Hemodynamics by Echocardiography
The Present: Image Guided Diagnosis and Intervention
Echocardiography

Anatomic Information

Functional Information
Echocardiography

Functional Information

- Systolic Function
- Wall Motion Analysis
- Diastolic Function
- Valvular Function
- Hemodynamic Function
Christian Doppler was an Austrian mathematician who lived between 1803-1853. He is known for the principle he first proposed in *Concerning the coloured light of double stars* in 1842. He hypothesised that the pitch of a sound would change if the source of the sound was moving. He didn't test this hypothesis until 1845.
Doppler Echocardiography History

- **1959 Satomura**
  detected arterial flow
- **1961 Franklin**
  measurement of flow velocity
- **1973 Johnson**
  located place of cardiac murmur
- **1978 Hatle**
  measured PG between LA and LV
- **1982 Namekawa**
  real time color Doppler using autocorrelator technique
Hemodynamic data that can be obtained with Doppler echocardiography

- **Volumetric measurements**
  - Stroke volume and cardiac output
  - Regurgitant volume and fraction
  - Pulmonary-systemic flow ratio (Qp/Qs)

- **Pressure gradients**
  - Maximal instantaneous gradient
  - Mean gradient

- **Valve area**
  - Stenotic valve area
  - Regurgitant orifice area

- **Intracardiac pressure**
  - Pulmonary artery pressure, LA pressure, LVEDP
Stroke Volume, Cardiac Output, Cardiac Index

• $SV(\text{cc}) = TVI(\text{cm}) \times CSA(\text{cm}^2)$

• $CO(\text{liters/min}) = SV(\text{cc}) \times HR(\text{beats/min})$

• $Cl(\text{liters/min/m}^2) = CO(\text{liters/min}) \times BSA(\text{m}^2)$
Pressure gradient from Doppler measurements

- *Pressure gradient* → *Modified Bernoulli Eq.*
  \[ \Delta P = 4 V^2 \]

Limitation of Doppler velocity
(and pressure gradient derived thereof)

→ *Volume and Rate-dependent*
Estimation of Pulmonary Arterial Pressure

Assume RAP 10mmHg

\[
PASP = TR^2 \times 4 + RAP \\
= 4.5^2 \times 4 + 10 \\
= 81 + 10 = 91 \text{ mmHg}
\]

\[
PADP = PR^2 \times 4 + RAP \\
= 3^2 \times 4 + 10 \\
= 36 + 10 = 46 \text{ mmHg}
\]
Estimation of Left Ventricular Enddiastolic Pressure

Systemic BP : 160/80mmHg

Diastolic BP = LVEDP + (AR enddiastolic velocity)^2 x 4

80 mmHg = LVEDP + 4^2 x 4

LVEDP = 80 - 64 = 16 mmHg
Simultaneous Measurement of Doppler and Catheter Derived Pressures

LV

DPG: 9.6 mmHg

DPG: 10 mmHg

PCWP
Measurement of dp/dt
As LV filling pressure ↑

Mitral E ↑

Annulus E’ ↓

E/E’ ↑

y = 1.9 + 1.24x

r = 0.87

n = 60

Nagueh et al: JACC, 1997
Ommen et al: Circ, 2000
Abnormal relaxation
Pseudo-normal
Restriction (reversible)
Restriction (irreversible)

Mean LAP
N - ✓
Grade diastolic dysfunction
I II III IV

15-25
>25
Measurement of jet area

Jet area (cm$^2$)
Grade 1 : 4 - 8
Grade 2 : 8 - 12
Grade 3 : 12 - 16
Grade 4 : > 16
Quantification of MR
- Volumetric method -

\[ MV \text{ Reg } V = MV \text{ flow } - LVOT \text{ flow} \]

\[ MV \text{ RF} = \frac{MV \text{ Reg } V}{MV \text{ flow}} \times 100 \]

**MV Reg V**: mitral valve regurgitant volume

**MV RF**: mitral valve regurgitant fraction(%)
Quantification of MR
- PISA method -

r = 1.1 cm
Alias Velocity = 29 cm/sec
MR Velocity = 4.3 m/sec
ERO = \( 6.28 \times (1.1)^2 \times 29 \)
\[
\frac{430}{430}
\]

\[ RV = ERO \times MR \ TVI \]
\[ = 0.51 \times 114 = 58 \text{ ml} \]
Advantage of Echo

- Inexpensive
- Safe
- Portable
- Repeat
- Hemodynamic information
  - Do not require offline analysis
Pitfalls of Echocardiography

- Image quality
  - Good vs poor
- Operator dependent
  - Expert vs beginner
- Subjective
- Machine factor
Echocardiography

Sometimes there are some discrepancies with patient’s clinical status........
New Advanced Technology in Echo

• Evaluation of LV Mechanics
  - 2D Strain and Strain rate
  - Twist and torsion
• Real time 3D Echo
  - Single beat 3D Echo
• LV vortex flow analysis with contrast Echocardiography
Evaluation of LV systolic function

- Normal
- CHF
73 year old man with DOE

HTN, DM for 10 yrs
20 year old man with ECG abnormality
Myocardial motion, strain
Tissue “Speckle or Feature” tracking

The basic concept
gray tissue is displaced from one frame to another

evaluate such a displacement at every point
Apical Rotational Mechanics

What to Measure?
LVEF 75%
E/A = 0.76
E/E' = 5.4
LAV 20 ml/m²
Rotation 19.8 deg
R Rate 109.5 deg/s
Rev Rot rate 113.5 deg/s

LVEF 62%
E/A = 0.79
E/E' = 8.6
LAV 36 ml/m²
Rotation 18.5 deg
R Rate 109.1 deg/s
Rev Rot Rate 100.5 deg/s

LVEF 40%
E/A = 2.34
E/E' = 10.8
LAV 42 ml/m²
Rotation 6.8 deg
R Rate 45.6 deg/s
Rev Rot Rate 20.5 deg/s

Normal

DD ± DHF

SHF + DHF
3D Strain
“3D echocardiography …..

At present, available evidence suggests that provides improved accuracy and reproducibility over 2D methods for LV volume and function calculation and the derivation of mitral valve area in patients with …..
3D Echocardiography

Real time 3-Dimensional Echocardiographic Volume Measurements
End Diastolic Volume

2D Biplane EDV

\[ y = 0.76x + 17.1 \]

\[ R^2 = 0.79 \]

RT3D ESV

\[ y = 0.89x + 4.3 \]

\[ R^2 = 0.93 \]

EDV: RT3D-MRI

EDV: 2D-MRI

Jacobs L et al., European Heart Journal 27: 460-468, 2006
End Systolic Volume

2D

2D Biplane ESV

$y = 0.79x + 4.3$

$R^2 = 0.85$

RT3D

ESV: RT3D-MRI

$y = 0.88x + 4.7$

$R^2 = 0.94$

Jacobs L et al., European Heart Journal 27: 460-468, 2006
2-D Echocardiography
Mitral Regurgitation
2-D Quantification of MR Flow EROA by PISA

A4C

Radius 7.8 mm
\( V_{\text{aliasing}} \) 23 cm/s
EROA: 0.23 cm\(^2\)

A2C

Radius 9.5 mm
\( V_{\text{aliasing}} \) 35 cm/s
EROA: 0.52 cm\(^2\)
Limitations of 2D PISA

Today’s Assumptions
– Centralized regurgitant jets
– Orifices are circular
– PISA shape is hemispheric

Today’s Results
– Manual multi-step process
– User dependency
– Excludes patients with eccentric jets

Reg Flow = 2π r² x Va
EROA = Reg Flow / PkV_{Reg}
Assessment of PISA:
Pediatric Population

Real time volume color Doppler

Real time volume Doppler - Volume PISA

Quantification of regurgitation based on 3D volume color Doppler

Accurate measurement free of geometric assumptions

Accurate measurement of derived clinical parameters (e.g. EROA, RV and RF)

Easy workflow
Quantification of Flow
RT-VCFD flow quantification
Automated quantification of mitral regurgitation
By 3D Real-Time Volume Color Doppler

• Regurgitant Volume
  - Mitral Inflow and LVOT Flow
Quantification of Flow
Automated Regurgitant Volume

81.7ml  95.5 ml  107.9ml
Quantification of Flow
Automated Regurgitant Volume

34.1ml  30.8ml  36.3ml
Quantification of Flow
Automated Regurgitant Volume

Average 95 ml

Average 33.7 ml

Regurgitant Volume 61.3 ml

81.7 ml 95.5 ml 107.9 ml
34.1 ml 30.8 ml 36.3 ml
Methods

• **Study population**
  – Consecutively enrolled 9 patients with
  – More than moderate degree of MR on 2D transthoracic echocardiography (TTE)
  – Undergoing CMR

• **2D TTE**
  – MR volume quantification by using
    • Proximal isovelocity surface area (PISA) method
    • Continuity equation (CE).
Methods

• **RT-VCFD**
  – Siemens Acuson SC2000, 4Z1c real-time volume imaging transducer (2.8 MHz).
  – Offline analysis using prototype software (Siemens Medical Solutions USA Inc.)

• **Cardiac MRI**
  – Phase contrast (PC)-CMR
  – Volumetric Stroke volume
  – Aortic VE Flow
RT-VCFD Analysis
RT-VCFD Analysis
RT-VCFD Analysis
**2D TTE: PISA**

ERO = 1.9 cm²

Regurgitant Volume = ERO X VTI = 1.9 X 96 = 182 ml
Mitral SV: 225cc - LVOT SV: 60cc = 165cc
Regurgitant Volume = MVI - LVO = 220.2 - 64.8 = 155.4 cc
Stroke volume = 191.6 ml

Regurgitant Volume = Stroke volume – AA forward flow volume

= 191.6 – 36.9 = 154.7 ml
Comparison

Regurgitant Volume = 154.7 ml

Regurgitant Volume = 182 ml

Regurgitant Volume = 165 ml

Regurgitant Volume = 155.4 ml
## RESULTS

**Quantification of Mitral regurgitant volume**

<table>
<thead>
<tr>
<th></th>
<th>MR volume (ml)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2D PISA</td>
<td>47.5 ± 24.2</td>
</tr>
<tr>
<td>2D CE</td>
<td>73.7 ± 50.8</td>
</tr>
<tr>
<td>3D RT-VCFD</td>
<td>78.1 ± 47.4</td>
</tr>
<tr>
<td>MRI</td>
<td>73.6 ± 44.3</td>
</tr>
</tbody>
</table>

**Differences in MR volume compared with PC-CMR**

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>2D PISA (ml)</td>
<td>25.7 ± 26.4</td>
</tr>
<tr>
<td>2D CE (ml)</td>
<td>26.9 ± 16.5</td>
</tr>
<tr>
<td>3D RT-VCFD (ml)</td>
<td>9.9 ± 10.8</td>
</tr>
</tbody>
</table>

*P = 0.016*
RESULTS

Correlation between PC-CMR and RT-VCFD (A), 2D PISA (B), 2D CE (C)

- **Figure A**: 
  - Correlation coefficient: $r = 0.95$
  - Significance: $p = 0.0001$

- **Figure B**: 
  - Correlation coefficient: $r = 0.79$
  - Significance: $p = 0.01$

- **Figure C**: 
  - Correlation coefficient: $r = 0.82$
  - Significance: $p = 0.03$
REULTS

Bland-Altman analysis comparing MR volume by RF-VCFD (A), 2D PISA (B), and 2D CE (C) with PC-CMR
3-D Echocardiography
### CASE

<table>
<thead>
<tr>
<th>2D PISA</th>
<th>3D PISA</th>
<th>MRI</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="2D_PISA_image" alt="" /></td>
<td><img src="3D_PISA_image" alt="" /></td>
<td><img src="MRI_image" alt="" /></td>
</tr>
</tbody>
</table>

**MR Regurgitant volume**

| 73.0 mL | 106.0 mL | 107.2 mL |
RESULT

Correlation between methods

3D-PISA vs. 2D-PISA

3D-PISA vs. PC-MRI

$r=0.49, P=0.15$

$r=0.95, P<0.01$
RESULT

Agreement between methods

**3D-PISA vs. 2D-PISA**

- Mean = -0.7
- ±1.96 SD = -64.6 ~ 63.2

**3D-PISA vs. PC-MRI**

- Mean = -5.6
- ±1.96 SD = -34.4 ~ 23.1
SUMMURY

- Automated quantification of MR with RT-V CFD
  - Feasible
  - Mitral regurgitation volume can be computed automatically from CFD data
  - More accurate than 2D TTE (PISA or continuity equation)
  - Improves quantification of regurgitation
Conclusion

• Using RT-VCFD
  – Automated quantification of MR is feasible and accurate.
  – It should be a promising tool of real-time 3D echocardiography in the evaluation of patients with MR.

• Can be applied in
  – Evaluating response to medical or device therapy
  – Quantification of AR
  – Rt side valvular regurgitation and pul HTN
  – Qp / Qs
Echo in a Heart Beat
Automated RV Function Analysis
Vortex...
LV Vortex Flow Analysis by Contrast Echo
LV Vortex Flow Analysis

LV vortex flow in normal

Hong et al. J Am Coll Cardiol Img. 2008;1: 705-717

Change of vortex size during cardiac cycle
LV Vortex Flow Analysis

LV vortex flow in heart failure

Hong et al. J Am Coll Cardiol Img. 2008;1: 705-717

Steady streaming
Pulsatility intensity

Change of vortex size during cardiac cycle
**LV vortex flow in LV diastolic function**

Normal M/45 EF=65%
LAVI / E/E’ : 20 / 5.5

Mild DD M/54 EF=62%
LAVI / E/E’ : 25 / 8.4

Severe DD M/57 EF=72%
LAVI / E/E’ : 32 / 16

Hong et al. ACC 2008 (abstract)
Vorticity Imaging
Phasic Changes- Normal vs SHF vs DHF
LV Vortex Flow Analysis in HF

Correlation to symptomatic status in NYHA I-II compensated HF

M/53, DOE (-), EF=29%, E/E’=11, LAVI=28

M/32, DOE (+), EF=27%, E/E’=13, LAVI=30
## LV Vortex Flow Analysis in HF

Comparison of conventional and vorticity parameters to symptomatic status in NYHA I-II compensated HF

<table>
<thead>
<tr>
<th>Parameter</th>
<th>DOE (-) (n=7)</th>
<th>DOE (+) (n=6)</th>
<th>p value</th>
</tr>
</thead>
<tbody>
<tr>
<td>EF (%)</td>
<td>35.8 ± 5.7</td>
<td>32.5 ± 6.4</td>
<td>NS</td>
</tr>
<tr>
<td>LAVI (ml/m²)</td>
<td>28.4 ± 4.7</td>
<td>30.5 ± 5.7</td>
<td>NS</td>
</tr>
<tr>
<td>E/E'</td>
<td>10.8 ± 3.7</td>
<td>12.3 ± 4.5</td>
<td>NS</td>
</tr>
<tr>
<td><strong>LVEDP</strong></td>
<td>10.5 ± 3.2</td>
<td>13.8 ± 5.2</td>
<td>0.07</td>
</tr>
<tr>
<td><strong>CI (l/min/m²)</strong></td>
<td>2.9 ± 0.8</td>
<td>1.9 ± 0.7</td>
<td>0.02</td>
</tr>
<tr>
<td>RS</td>
<td>1.65 ± 0.3</td>
<td>1.18 ± 0.2</td>
<td>0.01</td>
</tr>
<tr>
<td>VRS</td>
<td>0.81 ± 0.2</td>
<td>0.59 ± 0.2</td>
<td>0.01</td>
</tr>
<tr>
<td>VPC</td>
<td>0.84 ± 0.2</td>
<td>0.67 ± 0.1</td>
<td>0.01</td>
</tr>
</tbody>
</table>

Hong et al. 2007 AHA (abstract) & In Submission
**LV Vortex Flow Analysis**

**LV vortex flow in ischemic cardiomyopathy**
Clinical Usefulness of LV Vortex Flow Analysis for Predicting Apical Thrombus Formation in Patients with LV Dysfunction

Jang-Won Son, Geu-Ru Hong, Sang-Hee Lee, Jong-Seon Park, Dong-Gu Shin, Young-Jo Kim, Bong-Sup Shim

Division of Cardiology, Yeungnam University, Daegu, Korea

Presented at 2011 AHA, and In Revision
Apical thrombus with LV dysfunction

Thrombus (+)
M/73, LVEF 27%
LVEDD 67mm, LVMI 162g/m²

Thrombus (-)
F/70, LVEF 20%
LVEDD 63mm, LVMI 160g/m²
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Hong et al. In Revision
LA Vortex Flow Analysis

Normal

Af
New Environment: Equipment
Diwan and co-investigators report in this issue of Circulation that the interval between onset of mitral E and annular early diastolic velocity (Ea) by tissue Doppler, Te-Ea, can be used to estimate left ventricular (LV) filling pressure in patients with mitral valve disease. Garcia and colleagues were the first to report that the onset of Ea occurred 7.5±3.5 ms after peak mitral inflow velocity in 7 patients with restrictive cardiomyopathy, whereas Ea started 22±19 ms earlier than did E in the normal group. Subsequently, Te-Ea has been shown to correlate with the time constant of LV relaxation (τ) demonstrated by Hasegawa and associates in their elegant animal experiment. With worsening of heart failure by rapid pacing, Ea progressively decreased in velocity and delayed in onset. Mitral E occurred confirmed that both the ratio of IVRT to Te-Ea and to τ correlate well with PCWP in patients with mitral valve disease or atrial fibrillation. These authors proposed different IVRT/Te-Ea ratio cutoff values for different patient populations to predict PCWP >15 mm Hg: <3 for patients with mitral regurgitation, <4.16 for patients with mitral stenosis, and <5.59 for patients with mitral regurgitation who were evaluated prospectively or with atrial fibrillation. On repeat studies after the mitral valve procedure, an increase in the ratio by ≥1.5 identified most patients who had a decrease in mean PCWP ≥5 mm Hg.

Tajik and I wrote an editorial for the article by Rivas-Gotz and associates, in which history and clinical applications of various cardiac time intervals were reviewed, and our views.
Take Home Messages

• Echocardiography provides important data for therapeutic decision making in cardiology field
• New techniques for the ventricular mechanics, vortex flow analysis and 3D echocardiography hold great promise for improving the quality of care to the patients
경청해 주세요.
Echo remains the best imaging tool