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

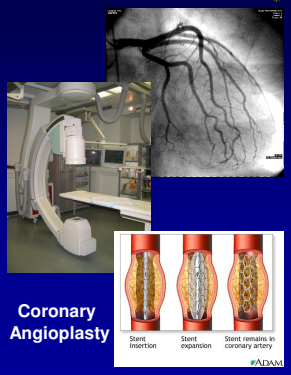
1. X-ray Guidance in Cardiac Interventions

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

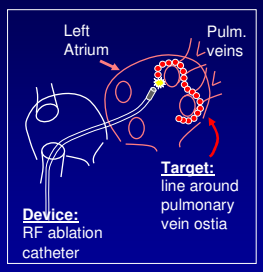
- XRF meets these requirements well in many types of interventions



Coronary Angioplasty

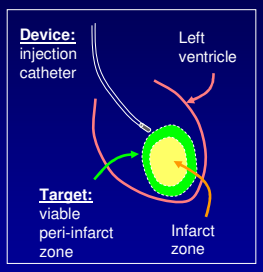
Lack of Tissue Contrast and Depth Focus

Ablation of Atrial Fibrillation



- Target anatomy lacks contrast
- Catheter position difficult to determine relative to 3D target

Endomyocardial Cell Therapy



- 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)

Case reports of skin injury, 1996-2001
Koenig, T. et al. AJR **177**, 3-11 (2001).

Coronary angiography & intervention:	44
Cardiac radiofrequency ablation:	11
TIPS placement:	6
Neuroradiologic intervention:	2
Other:	3

Coronary intervention vs. Cardiac RF ablation
Chida, K. et al. AJR **186**, 774-778 (2006).

	PCI	RF Abl.
Fluoro time (min):	37 +/- 23	121 +/- 63
Cine runs (#):	35 +/- 17	18 +/- 12
Max skin dose (Gy):	1.45 +/- 0.99	0.64 +/- 0.55

- Stochastic risk of cancer induction

Obesity and Radiation Dose in RF ablation of Atrial Fibrillation
Ector, J. et al. JACC **50**, 234-242 (2007).

BMI	n	Age	Calc. Effective Dose (mSv)	Lifetime Attributable Risk of cancer incidence
< 25	28	48 +/- 10	15.2 +/- 7.9	1/1000
25-30	41	51 +/- 7	26.8 +/- 11.6	1/633
≥ 30	16	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:

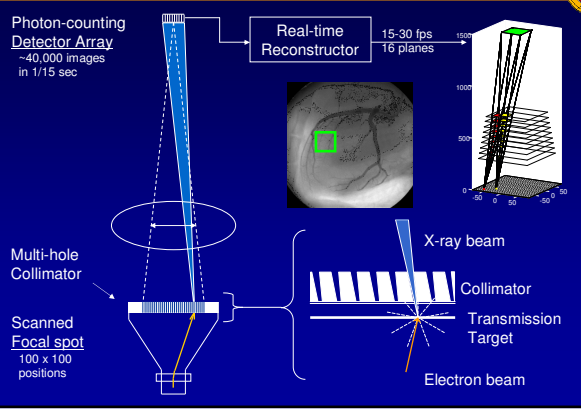
  1) Reducing x-ray dose while maintaining image quality
  2) Adding 3D context to the live image display

2. Inverse Geometry XRF

Scanning-Beam Digital X-ray (SBDX) Prototype

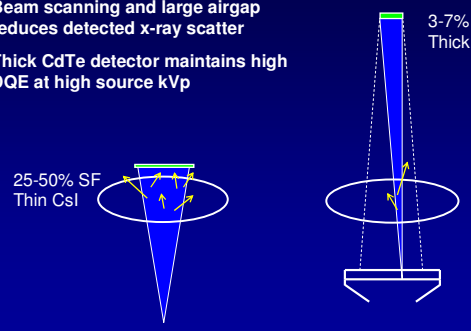
Operating Principles
Dose Reduction
Catheter Tracking

SBDX Operating Principles



Dose Reduction Principles

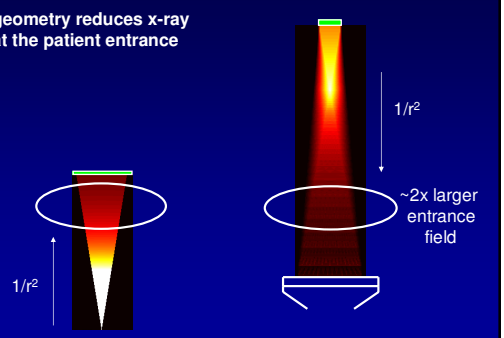
1. **Beam scanning and large airgap reduces detected x-ray scatter**
2. **Thick CdTe detector maintains high DQE at high source kVp**



Conventional **SBDX**

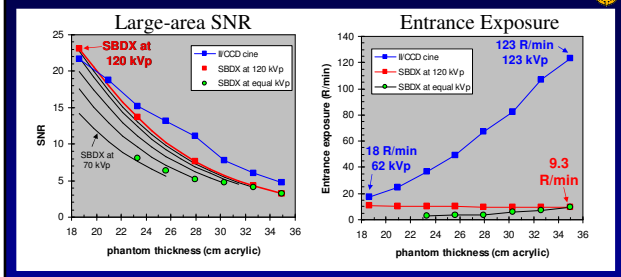
Dose Reduction Principles

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



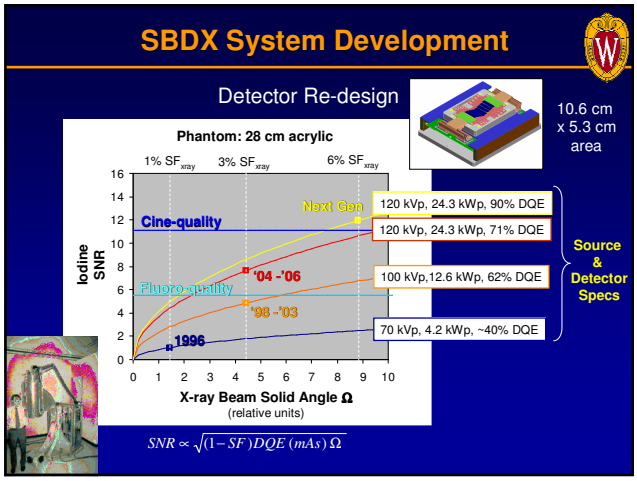
Conventional **SBDX**

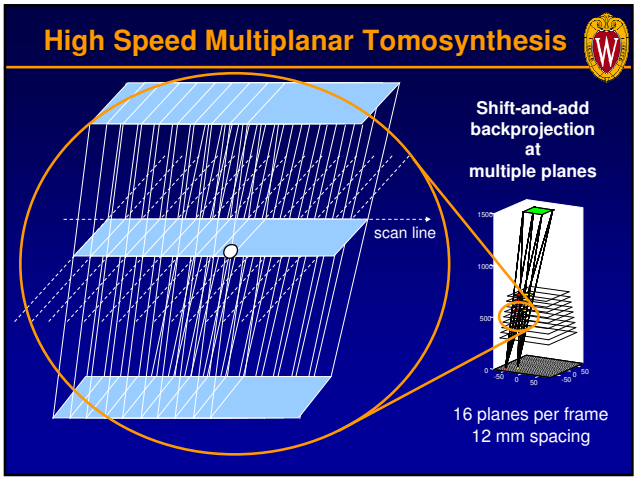
SBDX Prototype Performance (2006)

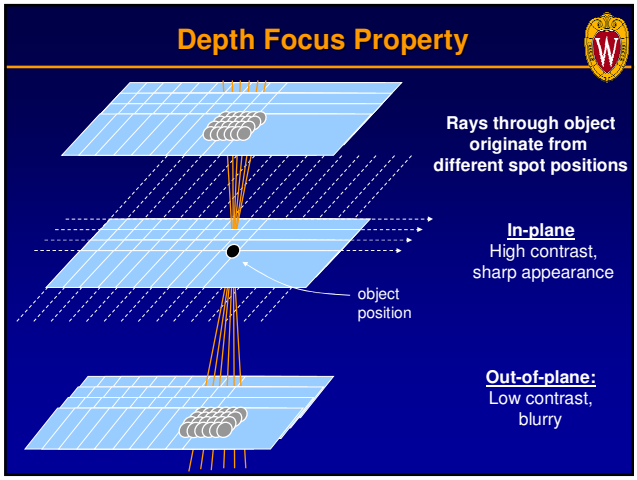


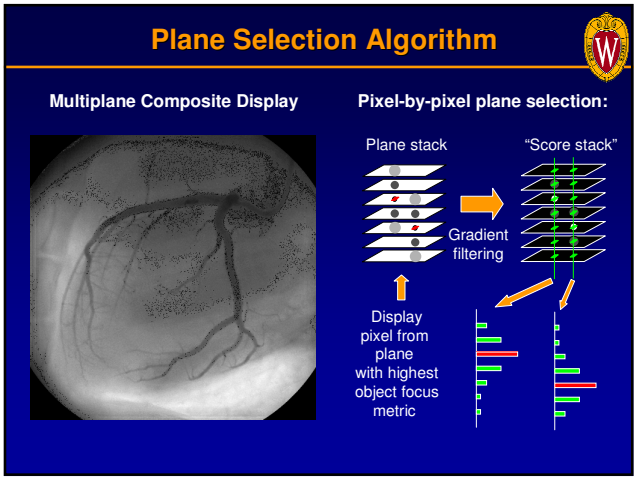
- SBDX operating at equal SNR: **15% - 31% entrance exposure**
  - Greatest dose reduction for largest phantoms

Speidel, M. et al. Comparison of entrance exposure and signal to noise ratio for an SBDX prototype. Med Phys **33**, 2728-2743 (2006).

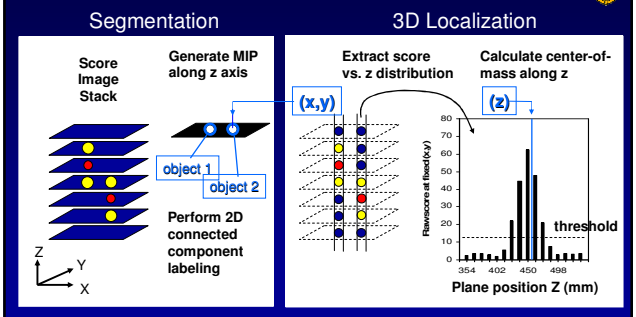

SBDX System Development
Detector Re-design
10.6 cm x 5.3 cm area
Phantom: 28 cm acrylic
1% SF xray
3% SF xray
6% SF xray
Iodine SNR
Cine-quality
Fluoro-quality
Next Gen
'04 -'06
'98 -'03
1996
120 kVp, 24.3 kWp, 90% DQE
120 kVp, 24.3 kWp, 71% DQE
100 kVp,12.6 kWp, 62% DQE
70 kVp, 4.2 kWp, ~40% DQE
Source & Detector Specs
X-ray Beam Solid Angle Ω
(relative units)
$SNR \propto \sqrt{(1-SF)DQE\,(mAs)\,\Omega}$


High Speed Multiplanar Tomosynthesis
Shift-and-add backprojection at multiple planes
scan line
16 planes per frame
12 mm spacing


Depth Focus Property
Rays through object originate from different spot positions
In-plane
High contrast, sharp appearance
object position
Out-of-plane:
Low contrast, blurry


Plane Selection Algorithm
Multiplane Composite Display
Pixel-by-pixel plane selection:
Plane stack
"Score stack"
Gradient filtering
Display pixel from plane with highest object focus metric

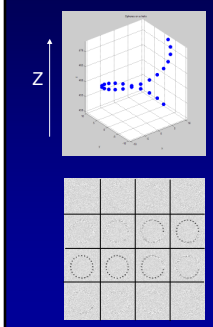
3D Catheter Tracking Algorithm



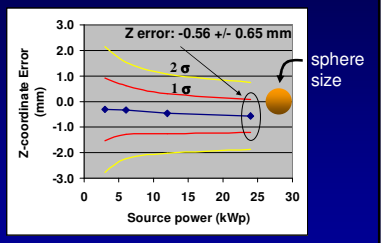
- Output is a set of (x,y,z) coordinates for each image frame

Tracking Simulation Study (2008)

Helix of 1-mm Pt spheres



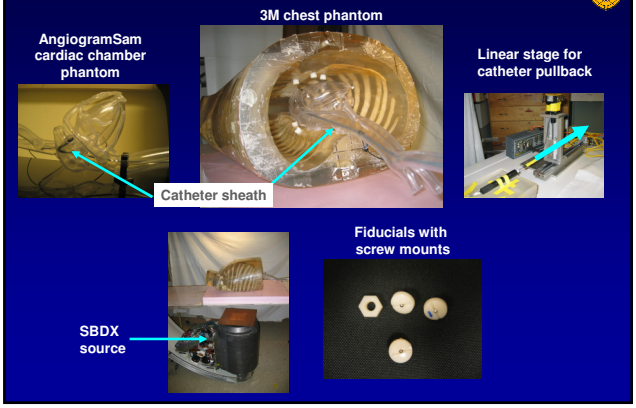
Tracking Accuracy & Precision
SBDX Prototype Geometry



- 12 mm plane-to-plane spacing
- 28 cm acrylic, 120 kVp
- Stationary helix

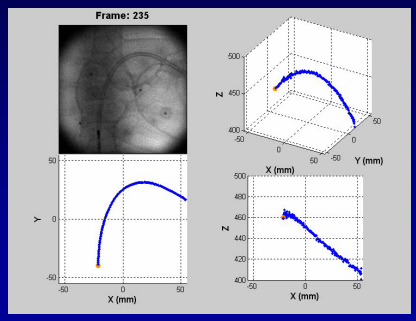
Speidel M. et al. Frame-by-frame 3D catheter tracking methods for an inverse geometry [...] Proc SPIE **6913** (2008)

Tracking Phantom Study



3D Tracking Demonstration

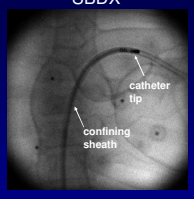
Ablation catheter in trans-septal sheath



- Tracking performed in software using stored detector images
- 10 mm/sec pullback rate
- 15 frame/sec SBDX imaging
- 1850 photons/mm^2 at isocenter

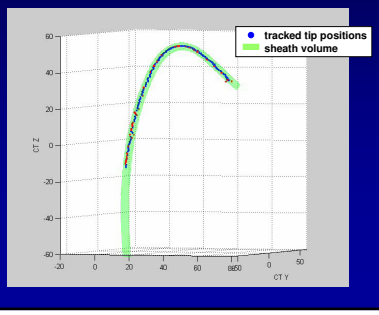
Comparison with CT

SBDX



CT scan

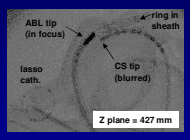
- Tracked tip to sheath centerline: 1.0 +/- 0.8 mm (Tip diameter = 2.5 mm)
- 82% of tracked positions inside sheath volume



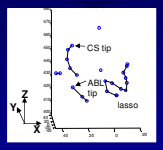
Inverse Geometry XRF & 3D Tracking

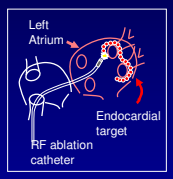
- Well-suited to long, complex cardiac interventions

Fluoroscopy at 15% skin dose rate



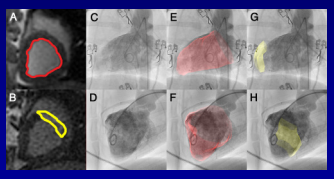
Real-time 3D tracking at end diastole





- 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

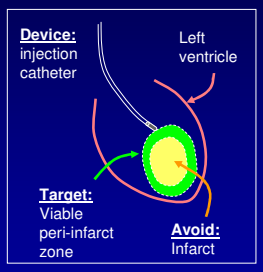


Laboratory of Amish Raval, M.D. UW-Madison Cardiology

Targeted Cell-based Therapy for MI

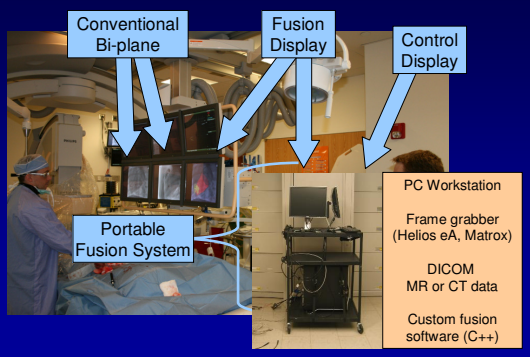
- Stem cell therapy may improve left ventricle function after recent myocardial infarction (acute MI) [1]
- Direct endomyocardial cell injection requires guidance system beyond XRF in order to:
  1) Target peri-infarct region
  2) Avoid perforating friable infarct
- XRF / 3D MRI fusion enables device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

Endomyocardial Cell Therapy



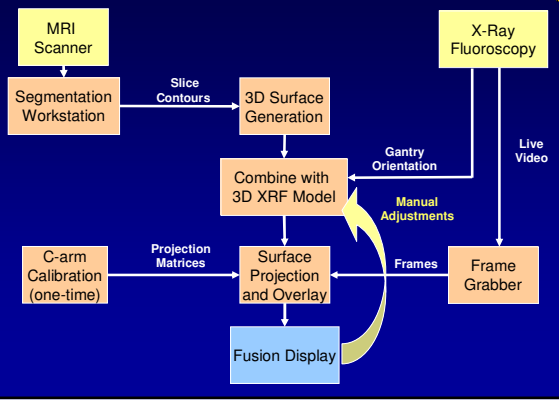
[1] Segers, V. and Lee, R. Stem-cell therapy for cardiac disease. Nature **451**, 937-942 (2008).
[2] de Silva, Gutierrez, et al. X-ray fused with magnetic resonance imaging to target endomyocardial injections. Circulation **114** (2006).

Bi-plane XRF / 3D Fusion System



Tomkowiak M. et al. Multimodality image merge to guide catheter based injection of biologic agents. RSNA, Chicago, IL, 2008.

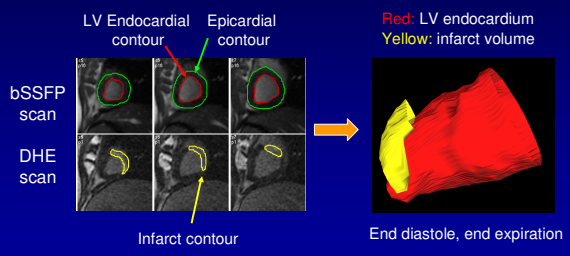
XRF / 3D Fusion Procedure



Porcine Study: Segmentation

Pre-intervention MRI

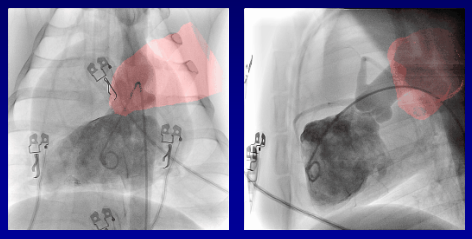
3D Model



Porcine Study: Registration

Manual Registration to Internal Anatomy

Biplane Ventriculogram (end diastole, end expiration)

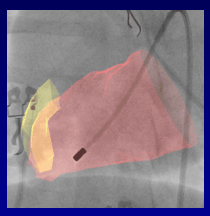


Frontal plane

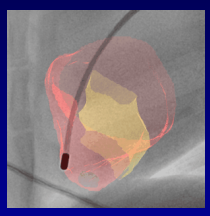
Lateral plane

Porcine Study: Injections

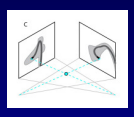
Frontal plane



Lateral plane



Virtual 3D marker



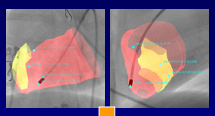
Bullseye display

Injected mixture
iodinated contrast : intra procedure myo. staining
iron oxide (SPIO) : MRI visualization of injections
tissue dye : for post procedure necropsy

Porcine Study: Targeting Accuracy

Cath lab:

Biplane XRF / 3D Fusion



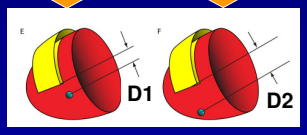
Post-procedure:

MRI

Necropsy

Yellow: infarct

Orange: injection



Supposed distance vs. Actual distance
injection point to infarct perimeter

6 animal studies:
Study time: 24 +/- 12 min

28 injection sites:
D2 – D1 = 3.6 +/- 2.3 mm

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

- 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 → Low dose fluoroscopy
  - Inverted x-ray field geometry
  - High speed multiplane tomosynthesis → 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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