CBCT: Past, Present and Future

Douglas Moseley PhD, DABR

UHN Princess Margaret Cancer Centre

AAPM 2017

Disclosures

- License Agreement Modus Medical
- Educational Consultant Elekta Oncology Systems

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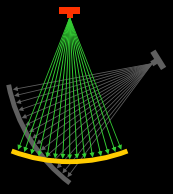
Computed Tomography

First CT Scanner

Sir Godfrey Hounsfield
Nobel Prize (1979)

"Third Generation" CT Scanner

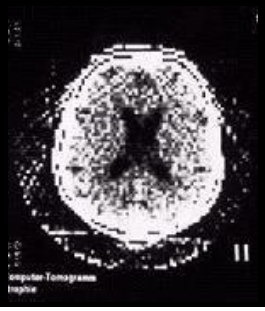


Fan-Beam X-ray Source
1-D Detector Array
Multiple Projections, $P(e,t)$

Br J Radiol. 1973 Dec;46(552):1016-22.

CT Slice

1975



Today

Siemens Medical Solutions

2007: kV Cone-Beam CT for IGRT

Varian TrueBEAM

Elekta Synergy

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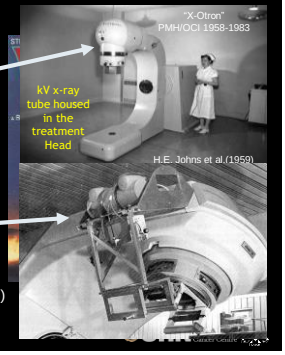
kV Sources for Guidance

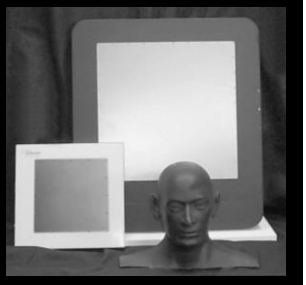
- A.F. Holloway,
  - Brit.J.Radiol. 31: 227 (1958)
- H.E. Johns et.al.,
  - Am.J.Roentgenol. 81: 4-12 (1959)
- Weissbluth et.al.,
  - Radiology 72: 242-253 (1959)
- L.M. Shevron et.al.,
  - Clin.Radiol. 17: 139-140 (1966)
- H.P. Culbert et.al.
  - IJROBP 10 Sup 2: 180 (1984)
- P.J. Biggs et.al.,
  - IJROBP 11: 635-643 (1985)
- R. Sephton et.al.,
  - Radiother.Oncol. 35:240-247 (1995)



a-Si Flat-Panel Detectors

"digital camera for x-rays"

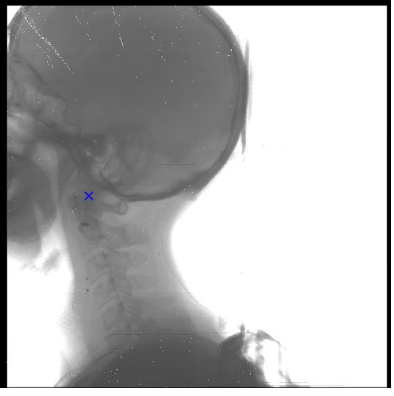
- Fast readout (30 fps)
- High Efficiency (DQE)
- Large FOV
- Robust (B Field, etc)
- Compact
- Distortion free



- Promising for radiography, fluoroscopy, mammography
- Ideally suited to cone-beam CT

Raw Projection Data

- 1024x1024
- Defects
- Unequal exposure



Processed Projections

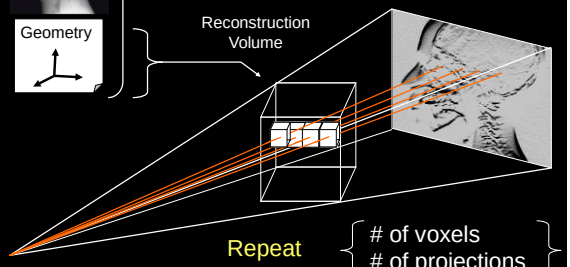
- attenuation = - ln(I/I_0)
- "white" bones

Filtered Back-Projection

Log & Weight → 1D FFT-based Hamming Filter → 4x 2D Interpolation

Geometry

Reconstruction Volume



Repeat { # of voxels, # of projections }

Feldkamp et al. (1984)

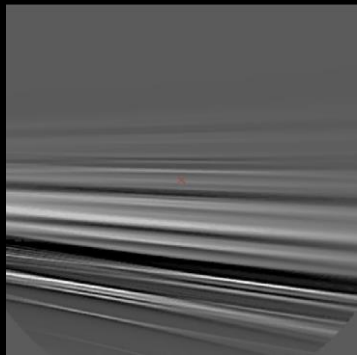
Processed Projections

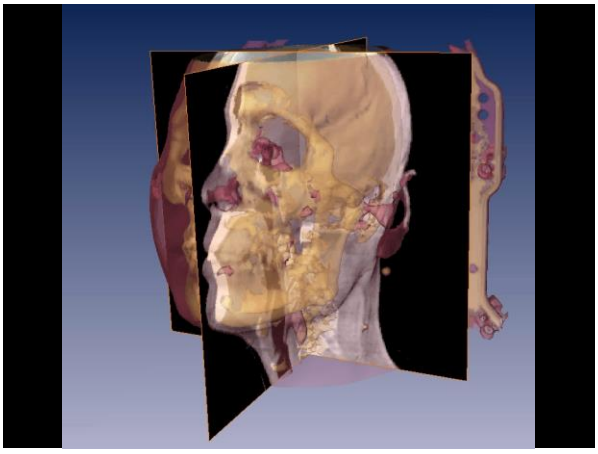
- Filtered
  - ramp + hamming=1
- Appears as edge enhancement

Axial Reconstruction

$$\Delta s \cdot \sum_{i=1}^{N} \mu_i = -\ln I/I_0$$

- 651 projections
- 360 deg
- 40cm x 40cm





QA for IGRT Systems

- Published AAPM reports
  - TG-58 (Portal Imaging)
  - TG-104 (Image-guidance systems)
  - TG-142 (General accelerator QA)
  - TG-148 (Tomotherapy)
  - TG-135 (Robotic Radiosurgery)
  - TG-154 (Ultrasound)
  - **TG-179 (CT-based IGRT)**

Quality assurance for image-guided radiation therapy utilizing CT-based technologies: A report of the AAPM TG-179

Jean-Pierre Bissonnette[a)]
Task Group 179, Department of Radiation Physics, Princess Margaret Hospital, University of Toronto, Toronto, Ontario, Canada, M5G 2M9

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CBCT Image Quality Metrics

- Spatial Integrity
  - Scale, orientation, isocentricity, chirality
- Spatial Resolution
- Uniformity
- Contrast/Noise (CNR)
  - Low Contrast Detectability
- CT Number Accuracy

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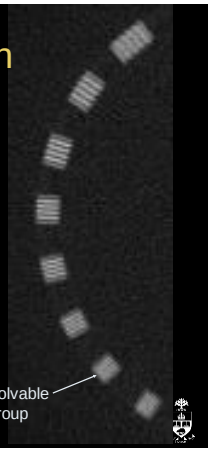
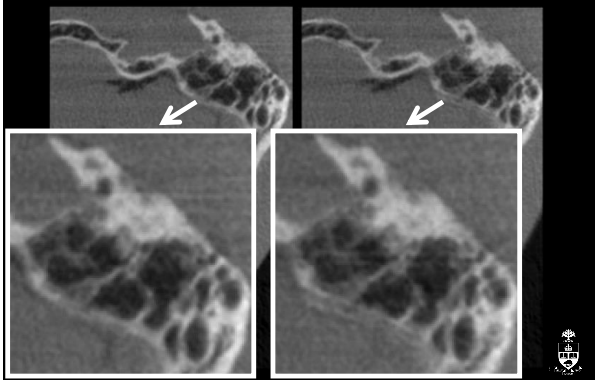
Spatial Resolution

Factors affecting spatial resolution:
Focal spot size
Detector pixel size
Slice thickness
Number of projections
Reconstruction filter (kernel)
Field of view
Patient motion

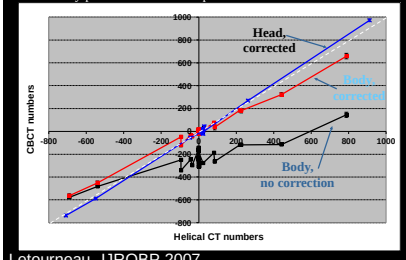
Metrics of spatial resolution:
Minimum resolvable line-pair
Point-spread function (psf)
Modulation transfer function (MTF)

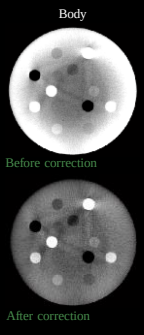


Effect of Incorrect Calibration



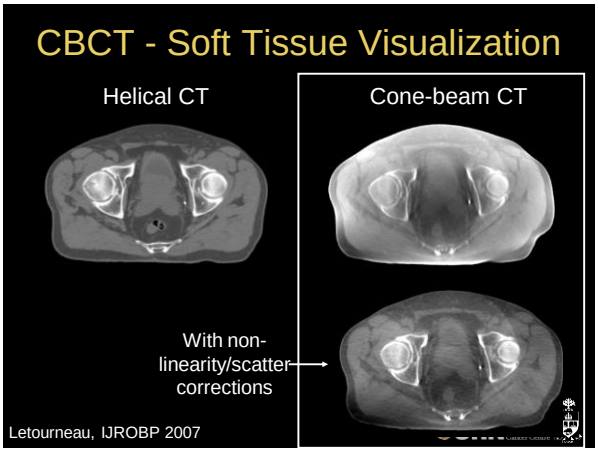
Quantitative Assessment of CT

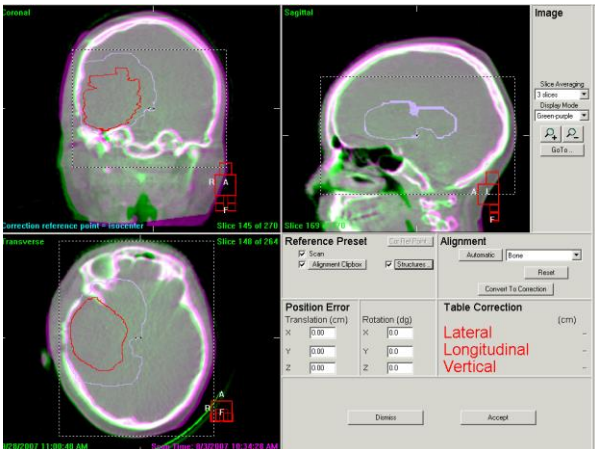


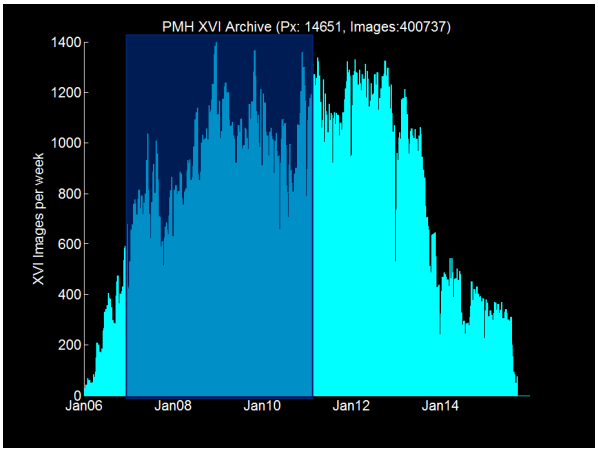


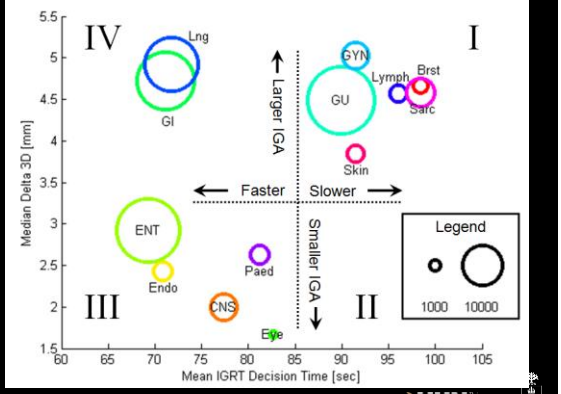
Letourneau, IJROBP 2007

Cupping: 164 to 40 HU


CBCT - Soft Tissue Visualization
Helical CT
Cone-beam CT
With non-linearity/scatter corrections
Letourneau, IJROBP 2007


Coronal
Sagittal
Image
Transverse
Reference Preset
Alignment
Position Error
Translation (cm)
Rotation (dg)
Table Correction
(cm)
Lateral
Longitudinal
Vertical
Dismiss
Accept


PMH XVI Archive (Px: 14651, Images:400737)
XVI Images per week
1400
1200
1000
800
600
400
200
0
Jan06
Jan08
Jan10
Jan12
Jan14



Li RadOnc 2016

Prostate Matching Objectives

- This continuing education exercise was developed with an aim to:

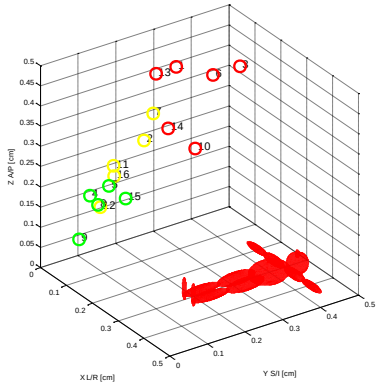
1. Determine baseline variation for soft-tissue matches
2. Determine expert consensus
3. Identify cases with large inter-observer variability
4. Identify opportunities and strategies to improve soft tissue prostate targeting among therapists to improve care to patients.

Characteristics of "Hard" GU Cases

1. **Patient Preparation**
   - Small Bladder
     - Deformation
   - Gas in rectum
     - Deformation
     - Streak artifacts
   - Prostate rotation
2. **Patient Setup**
   - Large baseline shift from bone

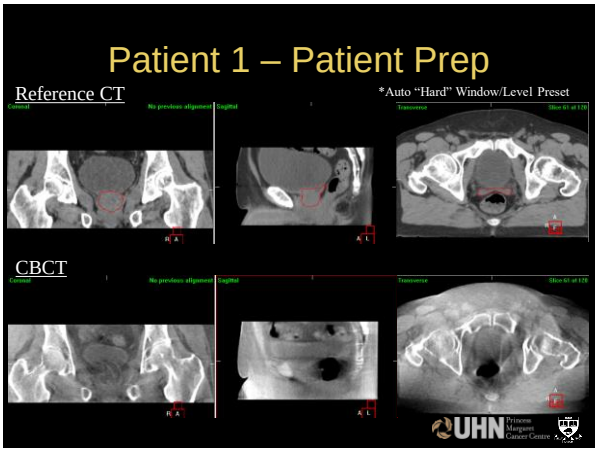
Standard Deviation of All Observers

- 5 experts
- 33 observers
- 16 cases

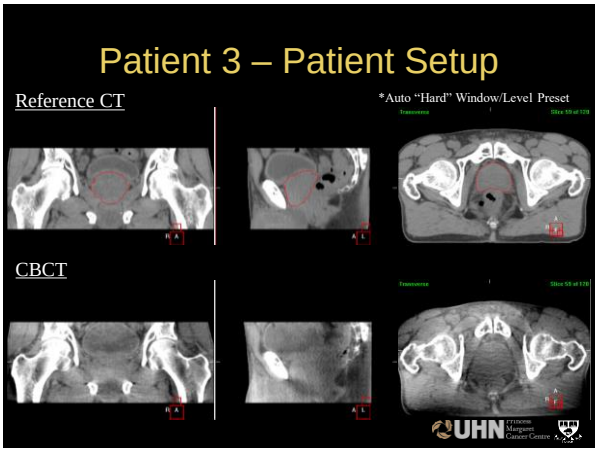


Easy
Medium
Hard

Patient 1 – Patient Prep

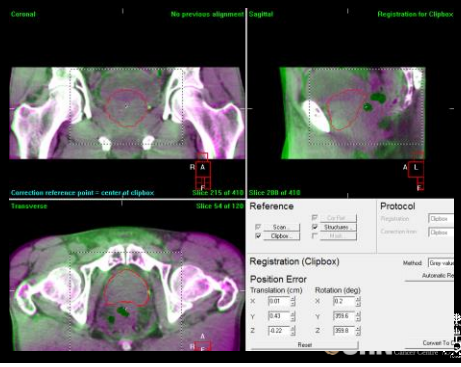


Patient 3 – Patient Setup



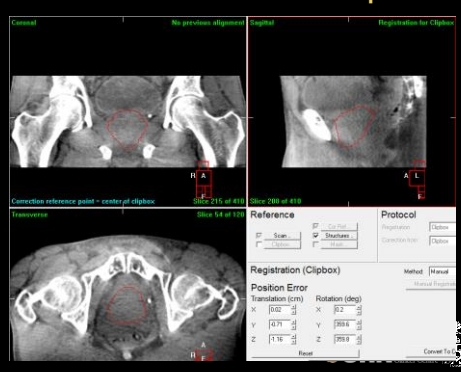
Patient 3 – Patient Setup

Bone Match



Patient 3 – Patient Setup

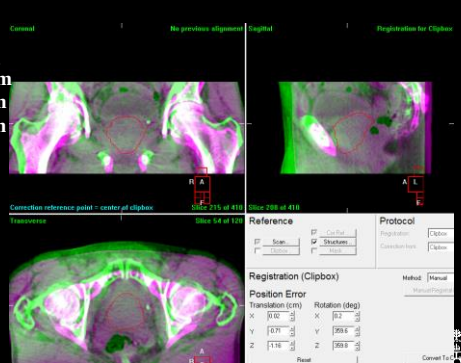
Prostate Match (Mean of Experts)



Patient 3 – Patient Setup

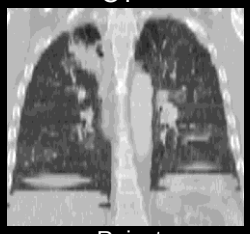
Absolute Difference

X = 0.01cm
Y = 1.14cm
Z = 0.94cm



Respiratory Motion Artifacts

CT



Cone-Beam CT

Reject

- Immobilize
- Fast Scanning
- Patient Preparation

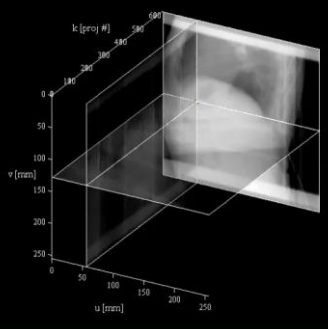
Correct

- Retrospective Sorting
- Gating
- Tracking

Patient Acquisition Sequence

- 79 yr old female with cholangiocarcinoma
- Treated with 54 Gy in 6 fx using respiratory gating
- Technique
  - 120kVp, 100mA
  - 13 ms/pulse
- ~1.2-2.0 cGy

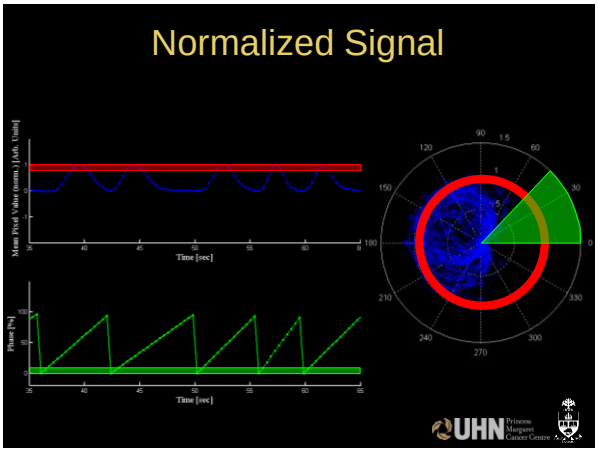
Central Axial Slice

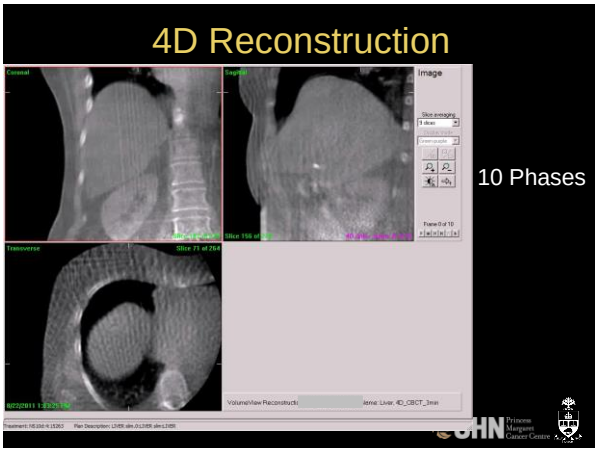


25.6 cm Axial FOV

Consistent data

Clearly see diaphragm motion


Normalized Signal
Time [sec]
Phase [%]
UHN


4D Reconstruction
10 Phases
UHN

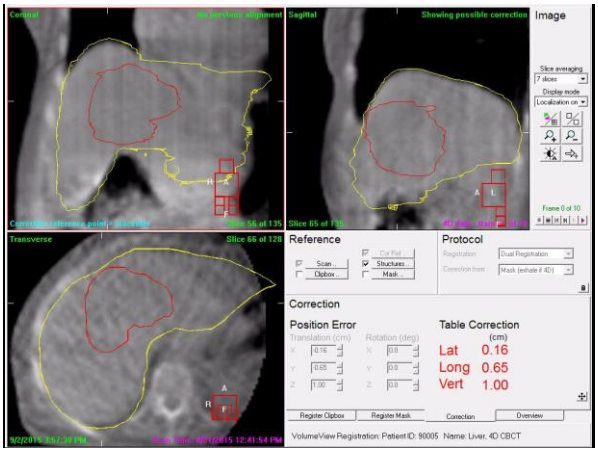
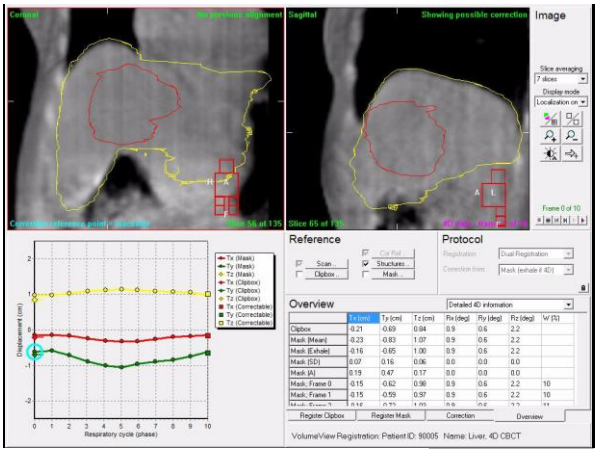


Image
Reference
Protocol
Correction
Position Error
Table Correction
Lat 0.16
Long 0.65
Vert 1.00



Motivation for measuring ventilation

- Changes in lung ventilation may predict radiotherapy-induced toxicities.

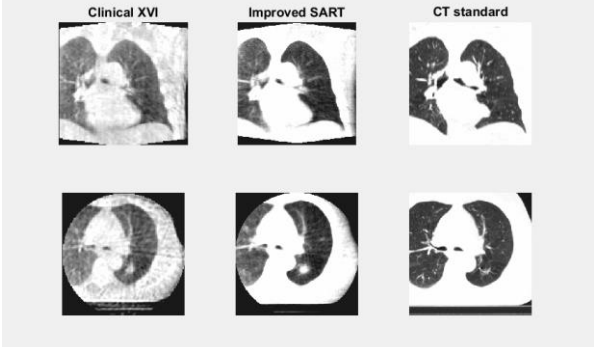
Elekta XVI 4D-CBCT

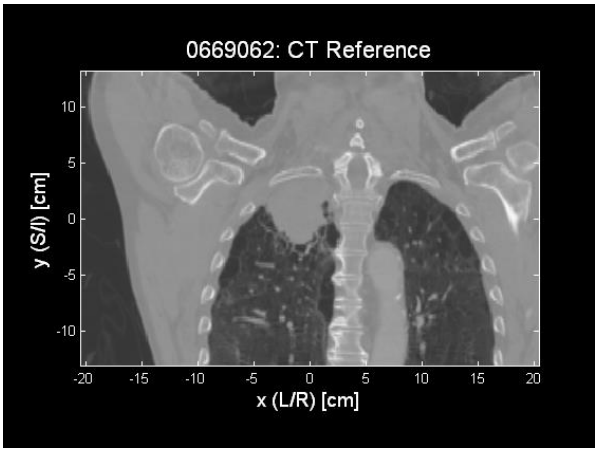
Philips 4D-CT

- 4D-CBCT limitation: Low image quality
- Approach: Improve 4D-CBCT and compare ventilation to 4D-CT

Kasper Jensen, Odense

Improvements of 4D-CBCT: Examples





CBCT derived radiosensitivity marker associated with radiation pneumonitis

Pencilla Lang*
Douglas Moseley*
Uffe Bernchou*
Cartsen Brink*
Andrew Hope*

*Department of Radiation Oncology, Princess Margaret Cancer Centre

*Institute of Clinical Research, University of Southern Denmark

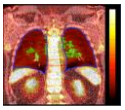
Presented by: Pencilla Lang, BEng, MD, PhD

Background

No patient-specific predictors of normal lung radiosensitivity in clinical use

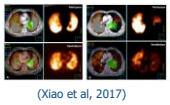
- Imaging features correlate with clinical pneumonitis

PET



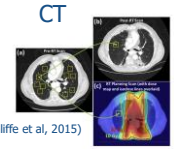
(Castillo et al, 2014)

VQ



(Xiao et al, 2017)

CT



(Cunliffe et al, 2015)

Methods - Overview

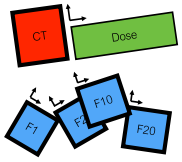


Image Extraction

Methods - Overview

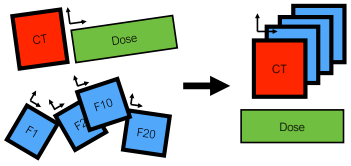
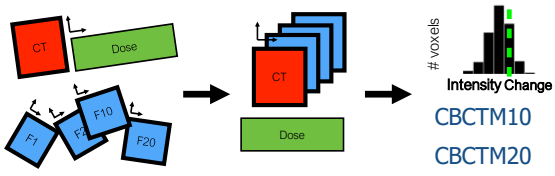


Image Extraction

Registration

Methods - Overview



CBCTM10
CBCTM20

Image Extraction

Registration

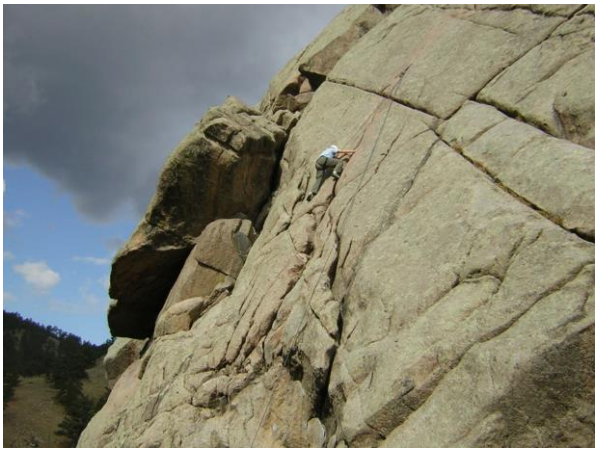
Analysis

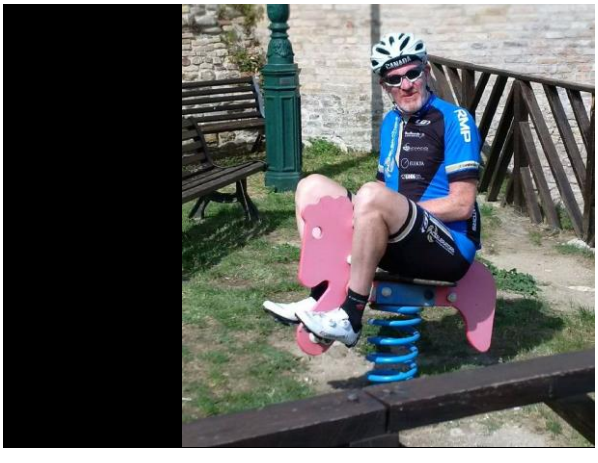
Results

- Univariate logistic regression of dosimetric parameters and CBCT markers with symptomatic pneumonitis:
  - CBCTM10, MLD, V20 not significant ($p > 0.05$)
  - CBCTM20 significant ($p < 0.01$)
- Multivariate logistic regression with CBCTM20 and V20 significant for both ($p < 0.05$)

Review of Module Objectives

- Introduce Cone-Beam CT System Components
- a-Si Flat Panel Detectors
- Reconstruction Process
- Image Quality Metrics (AAPM TG-179)
- Confounding Patient Factors
  - Motion, Setup





IGRT Systems: Ideal Properties

- Accurate, precise
  - Explicit interpretation
  - minimal training, operator independent
- Efficient, integrated
  - Rapid
  - Integrated with machine for remote intervention
  - Low impact on resources
- Broad/Universal application
  - Large number of anatomical sites
  - Large field of view
- Reduce radiation dose
  - non ionizing, or efficient detectors.
  - account for imaging dose?
- Real-time
  - continuous monitoring
- Images for planning & evaluation
- CHEAP!

G. Mageras, Semin. Radiat. Oncol. 15(3) 133-125 2005.

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Acknowledgements

- Pencilla Lang, Winnie Li, Jean-Pierre Bissonnette, Daniel Létourneau, David Jaffray
- NKI – Jan-Jakob Sonke,
- Christy - Marcel van Herk
- JHU – Jeff Siewerdsen
- Odense – Kasper Jensen, Carsten Brink, Uffe Bernchou

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