4D Cone-Beam CT: Developments and Applications

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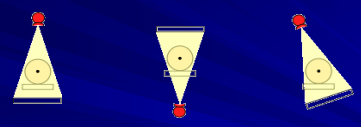
Disclosure

- I have received research funding from NIH and Varian Medical System.

Outline

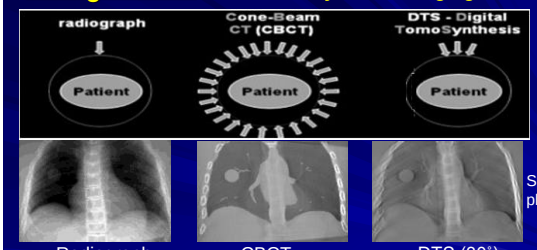
- Background
- Image acquisition approaches
- Projection sorting techniques
- Reconstruction techniques
- Imaging dose
- Clinical applications of 4D-CBCT

Background: On-board X-ray based Imaging Techniques



Radiograph | Cone beam CT (CBCT) | Digital Tomosynthesis (DTS)

Background - On-board X-ray based Imaging Techniques

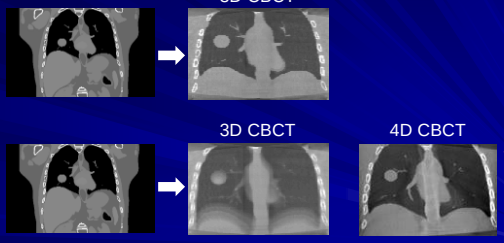


Q. J. Wu, IJROBP, 2007

Static phantoms

Radiograph	CBCT	DTS (30˚)
Scan angle: 0˚	Scan angle: 360˚/~200˚	Scan angle: 20˚ ~ 60˚
Scan time: <<1 s	Scan time: ~1 min	Scan time: < 10 s
Scan dose: <<1 mGy	Scan dose: ~1-8 cGy	Scan dose: < 1 cGy
Dimension: 2D	Dimension: 3D	Dimension: Quasi-3D

Background - Imaging for moving lung

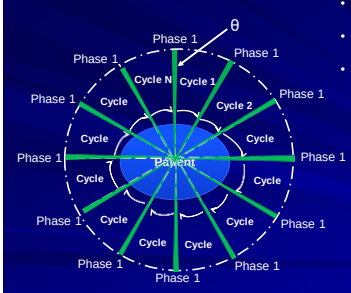


4D imaging needed

Background: Challenges with 4D-CBCT

- Image acquisition:
  Unevenly distributed projections, slow gantry rotation (~1deg/s, 3-4min over 200deg)
- Projection sorting:
  robust, automatic, fast
- Reconstruction:
  under sampled projection data for each phase

Image acquisition approach



- **θ: scan angle for a single phase in one cycle**
- **N_cycle: number of cycles scanned**
- **Ψ: total scan angle for a single phase**

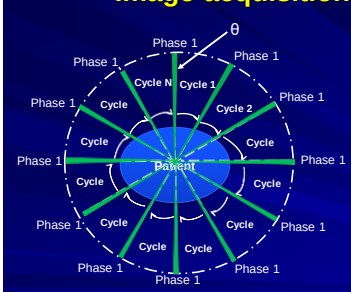
G: gantry rotation speed (≤6°/s)
T: patient respiratory period
N_phase: number of phase bins (typically 10)
Ω: total scanning angle (360° for half fan, 200° for full fan)

$$\theta = \frac{G * T}{N\_phase}$$

$$N\_cycle = \frac{\Omega}{G * T}$$

$$\Psi = \theta * N\_cycle = \frac{\Omega}{N\_phase}$$

Image acquisition approach



$$\theta = \frac{G * T}{N\_phase}$$

$$N\_cycle = \frac{\Omega}{G * T}$$

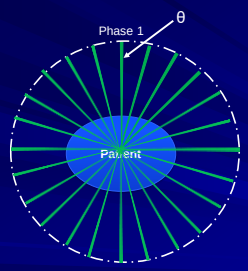
$$\Psi = \theta * N\_cycle = \frac{\Omega}{N\_phase}$$

G↓ ⟶ θ↓ N_cycle↑

Ψ no change, projections more spread out

G = 6°/s, T = 5s, N_phase = 10, Ω = 360° : θ = 3°, N_cycle =12, Ψ=36°

Image acquisition approach



$$\theta = \frac{G * T}{N\_phase}$$

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$$\Psi = \theta * N\_cycle = \frac{\Omega}{N\_phase}$$

G↓ ⟶ θ↓ N_cycle↑

Ψ no change, projections more spread out

G = 3º/s, T = 5s, N_phase = 10, Ω = 360º : θ = 1.5º, N_cycle =24, Ψ=36º

Slow gantry rotation for 4D-CBCT scan to spread out projections to reduce streak artifacts

Image acquisition approach

T=5s, N_phase = 10, Ω = 360º

G=6º/s

G=3º/s

G=1º/s

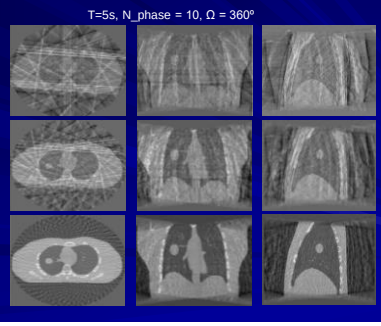


Image acquisition approach

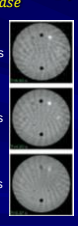
$$\theta = \frac{G * T}{N\_phase} \qquad N\_cycle = \frac{\Omega}{G * T}$$

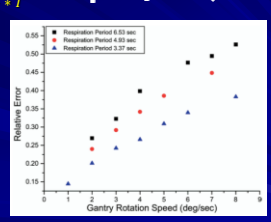
T↑ ⟹ θ↑ N_cycle↓ ⟹ image quality↓

T=6.53s

G=2º/s T=4.93s

T=3.37s





Slower gantry rotation needed for longer respiratory period

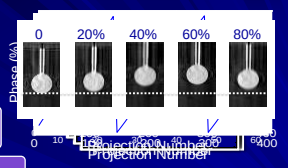
Li et al, 67(4), 1211-1219, *IJROBP*, (2007)

Projection sorting techniques

- 4D-CBCT reconstruction requires sorting of projection images into different respiratory phases.
- Phase sorting methods:
  - External surrogates: bellow system, RPM system, spirometry
    - Require additional devices
    - External internal mis-correlation
  - Internal surrogates: Marker based and markerless methods
    - Marker based method: invasive implantation, marker migration
    - Markerless methods:
      - Tracking structures with respiratory motion
      - Tracking image intensity fluctuation with breathing
      - Motion modeling method

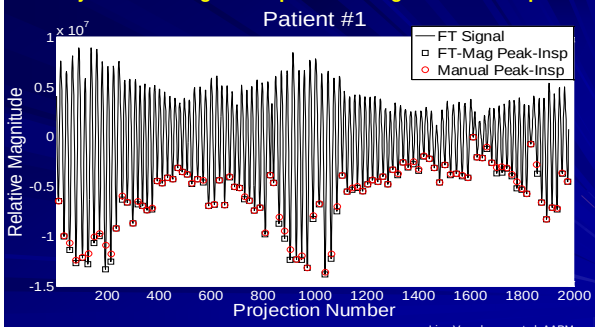
Projection sorting techniques : FT-Magnitude technique

Acquire projections
Perform 2D FT
Extract resp signal
Identify peak-insp
Assign phase
Sort/Bin projections
Recon 4D-CBCT



Irina Vergalasova et al, AAPM Annual Meeting, 2011

Projection sorting techniques : FT-Magnitude technique

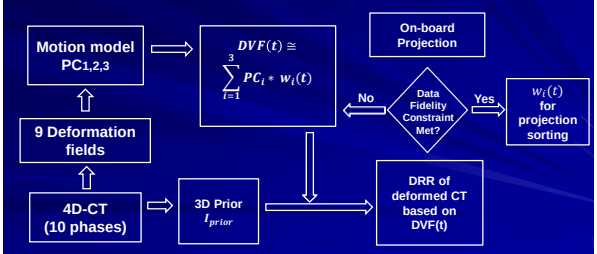


Irina Vergalasova et al, AAPM Annual Meeting, 2011

Projection sorting techniques: Motion modeling based method

Prior Knowledge

On-board volume at time t considered as a deformation of CT

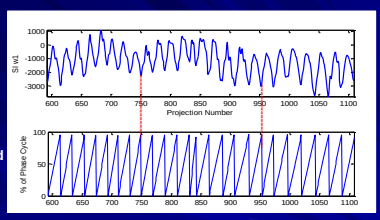


Lei Zhang et al, AAPM Annual Meeting, 2016

Projection sorting techniques: Motion modeling based method

PCA Coefficient SI w1

PCA Coefficient based Phase Sorting



- Robust against changes in tumor size, location, and breathing pattern changes.
- This method could be used in both CBCT full fan and half fan mode, and for different gantry rotation speeds.

Lei Zhang et al, AAPM Annual Meeting, 2016

Projection sorting techniques: Motion modeling based method

Patient Number	Average Phase Difference	Phase Difference within 10%	Phase Difference within 5%
P1 (FF)	2.23%	99.4%	88.9%
P2 (FF)	1.81%	98.7%	93.4%
P3 (HF)	1.62%	100%	99.8%
P4 (HF)	1.82%	100%	96.2%
P5 (HF)	1.63%	98.4%	96.6%

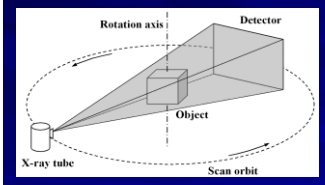
Lei Zhang et al, AAPM Annual Meeting, 2016

Reconstruction techniques

- Feldkamp back projection
- Iterative method with compressed sensing
- Prior image based method: MKB, PICCS
- Motion compensated
- Prior knowledge with motion modeling

Reconstruction techniques: FDK Method

Cone Beam---Feldkamp-Davis-Kress (FDK) algorithm



- A 3D realization of the filtered-back projection algorithm

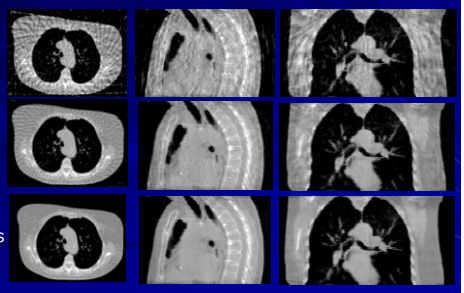
- **Fast, easy-to-implement**
- **Streak artifacts**

Reconstruction techniques: FDK Method

45 projections

90 projections

180 projections



Reconstruction techniques: Iterative method with TV

ART, SART, SIRT + regularizations (TV)

$$\mathrm{TV}(f) = \int ||\nabla f(x)||_1 dx$$

- **Remove streak artifacts for sparse projection sampling in 4D-CBCT**
- **Computationally expensive**
- **Image over smoothed**

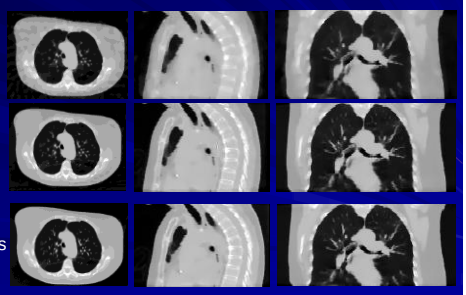
ART: algebraic reconstruction technique
SART: simultaneous algebraic reconstruction technique
SIRT: simultaneous iterative reconstruction technique
TV: total variation

Reconstruction techniques: Iterative method with TV

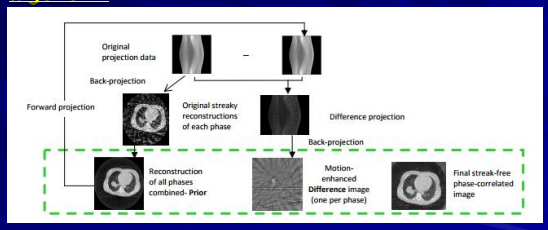
45 projections

90 projections

180 projections



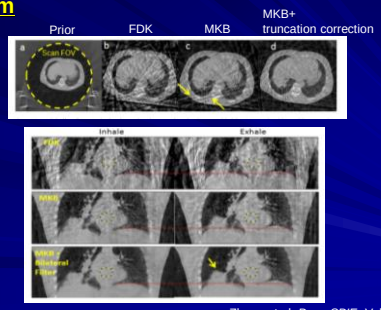
Reconstruction techniques: McKinnon-Bates (MKB) algorithm



- **Less streaks, no over smoothing**
- **Residual motion artifacts**

Zheng et al, *Proc. SPIE*. Vol. 7961, (2011).
McKinnon et al, *IEEE Transactions on Biomedical Engineering*, 2, 123-127, (1981)

Reconstruction techniques: McKinnon-Bates (MKB) algorithm

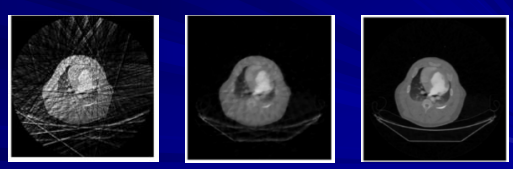


Zheng et al, *Proc. SPIE*. Vol. 7961, (2011).

Reconstruction techniques: prior image constrained compressed sensing (PICCS)

Construct prior image Xp by back projecting all phase projections

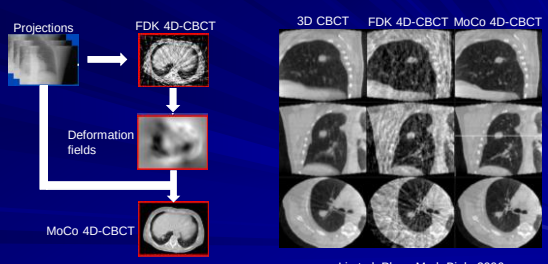
$$\min\left[\propto |\Psi_1(X - X_P)|_{l_1} + (1 - \propto)|\Psi_2 X|_{l_1}\right], \quad \text{s.t. } AX=Y$$



FBP TV PICCS

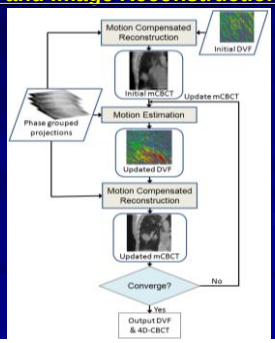
Chen et al, *Med. Phys*., (2008).

Reconstruction techniques: Motion compensated 4D-CBCT (MoCo 4D-CBCT)



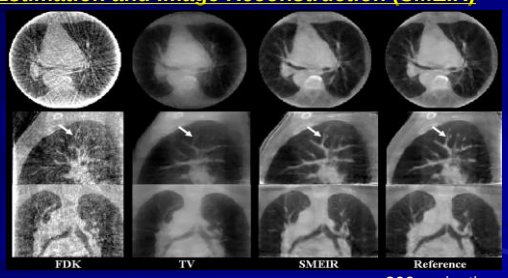
Li et al, Phys. Med. Biol., 2006
Brehm et al., RSNA, 2012
Rit et al, IEEE Trans. Med. Img, 2009

Reconstruction techniques: Simultaneous Motion Estimation and Image Reconstruction (SMEIR)



Wang and Gu, Med. Phys. 2013
Dang et al, IJROBP, 2015

Reconstruction techniques: Simultaneous Motion Estimation and Image Reconstruction (SMEIR)

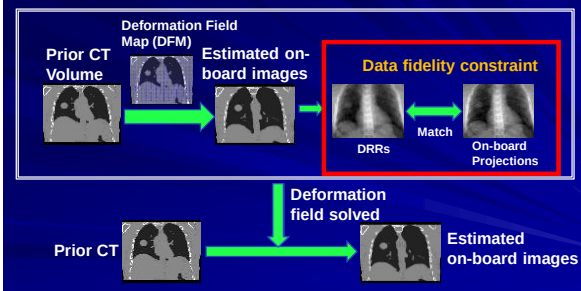


39 projections

200 projections

Dang et al, IJRBP 2015

Reconstruction techniques: prior knowledge based image estimation technique



Ren et al, Med. Phys., 2014

Reconstruction techniques: prior knowledge based image estimation technique

$$\|\mathfrak{M}CBCT_{new}(D, CT) - P\|^2 = 0$$

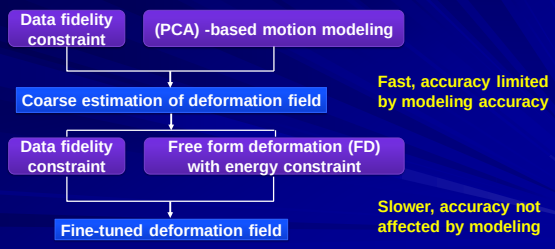
projections

1. $\boldsymbol{D}$ $\sim 10^7$ variables
2. limited-information acquired ($\sim 10^2$ projs)

ill-conditioned problem

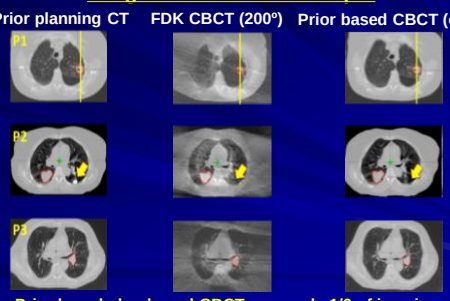
need dimension reduction(modeling) or regularization of $\boldsymbol{D}$

Reconstruction techniques: prior knowledge based image estimation technique



Reconstruction techniques: prior knowledge based image estimation technique

Prior planning CT | FDK CBCT (200°) | Prior based CBCT (ortho 15°)



Prior knowledge based CBCT uses only 1/6 of imaging dose of FDK 4D-CBCT scan

Harris et al, Med. Phys., 2017

4D-CBCT imaging dose

- 4D-CBCT protocol:
  200º, 4min, 1320 projections, 20mA
- PMMA phantom with D=32cm, Length=45cm. TLD every 1.5cm

$$CBDI = \frac{1}{L}\int_{-Y/2}^{Y/2} D(y)dy \qquad CBDI_w = \frac{1}{3}CBDI_{center} + \frac{2}{3}CBDI_{peripheral}$$

	Center	0º	90º	180º	270º	$CBDI_w$
$CBDI_{100}$ (mGy)	12.0±1.2	39.0±3.4	27.1±2.3	2.2±0.3	17.4±1.6	18.5±1.6
$CBDI_{450}$ (mGy)	12.5±0.9	36.3±2.6	25.4±1.9	2.4±0.2	16.6±1.2	17.6±1.3

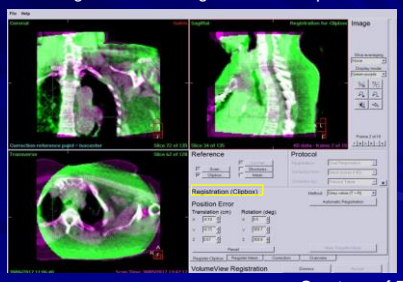
Thengumpallil et al, JACMP, 2016

Clinical applications: pretreatment 4D target localization

Courtesy of Edwin Sham

Clinical applications: pretreatment 4D target localization

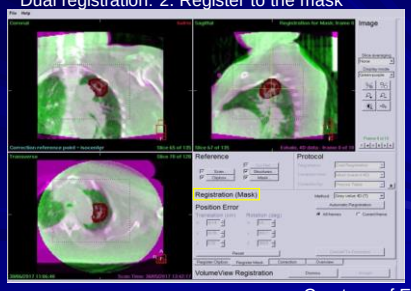
Dual registration: 1. Register to the Clipbox



Courtesy of Edwin Sham

Clinical applications: pretreatment 4D target localization

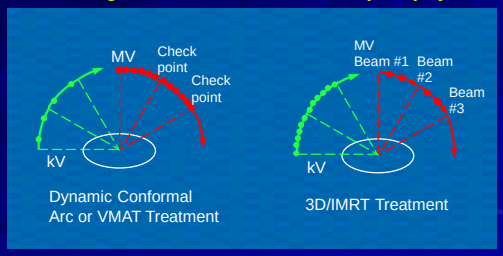
Dual registration: 2. Register to the mask



Courtesy of Edwin Sham

Clinical applications: intra-fraction 4D target localization

Limited-angle Intrafraction Verification (LIVE) System



Ren et al, Med. Phys., 2014

Clinical applications: intra-fraction 4D target localization

Concurrent kV-MV imaging scheme during treatment

Summary

- 4D-CBCT provides on-board 4D images of tumors with respiratory motion to minimize the motion artifacts for target localization.
- 4D-CBCT requires slow gantry rotation, automatic projection sorting and reconstruction algorithms using under sampled data.
- Applications for both inter- and intra-fraction 4D verification.

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