New Echocardiographic Modalities to Evaluate Ventricular Function in Congenital Heart Disease: Tissue Doppler & Strain Rate Imaging

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No Disclosures
Evaluation of Ventricular Function

- Intrinsic myocyte function
- Ventricular pump function

- Active force development (pressure generation)
- Wall properties
  - Elasticity
  - Fiber structure
  - Global geometry
- Deformation (volume ejection)
- Peripheral circulation
  - Loading conditions
Evaluation of LV Systolic Function
Echocardiography

Volumetric parameters
LVSF % and LVEF %

- Readily performed
- Load dependent
- Do not evaluate
  - Regional function
  - Longitudinal function
Evaluation of LV Diastolic Function

Echocardiographic Classification of Diastolic Dysfunction

<table>
<thead>
<tr>
<th>Stage I: Impaired Relaxation</th>
<th>Stage II: Pseudonormal</th>
<th>Stage III: Reversible Restrictive</th>
<th>Stage IV: Fixed Restrictive</th>
</tr>
</thead>
<tbody>
<tr>
<td>Normal Diastolic Function</td>
<td>0.75 &lt; E/A &lt; 1.5</td>
<td>0.75 &lt; E/A &lt; 1.8</td>
<td>E/A &gt; 1.8</td>
</tr>
<tr>
<td>DT &gt; 140 ms</td>
<td>DT &gt; 140 ms</td>
<td>DT &lt; 140 ms</td>
<td>DT &gt; 140 ms</td>
</tr>
</tbody>
</table>

Mitral Inflow

- ΔE/A < 0.5
- ΔE/A < 0.5
- ΔE/A < 0.5
- ΔE/A < 0.5

Mitral Inflow at Peak Valsalva Maneuver

- S/D
- S/D
- S/D
- S/D

Pulmonary Venous Flow

- Tp ≤ 45 ms
- Tp ≤ 45 ms
- Tp ≤ 45 ms
- Tp ≤ 45 ms

Color M-Mode Propagation Velocity

- E/Ea > 10
- E/Ea > 10
- E/Ea > 10
- E/Ea > 10

Deoxy Tissue Imaging of Mitral Annular Velocities

- LV Relaxation: Normal, Impaired, Impaired, Impaired, Impaired
- LV Compliance: Normal, Normal to ↓, ↓, ↓, ↓
- Atrial Pressure: Normal, ↑, ↑, ↑, ↑
Evaluation of RV Function

Echocardiography

• **Unique challenges with RV**
  - Geometry
  - Anatomic location
  - Different hemodynamics compared to LV
  - Right - left heart interaction
  - Effects of co-existing congenital heart disease
    - Loading conditions
Evaluation of Ventricular Function
Congenital Heart Disease

Challenges in congenital heart disease

- Complex anatomy
- Variable loading conditions
- Regional myocardial function
- RV function as relevant as LV function
Evaluation of Congenital Heart Disease

Segmental Approach

- Situs & Position
- Systemic & Pulmonary Venous Connections
- Atrial & AV Connection
- Ventricular morphology
- VA Connection
- Great Arteries

Hypoplastic Left Heart
Evaluation of Ventricular Function
Echocardiographic “Segmental Approach”

LV systolic function
- M-mode parameters
- Stress-velocity index
- LVSF % and LVEF %

LV diastolic function
- Mitral inflow Doppler
- Pulmonary venous Doppler
- Color flow propagation
- LA volume

LV global function
- Myocardial performance index

LV longitudinal function
- Tissue Doppler

LV regional function
- Strain and strain rate
- LV torsion
- LA volume
Evaluation of Ventricular Function
3-Dimensional Echocardiography
Evaluation of Ventricular Function
New Echo Modalities

Tissue Doppler

Strain & strain rate imaging
Tissue Doppler & Strain Rate Imaging

Potential Advantages

- Quantitative evaluation of myocardial motion & deformation
- Less geometric limitations
- Less impacted by loading conditions
- Better suited to serial evaluation
- Enable early identification of ventricular dysfunction
- Facilitate earlier and better treatment modalities
Tissue Doppler Imaging

Systole

Diastole

20 cm/s

IVC

Peak systole

IVRT

E

A
Tissue Doppler Imaging

**Background**

**Longitudinal and radial shortening and lengthening**
- Load “independent”
- “Myocardial”
- Systolic & diastolic components

**Heterogeneous distribution of TDI velocities**
- Cardiac translation & tethering
- Orientation of myocardial fibers
- Systolic and diastolic velocity gradients
Pulsed Wave Tissue Doppler
Longitudinal Velocities

Lateral mitral annulus

Septal annulus

Tricuspid annulus
Tissue Doppler Imaging
Assessment of LV Diastolic Function

• Magnitude of Ea velocity blunted with diastolic dysfunction (cath-derived tau)

• Loading conditions
  Ea less influenced by loading conditions

• Diastolic dysfunction
  Pseudonormal mitral inflow
  Elevated LV filling pressures

• Constriction vs restriction
Tissue Doppler in Normal Children

- TDI velocities impacted by cardiac growth
  - LV end-diastolic dimension
  - LV mass
- TDI velocities also impacted by
  - Age
  - Heart rate
- TDI not influenced by
  - Gender
  - Mitral inflow Doppler
  - LV SF, LV EF, LV & RV MPI

Eidem et al: JASE, 2004
### Clinical Outcome in DCM

<table>
<thead>
<tr>
<th>Variable</th>
<th>OR</th>
<th>95% CI</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Multivariate analysis</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tricuspid Ea velocity</td>
<td>0.683</td>
<td>0.509-0.917</td>
<td>0.011</td>
</tr>
<tr>
<td>LVEF</td>
<td>0.833</td>
<td>0.736-0.944</td>
<td>0.004</td>
</tr>
<tr>
<td><strong>Univariate analysis</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tricuspid Ea velocity</td>
<td>0.708</td>
<td>0.578-0.868</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>RV Tei index</td>
<td>1.073</td>
<td>1.002-1.149</td>
<td>0.04</td>
</tr>
<tr>
<td>LVEF</td>
<td>0.895</td>
<td>0.839-0.956</td>
<td>&lt;0.001</td>
</tr>
</tbody>
</table>

**LVEF in DCM**

- Control (Cntl) vs. DCM P- vs. DCM P+

**Tricuspid Ea in DCM**

- Normal (N) vs. Hypertrophy (NH) vs. Hypertrophy/Ischemia (H/I) vs. D/T vs. PEP+

McMahon CJ: Br Heart J, 2004
Tissue Doppler in HCM

Myocardial velocities in HCM

VO₂ max (mL/min/kg)

Myocardial velocities & VO₂ max

y = 54 - 2x
r = -0.74
P < 0.001
Tissue Doppler
Preclinical Diagnosis of HCM

Peak Systolic Septal Velocities

Reduced peak systolic velocities in M+ with normal wall thickness

Nagueh SF: Circulation, 2001
Assessment of Ventricular Function

Tissue Doppler - IVA

- Tissue Doppler Velocities
  - Affected by loading
- Isovolumic Acceleration
  - Begins at initial onset of LV pressure rise
  - Earliest of systolic events

Vogel M et al, Circ 2003
Assessment of Ventricular Function

Tissue Doppler - IVA

- LV & RV Contractility
  - Independent of physiologic Δ’s in preload & afterload
  - Correlates with invasive $E_{es}$ and $dP/dt_{max}$
  - Correlates with Δ’s in contractile state
  - Force - frequency
  - Atrial pacing

Vogel M et al, Circ 2002 & 2003
Tissue Doppler Detection of Allograft Rejection

- **Baseline**
  - ↓ Sa, Ea vs controls
  - IVA similar

- **△ with rejection**
  - ↓ FS%
  - ↑ M-mode score
  - ↓ Sa, Ea
  - ↓ IVA

Pauliks et al: JHLT 2005
Tissue Doppler Limitations

- Angle dependency
- Influenced by global heart motion
  - Cardiac translation & torsion
- Myocardial motion influenced by adjacent segments (tethering)
- Load dependency
Strain Rate Imaging

- **Strain** = myocardial deformation caused by fiber contraction
  \[ \frac{(L - L_0)}{L_0} \]
- **Strain rate** = rate of regional myocardial shortening & lengthening
  - Myocardial Doppler velocities at 2 different locations → spatial velocity gradient
  - Less load dependent
  - Less variation in different myocardial wall segments

**Elastic Deformation Properties**

\[ \text{Strain} = \frac{\Delta l}{l_0} \]

\[ \text{Strain rate} = \frac{V_1 - V_2}{d} \]

\[ \text{SR} = \frac{\Delta L/L_0}{\Delta t} = \frac{v(I_0) - v(\Delta L + L_0)}{L_0} \]

\[ \varepsilon(t) = \int_{t_0}^{t} \frac{L(t + dt) - L(t)}{L(t)} \]
Strain Rate Imaging

Velocities $\Delta r$ $V_1$ $V_2$

Natural Strain Rate $\varepsilon$

Natural Strain $\varepsilon$

Calculate spatial gradient

Integrate temporally

Strain (rate) estimation = velocity estimation + post processing
Strain Rate Imaging

Radial Function

- Peak systolic strain rate
- Thickening
- Thinning
- Peak systolic strain
- Strain rate (sec⁻¹)
- Strain (%)

Courtesy L Mertens
Strain Rate Imaging
Longitudinal Function

Shortening
Lengthening

Peak systolic strain rate
Peak systolic strain

Strain rate (sec\(^{-1}\))
Strain (%)

SYSSYS DIAST DIAST

-20

Courtesy L Mertens
Strain Imaging in Children
Normal Longitudinal Deformation

Systolic Strain

LV Sept
LV Lat
LV Inf
RV Free

Weidemann: JASE, 2002
Case Presentation

4 month old presents to local ER
- Poor feeding & weight gain
- Tachypnea, pallor
- Physical exam
  - Tachycardic, hypotensive
  - III / VI HSM apex --> axilla
  - Poor distal pulses & perfusion
- CXR --> cardiomegaly & pulmonary edema
- ECG --> Q-waves in leads I and AVL
- Echocardiogram performed in ER
Echocardiogram
Strain Rate Imaging
Clinical Outcome in CHD

- ALCAPA
  - Causes global LV ischemia
  - LV histological changes of “hibernating myocardium”

- Re-implantation of coronary artery results in “normalization of LV function”

Courtesy BCH
ALCAPA
Radial LV Function

Preop 1 week postop 5 mo postop

Strain %

80
40

Mertens L, Cardiol Young 2001
ALCAPA – Longitudinal Strain Rate

DiSalvo G: AJC, 2004
Duchenne Muscular Dystrophy

- Mutation in dystrophin gene
- Genetic model for dilated cardiomyopathy
- Young patients often have ‘normal’ LV function
- > 90% develop DCM later in life
## Routine Echocardiographic Results

<table>
<thead>
<tr>
<th></th>
<th>DMD &lt;12 yr</th>
<th>Normals</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Age</strong></td>
<td>7.4±2.6</td>
<td>7.3±2.8</td>
</tr>
<tr>
<td><strong>Heart rate</strong></td>
<td>102.2±9.9</td>
<td>82.1±13.8*</td>
</tr>
<tr>
<td><strong>LVEDD/BSA</strong></td>
<td>4.3±0.6</td>
<td>4.1±0.6</td>
</tr>
<tr>
<td><strong>LVESD/BSA</strong></td>
<td>2.9±0.5</td>
<td>2.6±0.4</td>
</tr>
<tr>
<td><strong>LV FS (%)</strong></td>
<td>33.7±3.2</td>
<td>35.6±3.7</td>
</tr>
<tr>
<td><strong>LV EF (%)</strong></td>
<td>64.9±5.6</td>
<td>66.5±5.6</td>
</tr>
<tr>
<td><strong>Mitral E</strong></td>
<td>1.0±0.2</td>
<td>1.0±0.1</td>
</tr>
<tr>
<td><strong>Mitral A</strong></td>
<td>0.5±0.1</td>
<td>0.5±0.1</td>
</tr>
<tr>
<td><strong>E/A ratio</strong></td>
<td>2.1±0.6</td>
<td>2.2±0.6</td>
</tr>
<tr>
<td><strong>Deceleration time</strong></td>
<td>126.6±29.4</td>
<td>131.6±22.8</td>
</tr>
</tbody>
</table>

*Mertens L: AEPC, 2004*
Correlation of Strain & Age in DMD

Mertens L, AEPC 2004
Hypertrophic Cardiomyopathy
Echocardiography
Strain Rate Imaging in HCM

Septal Deformation

Mid septal lengthening was found in 50% of the HCM’s patients

Yang H, JASE 2003
Strain vs Z score for IVSD thickness
LV Deformation in Pediatric HCM

Ganame: JASE, 2005

†P<0.001 vs controls; *P<0.01 vs controls
Hypertrophic Cardiomyopathy
Strain & Strain Rate Imaging

Strain in HCM

Strain Family history of HCM
Strain & Strain Rate Imaging

Limitations

- 1-dimensional technique
- Load dependent
- Angle dependent
- Frame rate >150 fps
- Aliasing
- Reverberation artifacts
- Data processing
Strain & Strain Rate Imaging

Myocardial Twist & Torsion
Strain & Strain Rate Imaging
Speckle Tracking
Strain & Strain Rate Imaging
Myocardial Twist & Torsion
Strain & Strain Rate Imaging
Myocardial Twist & Torsion

- **Myocardial twist mechanics**
  - Subendocardium
    - Right handed helix
  - Subepicardium
    - Left handed helix
  - Clockwise twist of base vs CCW at cardiac apex

- **Systole** - global LV twist related to ejection + stored energy

- **Diastole** - 2 phases
  - Early rapid recoil
  - Gradual later untwisting
Myocardial Deformation Imaging

Age, Loading Conditions & LV Twist

- LV twist ↑ from childhood → adulthood
  - Apical CCW rotation constant
  - Base CW rotation changes with age
    - Infancy → CCW rotation
    - Childhood → neutral
    - Adolescence → CW rotation
Hypertrophic Cardiomyopathy

Deformation Imaging

Figure 1. Example of 2-dimensional strain curves obtained in (A) athletes and (B) patients with HC.

Richland et al, AJC 2007
Evaluation of Systemic RV Function
Pressure - Volume Relationship

RV Pressure - Volume Loop
LV Pressure - Volume Loop

Redington A, Cardiol Clin 2002
Evaluation of Systemic RV Function
Strain & Strain Rate

- Systemic RV
  - Circumferential > longitudinal RV strain
    - Similar to normal LV strain pattern
  - Circumferential > longitudinal SR
    - compared to normal LV SR

Petterson E, JACC 2007
TDI & Strain Rate Imaging in CHD

Conclusions

• Sensitive techniques for detecting regional abnormalities
• New insights into pathophysiology of CHD
• Early identification and treatment of ventricular dysfunction
• Ongoing clinical validation studies