ADVANCES IN C-ARM CBCT FOR CARDIAC INTERVENTIONS

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- NIH Industry-Academia Partnership R01 with Varian (Ginzton Technology Center)
- Founder, Tibaray Inc.
- Employee, Siemens Healthcare, Sept. 1, 2015

What's happening in the Interventional Suite?

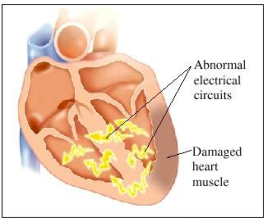
- Number and complexity of minimally invasive interventions ⬆
- Non-cardiac:
  - mechanical thrombectomy for stroke treatment
  - chemoembolization for hepatic tumor treatment
- Cardiac :
  - EP, IC, trans-catheter valve replacement
  - new molecular therapies for targeted treatment of ischemia are under development
- Quantitative imaging **during the procedure** is the goal…

Need for quantitative information

- Need information on the **current** status of the patient:
  - Size and location of ischemic tissue
  - Accurate 3D geometry for device sizing
  - Motion of the heart chambers, coronary arteries etc.
- Need for feedback during the intervention:
  - Are the lesions we create contiguous? Are they transmural? Are they big enough?
  - Have we changed the ventricle dynamics?

Cardiac arrhythmia

- Caused by unwanted electrical foci
- Risks associated with arrhythmia:
  - Atrial Fibrillation (AF) : 15% of all strokes (~70,000)
  - Ventricular Tachycardia (VT) : high risk of sudden cardiac death

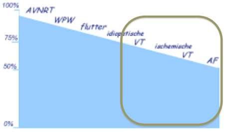


Motivation - RF ablation for arrhythmia

- Current treatments
  - medication (~50% successful)
  - implantable cardioverter-defibrillator
  - catheter ablation
- Radiofrequency ablation (RFA)
  - Often a first-line therapy
  - Radiofrequency (RF) energy
  - Burn undesirable electrical foci

Motivation - RF ablation

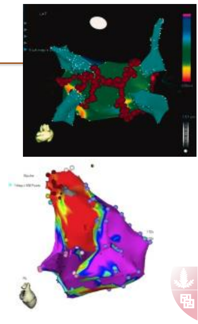
- Procedures take 2-5 hours
- Procedure success is highly variable
  - 50-80% effective for ventricular arrhythmias and atrial fibrillation
- Many follow-up procedures



Average Effectiveness of RF Ablation Procedure
http://www.mayoclinic.com/health/heart-arrhythmias/ 2007

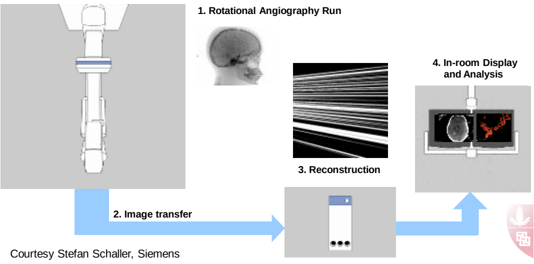
Motivation - RF ablation

- Currently indirect measurements of lesion formation:
  - RF energy delivered
  - temperature at catheter tip
  - mapping/catheter tracking



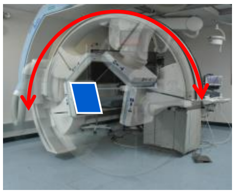
Crandall M A et al. Mayo Clin Proc. 2009;84:643-662

Creating 3D Images in the Interventional Lab



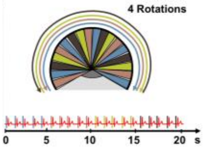
Courtesy Stefan Schaller, Siemens

C-arm System :: Clinical CT



C-arm CT with ECG gating

- Timing the return of each rotation properly provides sufficient data for a reconstruction of ¼ of the cardiac cycle e.g. in diastole



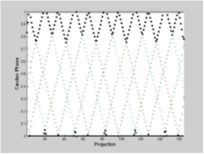
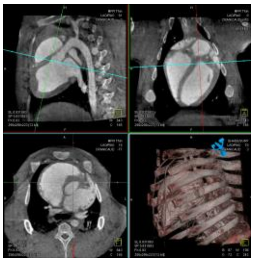


Image Quality under Ideal Conditions

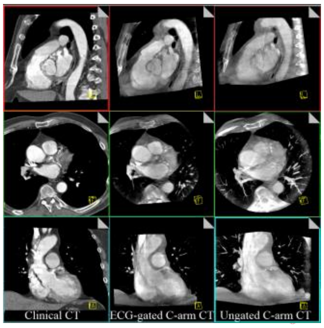
- Pig model
- 45-55 kg
- Ideal breath hold
- 'low'-ish scatter (ie. small thorax)
- Low heart rate (60 bpm)



First Humans

- 4 sweeps,
- 4s per sweep, ~200 projections per sweep
- Total scan time ~20 s (including time for C-arm turn around)
- total breath hold ~ 24 s

Al-ahmad, A., Wigstrom, L., Sandner-Porkristl, D., Wang, P.J., Zei, P.C., Boese, J., Lauritsch, G., Moore, Chan, F., Fahrig, R. "Time-resolved three-dimensional imaging of the left atrium and pulmonary veins in the interventional suite – A comparison between C-arm CT and Multislice CT." *Heart Rhythm* 5 (4), 513-519, (2008).



In vivo imaging protocol

150mL Omnipaque (350 mg/mL) peripheral venous (IVC) injection — no high-contrast streak uniform perfusion

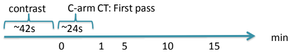
42 s delay for first-pass image — no high-contrast streak

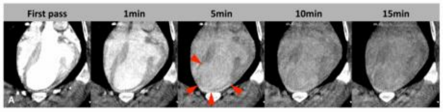
4 sweeps x 5s ECG-gated — freeze motion

90 and 70 kV, 1.2µGy/p (24mSv) — low contrast detectability

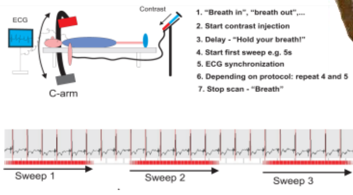
Collimate around heart — reduce scatter

Timing

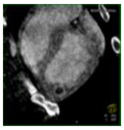




monitor radiofrequency ablation treatment

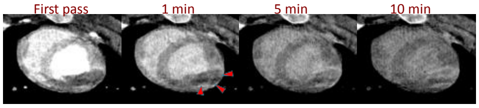


1. "Breath in", "breath out",...
2. Start contrast injection
3. Delay - "Hold your breath!"
4. Start first sweep e.g. 5s
5. ECG synchronization
6. Depending on protocol: repeat 4 and 5
7. Stop scan - "Breath"



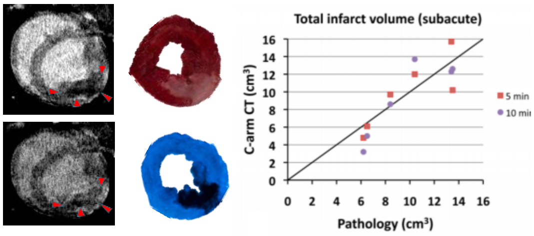
Imaging Myocardial Infarct

- The total volume of Acute Myocardial infarction and Microvascular Obstruction can be accurately assessed using ECG-gated C-arm CT
- An imaging time of ~1-5 min post contrast injection could be used to assess both total infarct size and Microvascular Obstruction volume



Girard EE, Al-Ahmad A, Rosenberg J, Luong R, Moore T, Lauritsch G, Chan F, Lee DP, Fahrig R, "Contrast-Enhanced C-arm Computed Tomography Imaging of Myocardial Infarction in the Interventional Suite." Invest. Radiol. 2015 Jan 29

Total Infarct Volume can be Measured



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But…

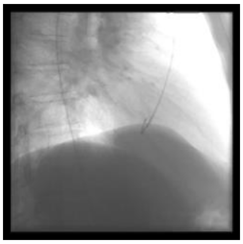
- **ECG gating : soft tissue contrast but long breath hold…**
- **Goals:**
  - 4-D reconstruction of cardiac chambers using single C-arm sweep
  - Extraction of quantitative functional parameters
- **Clinical applications:**
  - Ventricular procedures, e.g. ventricle ablation guidance
  - Mitral valve repair, e.g. guidance of annuloplasty
  - Functional analysis, e.g. identification of pathological regions

Two options for motion estimation / compensation

1. Surface-based
   - One chamber imaging, e.g. left ventricle (LV)
     → allows delineation of object in 2-D projections
   - Short acquisition (5 s)
   - Direct contrast administration
   - Min. 5 heart cycles → sinus rhythm
2. Volume-based
   - Two to four chamber imaging
     → overlapping objects in 2-D projections
   - Longer acquisition (14 s)
   - Systemic contrast administration
   - Min. 25 heart cycles → moderate heart pacing

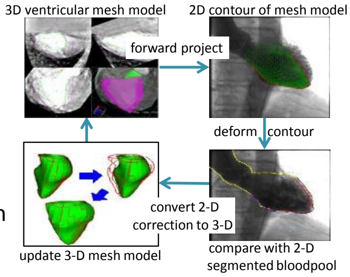
Option 1

- Surface-based motion correction
  - One chamber imaging, e.g. left ventricle (LV)
    allows delineation of object in 2-D projections
  - Short acquisition (5 s)
  - Direct contrast administration
  - Minimum 5 heart cycles … sinus rhythm



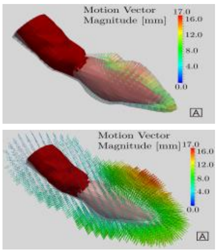
Surface-based Motion Estimation

- Tomographic reconstruction with only 5 views per cardiac phase is not possible
- Surface-based motion estimation



Dense Motion Vector Field

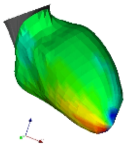
- Evaluation of interpolation methods from surface to voxel-based motion
  - Thin-plate splines
  - Linear methods



K. Müller et al., "Evaluation of interpolation methods for surface-based motion compensated tomographic reconstruction for cardiac angiographic C-arm data", *Medical Physics* **40**, 3 (Feb. 2013)

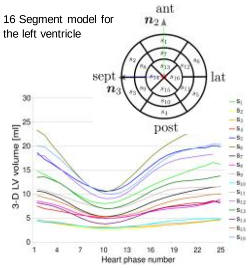
Wall Motion Analysis

- Quantitative wall motion analysis
  - Ejection fraction
  - Time to max. contraction
  - Systolic dyssynchrony index



color coded according to time to maximal contraction of the ventricle

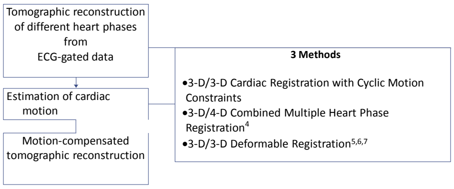
16 Segment model for the left ventricle



Contraction curves of the individual 16 left ventricular segments over one heart cycle.

K. Müller et al., "Interventional Heart Wall Motion Analysis with Cardiac C-arm CT Systems", *Physics in Medicine and Biology* **59**, 9 (Apr. 2014), pp. 2265–2284

Volume-based Approach



Tomographic reconstruction of different heart phases from ECG-gated data

Estimation of cardiac motion

Motion-compensated tomographic reconstruction

3 Methods

- 3-D/3-D Cardiac Registration with Cyclic Motion Constraints
- 3-D/4-D Combined Multiple Heart Phase Registration[4]
- 3-D/3-D Deformable Registration[5,6,7]

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[4] K. Müller et al., "4-D Motion Field Estimation by Combined Multiple Heart Phase Registration (CMHPR) for Cardiac C-arm Data", *IEEE Nuclear Science Symposium and Medical Imaging Conference Record (NSS/MIC), 2012*, Anaheim, CA, USA, 2012, pp. 3707–3712

[5] K. Müller et al., "Image Artifact Influence on Motion Compensated Tomographic Reconstruction in Cardiac C-arm ct", *Fully Three-Dimensional Image Reconstruction in Radiology and Nuclear Medicine, 2013*, Lake Tahoe, CA, USA, 2013, pp. 98–101

[6] K. Müller et al., "Image Artefact Propagation in Motion Estimation and Reconstruction in Interventional Cardiac C-arm ct", *Physics in Medicine and Biology* (2014), accepted for publication

[7] K. Müller et al., "Catheter Artifact Reduction (CAR) in Dynamic Cardiac Chamber Imaging with Interventional C-arm ct", *The Third International Conference on Image Formation in X-Ray Computed Tomography*, Salt Lake City, UT, USA, 2014, accepted for publication

3-D/3-D Deformable Registration

Choose a reference heart phase from K heart phases
For each reference phase, register $(K - 1)$ remaining heart phases

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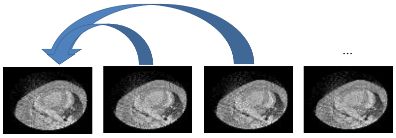

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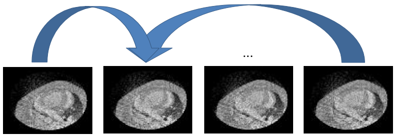
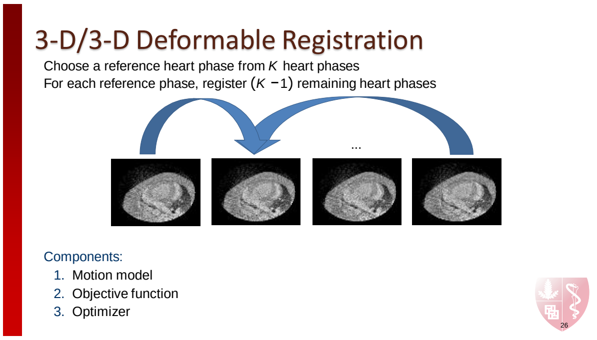




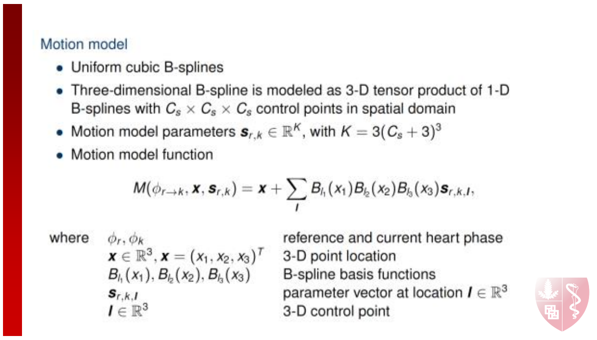
3-D/3-D Deformable Registration

Choose a reference heart phase from K heart phases

For each reference phase, register $(K-1)$ remaining heart phases

Components:

1. Motion model
2. Objective function
3. Optimizer

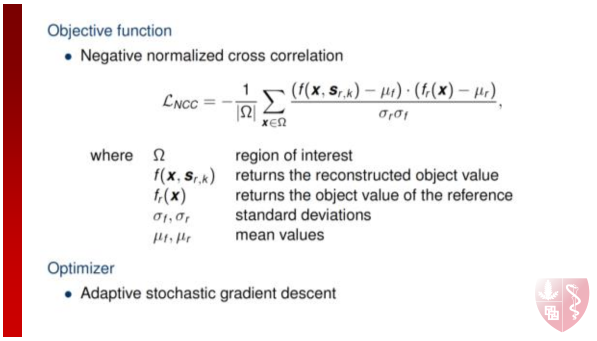


Motion model

- Uniform cubic B-splines
- Three-dimensional B-spline is modeled as 3-D tensor product of 1-D B-splines with $C_s \times C_s \times C_s$ control points in spatial domain
- Motion model parameters $\boldsymbol{s}_{r,k} \in \mathbb{R}^K$, with $K = 3(C_s + 3)^3$
- Motion model function

$$M(\phi_{r \to k}, \boldsymbol{x}, \boldsymbol{s}_{r,k}) = \boldsymbol{x} + \sum_{\boldsymbol{l}} B_{l_1}(x_1) B_{l_2}(x_2) B_{l_3}(x_3) \boldsymbol{s}_{r,k,\boldsymbol{l}},$$

where	ϕ_r, ϕ_k	reference and current heart phase
	$\boldsymbol{x} \in \mathbb{R}^3, \boldsymbol{x} = (x_1, x_2, x_3)^T$	3-D point location
	$B_{l_1}(x_1), B_{l_2}(x_2), B_{l_3}(x_3)$	B-spline basis functions
	$\boldsymbol{s}_{r,k,\boldsymbol{l}}$	parameter vector at location $\boldsymbol{l} \in \mathbb{R}^3$
	$\boldsymbol{l} \in \mathbb{R}^3$	3-D control point



Objective function

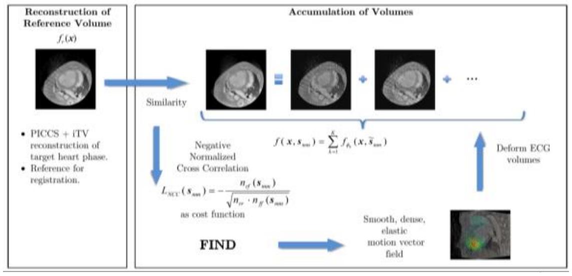
- Negative normalized cross correlation

$$\mathcal{L}_{NCC} = -\frac{1}{|\Omega|} \sum_{\boldsymbol{x} \in \Omega} \frac{(f(\boldsymbol{x}, \boldsymbol{s}_{r,k}) - \mu_f) \cdot (f_r(\boldsymbol{x}) - \mu_r)}{\sigma_r \sigma_f},$$

where	Ω	region of interest
	$f(\boldsymbol{x}, \boldsymbol{s}_{r,k})$	returns the reconstructed object value
	$f_r(\boldsymbol{x})$	returns the object value of the reference
	σ_f, σ_r	standard deviations
	μ_f, μ_r	mean values

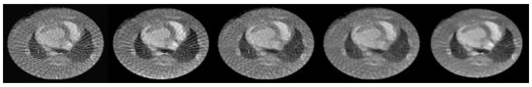
Optimizer

- Adaptive stochastic gradient descent



Volume-based Motion Estimation

Question:
Which 'image enhancement' approach is best suited for subsequent 3-D/3-D registration?



(a) ECG-gated FDK (FDK)

(b) Bilateral-filtered (FFDK)

(c) Catheter-removed (cathFDK)7

(d) Catheter-removed & bilateral-filtered (cathFFDK)

(e) Constrained iterative few-view (FV)

→ Motion-compensated reconstructions are denoted with suffix -MC

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[7] K. Müller et al., “Catheter Artifact Reduction (CAR) in Dynamic Cardiac Chamber Imaging with Interventional C-arm ct”, *The Third International Conference on Image Formation in X-Ray Computed Tomography*, Salt Lake City, UT, USA, 2014, accepted for publication

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Porcine in vivo model

- Artis zee systems (Siemens Healthcare)
- Acquisition 14.5 s, 30 fps, and 381 projection images
- Heartrate of 331 bpm through moderate pacing
- ~30 projections available for reconstruction of each heart phase

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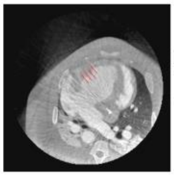
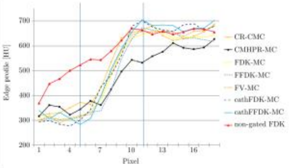
[8] K. Müller et al., “Left Ventricular Heart Phantom for Wall Motion Analysis”, *IEEE Nuclear Science Symposium and Medical Imaging Conference Record (NSS/MIC), 2013*, Seoul, Korea, 2013

[9] available online *https://conrad.stanford.edu/data/heart*

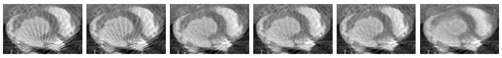
Edge Sharpness Evaluation





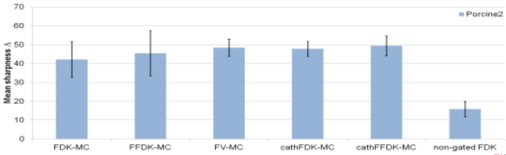
Quantitative Porcine Results

Results for porcine model 2 in a systolic heart phase

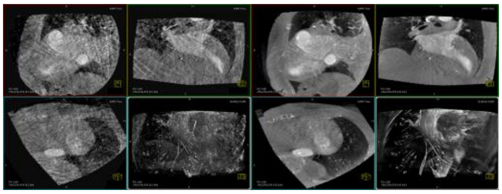


(a) FDK-MC (b) FFDK-MC (c) FV-MC (d) cathFDK-MC (e) cathFFDK-MC (f) non-gated FDK

Fig. 25: Zoomed results for porcine model 2.



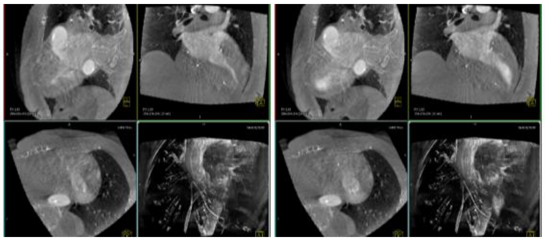
First Clinical Results



(a) FDK (b) cathFDK-MC

First results with cathFDK-MC reconstruction of a end-diastolic (3± 1 %) heart phase (W 2080 HU, C 110 HU, slice thickness 1 mm).

Image courtesy of Dr. med. Abt and Dr. med. Köhler, Herz- und Kreislaufzentrum Rotenburg a. d. Fulda, Germany.



Systolic heart phase

Diastolic heart phase

Image courtesy of Dr. med. Abt and Dr. med. Köhler, Herz- und Kreislaufzentrum Rotenburg a. d. Fulda, Germany.

Summary : Single-sweep

Trade-off: temporal resolution ↔ angular sampling

- Two approaches for motion-compensated tomographic reconstruction
  - Surface-based
    - Sensitive to surface mesh generation (-)
    - Potential for interventional wall motion analysis (+)
    - Short acquisition protocol (5 s) with sinus rhythm (+)
  - Volume-based
    - High computational demand (-)
    - Reconstruction of two to four heart chambers (+)
    - Improved image quality compared to state-of-the-art methods (+)

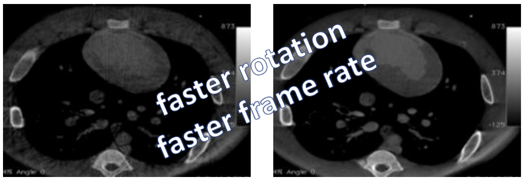
C-arm CT : The Future

Can we achieve clinical CT image quality in the interventional suite?

- Further reduce artifacts
- Reduce imaging time and x-ray dose for multi-sweep acquisitions
- Reduce computation time for single-sweep motion compensated reconstruction
- New applications on the horizon…

Cardiac Imaging

- Reduce residual motion and streaking
- Implement prospective gating



Conclusions

- C-arm CT has the potential to
  - increase accuracy,
  - reduce repeat interventions,
  - reduce total intervention time and
  - reduce x-ray dose
- Many new clinical applications are under investigation
- Plenty of work remains to increase clinical utility :
  - image display, 2D-3D, cross-modality integration
  - fast iterative reconstruction
  - new hardware

Thank you!

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Hewei Gao
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~~Andreas Maier~~
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Jang-Hwan Choi

Benjamin Keck
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Christine Niebler
Chris Schwemmer
Andreas Feiselmann
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Marily Sarmiento
Christine Niebler

Cardiac Imaging

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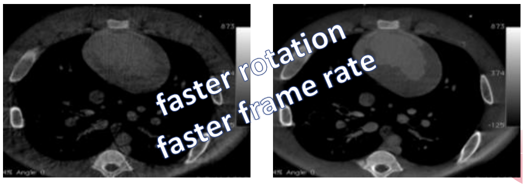
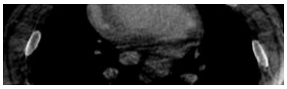


faster rotation
faster frame rate

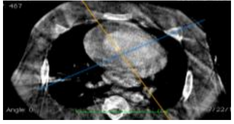
Sources of Major Artifacts

- motion
- beam hardening
- scatter
- undersampling
- dynamic range limits

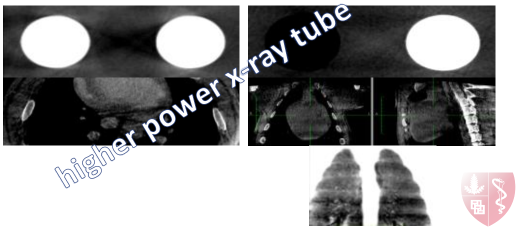
Shading



Streaking



Beam hardening



New Detector Technology Needed!

- provide high-resolution fluoroscopy
- increase x-ray detection efficiency at high energies for C-arm CT

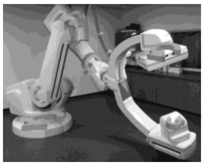
One Detector fits All?

- Competing requirements…
  - High resolution (75 µm for stent strut imaging, c[illegible]e, other typically high-contrast structures)
  - High frame rates for good sampli[illegible] acquisition times
  - Excellent low-contrast re[illegible]itative perfusion imaging at 600 µm resolution
  - Photon c[illegible] discriminating for dose reduction and beam harde[illegible]on

X-ray tube requirements?

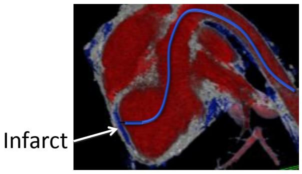
And while we're at it…

- the dream of continuous CT-gantry-like rotation…



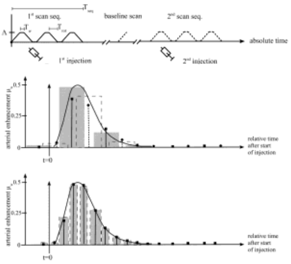
Guiding cellular or molecular therapies

- tool useful for clinical trials



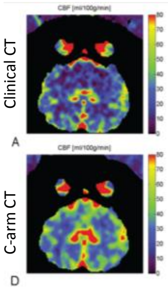
Perfusion Imaging

- minimum temporal sampling required for brain perfusion imaging < 3.5 s (depends on profile of injected iodine?)
- interleaved multi-sweep acquisitions with multi-segment reconstruction increases sampling



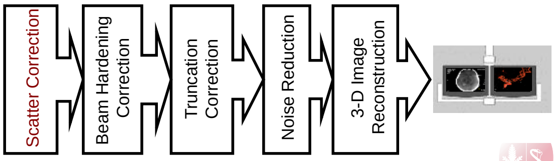
Cerebral Perfusion

- Clinical CT vs. C-arm CT (2-injection 6-sweep protocol)
- Correlation coefficient 0.88
- Concordance coefficient 0.75
- Two injection vs. 3-6 injections did not show significant degradation



Challenge #1 : Accurate HU values

- 10 HU noise (40 HU contrast) in a 10 mm slice acquired in 10 s, for detection of a 10 mm diameter object … 10^4



Existing Methods

- Remove or prevent scattered radiation
  - (scatter grid, slit scan)
- Compute scatter to subtract it
  - (Monte Carlo, convolution-based…)
- Measure scatter distribution and subtract it

Existing Methods

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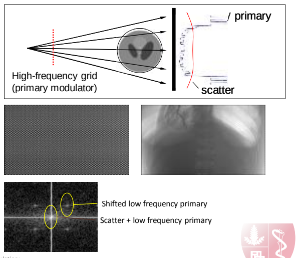
Primary Modulation-Based Scatter Estimation

- Idea: Insert high frequency modulation pattern between the source and the object scanned
- Assumption: The primary image is modulated. The scatter is created in the object and only consists of low frequency components.
- Method: Estimate low frequency primary without scatter by Fourier filtering techniques



L. Zhu, R. N. Bennett, and R. Fahrig, "Scatter correction method for x–ray CT using primary modulation: Theory and preliminary results," IEEE Transactions on Medical Imaging, vol. 25, pp. 1573–1587, Dec. 2006.

Primary Modulation-Based Scatter Estimation

- Advantages:
  - Measurement of the scatter distribution
  - Works with high accuracy on laboratory setups
  - Corrected projection data can still be used (fluoroscopy)
- Drawbacks:
  - Requires exact rectangular pattern on the detector
  - Very sensitive to non-idealities of the projected modulation pattern (blurring, distortion, manufacturing errors of the modulator).
  - Sensitive to non-linearities due to polychromacity of x-rays (=> ECCP).

R. Grimmer, R. Fahrig, W. Hinshaw, H. Gao, and M. Kachelrieß, Empirical cupping correction for CT scanners with primary modulation (ECCP)," Med. Phys., vol. 39, pp. 825-831, Feb. 2012.

Modulation process in the raw data domain

- Measured data:

measured intensity

primary intensity

$$c_\mathrm{M} = M \cdot c_\mathrm{P} + c_\mathrm{S}$$

Modulation pattern

Scatter intensity

- Solving for primary intensity:

$$c_\mathrm{P} = M^{-1} \cdot (c_\mathrm{M} - c_\mathrm{S})$$

- Error in the primary estimate:

$$c_\mathrm{P}^\mathrm{est} = M^{-1} \cdot (c_\mathrm{M} - c_\mathrm{S}^\mathrm{est})$$

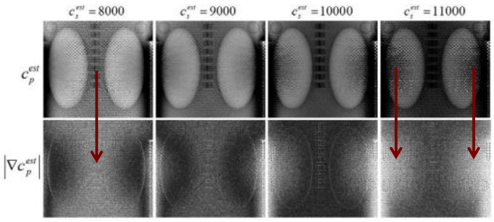
Error in scatter estimate

$$= M^{-1} \cdot (c_\mathrm{M} - \Delta_S - c_\mathrm{S})$$

$$= c_\mathrm{P} - \boxed{M^{-1} \cdot \Delta_S.}$$

L.Ritschl, R. Fahrig, M. Knaup, J. Maier, and M. Kachelrieß, Robust Modulation-based Scatter Estimation for Cone-Beam CT," accepted for publication in Med. Phys.

Cost function?



Gradient-based cost function

spatial gradient of the image

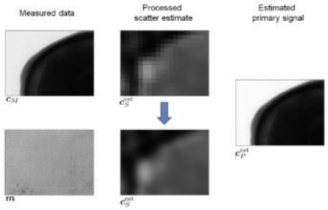
- Minimize $C(c_{\mathrm{P}}^{\mathrm{est}}) = \|D \cdot c_{\mathrm{P}}^{\mathrm{est}}\|_1 = \|D \cdot M^{-1} \cdot (c_{\mathrm{M}} - c_{\mathrm{S}}^{\mathrm{est}})\|_1$

  subject to

  $H \cdot c_{\mathrm{S}}^{\mathrm{est}} = 0$

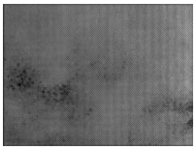
  high-pass filter

  - Minimized over 17x17 pixel sub-patches
  - One value of scatter is assumed per patch

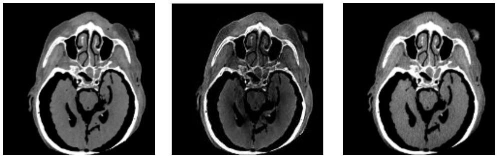


Scan Parameters Cadaver Head

- 80 kV
- 30 mA
- 13 ms pulse length
- 625 projections of 360°
- 244 mAs
- No antiscatter grid
- Modulator:
  - Erbium
  - Spacing between patches: 0.457 mm
  - Thickness: 0.0254 mm



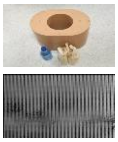
Cadaver Head Axial Slice



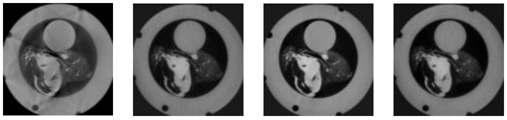
Slitscan Uncorrected Proposed Correction

C/W = 200 HU / 800 HU

Robust Algorithm… Accurate HU



- Erbium modulator reduces beam hardening effects but is non-uniform thickness
- new 'image based' (ie. non-Fourier) algorithm is robust against variation in modulator



no correction iPMSE slot scan inoise reduction

Ritschl, Fahrig and Kachelreiss

Streak Artifact Reduction

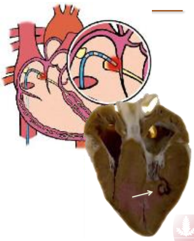
- Number of projections contributing to a reconstruction is low
- Correction should be FAST
- (see presentation in a few minutes…)

from Single-sweep to Multi-sweep…

- But we want more information…
- Can we image soft tissue in the beating heart?

- Rotation times are slow compared to CT at 0.5 s
- New solutions are needed…

Motivation - RF ablation for arrhythmia

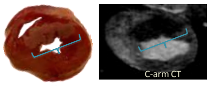


- Current treatments
    - medication (~50% successful)
    - implantable cardioverter-defibr
    - catheter ablation
- Radiofrequency ablation (RFA)
    - Often a first-line therapy
    - Radiofrequency (RF) energy
    - Burn undesirable electrical foci

We see dead tissue!

visualization of necrotic (dead) myocardial tissue

determine the size of a heart attack



monitor radiofrequency ablation treatment