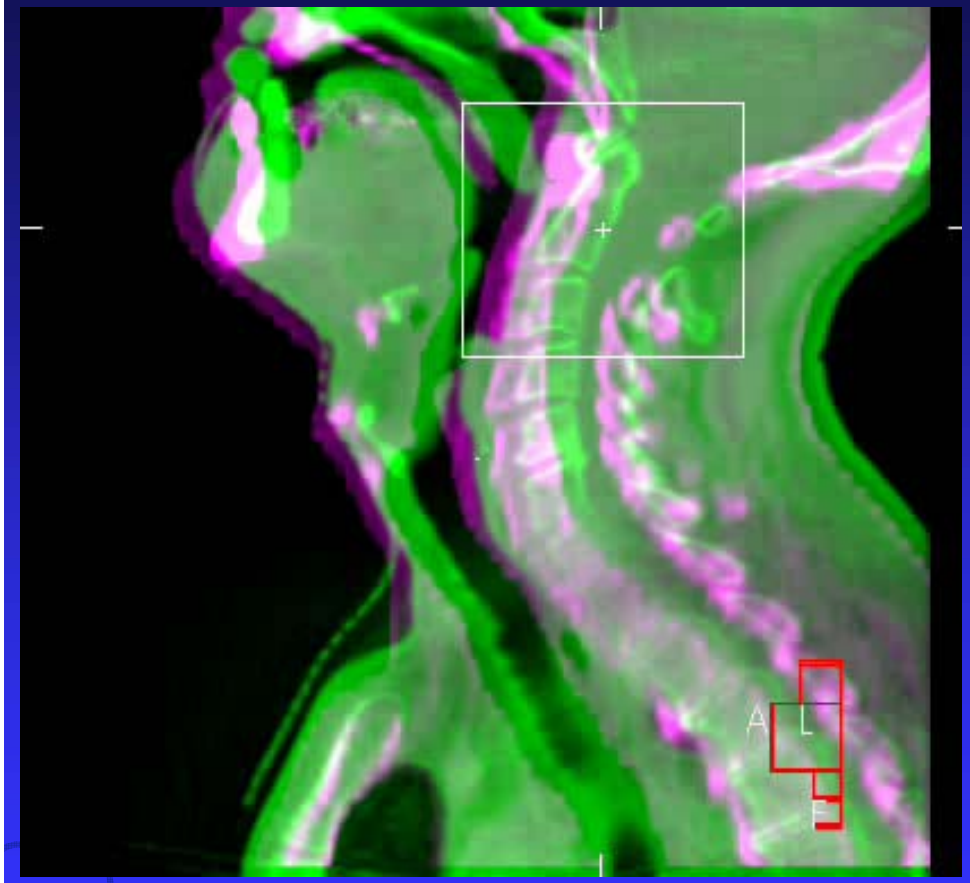
Reference image (planning CT)

Localization image (cone beam CT)

Mixed image (not matched)

Automatic matching on region of interest built-in in Synergy system

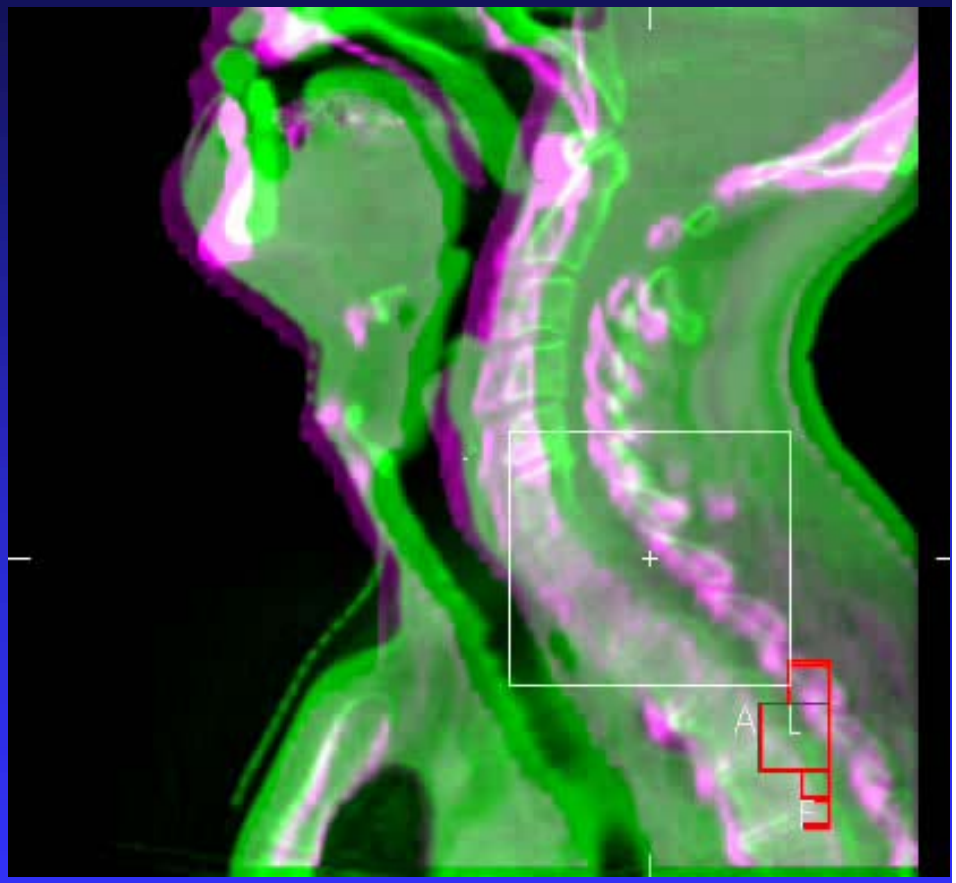
reference localization



Tumor in top of neck

Required table shift:
(-3.2, -1.5, -0.6) mm

reference localization



Tumor in lower part of neck

Required table shift:
(+1.5, -3.2, -6.1) mm

By zooming in on a region of interest, any target can be accurately localized even if the anatomy changes shape

Matching cone beam to planning CT on bone is highly accurate - example for lung treatment series - 10 days matched

Vertebrae are perfectly still

Estimated match accuracy << 1 mm SD, much better as EPID for lung

Can cone beam CT replace EPID ?

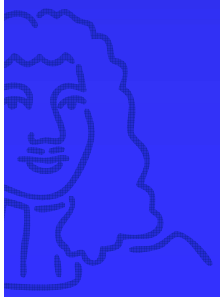
- As CBCT acquisition is slower but alignment is faster
- Cone beam CT is matched more accurately
- Imaging dose is similar or lower

- Cone beam CT can safely replace EPID for bony anatomy setup corrections

→ We replaced EPID with cone beam CT

→ The collected data is used to develop soft tissue protocols

Adaptive Radiation Therapy (ART)



Principle

Adaptive Radiation Therapy (ART *) uses imaging information of the first few treatment fractions to re-optimize the treatment plan

⇒ reduction systematic error

⇒ reduction treatment margins

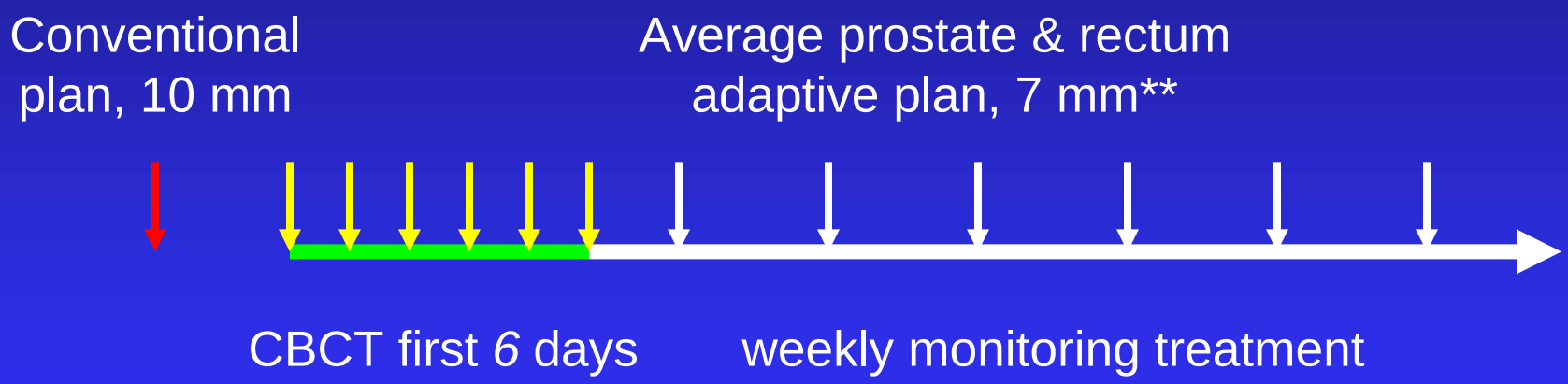
⇒ reduction dose to the rectal wall

⇒ reduction of rectal toxicity **

** Yan et al., IJROBP 50 (2001)*

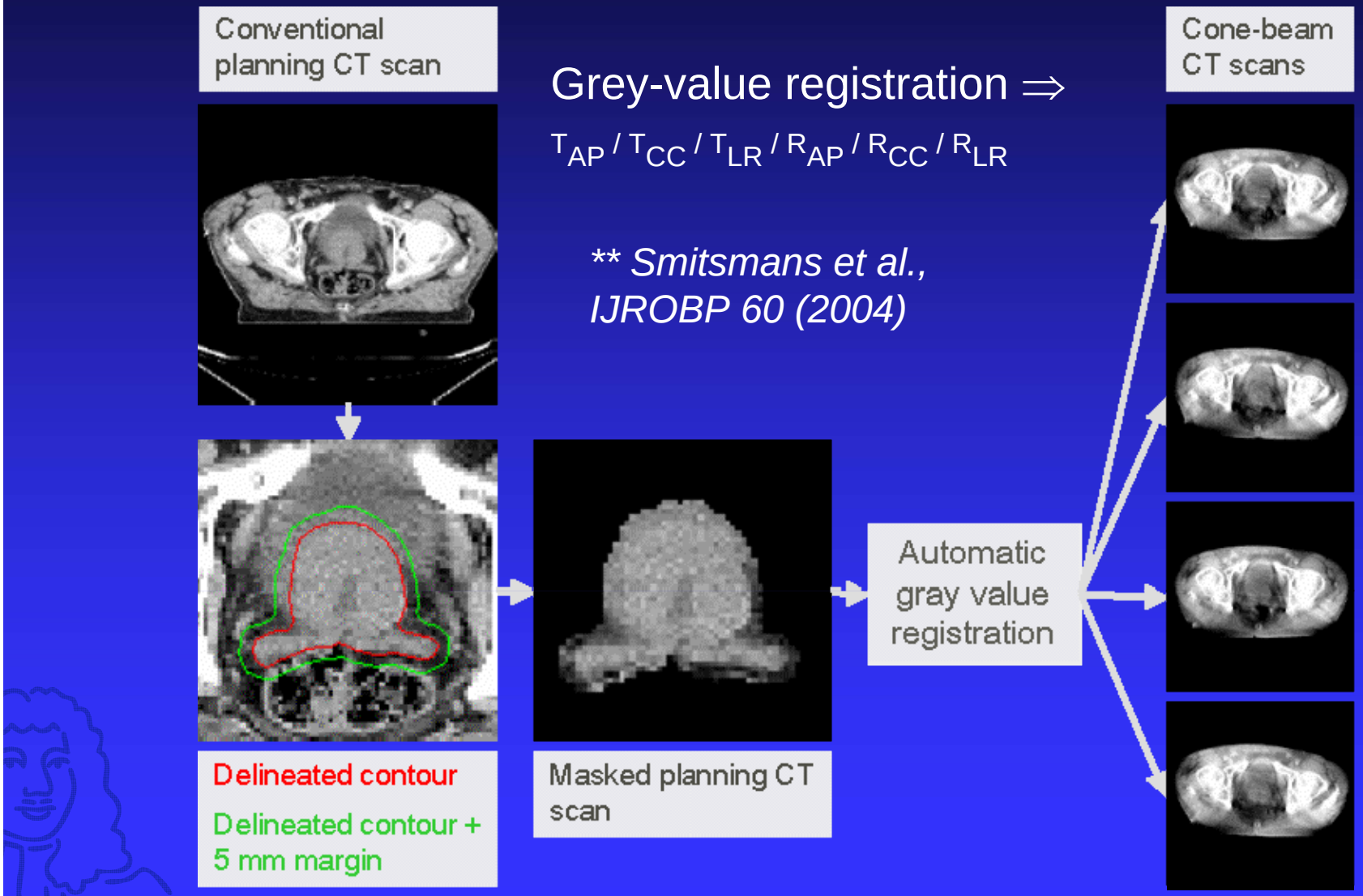
*** Peeters et al., IJROBP jan. (2006)*

ART treatment scheme

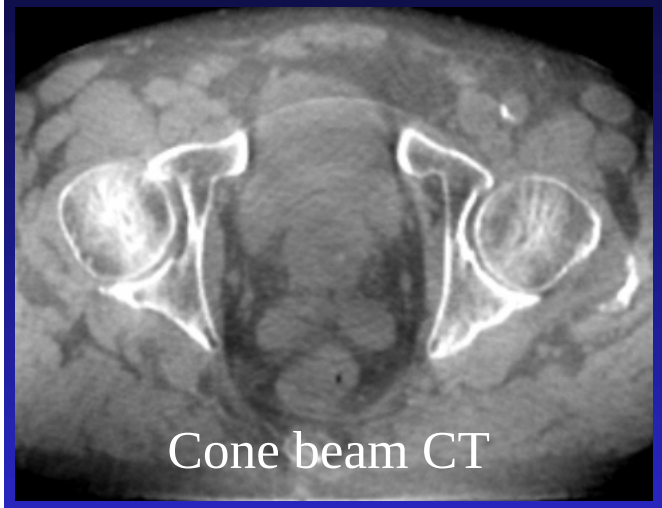


*** unpublished data: Tonnis Nuver (NKI/AVL)*

Average prostate

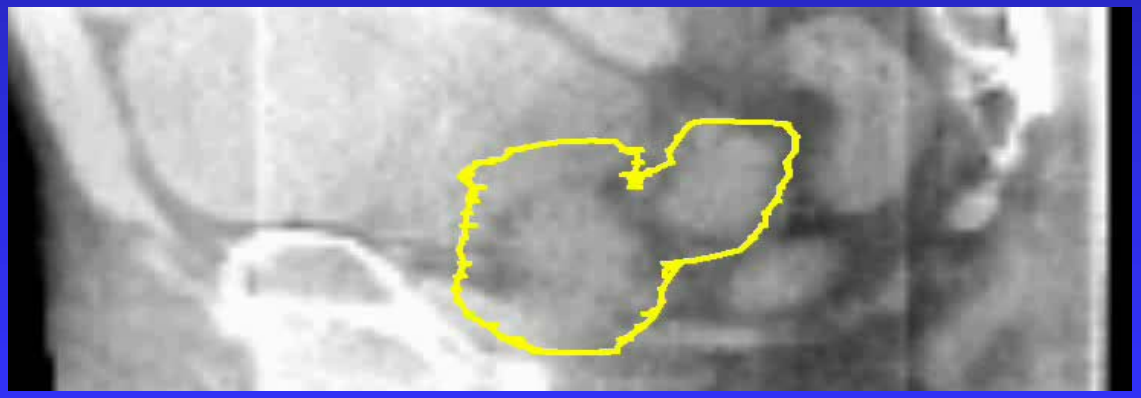


Automatic prostate localization in CBCT (30 s)



10 CBCT scans: automatic bone match

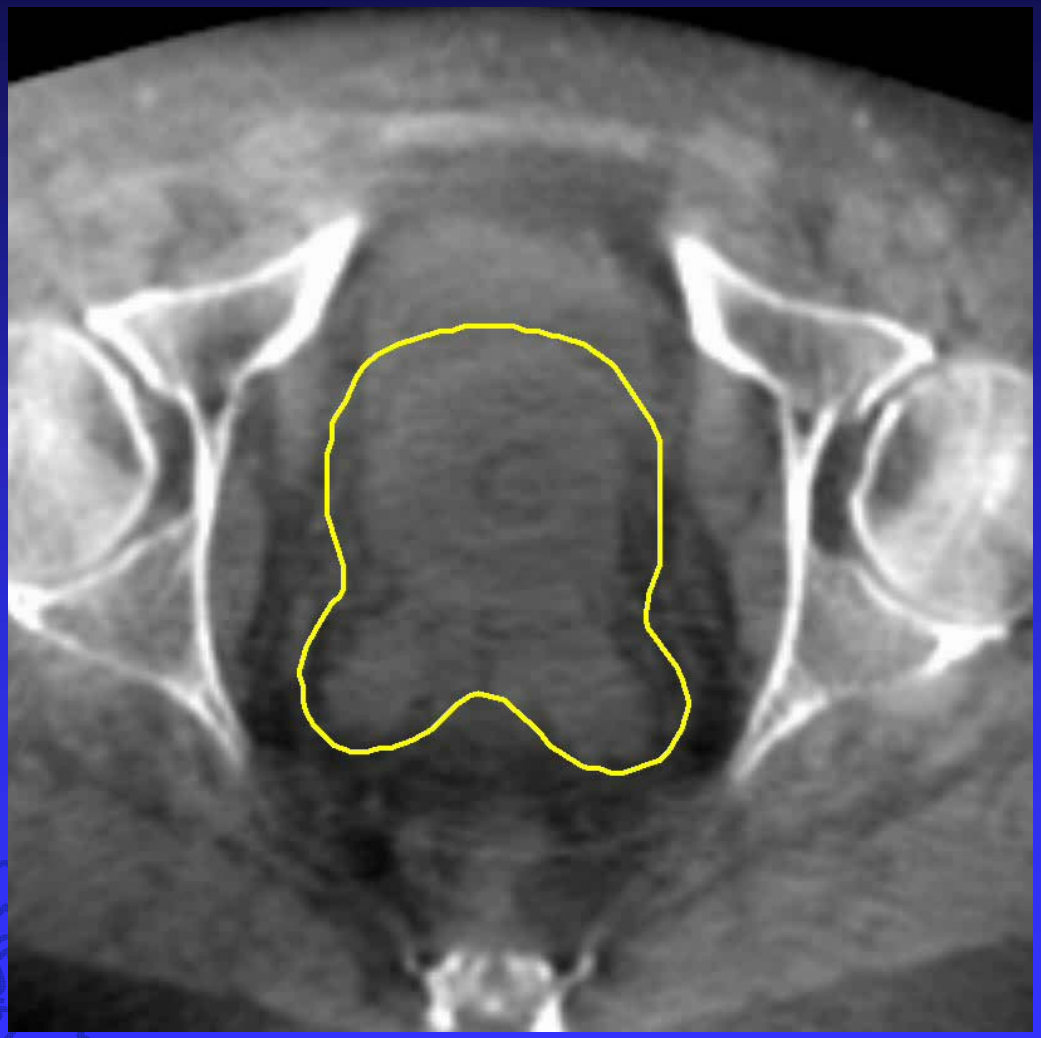
Planning CT contours
placed automatically



10 CBCT scans: automatic prostate match
help line (GTV+3.6 mm)

Smitsmans *et al.*, IJROBP 2004, 2005

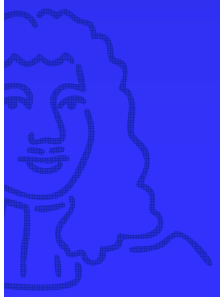
Monitoring the treatment



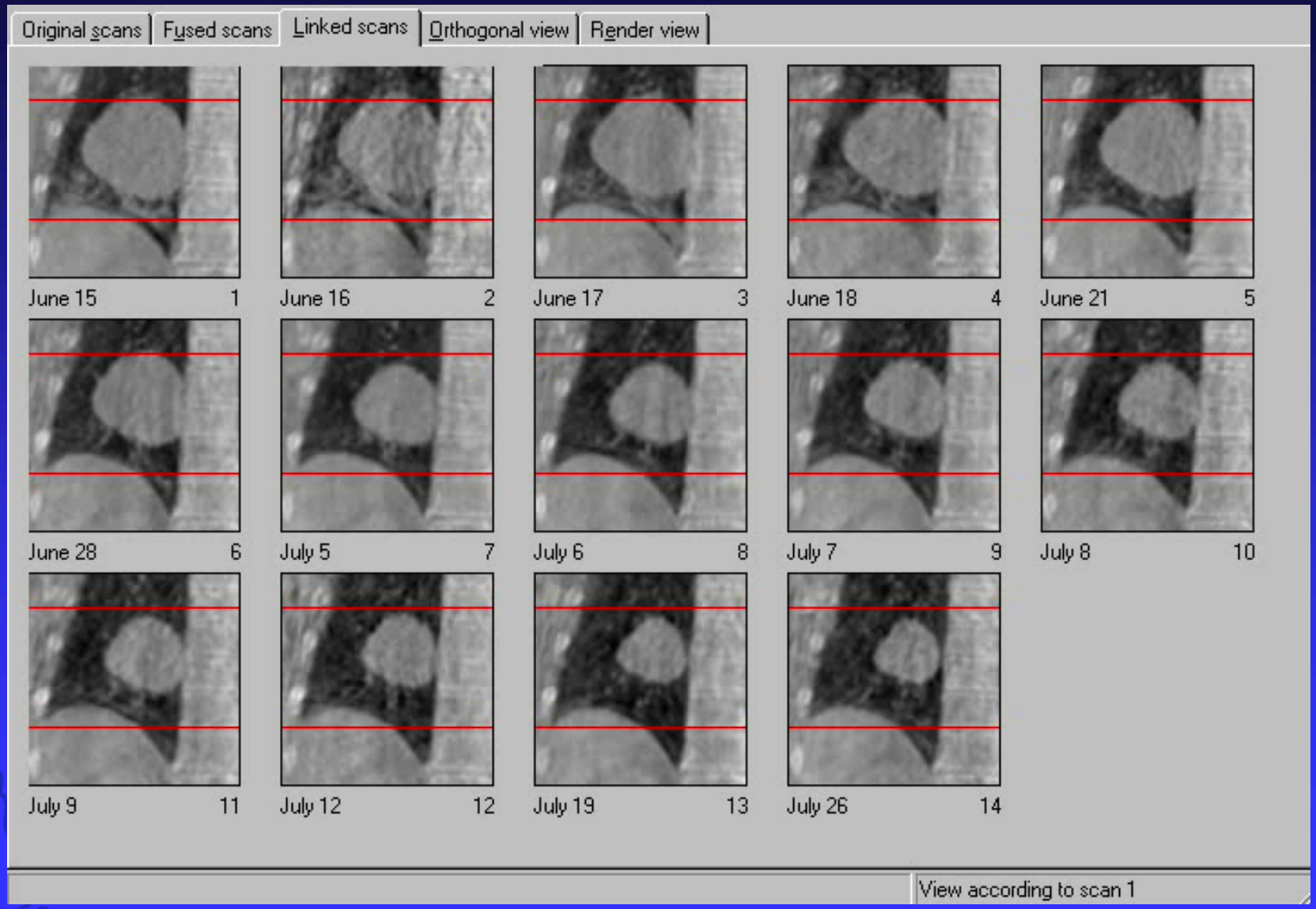
Visual assessment if the prostate + SV were inside average prostate + 7 mm

(PTV volume ART plan)

Variability of 4D CT Patient Models

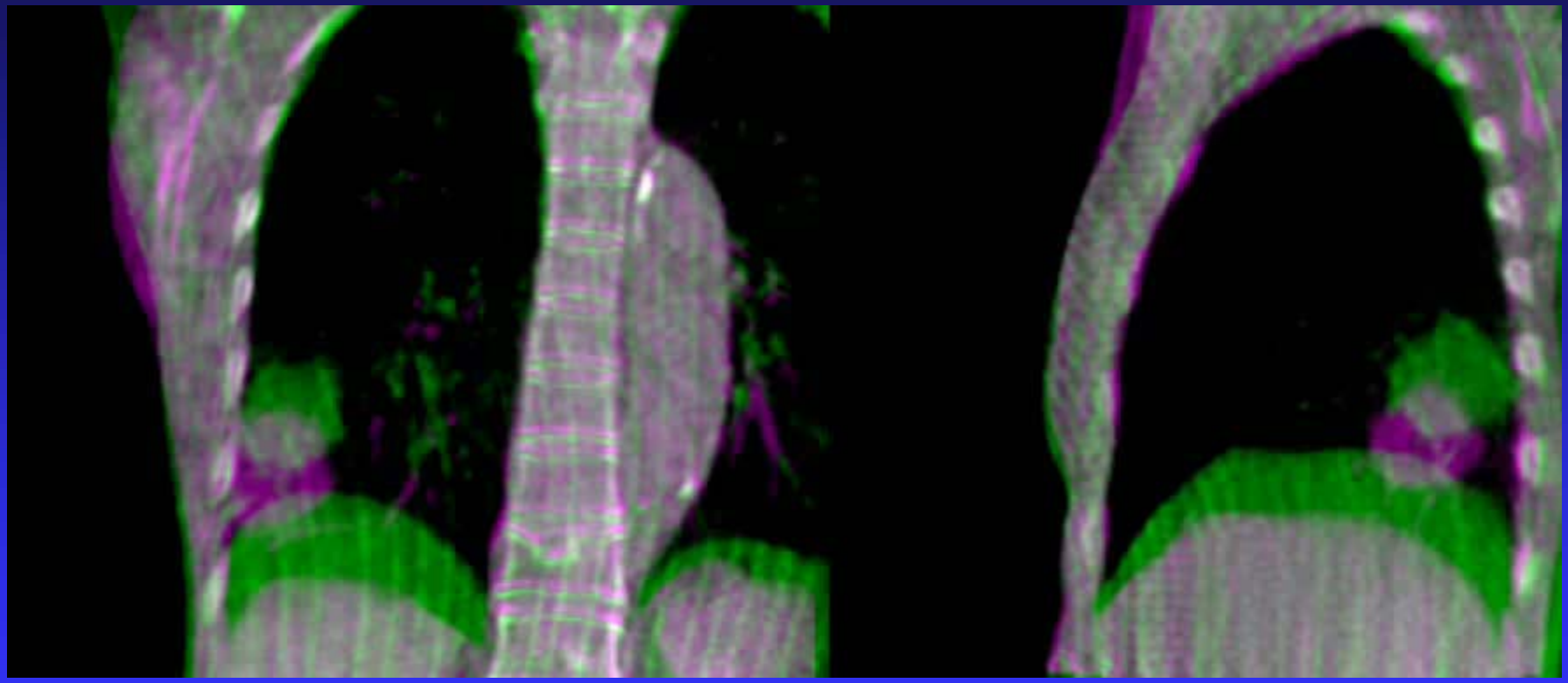


Repeat 4D cone beam CT



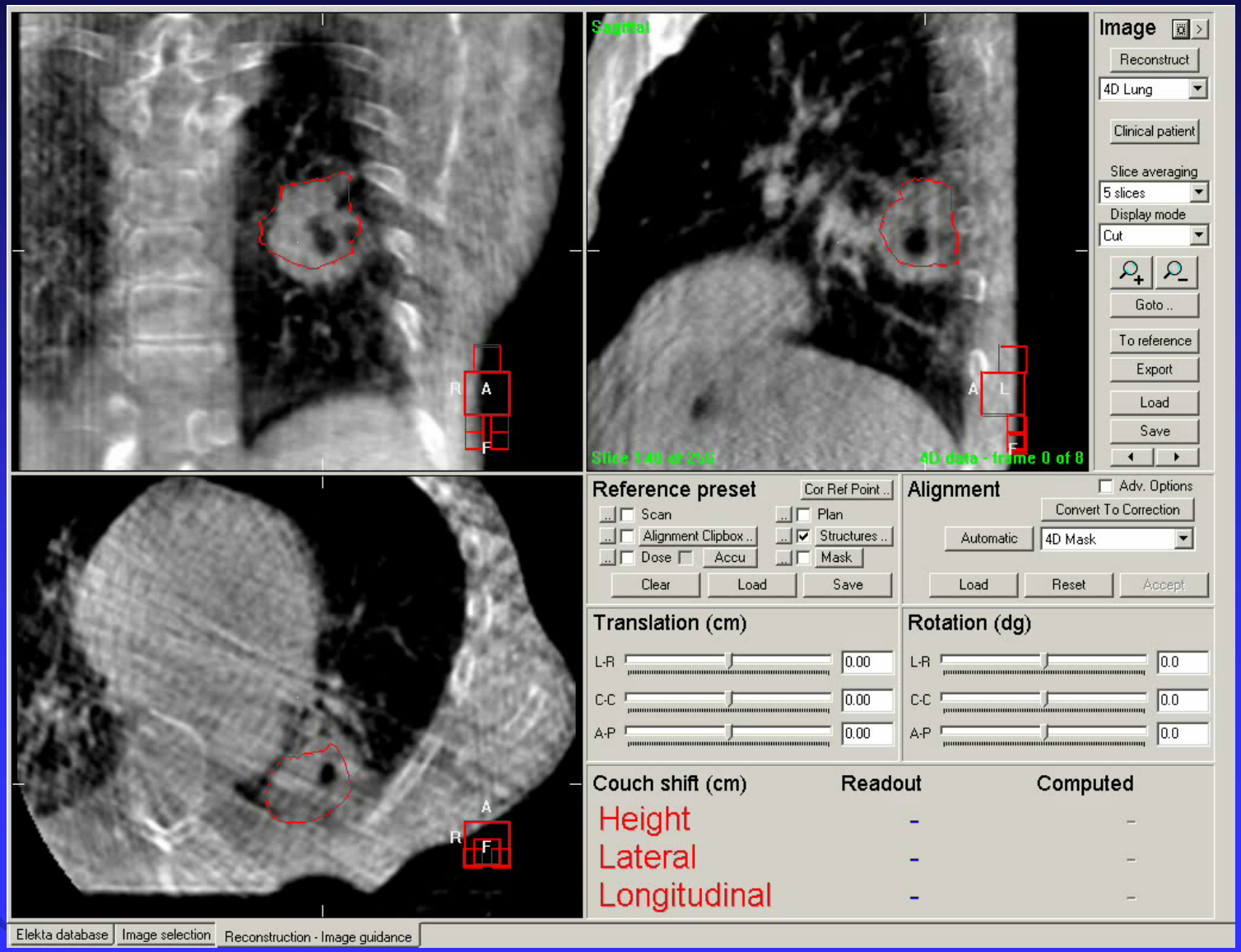
Shows respiration, tumor shrinkage and baseline position variation

Base line shifts

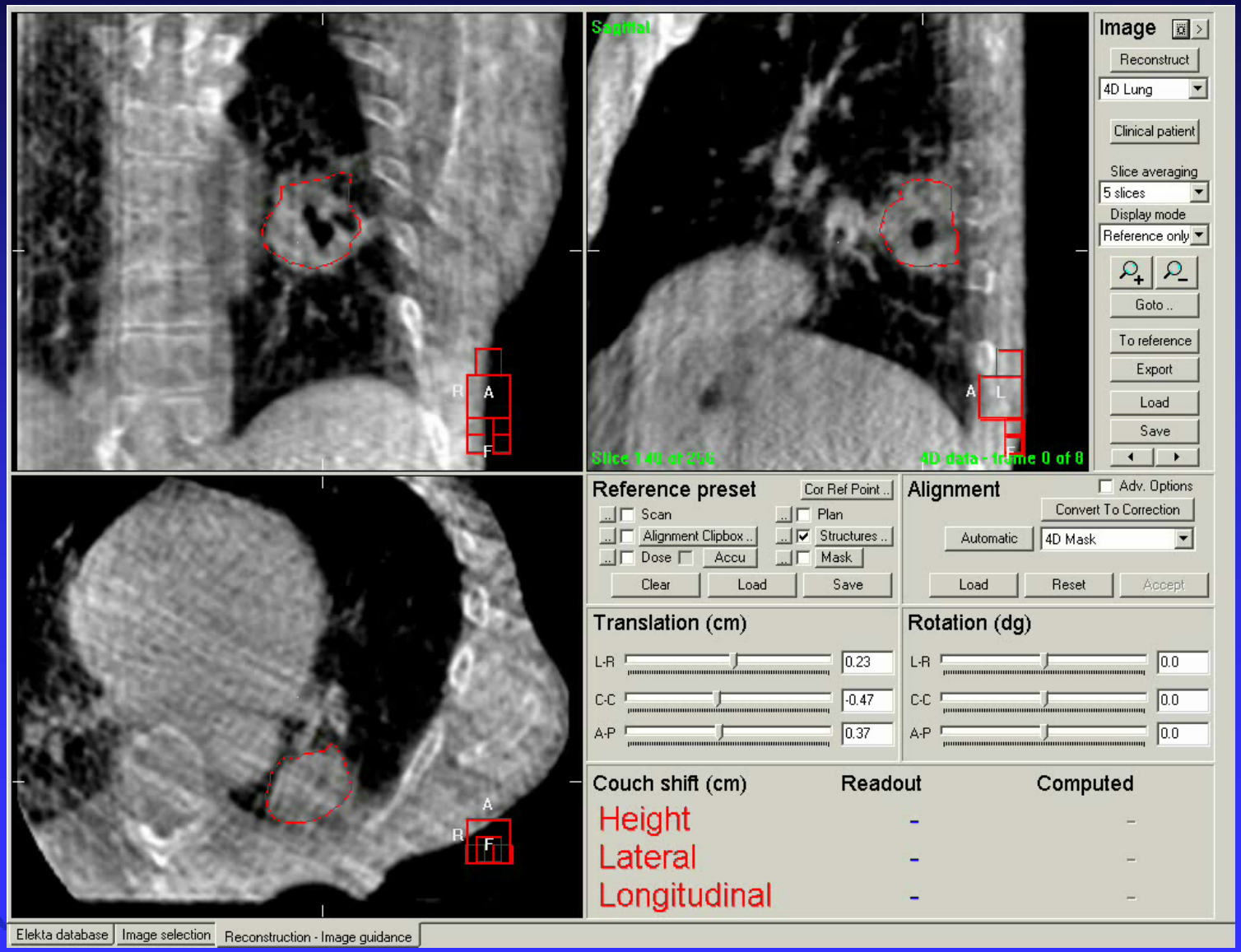


Tumor motion is very similar but occurs at very different places.
Verification is essential for accurate treatment

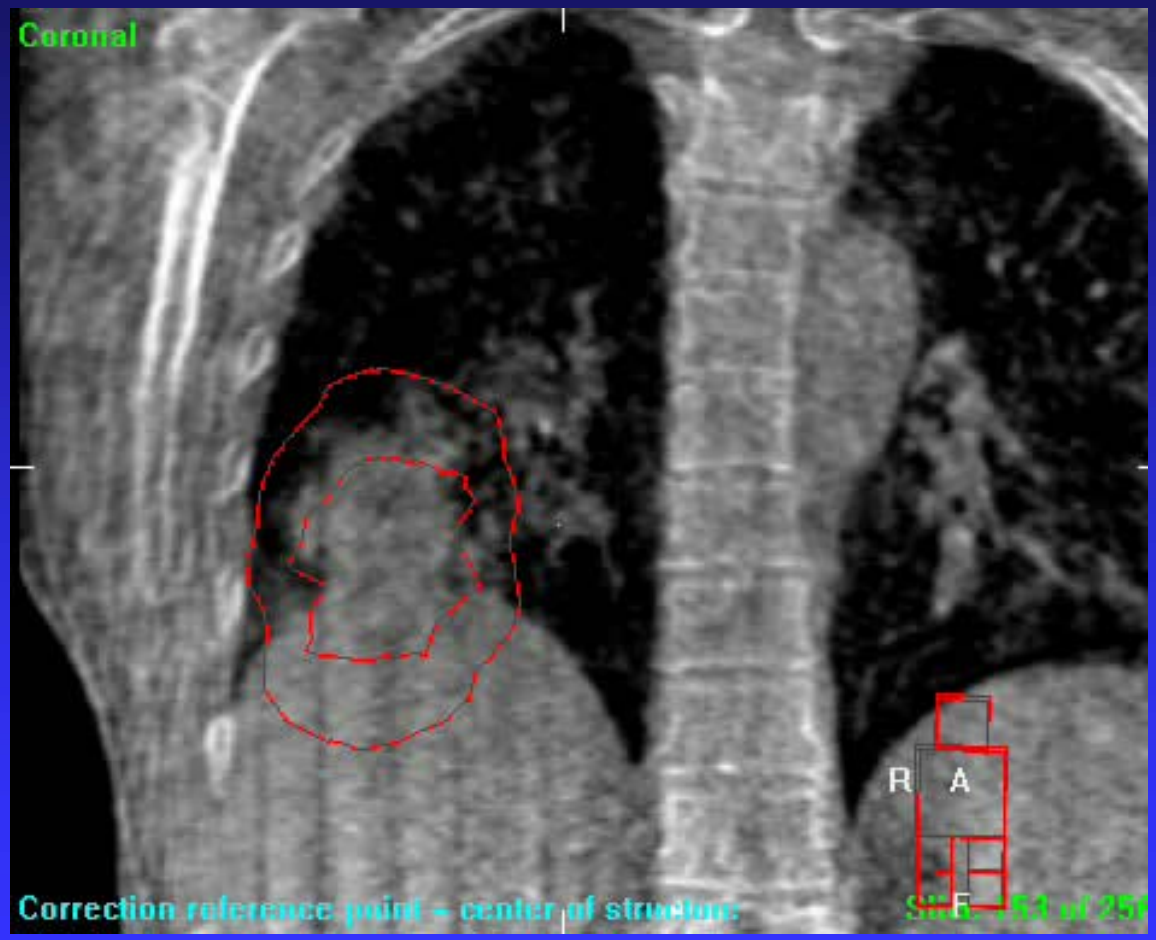
Local Rigid Body Registration



Visual Validation

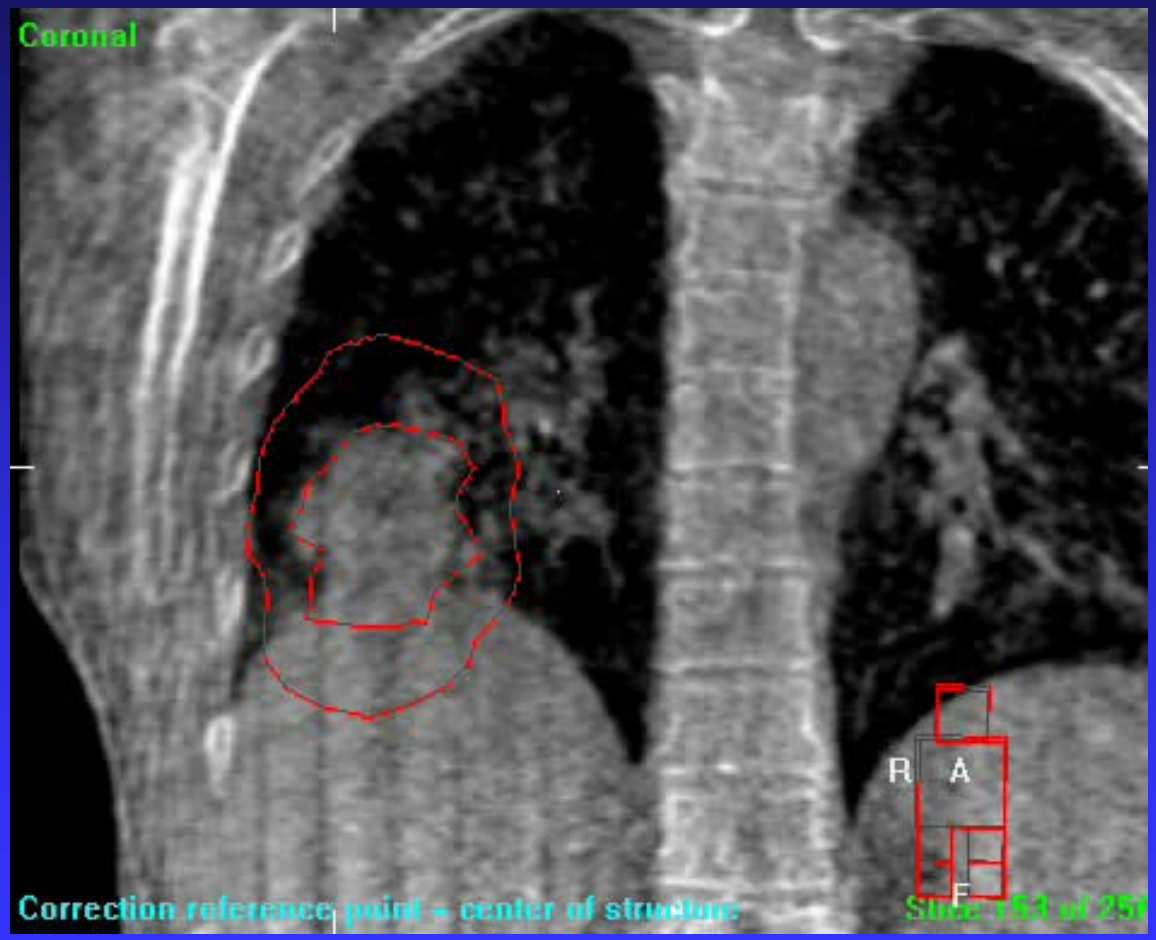


Multiple Targets



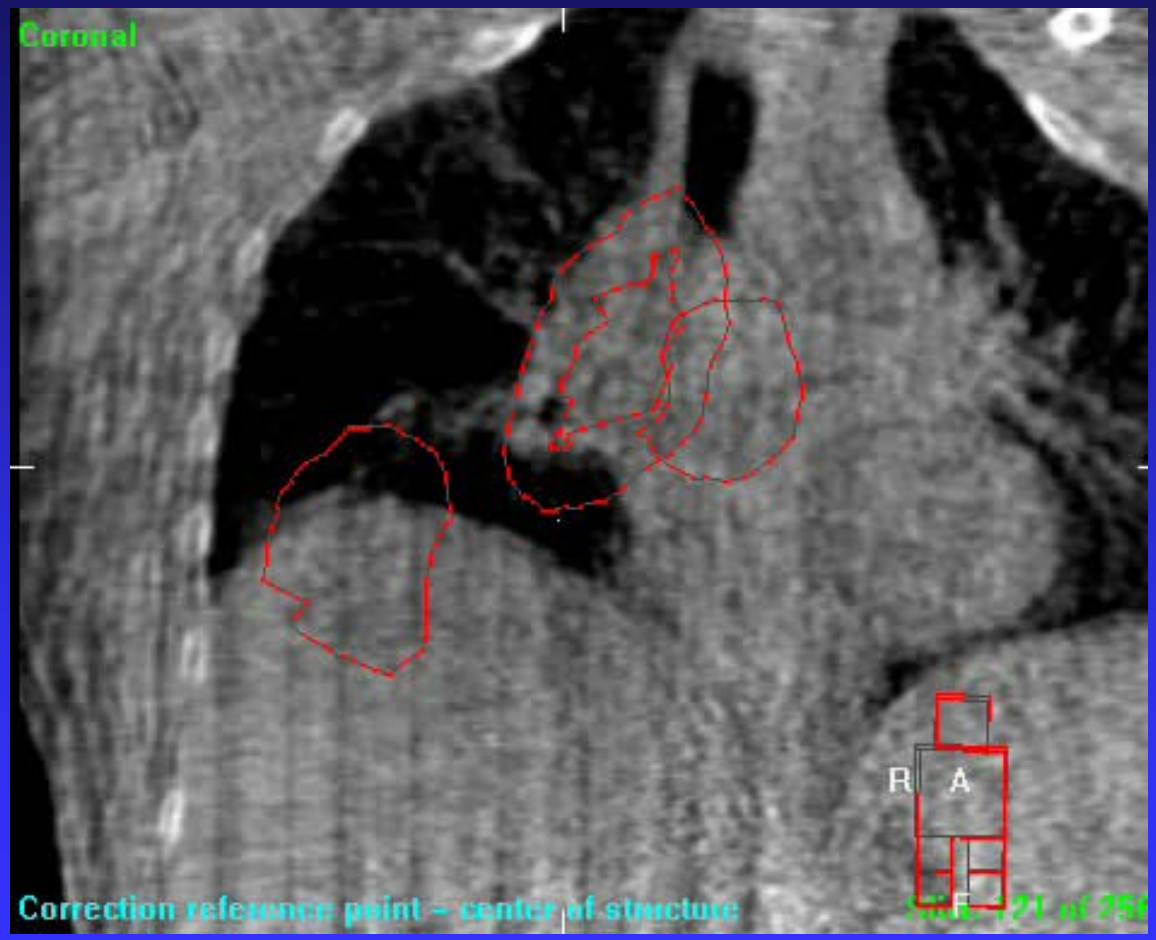
Misalignment of the primary target

Multiple Targets



Correcting alignment of the primary target

Multiple Targets



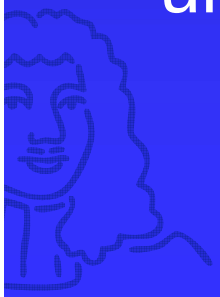
Correct alignment of primary target might misalign the nodes

Conclusions

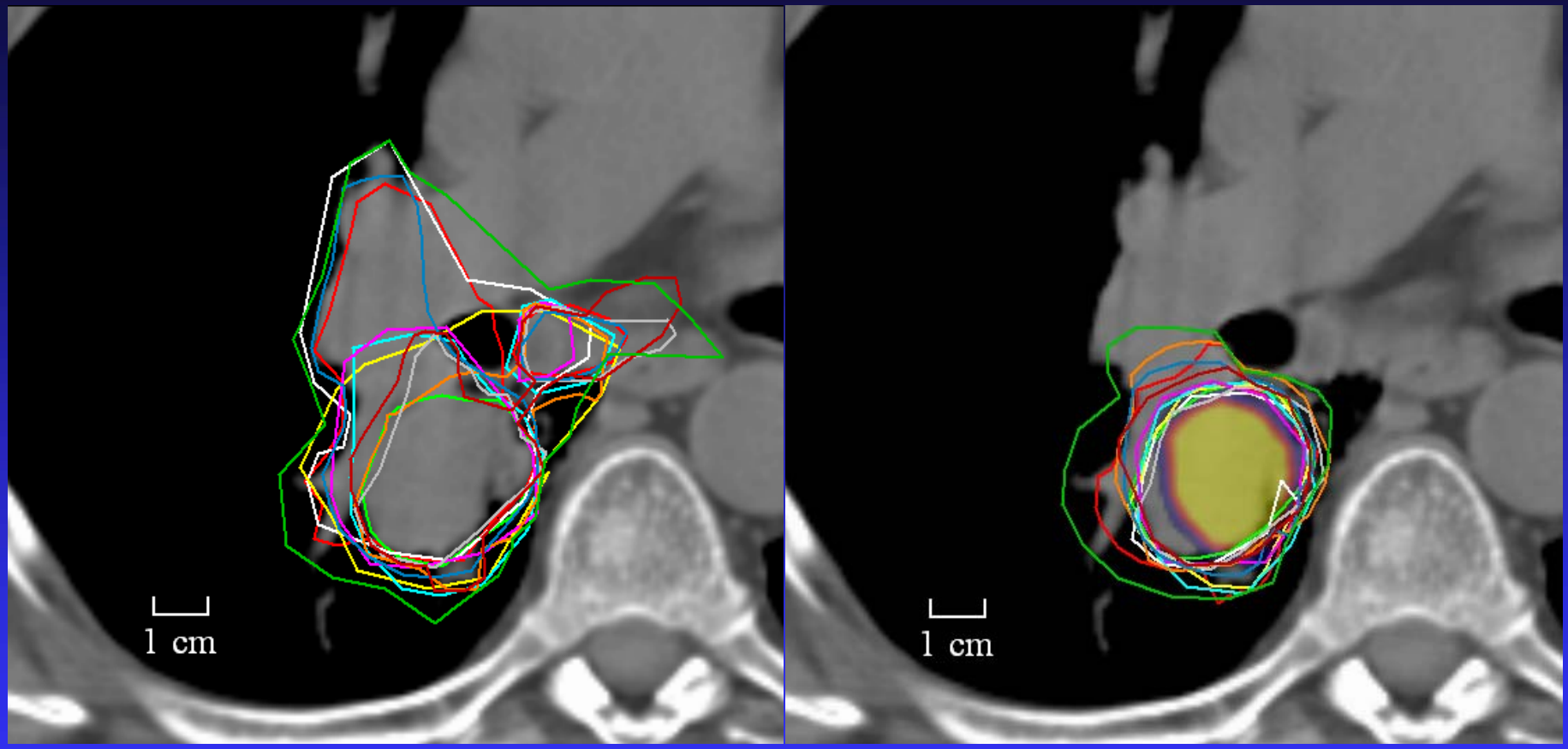
- Organ motion limits accuracy of radiotherapy
- Cone-beam CT provides soft tissue contrast, is efficient and does not require moving or touching the patient
- (4D) CBCT provides a wealth of information (and a huge amount of data!)
- Dose needed for CBCT scan is considerably smaller than for standard EPID localization fields
- Image quality sufficient for image guidance

Conclusions

- Several soft-tissue and bony anatomy based protocols in routine clinical use
- Substantial investment and support of vendors required to enable advanced image guided protocols
- Image Guidance is potentially dangerous. Do not underestimate the residual uncertainties!



Delineation variation: CT versus CT + PET



CT (T2N2)

SD 7.5 mm

CT + PET (T2N1)

SD 3.5 mm

The beams will be pointed to the target the physician draws !

Steenbakkers et al Radiother Oncol. 2005