מדידות המודינמיות באקו

פרופ' אהוד שוומנטל

המכון לשיקום חולי לב

מרכז רפואי ע"ש חיים שיבא

תל השומר

Valvular Hemodynamics

Pressure Gradient

Bernoulli's Law

Continuity Equation

Pressure Half-Time

Hemodynamics of Jets

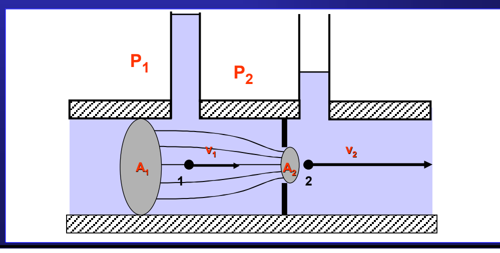
What causes a pressure gradients in the cardiovascular system?

- **Viscous friction**
- **Convective acceleration**
  (Bernoulli gradients)
- **local (flow) acceleration**
  (Rushmer or impulse gradients)

Bernoulli's Law

$$\Delta P = 1/2\ \rho\ (v_2^2 - v_1^2) + \int dv/dt\ ds + R_v$$

convective acceleration	local (flow) acceleration	viscous friction
(convective term)	(inertial term)	(viscous term)

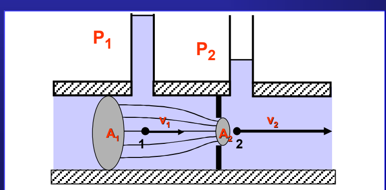


Conservation of energy dictates that an increase in kinetic energy (dynamic pressure/velocity) must result in a decrease in potential energy (lateral or static pressure)

$$E_{total} = E_{pot} + E_{kin} = const$$

$$\Delta E_{kin} = - \Delta E_{pot}$$

$$E_{kin} = 1/2\ \rho\ (v_2^2 - v_1^2) = P_1 - P_2$$

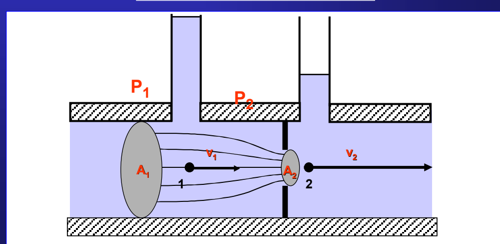


Bernoulli's Law

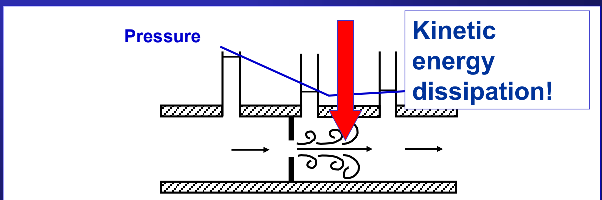
$\Delta P = 1/2\ \rho\ (v_2^2 - v_1^2) = 4\ v_2^2 - 4\ v_1^2$ (convective)

For $v_1 << v_2$, v_1 becomes neglibile (especially if < 1 m/s):

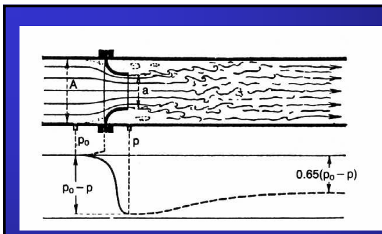
$\Delta P = 4\ v_2^2$ (simplified)



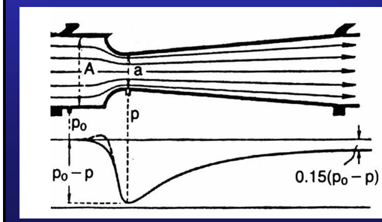
Pressure gradient across a stenotic valve - energy dissipation



Most of the kinetic energy is dissipated in turbulence and is therefore not reconverted into static pressure



In a nozzle meter (e.g. valve prosthesis) there is a head loss of 65%.

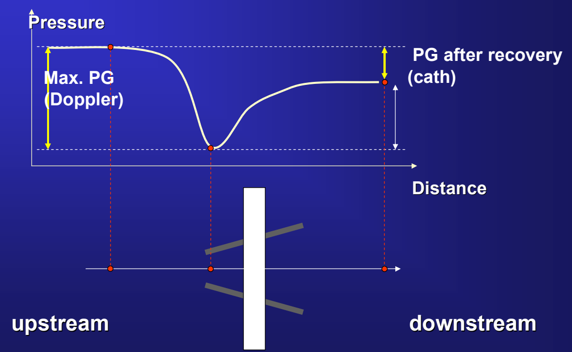


In a well-designed Venturi meter the head loss is only 15%.

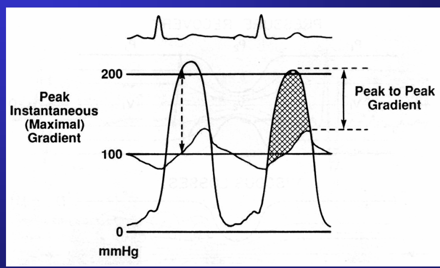
85% of the pressure drop is recovered !

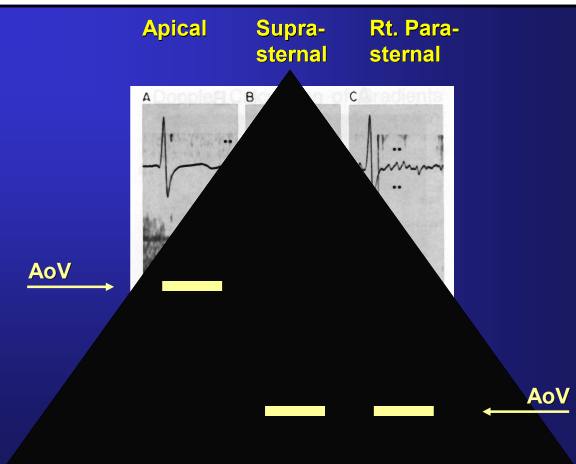
Prandtl L, Tietjens O: Applied Hydro- and Aeromechanics, New York, Dover 1957

Pressure recovery in bileaflet prosthesis (SJM type)



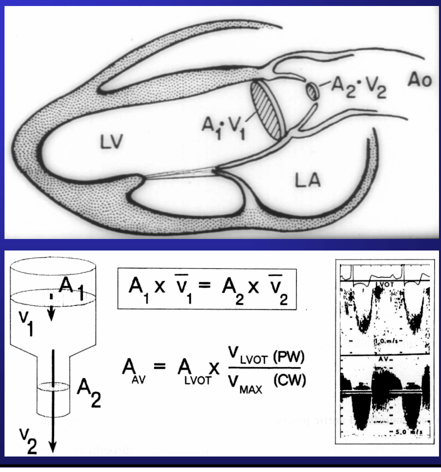
Peak Instantaneous, Peak-to-Peak, and Mean Pressure Gradient





When might pressure gradient calculation by the Bernoulli equation fail?

- Underestimation of poststenotic flow velocity v_2 (suboptimal angle to flow, calcified valve)
- Tunnel shaped muscular subaortic stenosis (viscous friction not negligible - underestimation)
- Prestenotic flow velocity v_1 not negligible (severe AR, high CO) or close to v_2 (prostheses) - overestimation
- Pressure recovery (tapered outlet geometry, e.g. bileaflet prostheses) - overestimation



Derivation of the Gorlin Formula from the Continuity Equation

Torricelli's Law

$$AVA = \frac{\text{Sys Flow}}{v_{\text{mean-CW}}} = \frac{\text{Sys Flow}}{k\sqrt{\text{mean PG}}}$$

Gorlin realized that valve area is Flow divided by velocity. Lacking a velocity measurement he calculated the velocity from the measured pressure gradient (first diagnostic application of the Bernoulli equation in Cardiology was in the cath lab!)

Aortic stenosis and LV dysfunction

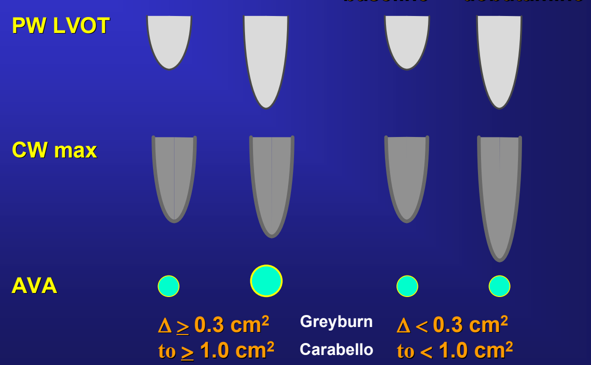
SEVERE STENOSIS → Significant LV dysfx → Low cardiac output → Low gradient

MILD STENOSIS → Significant LV dysfx → Low cardiac output → Low gradient

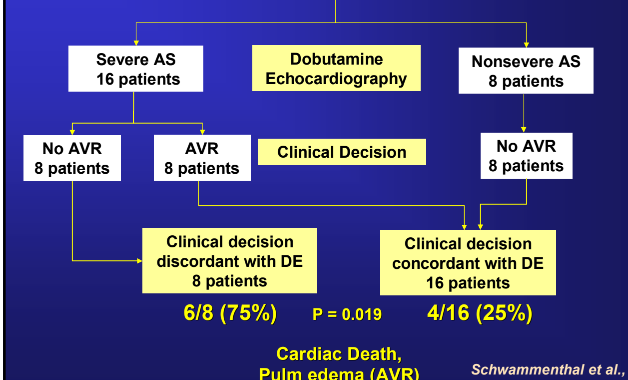
Aortic stenosis and LV dysfunction

- Calculated aortic valve area is flow-dependent.

  It may be disproportionally reduced in patients with left ventricular dysfunction and aortic stenosis and rather reflect low transvalvular flow than significant valvular disease.

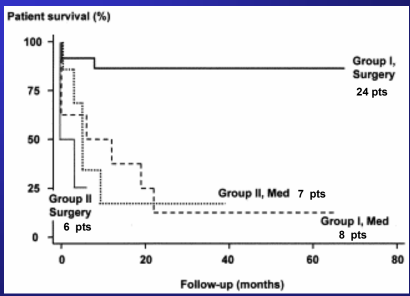


Follow-up up to 36 months



Schwammenthal et al., Chest 2001

Survival in 45 Patients With Severe Low-Gradient Aortic Stenosis, and LV-Dysfunction by Group and Treatment

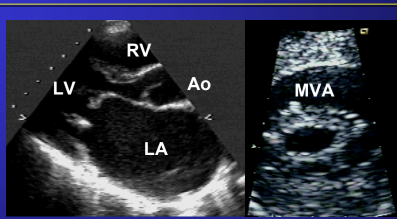


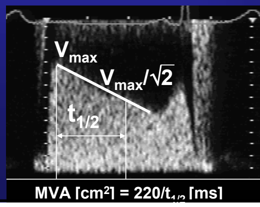
Group I = preserved contractile reserve
(SV increase by ≥ 20%)

Group II = no (insufficient) contractile reserve
(SV increase < 20%)

Monin JL, et al.
J Am Coll Cardiol 2001

Mitral stenosis

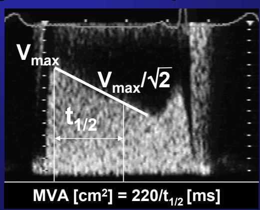




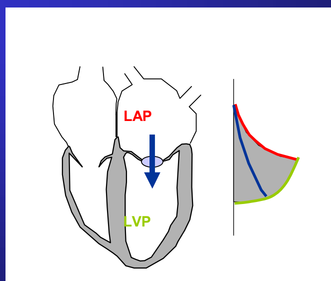
Pressure Half-Time

- Time the the pressure gradient needs to drop to half its initial value
- Because PG ~ v^2, i. e. $\sqrt{PG}$ ~ v:

  Time velocity needs to drop to $1/\sqrt{2}$ of its initial value:

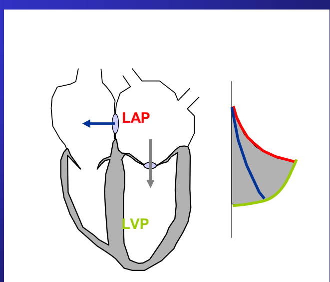


Pressure Half-Time



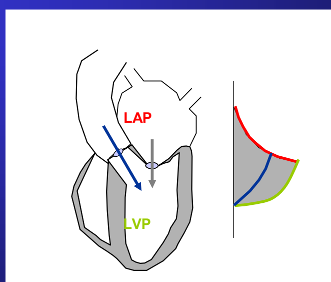
The larger the MVA, the more rapidly LAP drops, and diastolic LVP increases (equilibrium is reached quickly) - t1/2 will be shortened.

Pressure Half-Time



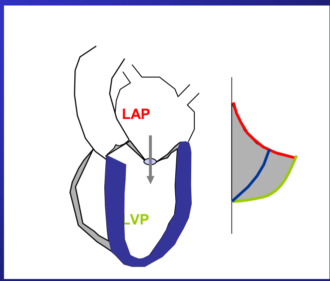
However, LAP may also drop rapidly if LA has a second outlet (ASD) - t1/2 will be shortened.

Pressure Half-Time



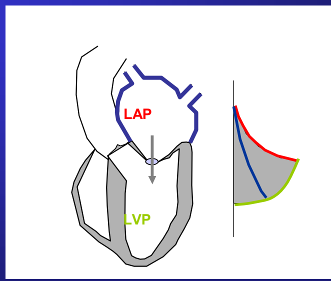
Or LVP may rise rapidly if LV fills from a second source (AR) - t1/2 will be shortened.

Pressure Half-Time



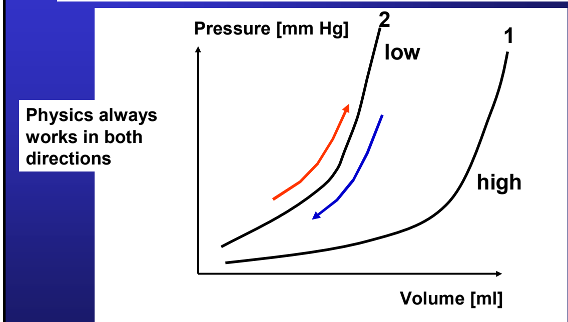
Or LVP may rise rapidly if LV is stiff (low ventricular compliance) - t1/2 will be shortened.

Pressure Half-Time

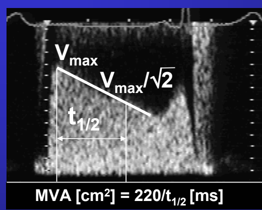


Or LAP may drop rapidly if LA is stiff (low atrial compliance) - t1/2 will be shortened.

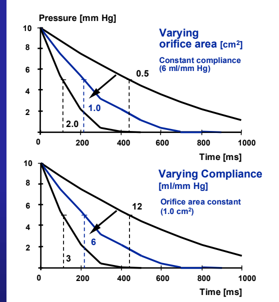
Low compliance means steep increase in pressure for a given volume entering the chamber (filling)



Low compliance means steep decrease in pressure for a given volume leaving the chamber (emptying)



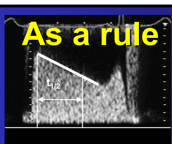
The decay of the pressure gradient across a stenotic mitral valve is not only determined by the size of the orifice but also by net AV compliance (C_n).



$$t_{1/2} = \frac{11.6 C_n \sqrt{p_o}}{MVA}$$

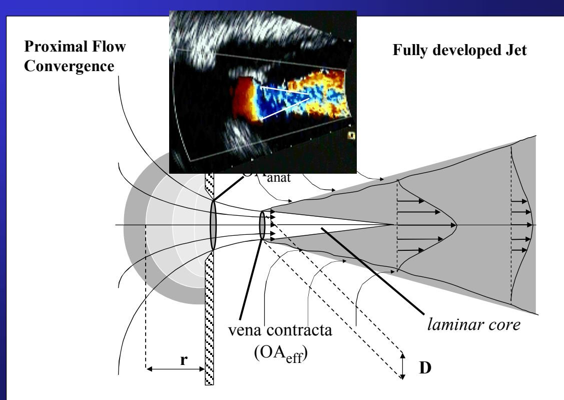
Thomas et al. JACC 1987 and 1989

As a rule

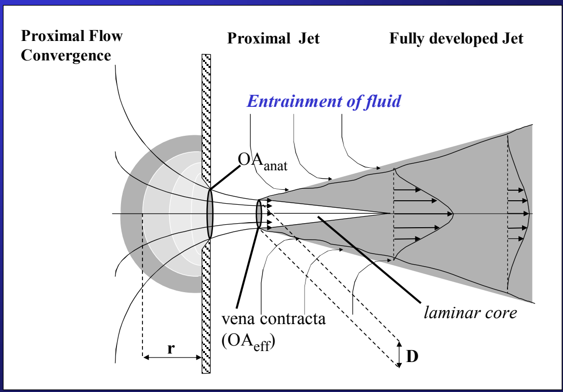


All factors affecting t1/2 (ASD, AR, reduced LA- or LV compliance) lead to overestimation of MVA.

- Therefore, t1/2 never underestimates MVA.
- Therefore, if t1/2 is > 200-220 ms, MS is always severe.
- However, if t1/2 is < 200 ms, look at the (mean) gradient, and pulmonary artery pressure, try planimetry of MVA, and consider exercise echo

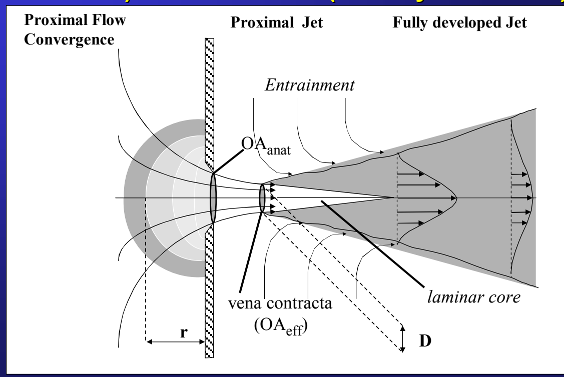


Jet consists significantly of entrained fluid



Conservation of mass not fulfilled!

As jet "grows" through entrainment of fluid (mass increases) its slows down (velocity decreases)



Conservation of momentum fulfilled!

What is Jet Momentum?

Extent of turbulant "damage" caused by the jet in the laminar flow field of the atrium

Jet size ~ mv or (per unit of time):

~ m/t v

Blood density constant: m/t can be replaced by V/t, i.e. flow Q

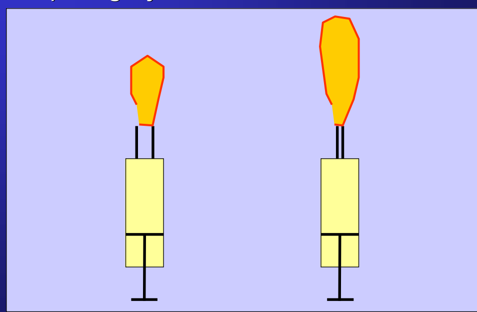
Jet size ~ Q x v

Flow Q = ROA x v

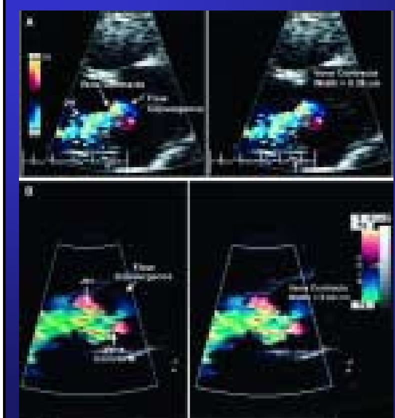
Jet size ~ ROA x v^2 or ROA x PG

Jet size depends on ROA and driving pressure!

If the same amount of fluid is injected with the same speed through a thinner needle (i.e. at a higher driving pressure) a larger jet results



This explains why mitral regurgitant jets (of the same flow rate) are larger in patients with hypertension, aortic stenosis, HOCM



Proximal jet diameter ≥ 6 mm

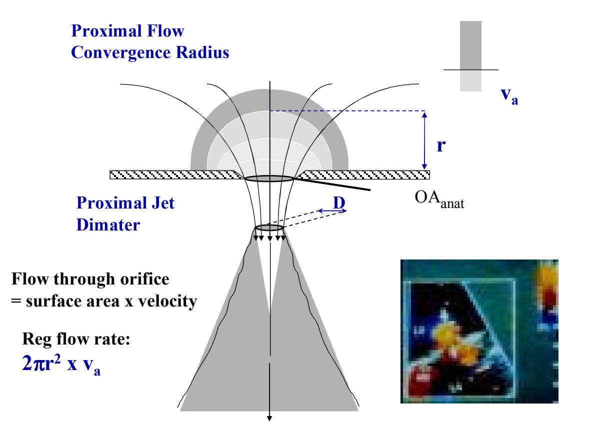
sensitivity of 95%,

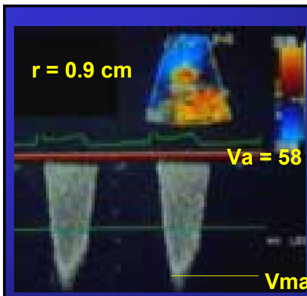
specificity of 90%

for diagnosing AR ≥ III

Tribouilloy et al Circulation 2000

Useful for quantifying excentric regurgitant jets





Va = 58 cm/s

Vmax =
420 cm/s

Flow rate [ml/s]
$= 2\pi r^2 \times v_a$

Reg Orifice Area [cm2]
= Flow Rate/Orifice Velocity (Vmax)

Reg Flow rate $= 2\pi (0.9)^2 \times 58 = 295$ ml/s

Reg Orifice Area = 295/420 = 0.7 cm^2

Definition of Signifcant MR by Different Quantitative Color Doppler Methods

Parameter	Cut-off value (III +IV vs I+II)	Positive predictive value	Negative predictive value
Jet Area	6-8 cm^2	74%	89%
Proximal Jet Diameter	0.55-0.65 cm	79%	92%
Max Reg Flow Rate (PFC)	130-190 ml/s	91%	100%
ROA (PFC)	0.3-0.4 cm^2	91%	100%

Diastology

Relaxation

Compliance

Pseudonormalization

Restrictive Filling

Flow Propagation Velocity

Myocardial Tissue Velocity

Diastolic Function

Left ventricular diastolic function is considered normal when an adequate filling volume can be achieved (sufficient to produce a normal stroke volume) at a normal filling pressure.

(mean left atrial and pulmonary venous pressure < 12 mm Hg, left ventricular enddiastolic pressure < 15 mm Hg)

Diastolic Dysfunction

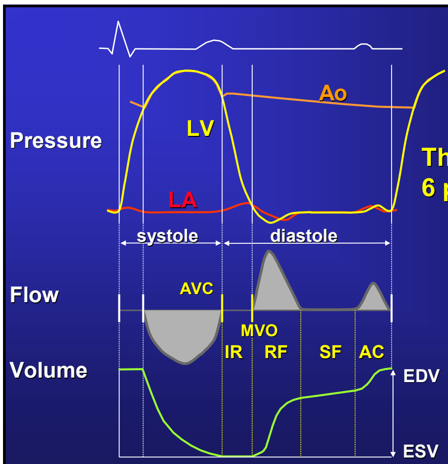
Left ventricular diastolic function is abnormal when a normal filling volume cannot be achieved without a compensatory increase in filling pressure.

(mean left atrial and pulmonary venous pressure $\geq$ 12 mm Hg, left ventricular enddiastolic pressure $\geq$ 15 mm Hg)

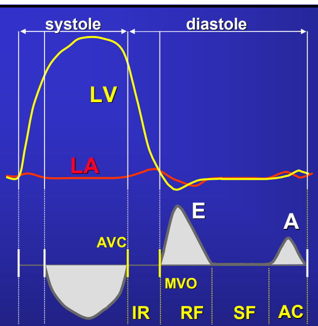
Diastolic Dysfunction

Left ventricular diastolic function is abnormal when flow rate is inappropriately decreased or left ventricular pressure is increased *at any time during the filling period.*

(even when mean left atrial and enddiastolic left ventricular pressure are normal)

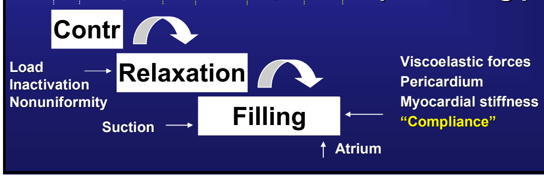


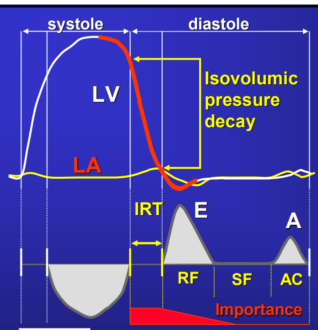
The Cardiac Cycle 6 phases?

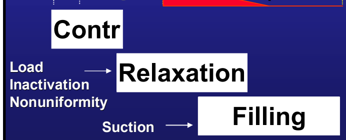


The 3 Phases of the Cardiac Cycle

Each of the three phases is dependent on the effects of the preceeding phase

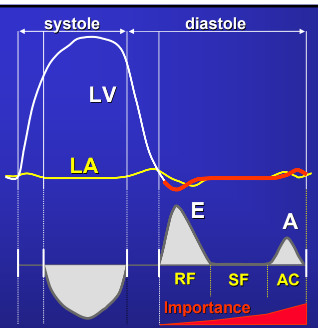


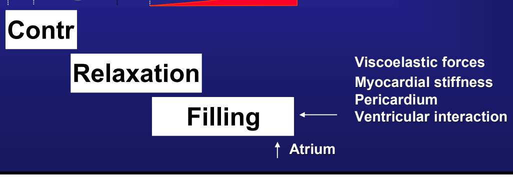




Relaxation

Active, energy-consuming process of inactivation of contractile proteins, which starts at the end of the ejection period and lasts well into the filling phase





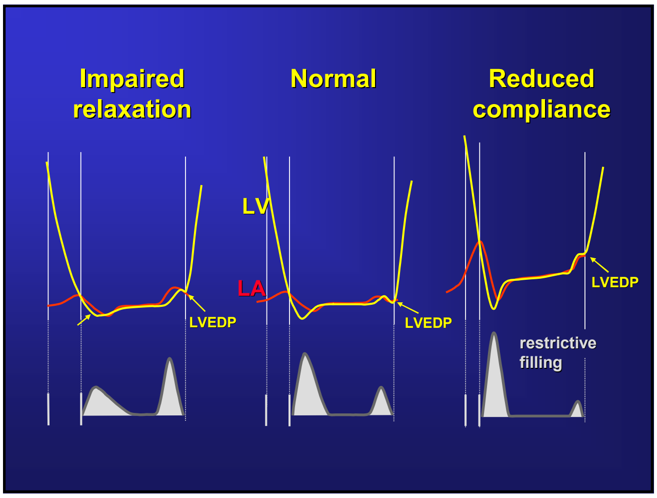
Compliance

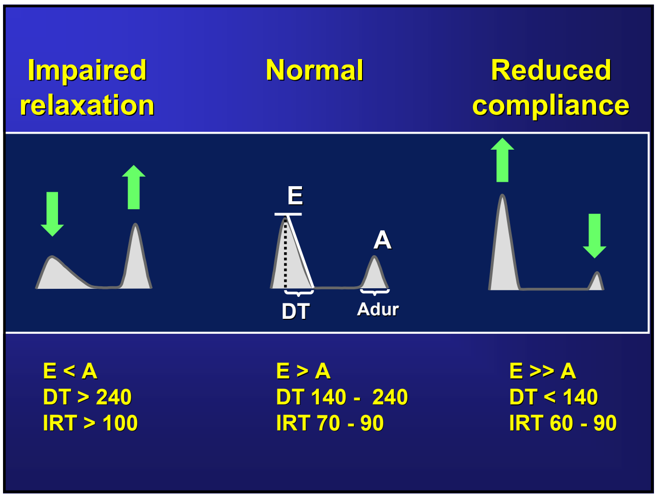
Passive distensibility of the left ventricular chamber (dV/dP)

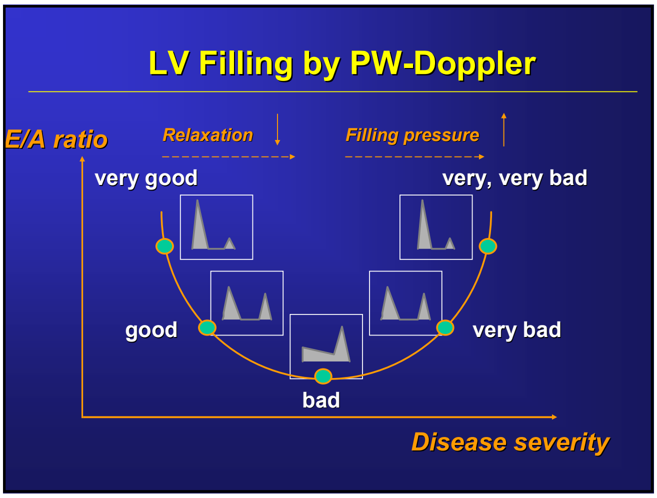
Mechanisms of Diastolic Dysfunction

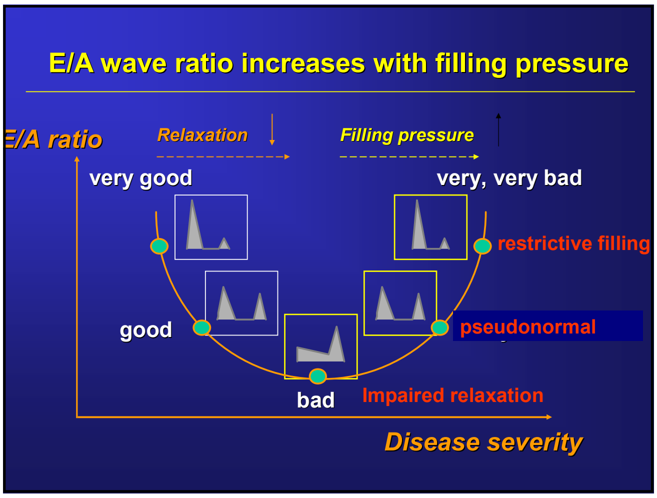
Resistance to filling by:

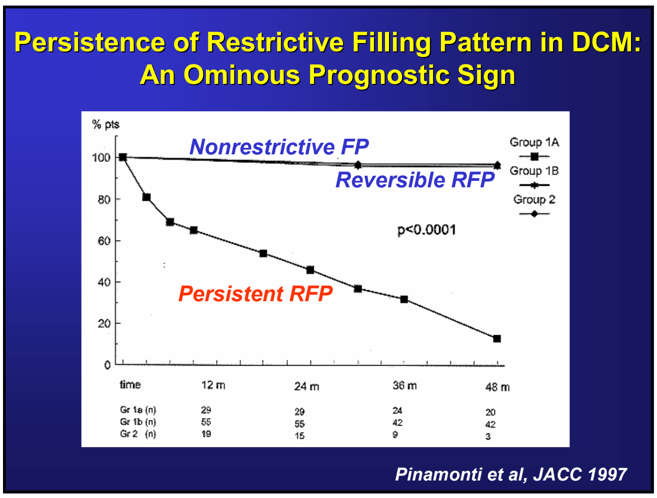
- Impaired relaxation (early diastole)
- Reduced compliance (mid- to late diastole)
  - Pericardial constraint

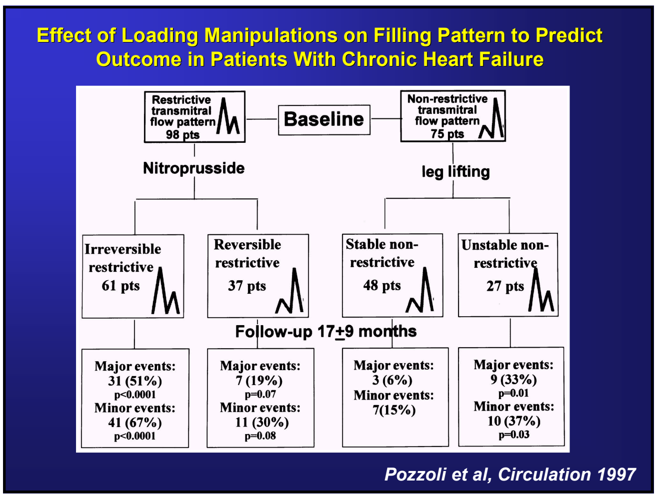

Impaired relaxation
Normal
Reduced compliance
LV
LA
LVEDP
LVEDP
LVEDP
restrictive filling

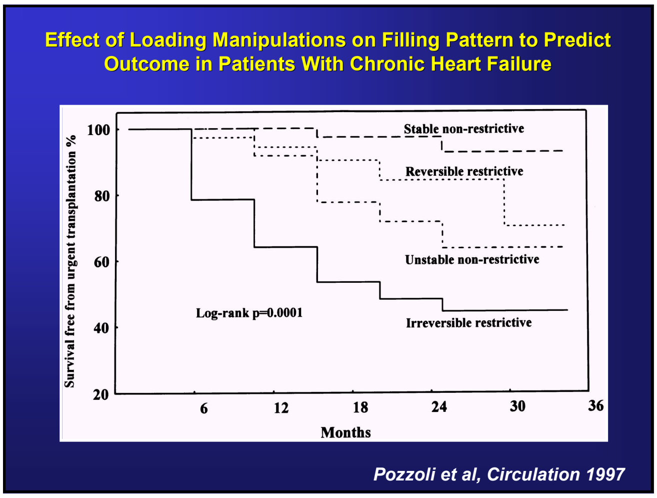

Impaired relaxation
Normal
Reduced compliance
E
A
DT
Adur
E < A
DT > 240
IRT > 100
E > A
DT 140 - 240
IRT 70 - 90
E >> A
DT < 140
IRT 60 - 90

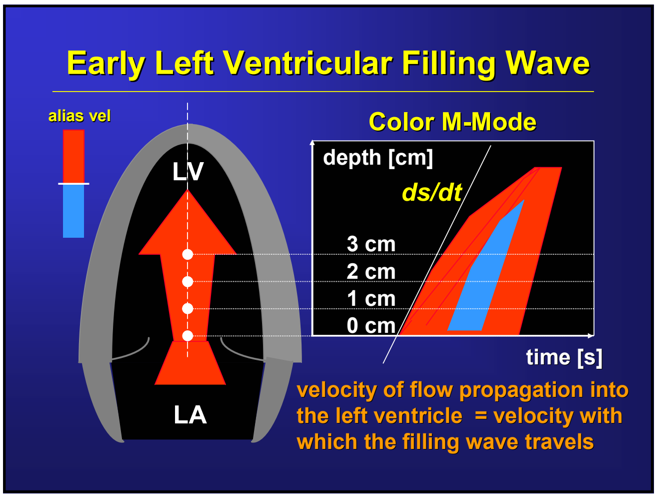

LV Filling by PW-Doppler
E/A ratio
Relaxation
Filling pressure
very good
very, very bad
good
very bad
bad
Disease severity

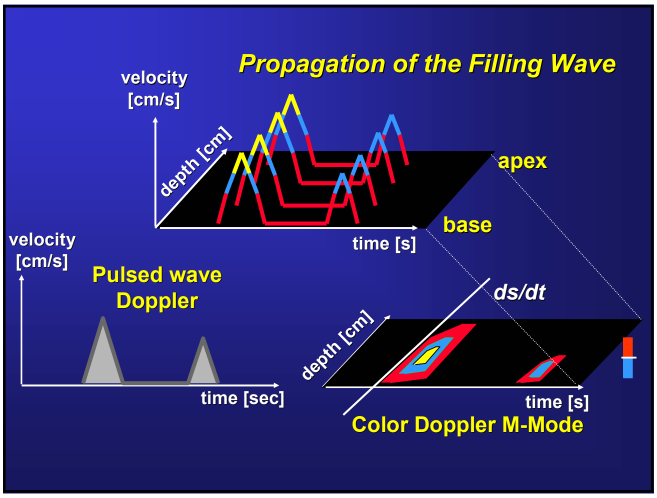

E/A wave ratio increases with filling pressure
E/A ratio
Relaxation
Filling pressure
very good
very, very bad
restrictive filling
good
pseudonormal
bad
Impaired relaxation
Disease severity

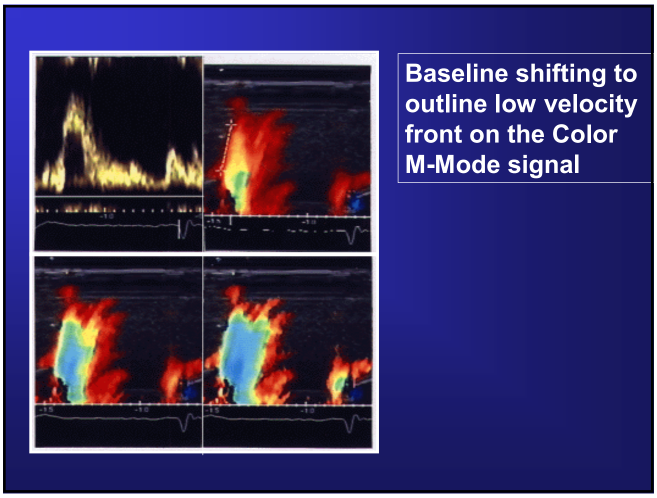

Persistence of Restrictive Filling Pattern in DCM: An Ominous Prognostic Sign
% pts
Nonrestrictive FP
Reversible RFP
Persistent RFP
p<0.0001
Group 1A
Group 1B
Group 2
100
80
60
40
20
0
time
12 m
24 m
36 m
48 m
Gr 1a (n) 29 29 24 20
Gr 1b (n) 55 55 42 42
Gr 2 (n) 19 15 9 3
Pinamonti et al, JACC 1997

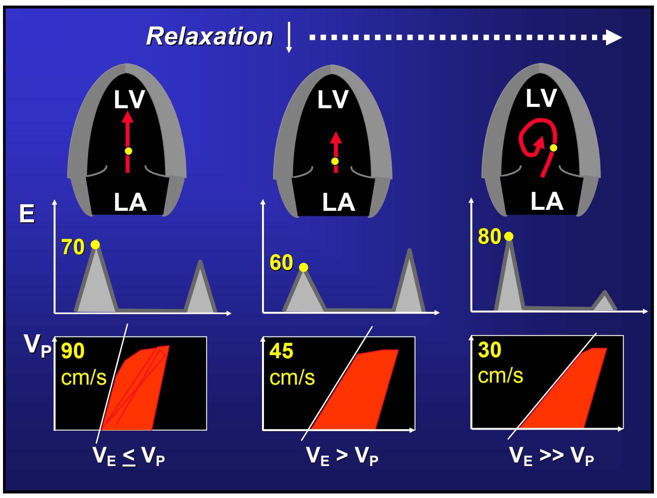

Effect of Loading Manipulations on Filling Pattern to Predict Outcome in Patients With Chronic Heart Failure
Restrictive transmitral flow pattern 98 pts
Baseline
Non-restrictive transmitral flow pattern 75 pts
Nitroprusside
leg lifting
Irreversible restrictive 61 pts
Reversible restrictive 37 pts
Stable non-restrictive 48 pts
Unstable non-restrictive 27 pts
Follow-up 17+9 months
Major events: 31 (51%) p<0.0001 Minor events: 41 (67%) p<0.0001
Major events: 7 (19%) p=0.07 Minor events: 11 (30%) p=0.08
Major events: 3 (6%) Minor events: 7(15%)
Major events: 9 (33%) p=0.01 Minor events: 10 (37%) p=0.03
Pozzoli et al, Circulation 1997

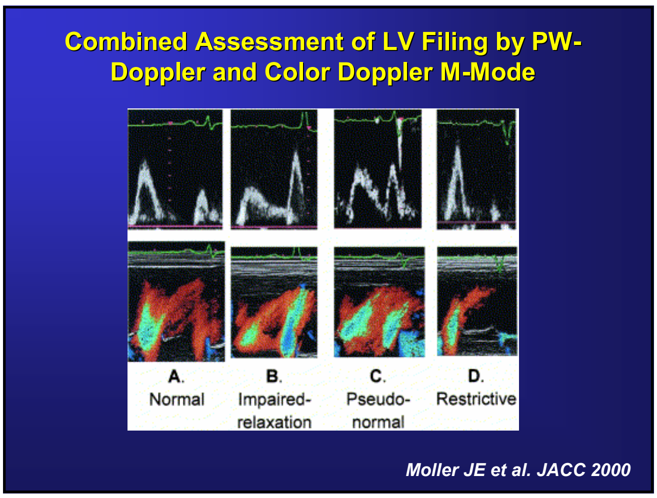

Effect of Loading Manipulations on Filling Pattern to Predict Outcome in Patients With Chronic Heart Failure
Survival free from urgent transplantation %
100
80
60
40
20
6
12
18
24
30
36
Months
Stable non-restrictive
Reversible restrictive
Unstable non-restrictive
Irreversible restrictive
Log-rank p=0.0001
Pozzoli et al, Circulation 1997


Early Left Ventricular Filling Wave
alias vel
LV
LA
Color M-Mode
depth [cm]
ds/dt
3 cm
2 cm
1 cm
0 cm
time [s]
velocity of flow propagation into the left ventricle = velocity with which the filling wave travels

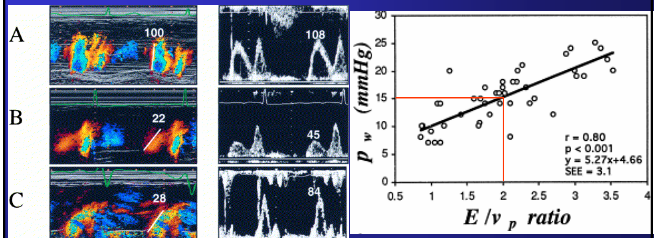

Propagation of the Filling Wave
velocity [cm/s]
depth [cm]
apex
base
time [s]
velocity [cm/s]
Pulsed wave Doppler
time [sec]
ds/dt
depth [cm]
time [s]
Color Doppler M-Mode


Baseline shifting to outline low velocity front on the Color M-Mode signal


Relaxation ↓
LV
LA
LV
LA
LV
LA
E
70
60
80
VP
90 cm/s
45 cm/s
30 cm/s
VE ≤ VP
VE > VP
VE >> VP


Combined Assessment of LV Filing by PW-Doppler and Color Doppler M-Mode
A. Normal
B. Impaired-relaxation
C. Pseudo-normal
D. Restrictive
Moller JE et al. JACC 2000

Estimation of Capillary Wedge Pressure by E/Vp



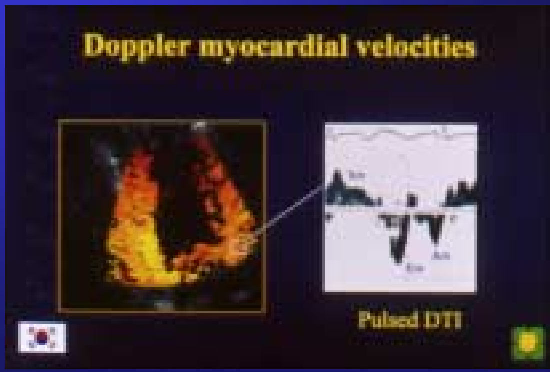
E ~ relaxation x filling pressure

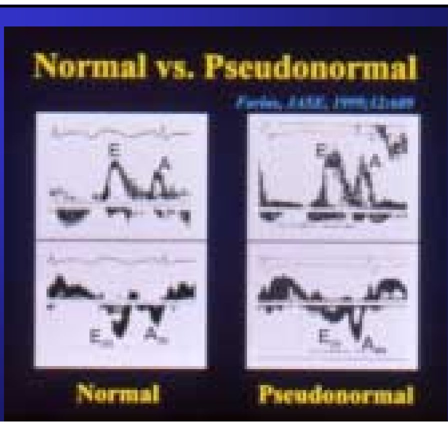
v_P ~ relaxation

E/ v_P ~ filling pressure

E/Vp > 2
elevated LAP

Garcia et al., JACC 1997





E/Em < 8	E/Em 8 - 15	E/Em > 15
Normal LAP	best cut-off: 10	Elevated LAP

Central Hemodynamics

Stroke Volume

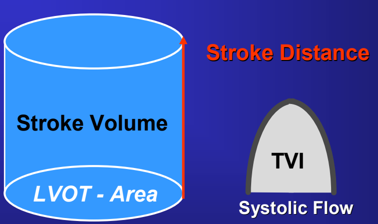
Cardiac Output

Pulmonary Artery Pressure

Left Atrial Pressure

Pulmonary Vascular Resistance

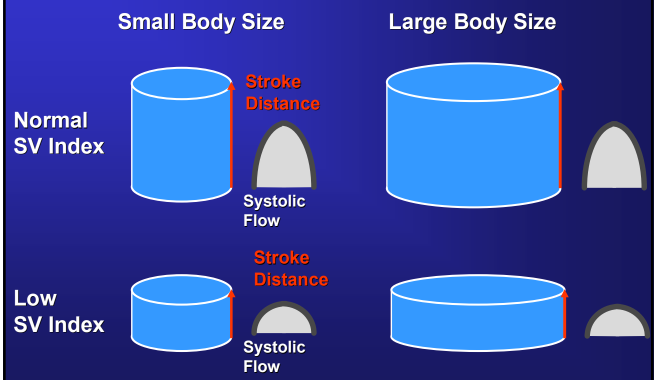
Stroke Volume and Stroke Distance



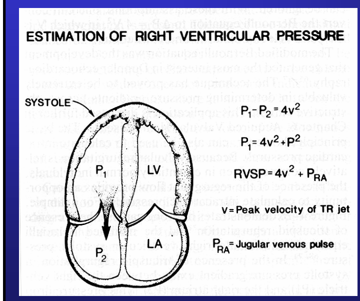
Stroke volume = Stroke Distance X LVOT - Area

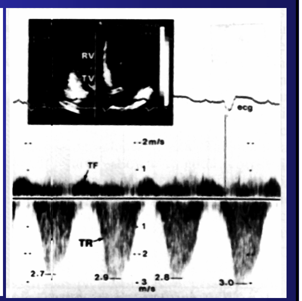
Stroke Distance = Stroke Volume / LVOT - Area

Stroke Volume, Body Size, and Stroke Distance

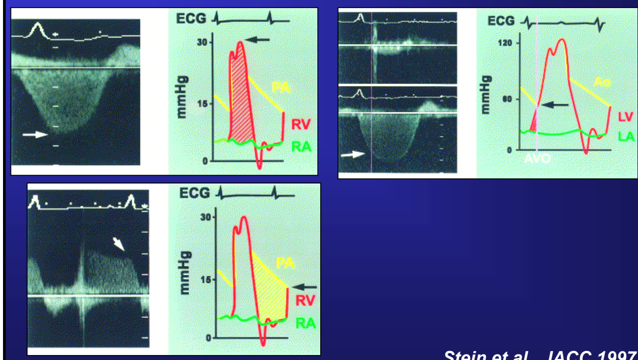


Estimation of right ventricular (pulmonary artery) systolic pressure from the tricuspid regurgitant velocity



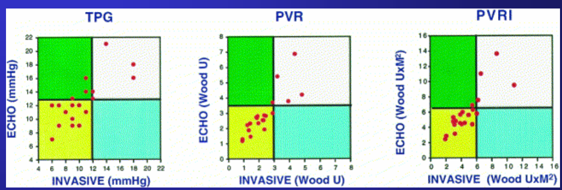


Echocardiography for Hemodynamic Assessment of Patients With Advanced Heart Failure



Stein et al., JACC 1997

Echocardiography for Hemodynamic Assessment of Patients With Advanced Heart Failure



Complete hemodynamic data set in 21/25 pts (84%)

All pts with a favorable hemodynamic profile by echocardiography also had a favorable hemodynamic profile by right heart catheterization.

Invasive studies not necessary in 70% of cases.

Stein et al., JACC 1997

שאלה 1

מדידות בחולה עם הצרות המסתם האאורטלי:
מהירות הזרימה במוצא מסלול חדר שמאל: 0.8 מ/ש
מהירות מקסימלית על פני המסתם: 4.0 מ/ש
שטח מוצא מסלול חדר שמאל: 3.0 סמ"ר

שטח המסתם הוא:

א. 0.6סמ"ר
ב. 0.7סמ"ר
ג. 0.8סמ"ר
ג. 0.9סמ"ר

שאלה 2

החישוב של שטח הרגורגיטציה (effective regurgitant orifice area) מתבצע כדלקמן:

א.קצב הרגורגיטציה בשיטת proximal flow convergence חלקי קוטר ה-vena contracta
ב. קוטר ה- vena contracta חלקי מהירות גל E
ג. קצב הרגורגיטציה בשיטת proximal flow convergence חלקי מהירות הזרימה ברגורגיטציה ב-continuous wave Doppler
ד. קוטר ה- vena contracta כפול מהירות ה-aliasing

שאלה 3

בחולה עם אי ספיקה אאורטלית קשה נמדד על פני המסתם המיטרלי המוצא זמן מחצית (pressure half-time)של 220 מ"ש. שטח המסתם המיטרלי הוא קרוב לוודאי :

א. קטן מ-1.0 סמ"ר
ב. שווה 1.0 סמ"ר
ג. גדול מ-1.0 סמ"ר
ד. שווה 2.2 סמ"ר

שאלה 5

בחולה עם גודש וורידי צווארי מובהק נמצאה אי ספיקה טריקוספידלית קלה ועל פני המסתם נמדדה מהירות הזרימה ברגורגיטציה של 3.5 מ/ש. הלחץ הסיסטולי בעורק הריאה הוא:

א. 45-50מ"מכ
ב. 50-55מ"מכ
ג. 55-60מ"מ כ
ד. 65-70מ"מכ
ה. לא תיתכן אי ספיקה טריקוספידלית קלה בחולה עם גודש וורידי צווארי מובהק

שאלה 4

בבדיקת אקו נמצא חודש לאחר אוטם קדמי EF של 35-40% , גל E' של הזרימה המיטרלית של 100 סמ/ש , גל E ב- tissue Doppler

של 5 סמ/ש. הלחץ בפרוזדור שמאל הוא

א. תקין
ב. מוגבר במידה קלה
ג. מוגבר במידה בינונית
ד. מוגבר במידה קשה