MR in the OR: The Growth and Application of MRI for Interventional Radiology and Surgery

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Disclosures

- Sponsored Research Project funding from Siemens AX, unpaid Advisory Board member
- Subcontract on NIH grant to Triple Ring Inc.
- NIH Industry-Academia Partnership R01 with Varian (Ginzton Technology Center)
- Founder, Tibaray Inc.
- Moving to Siemens (Head of Innovations, AX) September 2015
Fahrig Group @ RSL

Image Guidance during Minimally Invasive Procedures

- MR-Compatible Linear Accelerator  (NIH & U. Sydney)
- XMR: a hybrid x-ray/MR guidance platform  (Pelc & Fahrig @ Stanford, 1999-2013)
- MV-kV imaging for metal artifact reduction with high-efficiency MV detector  (NIH & Varian)
- Tomosynthesis-guided transbronchial needle biopsy using the ‘inverse geometry’ SBDX system  (NIH & Triple Ring)
- Image guidance for next generation radiation therapy: PHASER  (SLAC, Rad Onc)
- Weight-bearing C-arm CT imaging  (Siemens AX, NIH)
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Other Contributors to this Presentation

- Graham Wright, Sunnybrook Health Sciences Center and University of Toronto
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- John Pauly and MRSRL team, EE, Stanford University
- Kim Butts Pauly and Peiji Ganouni, RSL, Stanford University
Evolution of Interventional MR: an Intersection of Advances

Open/short-bore magnets for access to patients
Reduced Pt. anxiety

Improved MRA techniques; Gd-based blood pool agents

Rapid MR imaging sequences

Real-time anatomic and physiologic assessment
- flow rates
- organ perfusion, diffusion
- metabolism
- spectroscopy
- temperature
Configurations: Open Magnets

- Direct patient access
- Low field strength (0.2T-1.5T)
Configurations: Open Magnet

Applications: Percutaneous > Endovascular
Configurations: Hybrid Imaging Systems

Yale VISIUS MRI-DSA
31 worldwide installations and firm commitments (IMRIS website)

Stanford XMR concept
**DELIVERY SYSTEM:** Gadolinium-impregnated Embospheres

**IN VIVO MODEL:** Canine kidney

**PROCEDURE:**
- Catheterization under fluoroscopy
- Injection under real-time MR
Multimodality Imaging Interventional Suites

- Take advantage of best features of each type of imaging
- Minimize impact of patient movement
- Reduce reinterventions
- Enhance patient safety
Challenges

• Device safety
  ◦ heating
  ◦ artifact

• Device control

• Device visualization
  ◦ MR imaging sequence and resulting artifacts
  ◦ Real-time system interface and control
Device Safety: Labelling

- MR Safe
  - an item that poses no known hazards in all MRI environments

- MR Conditional
  - an item that has been demonstrated to pose no known hazards in a specified MRI environment with specified conditions of use

- MR Unsafe
  - An item that is known to pose hazards in all MRI environments
MR Conditional: the details

- Field conditions that define the MRI environment
  - Static magnetic field strength
  - Spatial gradient
  - dB/dT
  - RF fields
  - Specific absorption rate (SAR)
Device Safety

- Risk of RF heating due to inductive and/or capacitive coupling with transmitted $B_1$ field
  - Change geometry (e.g. coiled vs. linear)
  - Distributed RF traps along the length of the wire
  - Flexible transformers
  - ‘safety index’
Device Safety: Monitoring

- If transmit and receive RF fields have reverse polarization, then no hydrogen spins are excited, and no signal from tissue is detected (use e.g. birdcage coils).
- BUT a conductive object loading the coil can result in RF eddy currents.
- homogeneous circular polarization of the birdcage is disturbed and polarization errors are generated.

Result of Reverse Polarization

- Suppression of background
- Remaining signal arises from RF current alone
- Get estimate of local wire current, that is wire-geometry dependent
• Reverse-polarization projection images still clearly show the pacemaker leads

• Controlled prescan procedure designed to limit unsafe heating (local tissue heating cannot exceed 2 degrees over the trunk)
To define an interventional device as ‘MR Conditional’ all of the following are considered except:

- Static magnetic field strength (3%)
- Spatial Gradient (7%)
- Specific absorption rate (SAR) (9%)
- Radiofrequency (RF) fields (8%)
- MR image quality (72%)
Answer

- 5. MR image quality
Device Visualization

- RF ablation for LV tachycardia
  - Map area of infarct
  - Visualize lesion size
- Cross total chronic occlusions in the coronary arteries
- Extend to RF ablation for atrial fibrillation
  - Imaging of lesions still very challenging in the LA

Active Imaging

Current sensor

$B_{1}\text{wire}$

$I_{\text{wire}}$

IF-E99

PPM-2W

Photonic Power Module

JDSU PPM-2W

Photo-receiver

MRSL
Image-based current sensing
Current sensor reading vs image-based current computation

- **Current**: mA
- **Wire position**: cm

**Graph Details**:
- **B1 map** (red triangles)
- **Sensor** (blue dots)
- **Free space**
- **Phantom**

**Legend**:
- B1 map
- Sensor

**Axes**:
- Y-axis: Current (mA)
- X-axis: Wire position (cm)

**Graph Notes**:
- The graph shows the comparison between current sensor readings and image-based current computations.
- The graph includes two distinct regions: Free space and Phantom.
- The data points indicate a decrease in current as wire position increases.

**Institution**:
- MRsRL
- Stanford University
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
The Vision-MR™ Ablation Catheter looks, feels, and functions like a conventional ablation catheter, but our patented technology makes it uniquely MR-enabled.

An MR-enabled ablation catheter is not enough to make ablation procedures safe and effective in the MRI environment. The EP recording system and cardiac stimulator must also be MR-enabled to avoid dangerous electromagnetic interactions with the MRI scanner and to provide clear intra-cardiac electrograms and interference-free MR images.


“Imagine, now, that you can see these things, and you are there to treat them.”

Christopher Piorkowski M.D., Ph.D.
Head of the Department of Electrophysiology, University of Dresden Heart Center
Motivation - RF ablation

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

Systems Integration for Electrophysiology

GE MR Scanner

Imricor catheters

Catheter tracking with RTHawk (HeartVista) and Vurtigo visualization (Sunnybrook)

Voltage mapping overlays fused in Vurtigo

Oduneye S et al., IEEE Trans BME Sept 2013
Oduneye S et al., JCMR Apr 2015
RF Ablation
Lesion Characterization

Celik et al, Circ EP 2014
Device Control

- Lack of MRI compatible catheters and guidewires -> difficult to navigate under MRI guidance
- Other techniques
  - Catheter tip ferromagnetic beads
  - Smart material actuators
  - Hydraulic catheter
- Limited functionality
Current Steerable Approaches

- **Stereotaxis**
  - Two permanent magnet heads with custom guidewires with NdFeB tips
  - Single plane angiography system with modified tube (magnetically shielded) and detector

- **Mechanically Steerable**
  - Tip deflection via the use of a pull string
  - Not inherently MR-safe

- **Other**
  - PM beads
  - Shape memory polymers
  - Hydraulic
Two-Coil, Double Layer
2.5 French Microcatheter

Wilson et al, JVIR 2013
Deflection of Catheter Tip

Red Arrow = current flow
$B_0$ = main magnetic field of MR scanner
$M$ = magnetic moment of catheter
Curved arrows = direction of deflection

Catheter Deflection

- Double Layer Deflection Catheter (DHC-5)
  - Single layer activation
    - +100 mA inner
    - -100 mA inner
    - +100 mA outer
    - -100 mA outer
System Configuration in MRI Suite

Control Suite

RF Shield

Scanner Suite

Control System

Foot Pedal Actuator

MRI Bore

MRI System Configuration in MRI Suite
Swine Carotid Heating Experiment

No Cath Tip Current

With Cath Tip Current

H&E

H&E High Mag
And ... Focused Ultrasound

- large area ultrasound transducer array outside the body
- focused geometrically or electronically
- amplification
- significant intensities deep within the body, without damage to intervening tissues
Modern System

- 1000 elements
- cooled circulating water
- focusing/amplification
Temperature Mapping

- change in hydrogen bonding with temperature

- proton resonant frequency (PRF) shift = -0.0909 ppm/°C.

Phase image during heating

Pre-heat phase image

Difference

T, Thermal Dose
Monitoring: Temperature

- Temperature Goal: 58°C for 20 s, 3 times
- Thermal Dose

Martin, Ann of Neurology, 2009
Essential Tremor

Pretreatment

- 10 million Americans or 3% of the population have an essential tremor.

Posttreatment

- Immediate symptom relief.
Which of the below guidance/feedback techniques is not provided by MRI?

<table>
<thead>
<tr>
<th>Percentage</th>
<th>Technique</th>
</tr>
</thead>
<tbody>
<tr>
<td>35%</td>
<td>1. Differentiation of living tissue from dead tissue</td>
</tr>
<tr>
<td>2%</td>
<td>2. Perfusion</td>
</tr>
<tr>
<td>2%</td>
<td>3. Magnetic catheter navigation</td>
</tr>
<tr>
<td>45%</td>
<td>4. High-resolution (200 microns) real-time (15 fps) projection images</td>
</tr>
<tr>
<td>16%</td>
<td>5. Real-time temperature monitoring</td>
</tr>
</tbody>
</table>
4. MRI does not provide high-resolution projection images at 15 frames per second, and therefore visualization of small guidewires and small vessels is challenging under MR guidance alone.
MRI-guided Interventions

- Visualizes soft tissues and organs for enhanced targeting
- Can provide perfusion and diffusion data
- Provides real-time feedback
  - lesion size
  - temperature monitoring
- No ionizing radiation
MR-guided RT vs. MR-guided Interventions

- Very similar hardware-related challenges
- Access to physiological information for targeting
- Real-time feedback on motion

BUT

- No immediate tissue response
  - temperature monitoring
  - lesion size
Renal Denervation

“MRI guided renal denervation could provide a verifiable procedural endpoint that is missing today.”

Prof. Gerhard Hindricks M.D., Ph.D.
Director of the Department of Electrophysiology Leipzig Heart Center

The World Heath Organization (WHO) estimates that over one billion people worldwide are affected by hypertension\(^1\), a condition of raised blood pressure that contributes to nearly half of all cardiovascular disease\(^2\). Drug therapy is a popular treatment option for this disease, though some patients develop drug-resistant hypertension or experience adverse effects from long-term pharmaceutical treatment. For these patients, the immerging technology of renal denervation via radiofrequency ablation holds promise for long-term management.

However, major drawbacks of this procedure include difficulty in seeing and selecting the appropriate ablation location and, more importantly, verifying that the desired ablation lesions are formed during the procedure. MRI guided renal denervation has the potential to solve these problems.

Our MR-enabled renal denervation products are being evaluated in preclinical studies.

\(^1\)WHO/DCO/WHD/2013.2.

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