“Transmural” catheter interventions for congenital and structural heart disease

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* These are off-label or investigational applications in the USA. Do not construe these educational slides as marketing or promotion.

* I have invented some of these things. I am required to assign the inventions to NIH and I may be eligible to receive royalty payments.
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- Siemens Medical Systems (MRI); CRADA
- Transmural Systems Inc (Catheter Devices)
- Cook Medical (Catheter Devices); CRADA
Catheter versus surgical treatment

Catheter-based coronary stenting for acute myocardial infarction

- Tiny tube in groin; treatment guided by shadows
- Targets constrained by anatomy (“tubes and boxes”)

Endoscopic LIMA-LAD bypass surgery

- Big hole in chest; treatment guided by eyeball or camera
- Targets constrained by surgical injury (“no limits”)
# Mechanical treatments of heart disease

<table>
<thead>
<tr>
<th>Interventional cardiology</th>
<th>Surgery</th>
</tr>
</thead>
<tbody>
<tr>
<td>“Plumbing”</td>
<td>“General Contracting”</td>
</tr>
<tr>
<td>Less invasive, therefore less injurious</td>
<td>More invasive, therefore more injurious</td>
</tr>
<tr>
<td>Less access, therefore often less effective</td>
<td>More access, therefore often more effective</td>
</tr>
<tr>
<td>Catheters in (usually) awake patients via remote control under X-ray guidance</td>
<td>Large holes in unconscious patients via direct access &amp; visualization, often refrigerated and using temporary heart pumps</td>
</tr>
</tbody>
</table>
Transcatheter occlusion of patent ductus arteriosus (PDA)

5 months old, 5 kg

Baseline Amplatzer duct occluder-2 Successful PDA occlusion

Courtesy of Elena K. Grant
Pulmonary valvuloplasty

2 days old, 1.9 kg, Critical pulmonary valve stenosis

Baseline
No flow through pulmonary valve

Balloon pulmonary valvuloplasty

Afterwards, pulmonary valve is open

Courtesy of Elena K. Grant
Catheter-based pulmonary valve implantation

7 years old, 23 kg, Tetralogy of Fallot, “conduit failure” years after surgical repair

Severe pulmonary regurgitation

Valve implantation

Valve in place, no pulmonary regurgitation

Courtesy of Elena K. Grant
Transcatheter aortic valve implantation (TAVI)
Contemporary catheter treatments

• We can’t see much...
• We can accomplish quite a bit...
• .... As long as we stay within the existing pipes and walls.

• Wouldn’t it be nice to see what we are doing?
MRI Catheterization

Catheterization + soft-tissue imaging + radiation-free
Why perform MRI catheterization?

- MRI measurements are more accurate
  - Blood Flow
  - Heart function
- Seeing the body to guide catheters is good
- Avoiding radiation is desirable
- Versatility of available measurements (perfusion, flow, function, viability, inflammation, constraint)
- The clinical workflow is acceptable now
Illustrative MRI R heart cath: adult double-speed playback

RA → SVC
RV → MPA
IVC → RA
MPA → LPA
iCMR for children

NIH / CNMC MRI Catheter Suite

Children’s National Medical Center®
Illustrative MRI R heart cath: child
MRI cath provides more information

Screen for chronic thromboembolic pulmonary hypertension (CTEPH)

Normal MRI lung perfusion

CTEPH multiple Q defects

Direct visualization of structural defects:
Anomalous pulmonary venous return

RA & RV enlargement
Next steps

WHAT CAN WE DO WITH MRI CATHETERIZATION?
MRI endomyocardial biopsy

A groovy way to biopsy the heart; you can keep your eyes open while you close the forceps!
Problem: X-ray is the prevailing approach to guide heart biopsy

- Cannot distinguish normal from abnormal myocardium
- Cannot see vulnerable structures
MRI endomyocardial biopsy

Inversion recovery MRI highlights the lesion

Target heart muscle labeled with fluorescent beads

Toby Rogers [Unpublished]
MRI-guided cavopulmonary shunt

A groovy way to reduce the number of staged surgery procedures for children with single-ventricle physiology
MRI percutaneous superior cavopulmonary shunt

Kanishka Ratnayaka, et al, JACC Interventions, 2016 [In Press]

Caval-pulmonary needle

Purpose-built cavopulmonary shunt
MRI myocardial chemoablation

A different approach to interrupting “short circuits” causing electrical disease of the heart
Contemporary catheter ablation of rhythm disorders

Problem: Radiofrequency ablation is the main tool used to treat rhythm disorders

1: Not visible to physician
2: Partially reversible conduction block
Needle chemoablation: Instant depiction of irreversible necrosis

- Caustic agent doped with dilute gadolinium contrast
- Needle chemoablation catheter visualized as MRI antenna
- Interactive MRI “saturation” imaging to highlight lesions and darken blood
- Depth of ablation depends on needle length and injectate volume

Toby Rogers et al [In Press], Circulation Arrhythmia & Electrophysiology, 2016
Which agent for ablation?

**Ethanol** lesions are stellate; **Acetic acid** lesions are smooth and circumscribed

---

**Ethanol**

Lesion heterogeneity and islands of normal myocardium may contribute to slow conduction or reentry

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**Acetic Acid**

Homogeneous lesions are desirable

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Toby Rogers et al [In Press], Circulation Arrhythmia & Electrophysiology, 2016
Isthmus chemoablation

Endocardial (internal) and epicardial (outer surface) fragmented and low abnormal voltage activities (LAVA) are abolished.

Toby Rogers et al [In Press], Circulation Arrhythmia & Electrophysiology, 2016
Summary MRI Catheterization

• MRI catheterization is available now for simple procedures in adults and children
• With MRI-safe catheter devices, more advanced procedures will be possible in patients
  – Rhythm disorders
  – Structural heart disorders
X-ray guided transmural procedures

- Transcaval access to the aorta
- Intentional perforation of the right atrium
- TRAIPTA tricuspid annuloplasty
- Mitral cerclage annuloplasty
- Backstabbing to access the left atrium
Transcaval access to the aorta

A transcatheter approach to deliver appliances too large for femoral arteries
GOAL

- Introduce large CATHETER devices into aorta when conventional access is unattractive
- For TAVR, TEVAR, pVAD, etc., when 6-9 mm femoral artery sheaths can’t fit

RATIONALE

- Femoral veins - larger, more compliant
- Aorto-caval fistulas from ruptured AAA often not immediately life threatening
- IVC is near aorta without interposed structures

Halabi JACC 2013;61:1745
Transcaval aortic access for TAVI

180 patients as of 3/15/2016 in 25 centers

Back end of 0.014" guidewire

Electrosurgery pencil

0.014" guidewire

0.014" to 0.035" wire convertor

0.035" microcatheter

Electrified wire crossing into aortic snare

CT-based plan

Angiogram

Lateral “bullseye”

180 patients as of 3/15/2016 in 25 centers

Introducer sheath from femoral vein into aorta

Amplatzer muscular VSD occluder 8mm

Final

Halabi .. Lederman, JACC, 2013

Greenbaum, O’Neill .. Lederman, JACC, 2014
Lessons from a medical complication

• What is a femoral artery pseudoaneurysm?

  Answer: A contained arterial rupture.

  An important but not usually catastrophic complication.

  When it drains into a vein “arteriovenous fistula” it is less serious.
Intentionally un-repaired fistula in pig: no hemorrhage

Time-resolved CTA
Marcus Chen

Halabi  JACC 2013;61:1745
Catastrophic failure: Physiology of aorto-caval shunt

Intuition: exsanguination
Observation: venous decompression
Pressure measurement across tract
Patterns of Completion Angiography

Type 0: Complete occlusion
Type 1: Caval-aortic fistula with long tunnel, no extravasation (16%)
Type 2: Caval-aortic fistula + “cruciform” extra-aortic contrast. Most common pattern (55%)
Type 3: Extravasation (8%)
Patterns of CT

- **Gorgeous**
- **Peri-aortic hematoma**
- "Cruciform" pattern
- Retroperitoneal hematoma + organ displacement
Transcaval performed in a human cadaver

Foot

Head

Empty space

IVC

Aorta

R renal vein

Courtesy of James M. McCabe, MD
University of Washington, Seattle
Henry Ford 55th Case
ADO 10/8 Pull-through

Aorto-caval fistula without closure device. BP steady.

5Fr MPA over 0.014” FFR wire
CT follow-up

No retroperitoneal blood evident
Worldwide transcaval TAVI experience

<table>
<thead>
<tr>
<th>Center</th>
<th>Total</th>
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<tbody>
<tr>
<td>Henry Ford, Detroit, MI</td>
<td>73</td>
</tr>
<tr>
<td>Angiografia de Occidente, Cali, Colombia</td>
<td>15</td>
</tr>
<tr>
<td>Detroit Med Ctr, MI</td>
<td>3</td>
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<tr>
<td>Spectrum, Grand Rapids, MI</td>
<td>1</td>
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<tr>
<td>Emory U, Atlanta, GA</td>
<td>24</td>
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<tr>
<td>U Utah, Salt Lake City</td>
<td>2</td>
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<tr>
<td>Oklahoma Heart, Tulsa, OK</td>
<td>9</td>
</tr>
<tr>
<td>Columbia U, New York, NY</td>
<td>2</td>
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<td>German Heart Ctr, Munich, Germany</td>
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<td>Wake Forest Baptist, Winston Salem, NC</td>
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<td>Good Samaritan, Cincinnati, OH</td>
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<td>Edward Hospital, Naperville, IL</td>
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<td>Cleveland Clinic, OH</td>
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<td>Wellspan Hospital, York, PA</td>
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<td>University of Virginia</td>
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<td>Vanderbilt University, TN</td>
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<td>Bon Secours, Richmond, VA</td>
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<tr>
<td>St Vincent, Indiannapolis, IN</td>
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<td>Inst Dante Pazanesse, Sao Paolo, BRAZIL</td>
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<td>Terrebonne Med Ctr, Houma, LA</td>
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<td>Lexington Med Ctr, Columbia, SC</td>
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<td>Washington Hosp Ctr, DC</td>
<td>1</td>
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<tr>
<td>Ochsner Clinic, New Orleans, LA</td>
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<tr>
<td><strong>TOTAL</strong></td>
<td><strong>181</strong></td>
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</table>
### Temporal trends

<table>
<thead>
<tr>
<th></th>
<th>HFH Early (n=28)</th>
<th>HFH Recent (n=44)</th>
<th>Other Centers§ (n=87)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transcaval success</td>
<td>100%</td>
<td>100%</td>
<td>100%</td>
</tr>
<tr>
<td>Emergency surgery repair</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
</tr>
<tr>
<td>Transfusion during or after</td>
<td>79%</td>
<td>22%</td>
<td>38%</td>
</tr>
<tr>
<td>Covered stents</td>
<td>6 (21%)</td>
<td>4 (9%)</td>
<td>8 (10%)</td>
</tr>
<tr>
<td>Length of stay – days</td>
<td>9 ± 8</td>
<td>5 ± 5</td>
<td>4 ± 3</td>
</tr>
</tbody>
</table>

§ excludes Cali, Colombia – no data avail
Rapid high flow heart support?

5.0L Impella fully percutaneous
A purpose-built closure device?

- Hemostatic covering
- Central guidewire lumen
- Telescoping variable distance
- Designed to resist pull-through
- Effective *in vivo*

Transmural Systems, Inc
Summary: Transcaval access

Even thought it is counterintuitive....

- Transcaval access & closure is feasible, teachable, and has been applied in > 180 TAVI to date
- NHLBI is sponsoring an IDE protocol using *Amplatzer* devices
- There may be other applications, such as pVAD, TEVAR
- Closure is imperfect with marketed *Amplatzer* devices
- With a purpose-built closure device, transcaval access may avert surgical access for TAVI
Mitral Cerclage Annuloplasty

A groovy transcatheter approach to reduce mitral annular area
Functional Mitral & Tricuspid Regurgitation

PROBLEMS

- Annular circumferential dilation
- Leaflet traction

SOLUTIONS

- Annular circumferential tension
- “Tilt” to accommodate papillary muscle (mitral)
Solution: encircle the valves

Trans-Auricular Intra-Pericardial Tricuspid Annuloplasty: TRAIPTA

Transcatheter mitral cerclage annuloplasty
Transcatheter mitral cerclage annuloplasty

June-Hong Kim, JACC 2009
Necropsy after cerclage

Viewed from right ventricle

Anterior

Septum

R.Atrium

septal reentry
Coronary artery compression & protection

(-) Protection; 0-400 g Tension

(+0 Protection; 0-800 g Tension
Regurgitation grade (1-4)

Categorical mitral regurgitation

Mitral regurgitation measured using MRI

Regurgitant fraction (%)

p=0.04

(-) Tension (+) Tension

Immediate impact of cerclage

Kim JH et al/JACC 2009;54:638
Immediate impact of cerclage

Baseline
RF = 0.42

Cerclage
RF = 0.08

Kim JH et al/JACC 2009;54:638
First in human mitral cerclage

June-Hong Kim, MD; Pusan National University, Republic of Korea

ACC 2016, Session 627, April 2 2016, 14:50, Rm S102

n=4 to date
TRAIPTA

A groovy way to squeeze the tricuspid annulus to treat functional tricuspid valve regurgitation
TRAIPTA: Trans-Atrial Intrapericardial TRICUSPID Annuloplasty

Animal model of functional TR

Baseline

TRAIPTA

Toby Rogers JACC Intv 2015;8:483
Intentional right atrial perforation and exit

A groovy way to enter the pericardium when it’s empty, without causing a nasty scrape
The “healthy” pericardial space is hard to get to without surgery

- Pericardial access
  - to close the left atrial appendage (to prevent stroke)
  - to ablate ventricular tachycardia
Transatrial Pericardial access

SL2 sheath + Edwards T-tip BWEC

“Power position”

Roadrunner 0.014” back-end
Renegade 018 STC 2.8Fr
Withdraw wire; connect CO$_2$
50 mL CO2

100 mL CO2

Subxiphoid needle entry

RAA wire out after TSP

Rogers, Ratnayaka... Lederman, Catheter Cardiovasc Interv. 2015;86(2):E111-8

Greenbaum, Rogers... Lederman, JACC Clin Electrophysiol. 2015;1(5):434-441
Endo + Epi wire dock

Lariat around LAA

LAA angio

Endo + Epi wire dock

Lariat tightened

Completion
MRI- or XFM-guided backstabbing

A groovy way to enter the heart coaxial with the mitral annulus;
an acceptable way to act at academic medical centers
Backstabbing as a therapeutic procedure to access the mitral valve

Transapical injures myocardium

Why not through the back...?
MRI transthoracic LA access

This approach provides direct access to the mitral valve

Toby Rogers, Circ Interv. 2015 Jun;8(6):e0025
Can it be done without MRI?
What about humans?

Coaxial trajectories in all CTs examined

Toby Rogers, Circ Interv. 2015 Jun;8(6):e0025
Summary: novel catheter procedures

• Take advantage of conventional (X-ray) or enhanced (MRI) imaging guidance
  – Congenital (for example cavopulmonary shunt)
  – Rhythm disorders (for example, chemoablation of myocardium)
  – Valve disorders (for example, cerclage mitral or TRAIPTA tricuspid)
  – Access (transcaval, “backstabbing”)

• Convergence of surgical and catheter procedure capabilities that “break down barriers”
Transmural catheterization at NHLBI

Image guidance beyond X-ray fluoroscopy is enabling new catheter-based treatments for structural heart disease.

<table>
<thead>
<tr>
<th>Application</th>
<th>What to expect next</th>
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<tbody>
<tr>
<td>MRI Catheterization</td>
<td>• New catheter tools &amp; wider adoption</td>
</tr>
<tr>
<td>MRI Cavopulmonary Shunt</td>
<td>• Preclinical</td>
</tr>
<tr>
<td>MRI Endomyocardial Biopsy</td>
<td>• Commercial development</td>
</tr>
<tr>
<td>MRI Chemoablation</td>
<td>• Preclinical</td>
</tr>
<tr>
<td>Transcaval access</td>
<td>• Finish IDE</td>
</tr>
<tr>
<td>Cerclage mitral annuloplasty</td>
<td>• Purpose-built closure device</td>
</tr>
<tr>
<td>Transatrial pericardial CO2 insufflation</td>
<td>• New applications: TEVAR, pVAD/ECMO</td>
</tr>
<tr>
<td>TRAIPTA Tricuspid Annuloplasty</td>
<td>• ? RCT for alternative access</td>
</tr>
<tr>
<td>Backstabbing posterior left atrial access</td>
<td>• IDE Protocol 2018 Transmural systems</td>
</tr>
<tr>
<td></td>
<td>• Done</td>
</tr>
<tr>
<td></td>
<td>• IDE Protocol 2017-2018 Cook Medical</td>
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<tr>
<td></td>
<td>• Clinical application</td>
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Cardiovascular Intervention Program at NHLBI