Emerging X-ray Fluoroscopic Guidance Technologies for Challenging Cardiovascular Interventions

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Objectives

1. Review the demands and limitations of x-ray fluoroscopy (XRF) in guided cardiac interventions
   - Lack of tissue contrast and depth information
   - X-ray dose concerns

2. Understand the principles of Inverse Geometry XRF
   - Scanning-Beam Digital X-ray (SBDX) prototype system
   - Reduction of patient x-ray dose
   - 3D tracking of catheter devices

3. Discuss x-ray fluoroscopy combined with 3D roadmaps
   - Visualization of 3D soft tissue targets
   - Endocardial stem cell therapy

X-Ray Fluoroscopic (XRF) Guidance

- Basic demands on a guidance system in the cardiac cath lab:
  1. Real time continuous feedback
  2. High spatial, temporal resolution
  3. Device position relative to anatomy
  4. Simple to set up and use
  5. Compatible with catheter devices

- XRF meets these requirements well in many types of interventions

1. X-ray Guidance in Cardiac Interventions

- Coronary Angioplasty
Lack of Tissue Contrast and Depth Focus

Ablation of Atrial Fibrillation
- Device: RF ablation catheter
- Target: Line around pulmonary vein ostia
- Left Atrium
- Pulmonary veins

Endomyocardial Cell Therapy
- Device: Injection catheter
- Target: Viable peri-infarct zone
- Infarct zone
- Left ventricle

- Target anatomy lacks contrast
- Catheter position difficult to determine relative to 3D target
- Requires delineation of soft tissue based on functional status
- Experimental procedure

X-ray Radiation Dose in the Cath Lab

- Deterministic risk of skin injury (> 2 Gy to skin)
- Fluoro time (min): PCI = 121 ± 63, RF Abl = 18 ± 12
- Cine runs (#): PCI = 35 ± 17, RF Abl = 36 ± 17
- Max skin dose (Gy): PCI = 1.45 ± 0.99, RF Abl = 0.64 ± 0.55

- Stochastic risk of cancer induction

Obesity and Radiation Dose in RF ablation of Atrial Fibrillation

BMI  | Age  | Dose (mGy) | Lifetime Attributable Risk of cancer incidence
--- | --- | --- | ---
< 25 | 48 ± 10 | 15.2 ± 7.9 | 1/1000
25-30 | 51 ± 7 | 26.8 ± 11.8 | 1/633
≥ 30 | 46 ± 10 | 39.0 ± 14.7 | 1/405

Guidance Solutions for the Cath Lab

- Pursue non-fluoroscopic technologies
  - E.g. Electroanatomic mapping systems (EAM)
  - 3D tracking of specialized catheters
  - Point-by-point endocardial surface mapping
  - Cardiac ablation guidance

- Or seek to modify / enhance XRF guidance by:
  1) Reducing x-ray dose while maintaining image quality
  2) Adding 3D context to the live image display

2. Inverse Geometry XRF

Scanning-Beam Digital X-ray (SBDX) Prototype

Operating Principles
- Dose Reduction
- Catheter Tracking
**SBDX Operating Principles**

- Photon-counting Detector Array
- Real-time Reconstructor
- 15-30 fps
- ~40,000 images in 1/15 sec

**Dose Reduction Principles**

1. Beam scanning and large airgap reduces detected x-ray scatter
2. Thick CdTe detector maintains high DQE at high source kVp

**SBDX Prototype Performance (2006)**

- Large-area SNR
- Entrance Exposure

- SBDX operating at equal SNR: 15% - 31% entrance exposure
- Greatest dose reduction for largest phantoms

**Dose Reduction Principles**

3. Inverse geometry reduces x-ray fluence at the patient entrance

- Conventional
- SBDX

SBDX System Development

Detector Re-design

Phantom: 28 cm acrylic

\[ \text{SNR} = \sqrt{1 - \text{SF} \times \text{DQE} \times \text{SNR}} \]

**X-ray Beam Solid Angle**

Ω(\text{relative units})

**Iodine SNR**

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**Source & Detector Specs**

- **70 kVp, 4.2 kWp, ~40% DQE**
- **100 kVp, 12.6 kWp, 62% DQE**
- **120 kVp, 24.3 kWp, 71% DQE**

**Fluoro-quality**

- **120 kVp, 24.3 kWp, 90% DQE**

**Cine-quality**

- **100 kVp, 12.6 kWp, 62% DQE**

**Next Gen**

- **100 kVp, 24.3 kWp, 110% DQE**

**High Speed Multiplanar Tomosynthesis**

- **Shift-and-backprojection at multiple planes**
- **16 planes per frame**
- **12 mm spacing**

Depth Focus Property

- **Rays through object originate from different spot positions**
- **In-plane**
  - High contrast, sharp appearance
- **Out-of-plane**
  - Low contrast, blurry

Plane Selection Algorithm

- **Multiplane Composite Display**

- **Pixel-by-pixel plane selection:**
  - Display pixel from plane with highest object focus metric
  - “Score stack” Gradient filtering
3D Catheter Tracking Algorithm

- Score Image Stack
  - Generate MIP along z axis
  - Perform 2D connected component labeling

- Extract score vs. z distribution
- Calculate center-of-mass along z

Output is a set of (x,y,z) coordinates for each image frame

Tracking Simulation Study (2008)

- Helix of 1-mm Pt spheres
- Tracking Accuracy & Precision

SBDX Prototype Geometry

- 0 5 10 15 20 25 30
  - Source power (kWp)
  - Z-coordinate Error (mm)
  - Z error: -0.56 ± 0.65 mm

Tracking Phantom Study

- 3M chest phantom
- Linear stage for catheter pullback
- Ablation catheter in trans-septal sheath

3D Tracking Demonstration

- Tracking performed in software using stored detector images
- 10 mm/sec pullback rate
- 15 frame/sec SBDX imaging
- 1850 photons/mm² at isocenter
Comparison with CT

- Tracked tip to sheath centerline: 1.0 +/- 0.8 mm (Tip diameter = 2.5 mm)
- 82% of tracked positions inside sheath volume

Inverse Geometry XRF & 3D Tracking

- Well-suited to long, complex cardiac interventions
  - Fluoroscopy at 15% skin dose rate
  - Real-time 3D tracking at end diastole

- Tracking works with standard catheters, any number of elements, and uses a single gantry angle, automatically registered to XRF system without calibration

3. XRF / 3D Roadmap Fusion

Laboratory of Amish Raval, M.D.
UW-Madison Cardiology

Targeted Cell-based Therapy for MI

- Stem cell therapy may improve left ventricle function after recent myocardial infarction (acute MI) [1]
- Direct endomyocardial cell injection requires guidance system beyond XRF in order to:
  1) Target peri-infarct region
  2) Avoid perforating friable infarct
- XRF / 3D MRI fusion enables device & target visualization while minimizing tissue contact [2]

**Bi-plane XRF / 3D Fusion System**

- Conventional Bi-plane
- Portable Fusion System
- Control Display
- Fusion Display
- PC Workstation
- Frame grabber (Helios eA, Matrox)
- DICOM
- MR or CT data
- Custom fusion software (C++)

**XRF / 3D Fusion Procedure**

- MRI Scanner
- Segmentation Workstation
- Slice Contours
- 3D Surface Generation
- Combine with 3D XRF Model
- C-arm Calibration (one-time)
- Projection Matrices
- Surface Projection and Overlay
- Fusion Display
- X-Ray Fluoroscopy
- Live Video
- Gantry Orientation
- Manual Adjustments
- Frames
- Frame Grabber

**Porcine Study: Segmentation**

- Pre-intervention MRI
- 3D Model
  - Red: LV endocardium
  - Yellow: infarct volume
- LV Endocardial contour
- Epicardial contour
- bSSFP scan
- DHE scan
- Infarct contour
- End diastole, end expiration

**Porcine Study: Registration**

- Manual Registration to Internal Anatomy
- Biplane Ventriculogram (end diastole, end expiration)
- Frontal plane
- Lateral plane
Porcine Study: Injections

Injected mixture:
- Iodinated contrast: intra-procedural myo. staining
- Iron oxide (SPIO): MRI visualization of injections
- Tissue dye: for post-procedure necropsy

Virtual 3D marker
Bullseye display

Porcine Study: Targeting Accuracy

Cath lab:
- Biplane XRF / 3D Fusion

Post-procedure:
- MRI
- Necropsy

6 animal studies:
- Study time: 24 +/- 12 min
- 28 injection sites:
  - Supposed distance: D2 – D1 = 3.6 +/- 2.3 mm

Yellow: infarct
Orange: injection

XRF / MRI Roadmap Fusion

- Targeting accuracy depends on the quality of:
  - Modeling of XRF system (gantry calibration)
  - Segmentation of 3D images (depends on modality)
  - Registration of 3D surface to live x-ray (landmarks)

- MRI and X-ray fusion method feasible and safe for targeted injections to the peri-infarct region
  - No myocardial perforation
  - Targeting error ~ MR slice thickness & in-plane resolution

- Portability and vendor-independence

Fusion System Development

- Desired features:
  - Respiratory and patient motion compensation
  - Ability to re-check registration throughout procedure
  - Cardiac gating
  - Automation, to the extent it is safe and reliable

- Automated device and anatomic landmark tracking
  - Conventional XRF tracking (2D imaging)
  - Ultrasound (3D imaging)
  - EAM systems (3D points)
  - Inverse Geometry XRF (tomosynthesis, 3D tracking)
Conclusion

Emerging Fluoroscopic Technologies

- Narrow scanning x-ray beam
- Inverted x-ray field geometry
- High speed multiplane tomosynthesis
- Low dose fluoroscopy
- 3D tracking capability

XRF Guidance: Advantages and limitations
- High quality, real-time imaging
- Device compatibility
- Simple, easy use
- Poor 3D visualization of devices and endocardial targets
- Radiation dose in long procedures

Inverse geometry XRF: Unique design and capabilities
- Narrow scanning x-ray beam
- Inverted x-ray field geometry
- High speed multiplane tomosynthesis
- Low dose fluoroscopy
- 3D tracking capability

XRF / 3D Fusion: 3D anatomy & function in the cath lab
- Enables novel cardiac interventions
- Non-contact visualization of function
- 3D soft tissue anatomy

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