Doppler techniques and quantification

Bart Bijnens
The heart as a volume pump

- The main function of the heart is to maintain the required **cardiac output**
- Thus, it is a volume pump, trying to **generate a certain volume flow** under all cardiac conditions.
- The heart muscle has to develop force to **generate pressure gradients** that result in volume flow.
- For this, the heart muscle has a **unique structure and resulting deformation pattern**.

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Braunwald, Heart Disease (6th ed)

Anderson & Becker
Cardiac Anatomy '80
Blood flow is continuous, accelerating and decelerating during the cycle due to pressure gradients, without sudden changes in the momentum of the particles, to obtain energy efficiency.
Hemodynamic data: what to quantify?

Hemodynamics = dynamics of the blood = temporal behaviour of blood flow

• (I) Resulting volume displacements during the cardiac cycle
  – Stroke volumes and cardiac output
  – Regurgitant volumes due to valve incompetence
  – Shunt volumes and pulmonary-systemic flow ratio

• (II) Altered flow due to altered valve geometry (valve area)
  – Stenosis
  – Regurgitation
  – Abnormal connections (VSD, ASD,…)

• (III) Pressures & pressure gradients as driving forces for blood flow
  – $\Delta P$ between ventricles and atria determining filling
  – $\Delta P$ between ventricles and large arteries determining ejection
  – P in the different heart chambers determining the $\Delta P$ controlling the blood flow
    • LV ED pressure
    • LA pressure
    • PA pressure
  – P generation is related to myocardial function
Continuity of flow

\[ A_1 \times V_1 = A_2 \times V_2 \]

\[ A_2 = \frac{A_1 \times V_1}{V_2} \]

if there is no loss of fluid, at each cross section of the tube, the same volume-flow (cross section \( \times \) velocity) is passing.

Bernoulli equation

describes the relation between pressures and velocities for fluid flow, based on the conservation of energy.

\[ P_1 + P_2 = \frac{1}{2} \rho (V_2^2 - V_1^2) + \rho \frac{d}{dt} \left( \begin{array}{c} \frac{1}{2} \frac{dV}{dt} \end{array} \right) + R(V) \]

\[ \text{Pressure gradients} \]

Volumes and valve areas

Doppler echocardiography continuity equation
Available information from echocardiography?

- Geometry
- Velocities
- Flow patterns
CW systems

- No spatial information
- Several velocities in the beam: broad spectrum
- Attenuation: velocities from deeper tissue contribute less

www.echoincontext.com: Kisslo & Adams
- Spatial information
- Aliasing!
  - PRF as high as possible to detect high velocities and avoid aliasing
  - but limited by depth: time to travel back
  - velocities are digitized into a limited number of bits: typical 8 bit = 256 values try to optimize resolution = highest velocity is highest value

⇒ choose PRF as low as possible to just avoid aliasing
Doppler velocities: Angle dependency

Align the ultrasound beam with the direction of the jet angle dependency has dramatic effects…

www.echoincontext.com: Kisslo & Adams

H. Kühl, Univ. Hosp. Aachen
Doppler velocities: measurement position

Effect of sample volume position

Mitral inflow pattern

Appleton, JASE 1997
Haemodynamics: Volumes and volume changes

- **Volume flow rate** = cross sectional area \( \times \) velocity = \( A \times v \)
  - In cardiovascular applications: velocity is time and spatially variant!
    - Measure a spatially averaged velocity: Doppler sample volume
    - Include temporal variation and time: tracing of the spectrum = FVI

- **Volume** = volume flow \( \times \) time

- **Area from diameter**: \( A = \pi \times (D/2)^2 = \pi/4 \times D^2 = 0.785 \times D^2 \)

- **FVI (flow velocity integral)**: trace the Doppler spectrum (units: \( v \times t \rightarrow m/s \times s = m \))

- **Stroke volume** = \( A \times FVI \)

- **Cardiac output**: \( CO = SV \times HR \) (heart rate)

- **Cardiac index**: \( CI = CO/BSA \)

**Note terminology**
- TVI: time velocity integral
- VTI: velocity time integral
- FVI: flow velocity integral
Example: CO measurement

- CO = SV × HR = A × FVI × HR
- LVOT area:
  - Parasternal long axis view: D = 2.2 cm
  - A = 0.785 × 2.2² = 3.8 cm²
- Apical view: tracing FVI = 15 cm
- SV = area × VI = 3.8 cm² × 15 cm = 57 cm³ = 57 ml
- CO = 57 ml × 80 bpm = 4.6 l/min
Regurgitant volumes

Approach:

1. Direct measurement of regurgitant volume based on $SV = A \times FVI$
   needs the effective valve area!

2. Indirect measurement by making the volume balance of the ventricle
   \[ V_{\text{tot}} = V_{\text{stroke}} + V_{\text{regurg}} \]

   \[ V_{\text{tot}} = V_{\text{stroke}} + V_{\text{regurg}} \rightarrow V_{\text{regurg}} = V_{\text{tot}} - V_{\text{stroke}} \]

   - $V_{\text{tot}} = $ mitral inflow $= A_{\text{mitral}} \times FVI_{\text{mitral}}$
   - $V_{\text{stroke}} = $ aortic outflow $= A_{\text{LVOT}} \times FVI_{\text{LVOT}}$
   - $V_{\text{regurg}} = A_{\text{mitral}} \times FVI_{\text{mitral}} - A_{\text{LVOT}} \times FVI_{\text{LVOT}}$

Regurgitant fraction $= \frac{V_{\text{regurg}}}{V_{\text{tot}}} \times 100\%$

The Echo Manual, J. Oh, J. Seward, A. Tajik
Haemodynamics: Effective valve area

- **Use**?
  - Direct regurgitant volume measurements: \( V_{\text{regurg}} = A \times FV_{\text{regurg}} \)
  - Direct evaluation of stenosis/regurgitation valve area

- **Methods to determine effective valve area**?
  - Continuity equation
  - PISA
  - Pressure half time
Valve area: continuity equation

- Blood = incompressible & no extra shunts/regurgitation present
- Conservation of volume:
  - what passes before the valve has to pass through the valve
  - what passes through the MV has to pass through the AV

Before & after a valve

Mitral inflow vs aortic outflow

EAE/ASE recommendations AS Eur J Echocard 2009

Caveat: no regurgitations & arrhythmias!!
Example: continuity mitral-aortic

**Advantage**
- Functional area
- Best correlation with cath. area

**Problems**
- Only with no or minor MR and AR
- With AR, RVOT SV - more difficult
- Atrial fibrillation

\[
A_{\text{LVOT}} = 2.54 \text{ cm}^2
\]
\[
FVI_{\text{LVOT}} = 16.5 \text{ cm}
\]
\[
\Rightarrow SV_{\text{LVOT}} = 42 \text{ ml}
\]
\[
FVI_{\text{mitral}} = 102 \text{ cm}
\]
\[
A_{\text{mitral}} = \frac{FVI_{\text{mitral}}}{SV_{\text{LVOT}}} = \frac{42 \text{ ml}}{102 \text{ cm}} = 0.4 \text{ cm}^2
\]

Hatle 98
PISA for determining valve orifice area / regurgitant volume

- Based on continuity equation between valve orifice and a distance from it
- **PISA:** Proximal Isovelocity Surface Area
  - Flow converges hemispherical towards the orifice
  - Detect isovelocity surface $V_{\text{PISA}}$ using aliasing of velocities: blue-red color change change baseline and velocity scale.
  - Determine area of the isovelocity surface (assume half sphere: $2\pi R^2$)
  - Continuity: $2\pi R^2 \times V_{\text{PISA}} = A_{\text{orifice}} \times V_{\text{orifice}} \Rightarrow A_{\text{orifice}} = 2\pi R^2 \times V_{\text{PISA}} / V_{\text{orifice}}$  
- $V_{\text{regurg}} = A_{\text{orifice}} \times FVI_{\text{orifice}}$

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The Echo Manual, J. Oh, J. Seward, A. Tajik

PISA problems: non-hemispherical convergence

http://me.queensu.ca/people/sellens/research/sprayFlow/
Haemodynamics: pressure (gradients)

- **Bernoulli:** relation between pressures and velocities for fluid flow
- Simplified Bernoulli (in mmHg):
  \[ \Delta P = 4 \times v^2 \]
- Can be used in all cases where a velocity gradient is present
  - Stenosis
  - Regurgitation
  - Abnormal connection (VSD,...)
- Simplified !!
  - \( v_1 < v_2 \) → not valid for high LVOT flow
    (complex stenosis, AI)
  - \( \frac{dv}{dt} = 0 \) → no acceleration, only valid at velocity reversal = peak velocity
  - Viscous forces = 0 → normal blood properties, low velocities

Feigenbaum, Echocardiography
Example: $\Delta P$ aortic stenosis

Velocities represent pressure differences $\sim (p_1 - p_2)$

Changes in velocity curves can be due to changes in $p_1$ or $p_2$ (or both)

- $\Delta P = 4v^2$
  - $= 4 \times 3.7^2 \text{mmHg} = 55 \text{mmHg}$

- Mean gradient $\rightarrow$ mean velocity $\Rightarrow$ tracing of the velocity signal
Mitral Valve Area: Pressure half-time

\[ P \sim v \]
\[ \frac{P}{2} \sim v \sqrt{2} = 0.71v \]

\[ P = 0 \sim v = 0 \]

Pressure half-time
\[ = t_B - t_A \]
\[ = 0.29 \times \text{basetime} \]

\[ A_{\text{mitral}} = \frac{220}{P_{\text{half-time}}} \]
Max. velocity of regurgitations

→ pressure differences:

AR – between aorta and LV in diastole
PR – between PA and RV in diastole
MR – between LV and LA in systole
TR – between RV and RA in systole
Ventricular performance: 

\[ \frac{dP}{dt} \text{ from regurgitation velocity} \]

\[
\frac{dP}{dt} = \left( 4 \times v_3 \text{m/sec}^2 - 4 \times v_1 \text{m/sec}^2 \right) / dt \text{ (dt in s)}
\]

\[
= ( 4 \times 3^2 - 4 \times 1^2 ) / dt
\]

\[
= 32 / dt \text{ (mmHg/s)}
\]

Example: RV function from tricuspid regurgitation

\[
\text{dp/dt} = 1180 \text{ mm Hg/s}
\]

\[
\text{dp/dt} = 680 \text{ mm Hg/s}
\]
e.g. elevated $P_{\text{left atrial}}$: mitral inflow

- $\Delta P$ higher:
  - MV opens earlier: decreased IVRT
  - higher $V_{E\text{-wave}}$
- $P_{LV}$ increases faster $\Rightarrow$ shorter deceleration time
- Higher LV $P_{\text{diast}}$ $\Rightarrow$ lower A vel
- Increased pulmonary vein reversal flow
Mitral flow vs annular velocity

LV Systole       Early Diastole       Late Diastole

\[ \text{Vel}_{\text{mitral}} \sim P_{\text{LA}} - P_{\text{LV}} \]

\[ \text{annular vel} \sim \text{total deformation} \sim \Delta V \]
Flow morphology ↔ force development

Normal to Severe aortic stenosis:
- Active wall stress
- Shape of outflow velocities relates to force development

Stress (kPa):
- Normal
- Mild
- Moderate
- Severe

LV and AO images:
- No CAD
- Severe CAD

Liv Hatle / P. Claus
Doppler techniques are useful in the evaluation and quantification of cardiac haemodynamics and function

- Stroke and regurgitant Volumes
- Valve areas
- Pressure differences
- Pressure (force) development