C-arm Cone Beam CT: Basic Principles, Artifacts, and Clinical Applications

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Learning Objectives

- **Basic ideas and methods in C-arm CBCT image reconstruction: FDK Algorithm.**
- **Image artifacts in C-arm CBCT caused by: (1) Geometric mis-calibration, (2) insufficient data acquisition, (3) view angle truncation, (4) detector truncation, and (5) scattered radiation.**
- **Applications of C-arm CBCT in neuro- and cardiac interventions.**

Basic ideas and methods in cone beam reconstruction: FDK algorithm

Logical line of development:

2D Parallel Beam Reconstruction

↓

2D Fan Beam Reconstruction

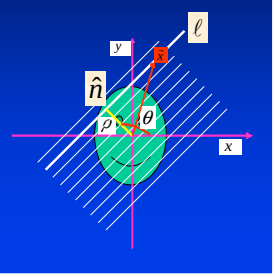
↓

3D Cone Beam Reconstruction

X-ray parallel-beam projections

A line integral of a function f(x,y) along a straight line is given by:

$$R(\rho,\theta) = \int_{\ell} dl f(x,y)$$



2D Radon transform

$$R(\rho,\theta) = \iint dxdy f(x,y)\delta(x\cos\theta + y\sin\theta - \rho)$$

Observation: The two-dimensional Radon transform of a two-dimensional object is a line integral of the object. This coincides with the definition of the two dimensional X-ray parallel beam projections.

Idea and method: Two-dimensional x-ray CT image reconstruction can be performed by a two-dimensional inverse Radon transform (Radon, 1917):

$$f(x,y) = \int_0^{\pi} d\theta \int_{-\infty}^{+\infty} d\rho \frac{R(\rho,\theta)}{(\rho - x\cos\theta - y\sin\theta)^2} = \int_0^{\pi} d\theta \frac{1}{\rho^2} \otimes R(\rho,\theta)\big|_{\rho' = x\cos\theta + y\sin\theta}$$

Parallel Beam FBP Reconstruction

Acquire Projection Data $R(\rho,\theta)$

Filter the projection data

$$F(\rho,\theta) = \frac{1}{\rho^2} \otimes R(\rho,\theta)$$

Fourier transform the projection data

$$\tilde{R}(k,\theta) = \int_{-\infty}^{+\infty} d\rho R(\rho,\theta) e^{-i2\pi k\rho}$$

Ramp Filter the projection data

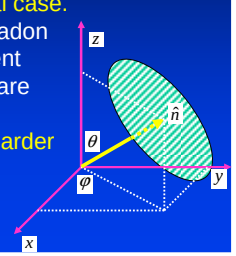
$$F(\rho,\theta) = \int_{-\infty}^{+\infty} dk\, |k|\, \tilde{R}(k,\theta) e^{i2\pi k\rho}$$

Backproject the Filtered Data

$$f(x,y) = \int_0^{\pi} d\theta F(\rho = x\cos\theta + y\sin\theta, \theta)$$

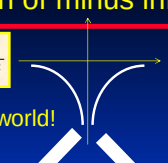
Fully 3D reconstruction is different!

The three-dimensional Radon transform of a three-dimensional object is a planar integral of the function. This situation is different from the two dimensional case. Namely, the three-dimensional Radon transform is fundamentally different from the X-ray projections which are line integrals. Fully 3D image reconstruction problem is much harder to solve!

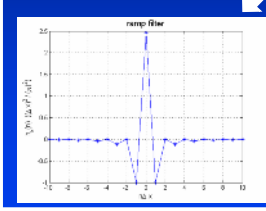


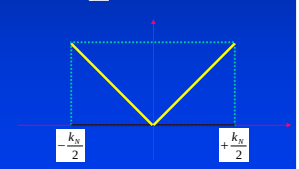
Regularization of minus infinity

$$-\frac{1}{\rho^2}$$



Salvation of the fallen world!

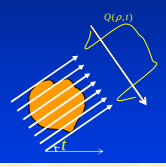




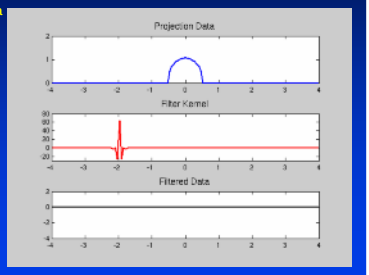
Demonstration: FBP Reconstruction

- Parallel beam FBP

Step 1 Acquire projection data
Step 2 Filter the projection data using a shift-invariant Ramp filtering kernel



$$Q(\rho,\theta) = R(\rho,\theta) \otimes \frac{1}{\rho^2}$$

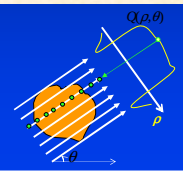


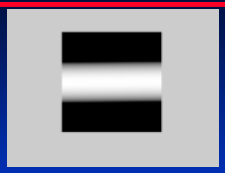
Demonstration: Backprojection

- Parallel beam FBP

Step 1 Acquire projection data
Step 2 Filter the projection data using a shift-invariant Ramp filtering kernel
Step 3 Backproject from each view angle

$$f(x,y) = \int_0^{\pi} d\theta Q(\rho,\theta)|_{\rho = x\cos\theta + y\sin\theta}$$



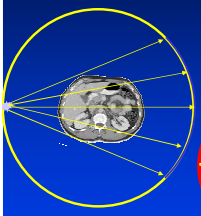


Unfiltered backprojection

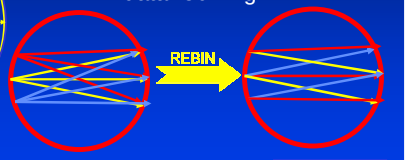
Filtered backprojection

Fan-beam Reconstruction

Question: How to reconstruct image from fan-beam data which is how the CT data is acquired?



The easiest and the most powerful idea: data rebining

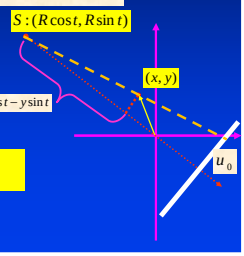


Fan-beam reconstruction ⇒ Parallel-beam reconstruction

Fan-beam Reconstruction

$$f(x,y) = \frac{1}{4\pi^2} \int_0^{2\pi} dt \frac{R}{U^2(x,y;t)} F(t, u = u_0)$$

$$U = R - x\cos t - y\sin t$$



The distance between the source point and the projection of the image point onto the iso-ray!

Fan-beam Reconstruction: Short scan condition

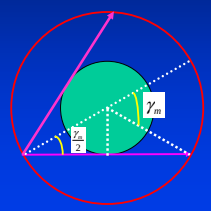
Conditions to make sense of the above coordinate transform (fan to parallel):

(1)No data truncation

(2)Angular range should not be shorter than the co-called short-scan condition

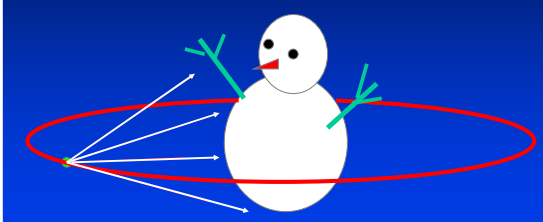
Short-scan Angular range:

$$\pi + \text{fan angle}\,(\gamma_{\mathrm{m}})$$



FDK cone beam reconstruction

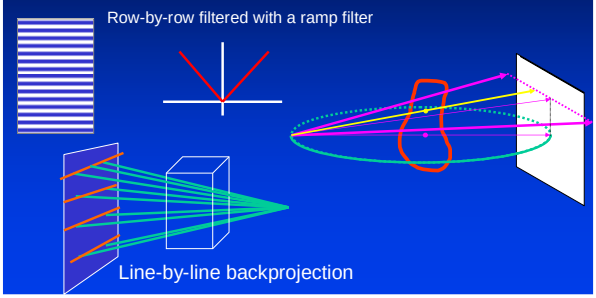
FDK algorithm (Feldkamp, Davis, and Kress,1984)



FDK Algorithm

Basic Idea: Treat a cone-beam reconstruction problem as a fan-beam reconstruction problem! This is only an approximation.

Row-by-row filtered with a ramp filter

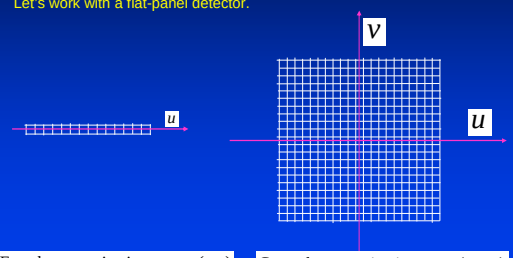


Line-by-line backprojection

FDK Image Reconstruction

With the ideas being told, let's write down something you can work with your computer!

Let's work with a flat-panel detector.

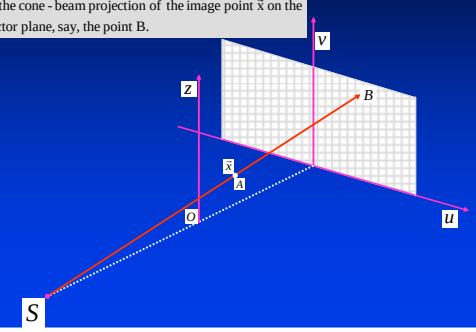


Fan - beam projections : $g_{\mathrm{m}}(t,u)$

Cone - beam projections : $g_{\mathrm{m}}(t,u,v)$

Step 1: Find a detector row for a given image point

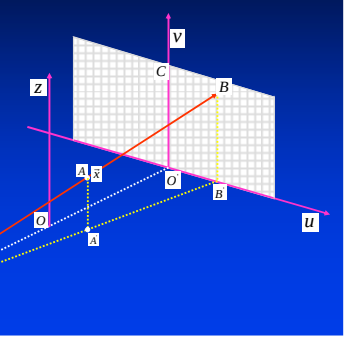
STEP 1: For a given image point $\bar{x}$ and a given focal spot position S, find the cone-beam projection of the image point $\bar{x}$ on the detector plane, say, the point B.



Step 2: Cosine weight

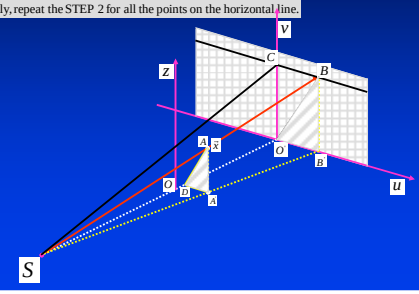
STEP 2: Project the cone-beam data detected at the point B, (u, v), onto the scaning plane by multiplying a factor $\cos\tau$.

$$g_m'(t,u) = g_m(t,u,v)\cos\tau$$
$$= g_m(t,u,v)\frac{|\vec{SB'}|}{|SB|}$$
$$= g_m(t,u,v)\frac{\sqrt{D^2+u^2}}{\sqrt{D^2+u^2+v^2}}.$$



Step 3: Repeat cosine weight for all measured data along the selected detector row

STEP 3: Draw a horizontal line (BC) passing throught the point B in the detector plane. Project the cone-beam data along the line BC onto the scanning plane by the same scaling factor $\frac{\sqrt{D^2+u^2}}{\sqrt{D^2+u^2+v^2}}$. Namely, repeat the STEP 2 for all the points on the horizontal line.



Step 4: fan-beam reconstruction

STEP 4: Use the projected cone-beam data $g_m'(t,u)$ and the fan-beam reconstruction formula to reconstruct an image. We treat this reconstructed image as a slice of image at $z = z_0$.

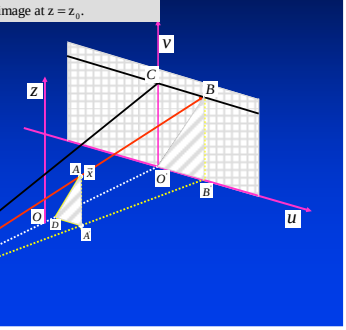
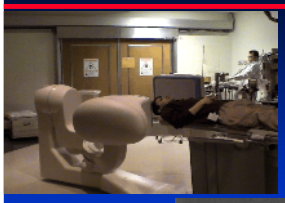


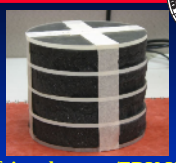
Image Artifacts in C-arm Cone Beam CT

Image artifacts related to image reconstruction:

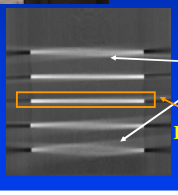
1.Circular scan never provides us sufficient information for a perfect reconstruction of a 3D image object. (Cone Beam Artifacts or FDK artifacts)
2.We have assumed a perfect circular source trajectory in image reconstruction. In practice, this condition is often violated by mechanical instability and gravitational force. (Geometric calibration artifacts)
3.We have assumed that detector is wide enough to cover the entire image cross section, but in reality, flat-panel detector is often not wide enough. (Data truncation artifacts)
4.We have assumed data acquisition must satisfy the short scan condition, but this can be violated in practice. (View truncation artifacts)

Cone beam artifacts/FDK artifacts

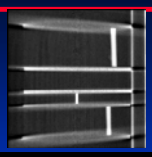




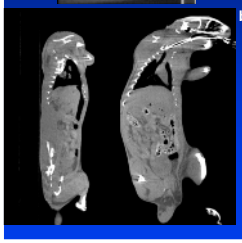
Defrise phantom/FDK Killer



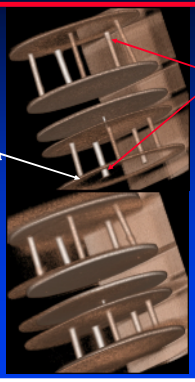
Cone-beam artifacts



High Threshold Values



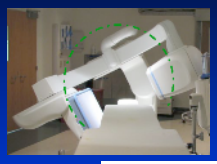
Disc becomes a ring!

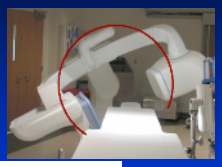


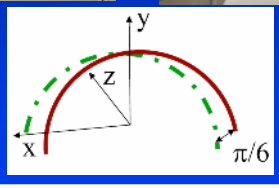
Radius Change

Low Threshold Values

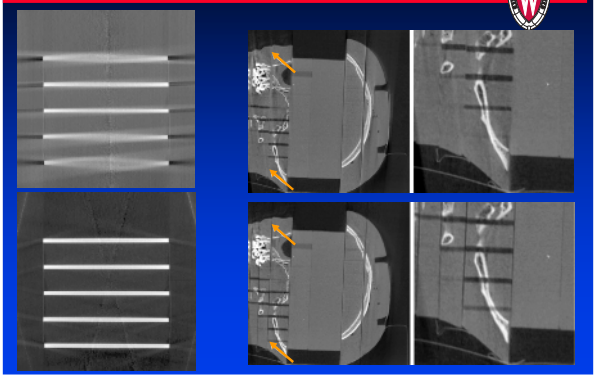
Solution of cone-beam artifacts: Complete scanning protocols







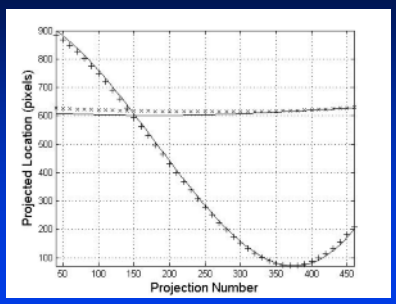
CC-Arm based cone-beam CT Results



Calibration phantom: Helical BB

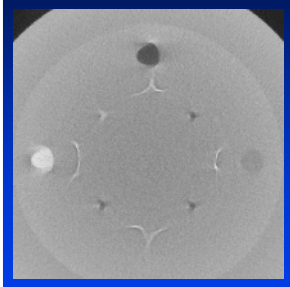
- The helix has a total of 41 beads. The central bead is larger than all the others.
- Diameter is 130 mm and overall length is 250 mm.
- Large helix size provides a good filling of the field of view.

Angular positions and projection onto detector plane: Theoretical and experimental values

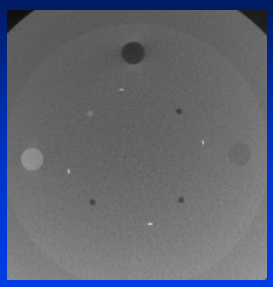


Phantom Results: Catphan Phantom

Without calibration

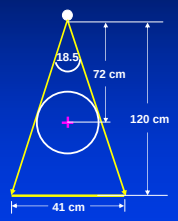


With calibration



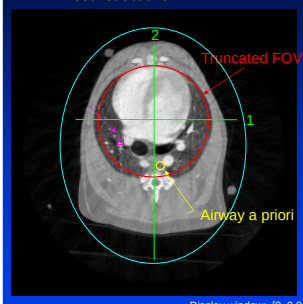
Truncation artifacts

Flat Panel Detector: 41 cm x 41 cm
Scanning Field of View: 25 cm x 25 cm



Truncation artifacts

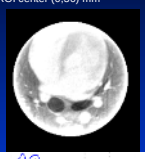
FDK reconstructions

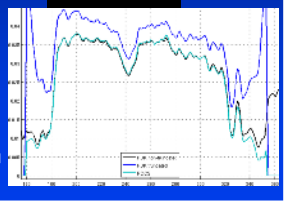


Full FOV
ROI radius 110mm
ROI center (0,0) mm

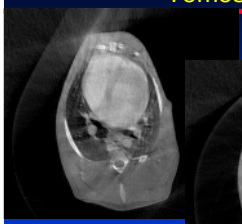
Display window: [0, 0.04]
Image matrix: 512x512
Image size: 240x240mm

Fully truncated reconstruction
ROI radius 48mm
ROI center (0,30) mm

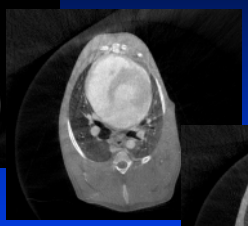




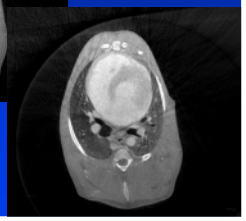
View angle truncation artifacts: Tomosynthesis artifacts



150 degrees

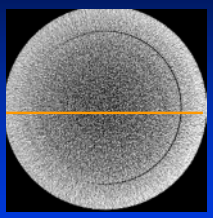


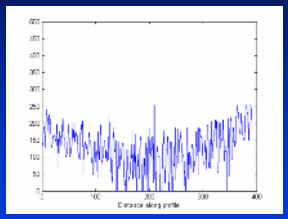
180 degrees



210 degrees

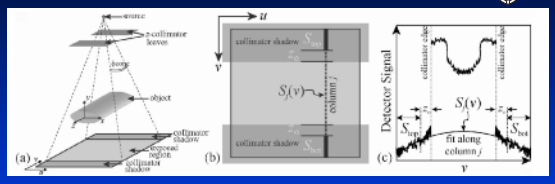
Scatter artifacts





Zhuang, Zambelli, et al , SPIE(2008)

Principle of a scatter correction algorithm

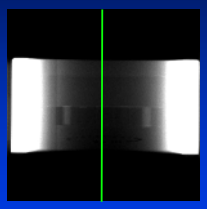


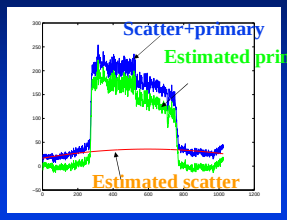
SPECS Algorithm :
Scatter and Primary Estimation from Collimator Shadows

Estimate the scatter fluence by interpolating the measured data in the collimator shadows

Siewerdsen et al., Med. Phys. 33 :187-97 (2006)

An example from Catphan



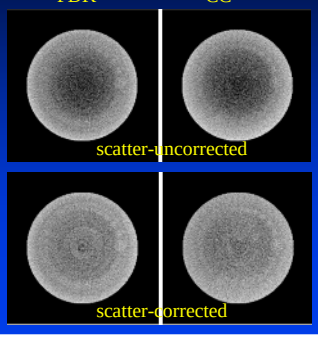


Zhuang, Zambelli, et al SPIE (2008)

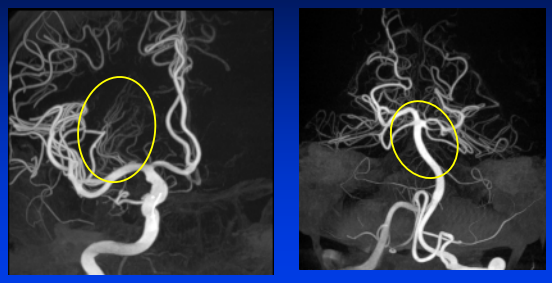
C-Arm based cone-beam CT
Results: Low contrast resolution

FDK CC

70 kVp

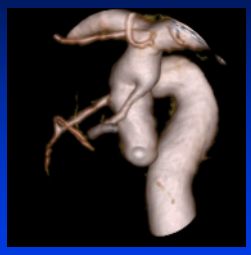


Good spatial resolution

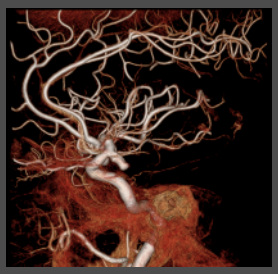


Vasculature visualization

Analysis of the relationships between aneurysm and adjacent vessels



Intracranial aneurysm



Initial 3D image produced by Innova 3D

Bone removal using Auto-Select interactive tools on AW (movie)

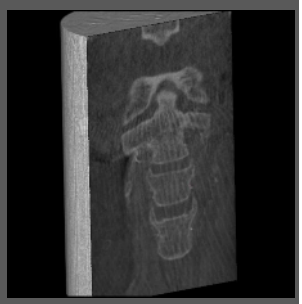
AVM (arteriovenous malformation)

Coronal cross-sections (movie)

Sagittal cross-sections (movie)

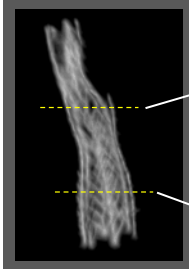
Medula AVM

Volume Rendering (movie)

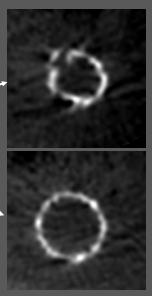


Fused Volume Rendering (movie)

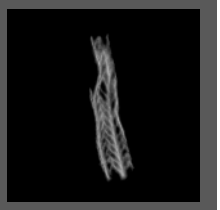
Common carotid stenosis – Post-stenting



One strut of the stent got broken, because of difference in diameters between proximal and distal parts of the stented segment



Axial cross-sections



Movie loop, with posterior part of the stent removed for better visibility of the broken strut

Analysis of stent deployment with Innova 3D/CT

Cardiac C-arm CT: Preclinical results

Gantry rotation speed: 15 deg/second

Short scan angular range: 210 degrees

Gantry rotation time: 14 seconds

Detector readout speed: 30 fps (33ms/frame)

Heart rate: 83-85 bpm

kVp: 70

mA: 200

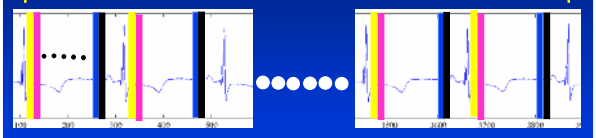
Pulse width: 5ms

mAs/view: 1 mAs

Total mAs: 420 mAs

In vivo animal experiments

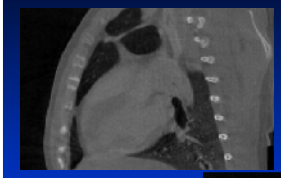
420 projections/gantry rotation (short scan)



About 20 heart beats during the 14 seconds data acquisition time.

Chen et al, SPIE (2009)

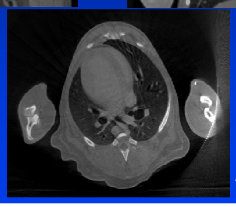
Prior Images Used in PICCS



Coronal Slice

Sagittal Slice

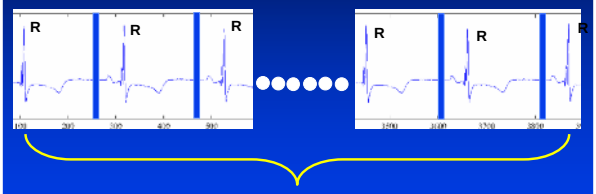
No Temporal information in Prior images!



Axial Slice

Retrospective ECG-Gating

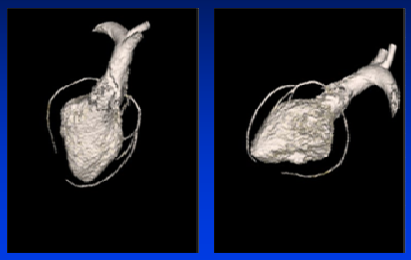
Acquired 420 projections are gated into different cardiac phases using % R-R interval.



19 heart beats: 19 cone-beam projections/cardiac phase

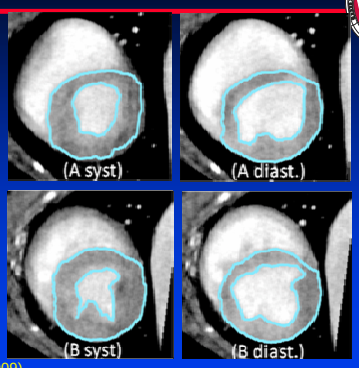
Chen et al, SPIE (2009)

PICCS-CT: vascular imaging



Chen et al, SPIE (2009)

PICCS-CT: cardiac function imaging

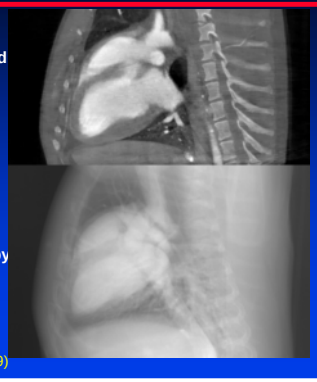


Chen et al, SPIE (2009)

Validation using real-time x-ray fluoroscopy

PICCS Time-Resolved Cardiac Imaging
30 frame/second

Real-time fluoroscopy
30 frame/second



Chen et al, SPIE (2009)

Summary: Take Home Message

1. FDK cone beam reconstruction is a hybrid of fan beam reconstruction and data projection onto the scanning plane.
2. Common artifacts: cone-beam, gantry miscalibration, truncation, scatter.
3. Applications of C-arm CBCT in image guided vascular interventions: vasculature, aneurism, AVM, stent
4. Potential applications of C-arm CBCT in image guided cardiac interventions

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