ADVANCES IN C-ARM CBCT FOR CARDIAC INTERVENTIONS

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Disclosures

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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

![Image of RF ablation effectiveness chart]

Average Effectiveness of RF Ablation Procedure

Motivation - RF ablation

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

![Image of RF ablation visualization]


Creating 3D Images in the Interventional Lab

1. Rotational Angiography Run
2. Image transfer
3. Reconstruction
4. In-room Display and Analysis

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 (i.e. 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

**In vivo imaging protocol**

150mL Omnipaque (350 mg/mL) peripheral venous (IVC) injection
42 s delay for first pass image
4 sweeps x 5s ECG-gated
90 and 70 kV, 1.2 μGy/p (24 mSv)
Collimate around heart

**Timing**

- First pass
- 1 min
- 5 min
- 10 min
- 15 min
- Contrast C-arm CT: First pass
- 42 s

**Monitor radiofrequency ablation treatment**

1. “Breathe in, “Breathe out”...
2. Start contrast injection
3. Delay: Hold your breath
4. Start first sweep x 5s
5. ECG synchronisation
6. Collimate around heart: steps 1 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.

Total Infarct Volume can be Measured

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)
     \( \rightarrow \) allows delineation of object in 2-D projections
   - Short acquisition (5 s)
   - Direct contrast administration
   - Min. 5 heart cycles \( \rightarrow \) sinus rhythm
2. Volume-based
   - Two to four chamber imaging
     \( \rightarrow \) overlapping objects in 2-D projections
   - Longer acquisition (14 s)
   - Systemic contrast administration
   - Min. 25 heart cycles \( \rightarrow \) 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 \( \rightarrow \) 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

Wall Motion Analysis

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

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/5-5 Cardiac Registration with Cyclic Motion Constraints
- 3-D/5-5 Combined Multiple Heart Phase Registration
- 3-D/5-5 Deformable Registration
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
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 \(C_x \times C_y \times C_z\) control points in spatial domain
- Motion model parameters \(\mathbf{s}_{x,i} \in \mathbb{R}^K\), with \(K = 3(C_x + 3)^3\)
- Motion model function
  \[
  M(\phi_{x,i}, \mathbf{x}, \mathbf{s}_{x,i}) = \mathbf{x} + \sum_{l \in \mathbb{R}^3} \mathbf{B}_{l}(\mathbf{x}) \mathbf{B}_{l}^T(\mathbf{x}) \mathbf{s}_{x,l}
  \]
  where
  - \(\mathbf{x} \in \mathbb{R}^3\), \(\mathbf{x} = (x_1, x_2, x_3)^T\) reference and current heart phase
  - \(\mathbf{B}_{l}(\mathbf{x})\) - B-spline basis functions
  - \(\mathbf{s}_{x,l}\) - parameter vector at location \(l \in \mathbb{R}^3\)
  - \(3\)-D control point

**Objective function**
- Negative normalized cross correlation
  \[
  L_{NCC} = \frac{1}{|\Omega|} \sum_{(x,y) \in \Omega} \frac{(f(x, y) - \mu_r)(f'(x) - \mu_r)}{\sigma_r \sigma_r'},
  \]
  where
  - \(\Omega\) - region of interest
  - \(f(x, y)\) - returns the reconstructed object value
  - \(f'(x)\) - returns the object value of the reference
  - \(\sigma_r, \sigma_r', \mu_r, \mu_r'\) - standard deviations, 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?

- ECG-gated FDK (FDK)
- Bilateral filtered (FFDK)
- Catheter-removed (cathFFDK)
- Catheter-removed & bilateral filtered (cathFFDK)
- Constrained iterative reconstruction (FV)

Motion-compensated reconstructions are denoted with suffix -MC.

Porcine in vivo model

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

Quantitative Porcine Results
Results for porcine model 2 in a systolic heart phase

First Clinical Results
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.
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

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Cardiac Imaging

- Reduce residual motion and streaking
- Implement prospective gating

- faster rotation
- faster frame rate
Sources of Major Artifacts
- motion
- beam hardening
- scatter
- undersampling
- dynamic range limits

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, etc., other typically high-contrast structures)
  - High frame rates for good sampling during shortest acquisition times
  - Excellent low-contrast resolution for quantitative perfusion imaging at 600 μm resolution
  - Photon counting / energy discriminating for dose reduction and beam hardening

And while we’re at it...

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

x-ray tube requirements?
Guiding cellular or molecular therapies

- tool useful for clinical trials

![Infarct](image)

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 ...

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
**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.

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**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).

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**Modulation process in the raw data domain**

- **Measured data:**
  \[ c_M = M \cdot c_P + c_S \]
- **Solving for primary intensity:**
  \[ c_P = M^{-1} \cdot (c_M - c_S) \]
- **Error in the primary estimate:**
  \[ c_{err} = M^{-1} \cdot (c_M - c_S) - c_P \]
Cost function?

Gradient-based cost function

- Minimize subject to
  \[ C(c_{gt}) = \| D \cdot c_{gt} \|_1 \]
  \[ = \| D \cdot M^{-1} \cdot (c_M - c_{gt}) \|_1 \]

- 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

<table>
<thead>
<tr>
<th>Slitscan</th>
<th>Uncorrected</th>
<th>Proposed Correction</th>
</tr>
</thead>
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C/W = 200 HU / 800 HU

Robust Algorithm... Accurate HU

- Erbium modulator reduces beam hardening effects but is non-uniform thickness
- New ‘image based’ (i.e. non-Fourier) algorithm is robust against variation in modulator

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

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  - catheter ablation
- Radiofrequency ablation (RFA)
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  - Burn undesirable electrical foci

We see dead tissue!

visualization of necrotic (dead) myocardial tissue