Basic Hemodynamics

July 19, 2006

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UTHSCSA and STVHCS

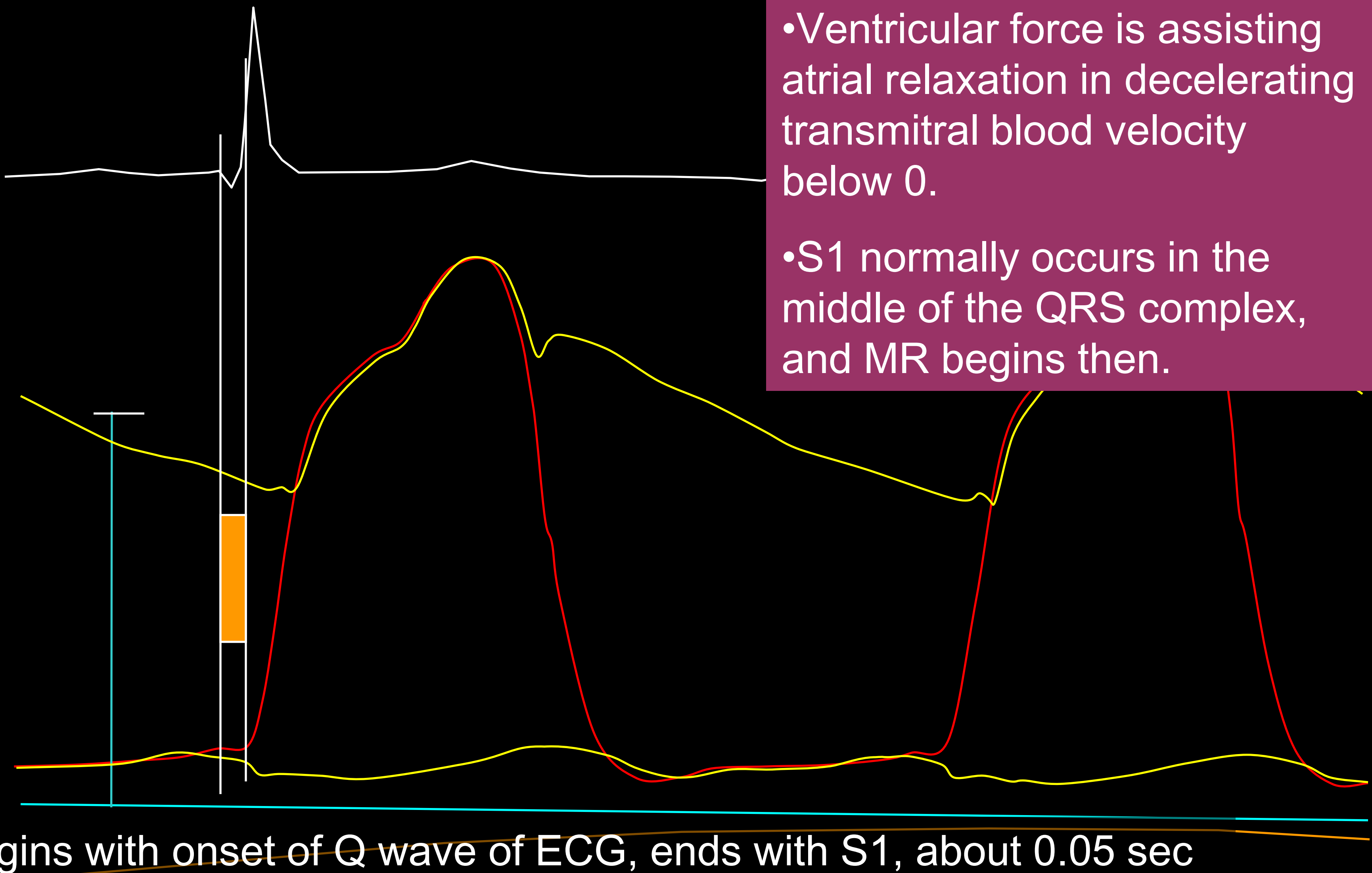
Outline

- The Cardiac Cycle
- Types of Measures
  - Pressure
  - Flow (Calculated from Temperature, O_2 Saturation, Indicator Concentration, Electromagnetic Flow Velocity or Image Measures)
  - Calculated Measures
  - Image Measures
    - Volume, Distance, Area
    - Flow (volume change by cine frame)
- Normal values

The Cardiac Cycle

The Cardiac Cycle

1. Electromechanical delay, Q-M1

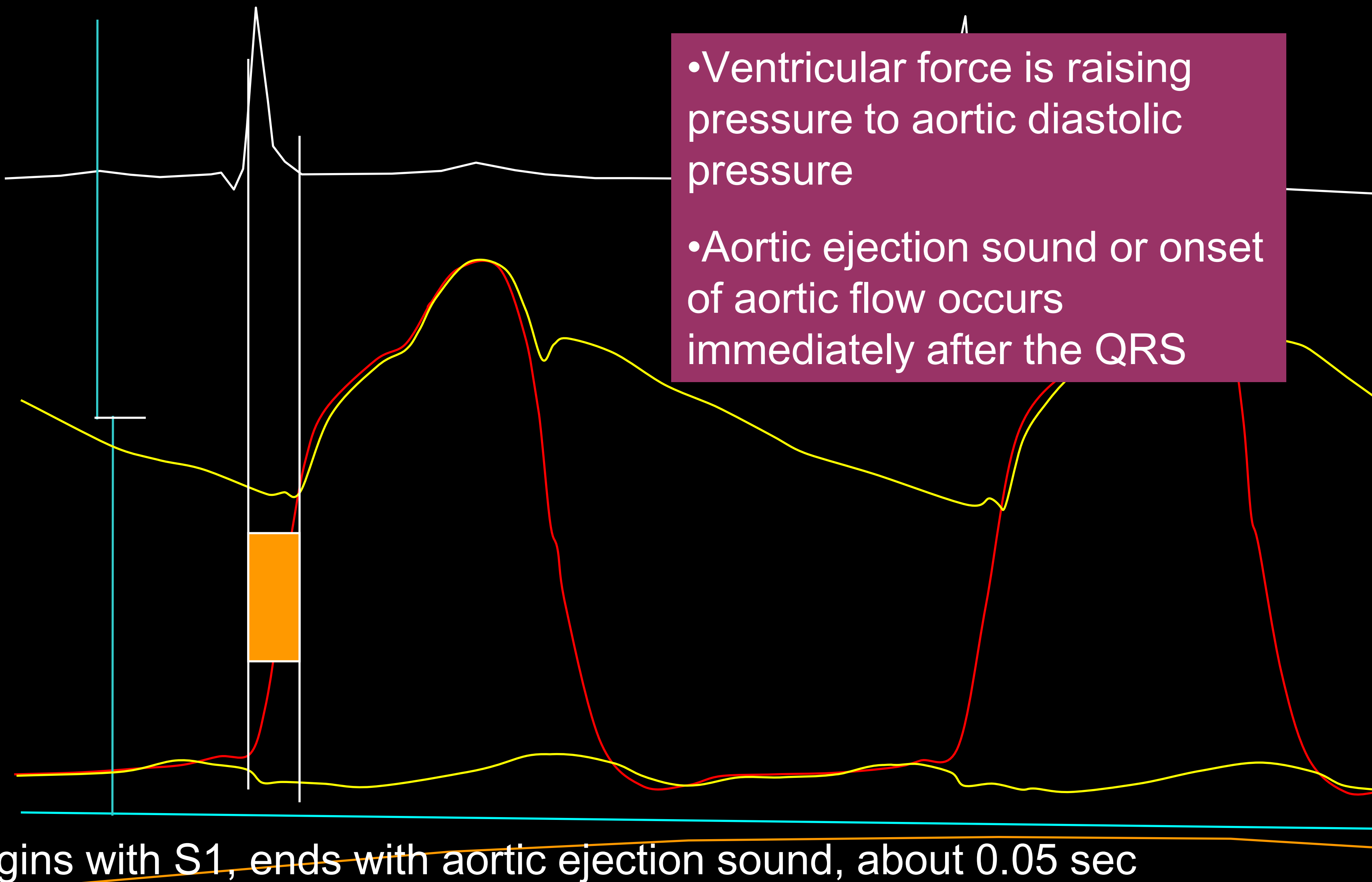


- Ventricular force is assisting atrial relaxation in decelerating transmitral blood velocity below 0.
- S1 normally occurs in the middle of the QRS complex, and MR begins then.

Begins with onset of Q wave of ECG, ends with S1, about 0.05 sec
Prolonged in mitral stenosis, reported prolongation in systemic hypertension, WPW, MR, VSD, PDA, Ebstein's

The Cardiac Cycle

1. Electromechanical delay, Q-M1
2. **Isovolumic contraction time**

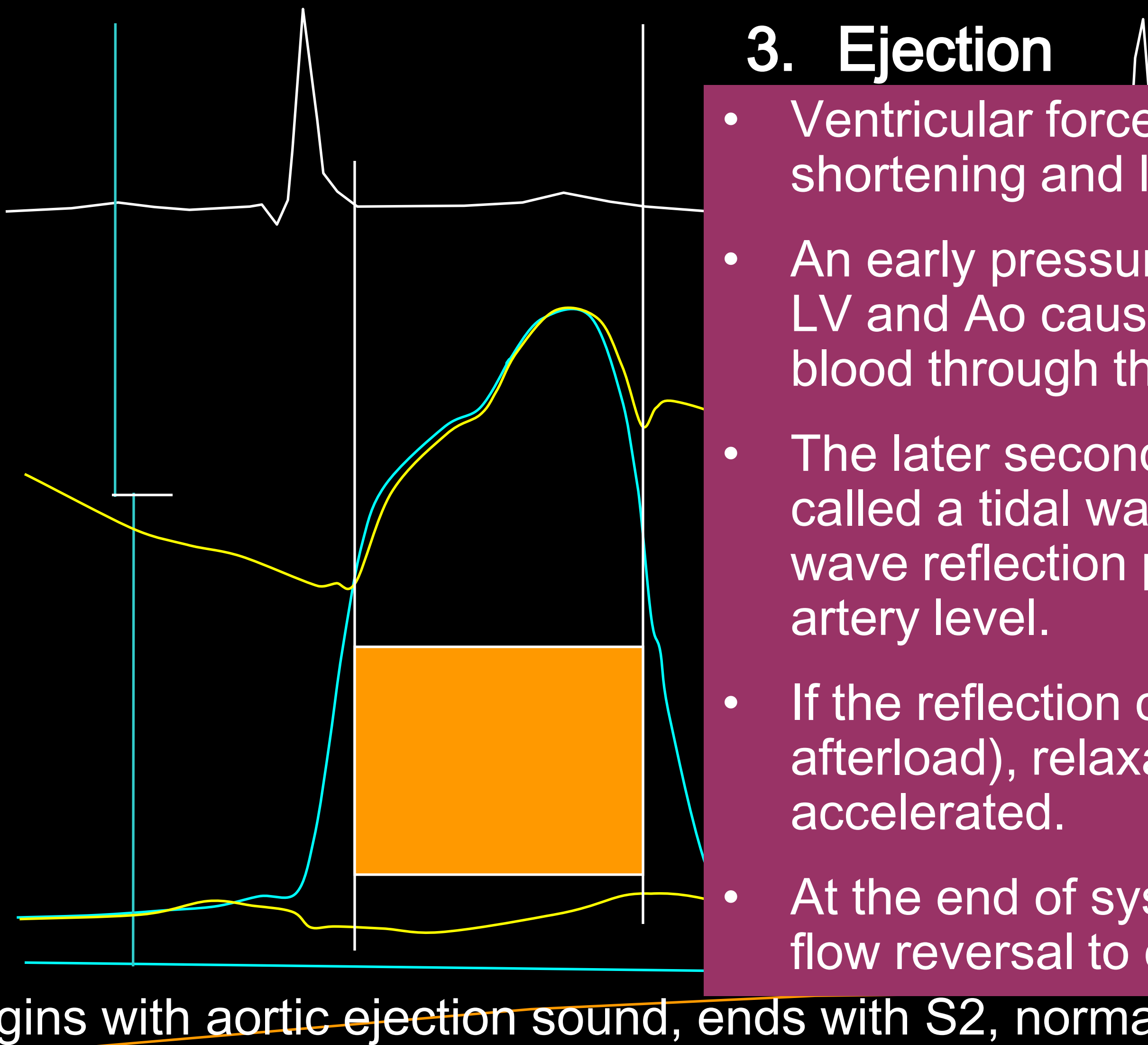


- Ventricular force is raising pressure to aortic diastolic pressure
- Aortic ejection sound or onset of aortic flow occurs immediately after the QRS

Begins with S1, ends with aortic ejection sound, about 0.05 sec
Shortened in increased contractility, increased EDV or SV (AR)
Prolonged in decreased contractility or CO, acute HTN, LBBB

The Cardiac Cycle

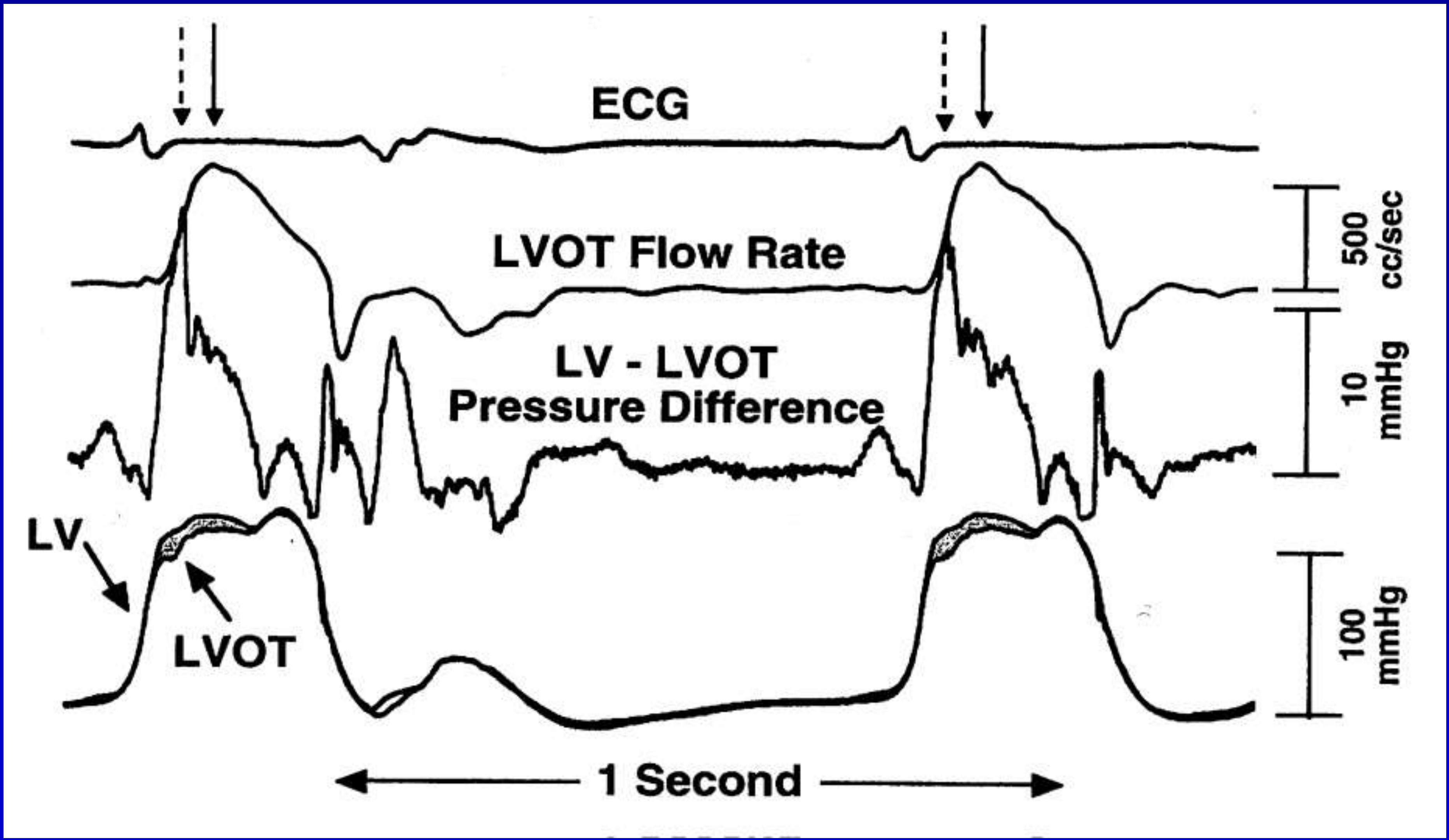
1. Electromechanical Delay, Q-M1
2. Isovolumic Contraction time
3. **Ejection**



- Ventricular force results in fiber shortening and less pressure rise.
- An early pressure gradient between the LV and Ao causes rapid acceleration of blood through the aortic valve.
- The later secondary pressure rise is called a tidal wave and is due to aortic wave reflection primarily from the renal artery level.
- If the reflection comes late (late afterload), relaxation would be accelerated.
- At the end of systole, there is brief aortic flow reversal to close the aortic valve.

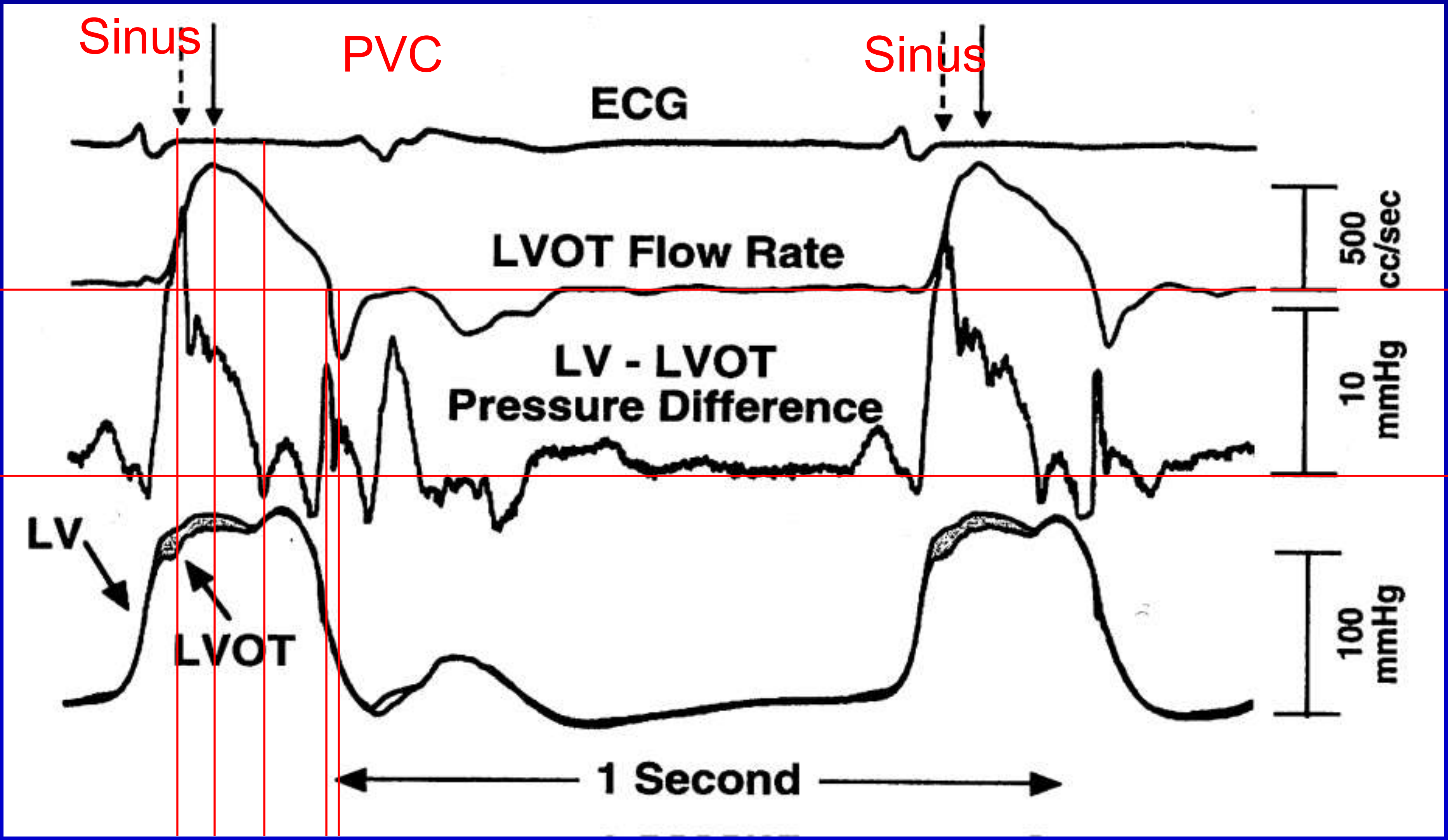
Begins with aortic ejection sound, ends with S2, normal about 0.28 sec
Shortened in HF, MR, and increased contractility (thyrotoxicosis)
Prolonged in AS, HCM, but not necessarily AR or PDA

Left Ventricular Ejection



Murgo, JP. J Am Coll Cardiol 1998;32:1596

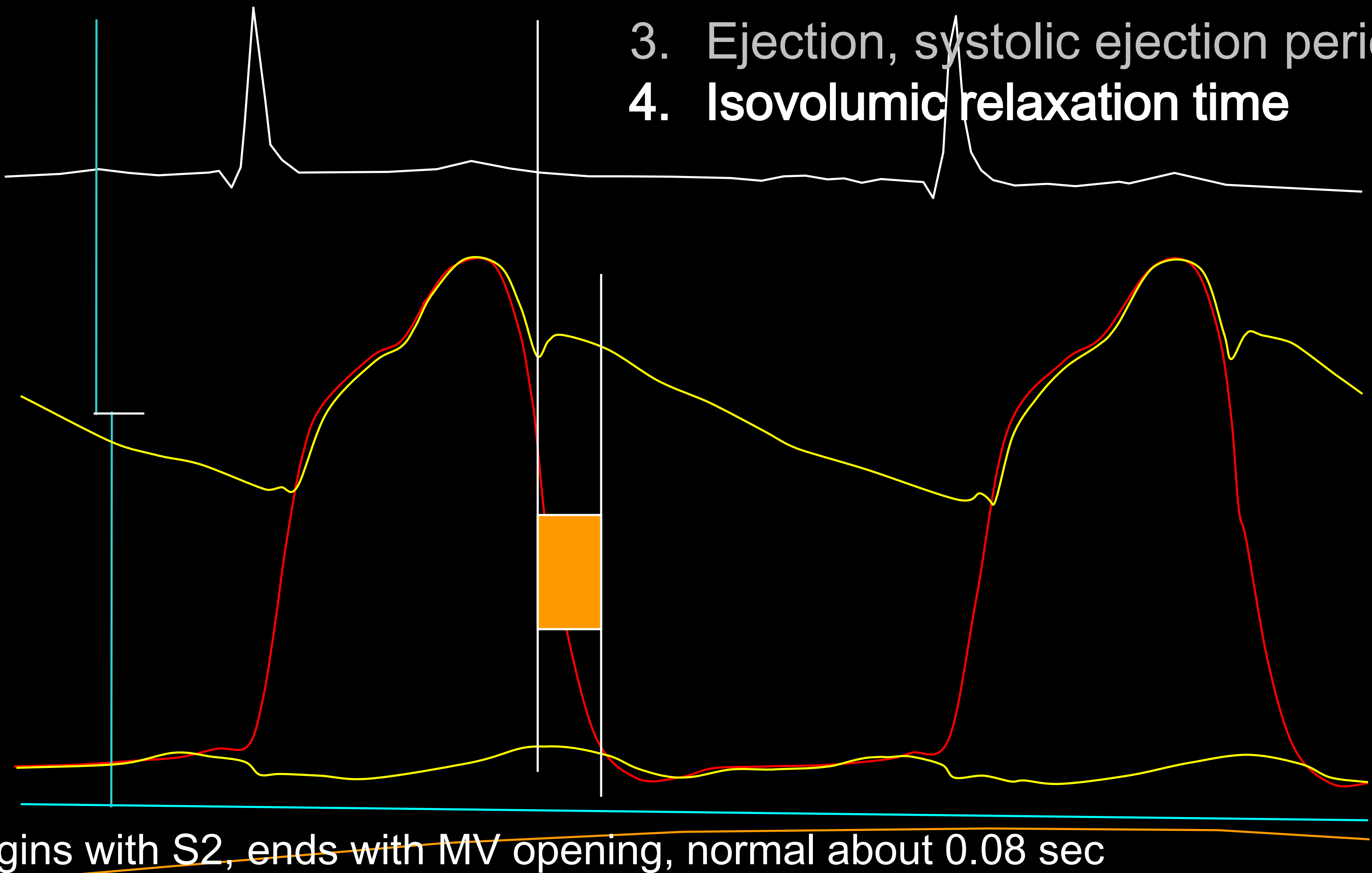
Left Ventricular Ejection



Murgo, JP. J Am Coll Cardiol 1998;32:1596

The Cardiac Cycle

1. Electromechanical delay, Q-M1
2. Isovolumic contraction time
3. Ejection, systolic ejection period
4. **Isovolumic relaxation time**



Begins with S2, ends with MV opening, normal about 0.08 sec
Shortened in elevated LV filling pressures, mitral stenosis
Prolonged in impaired relaxation

The Cardiac Cycle

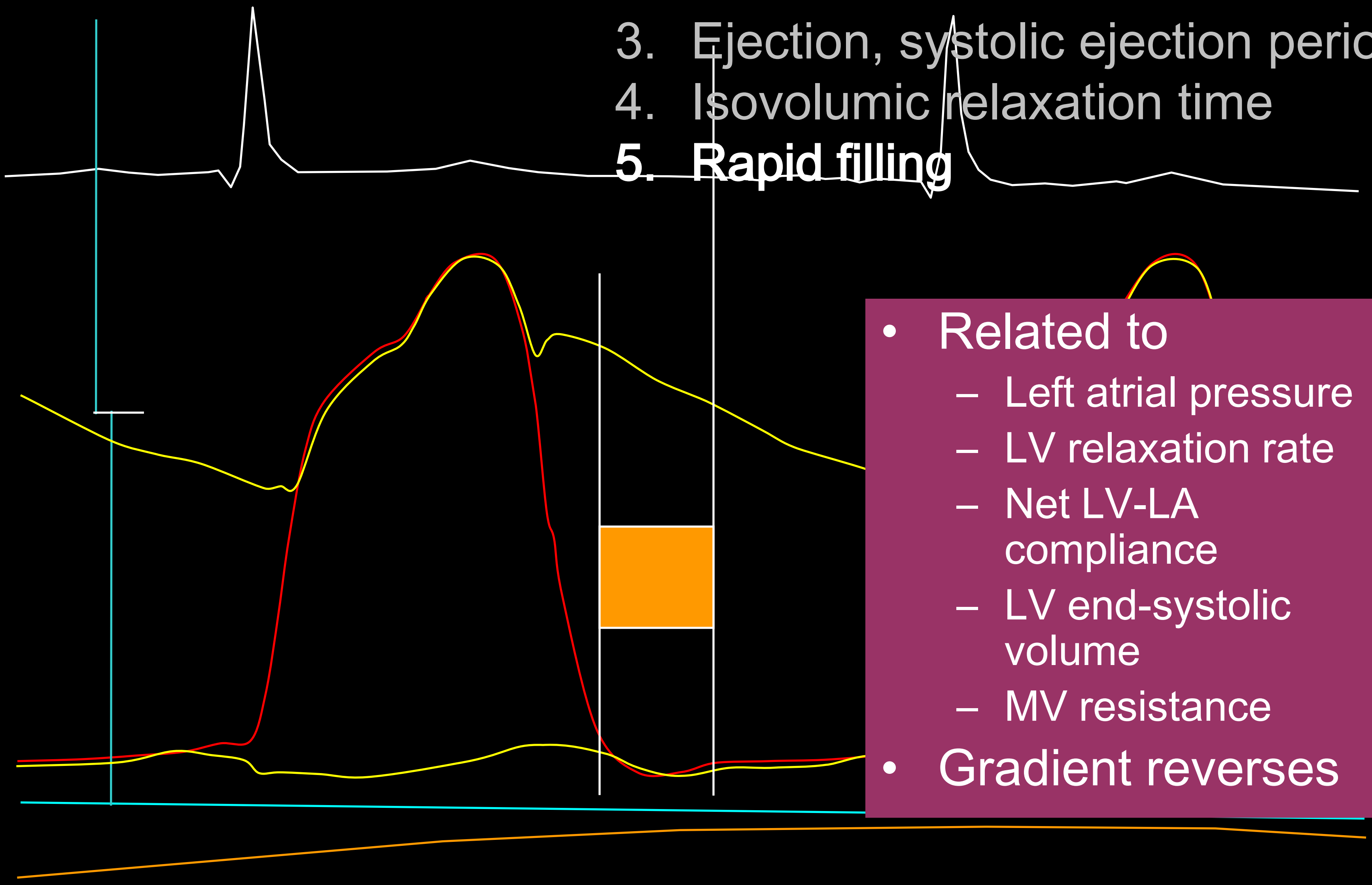
1. Electromechanical delay, Q-M1
2. Isovolumic contraction time
3. Ejection, systolic ejection period
4. **Isovolumic relaxation time**

- Related to
  - Height of LV pressure at dicrotic notch
  - Rate of pressure decline
  - Height of LA pressure at mitral crossover
- Normally a monoexponential decay, characterize by time constant of relaxation (τ), analyzed from peak –dP/dt to 5 mmHg above LVEDP, normal value of τ is 25-40 msec
- Relaxation is considered 97% complete by 3* τ or about 140 msec after A2

Begins with S2, ends with MV opening, normal about 0.08 sec
Shortened in elevated LVEDP, MS, Prolonged in impaired relaxation

The Cardiac Cycle

1. Electromechanical delay, Q-M1
2. Isovolumic contraction time
3. Ejection, systolic ejection period
4. Isovolumic relaxation time
5. **Rapid filling**



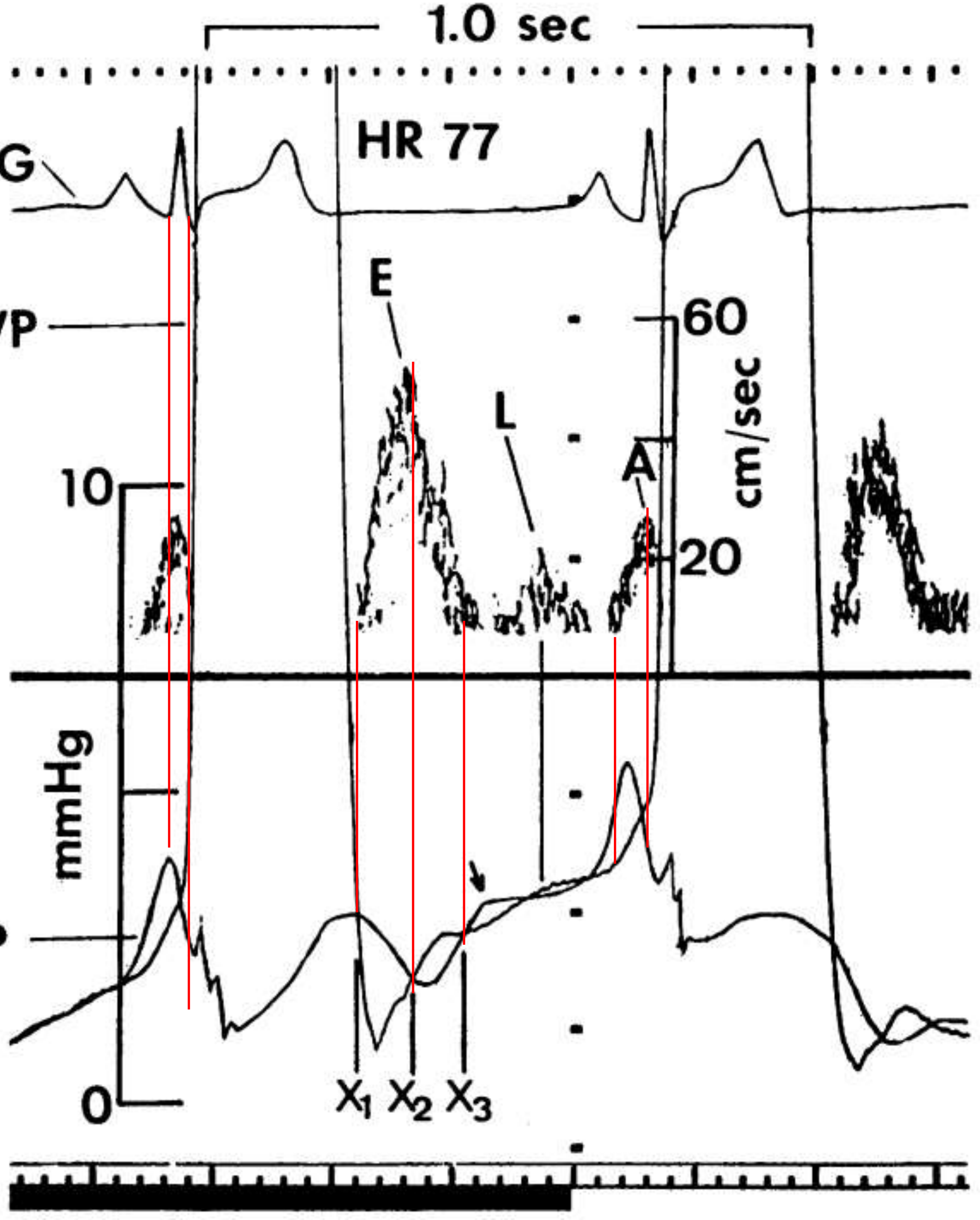
- Related to
  - Left atrial pressure
  - LV relaxation rate
  - Net LV-LA compliance
  - LV end-systolic volume
  - MV resistance
- Gradient reverses

Begins with mitral opening, ends with S3, normal about 0.10 sec

Pressure and Flow

High fidelity LA and LV pressures and Transmitral Doppler

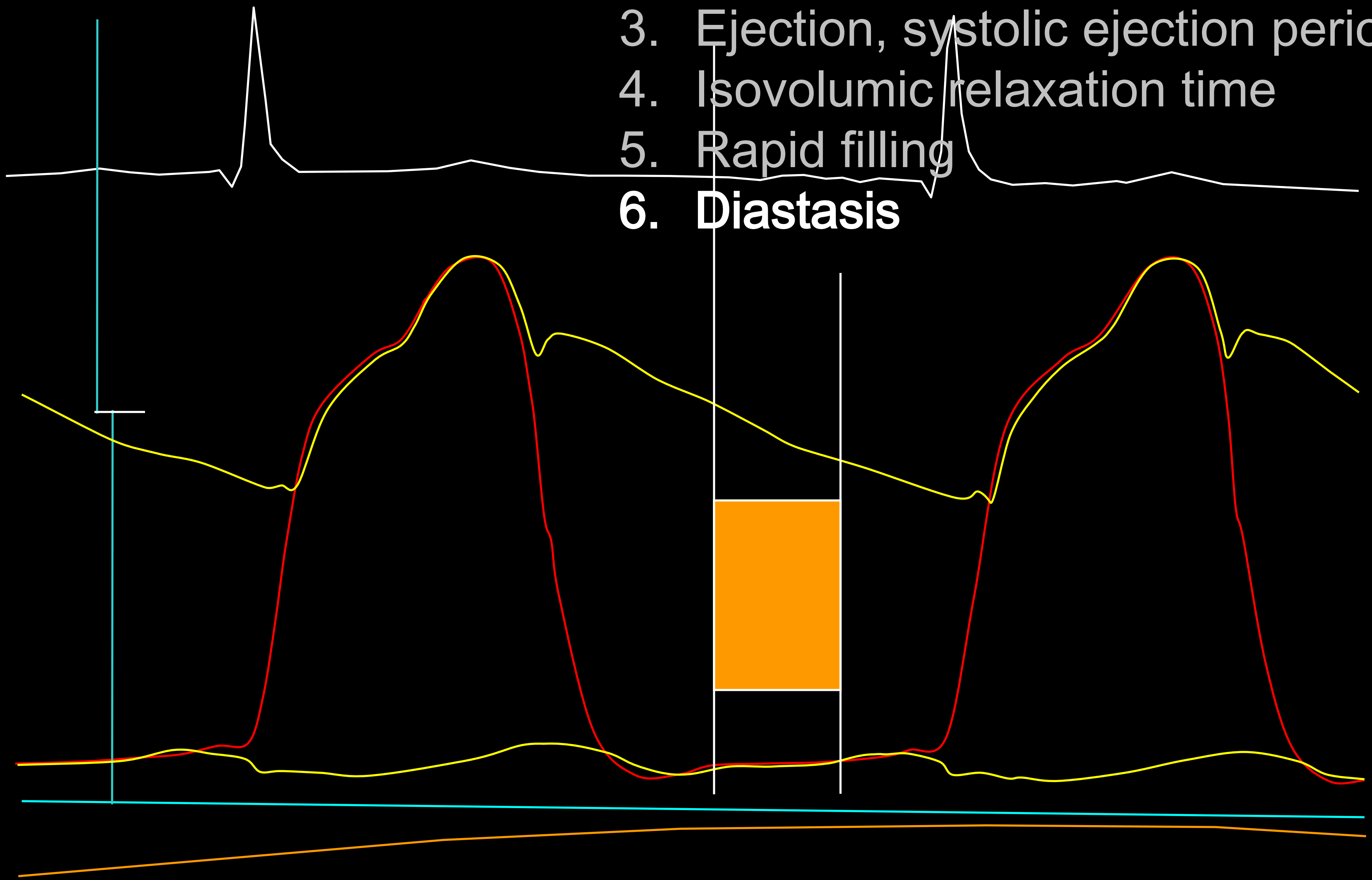
Closed chest canine



Courtois M et al. Circulation 1988;78:661

The Cardiac Cycle

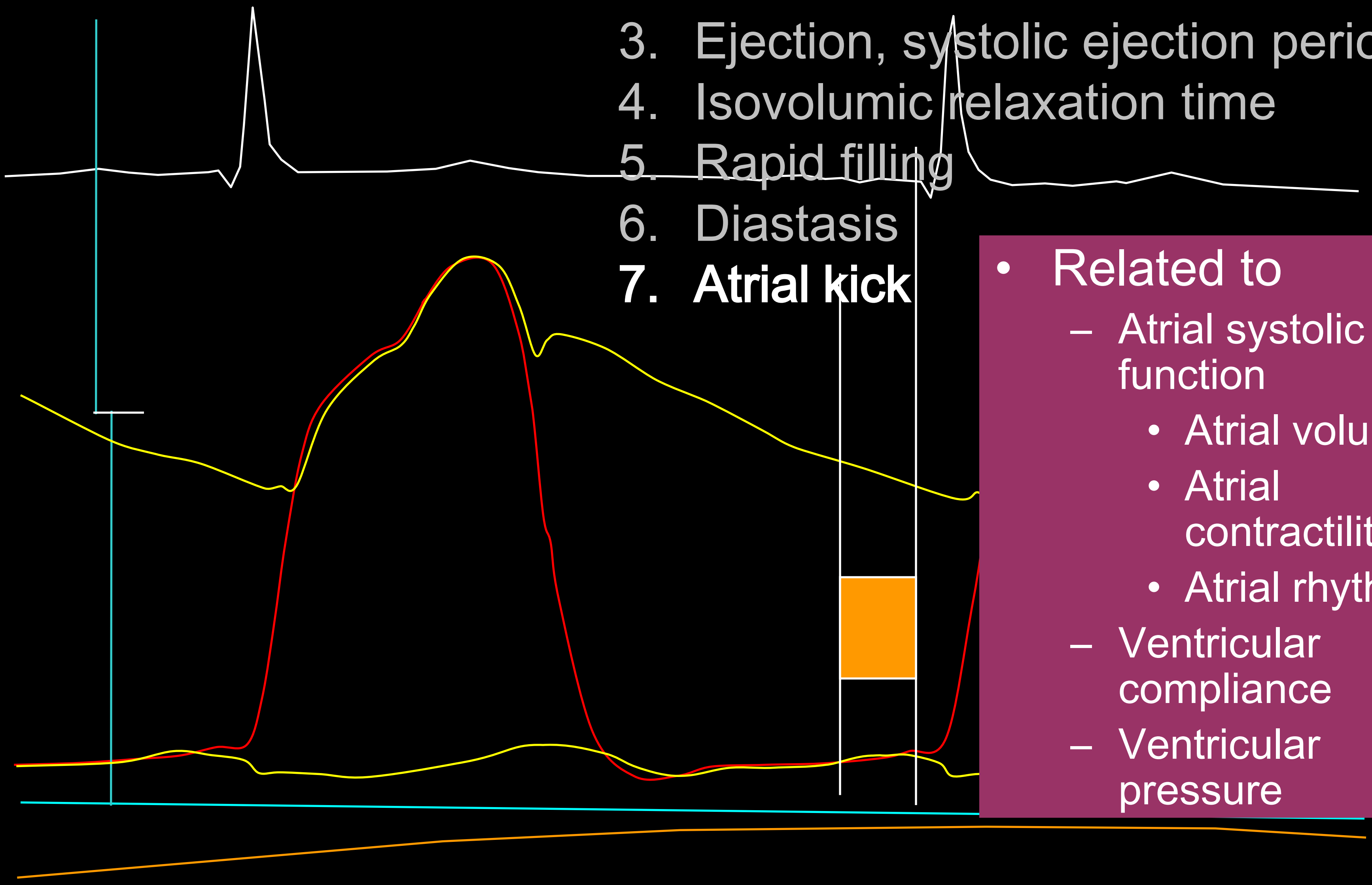
1. Electromechanical delay, Q-M1
2. Isovolumic contraction time
3. Ejection, systolic ejection period
4. Isovolumic relaxation time
5. Rapid filling
6. **Diastasis**



Begins with S3, ends with onset of atrial pressure rise, normal duration quite variable. Represents a form of "heart rate reserve"

The Cardiac Cycle

1. Electromechanical delay, Q-M1
2. Isovolumic contraction time
3. Ejection, systolic ejection period
4. Isovolumic relaxation time
5. Rapid filling
6. Diastasis
7. **Atrial kick**

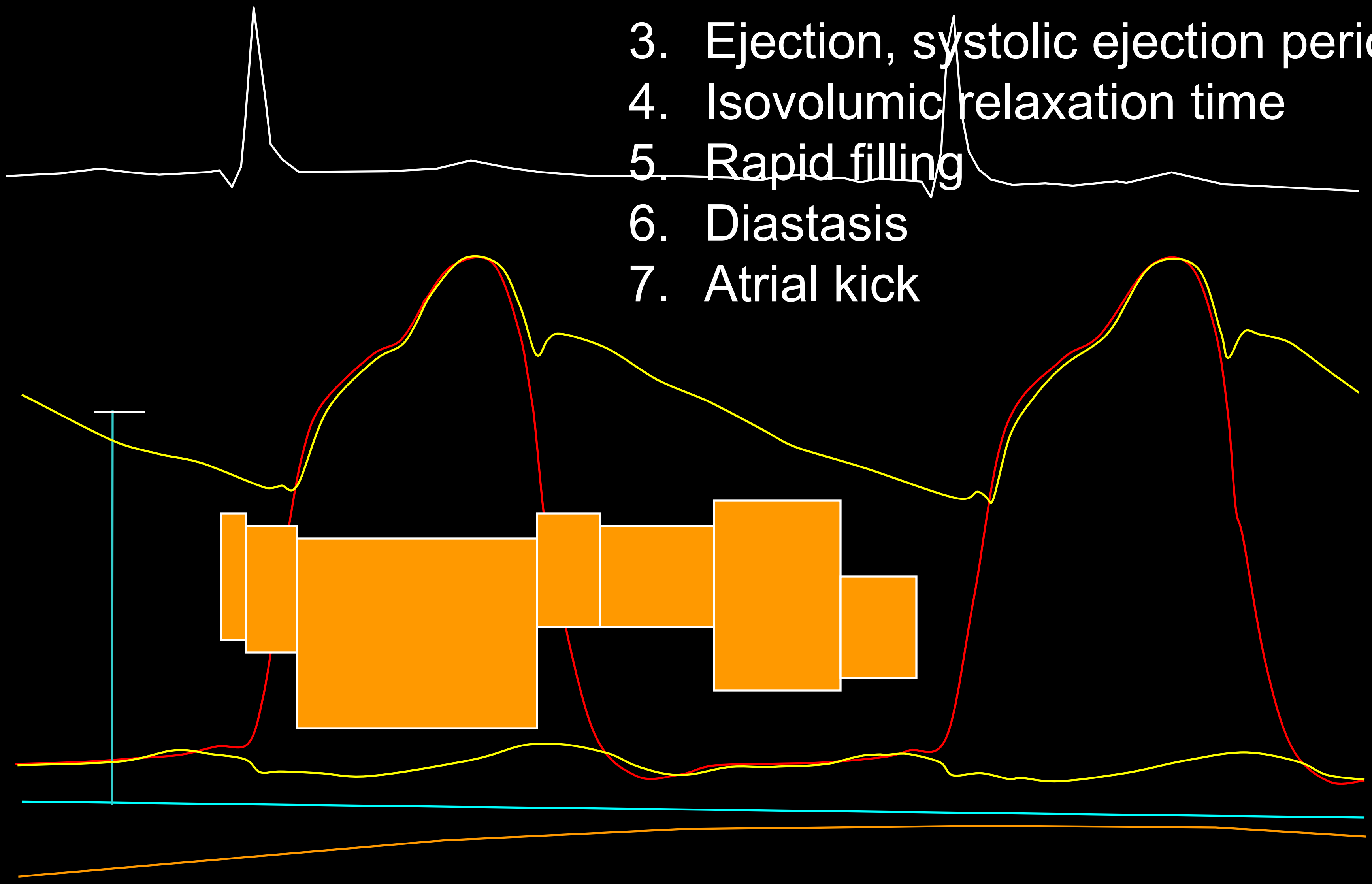


- Related to
  - Atrial systolic function
    - Atrial volume
    - Atrial contractility
    - Atrial rhythm
  - Ventricular compliance
  - Ventricular pressure

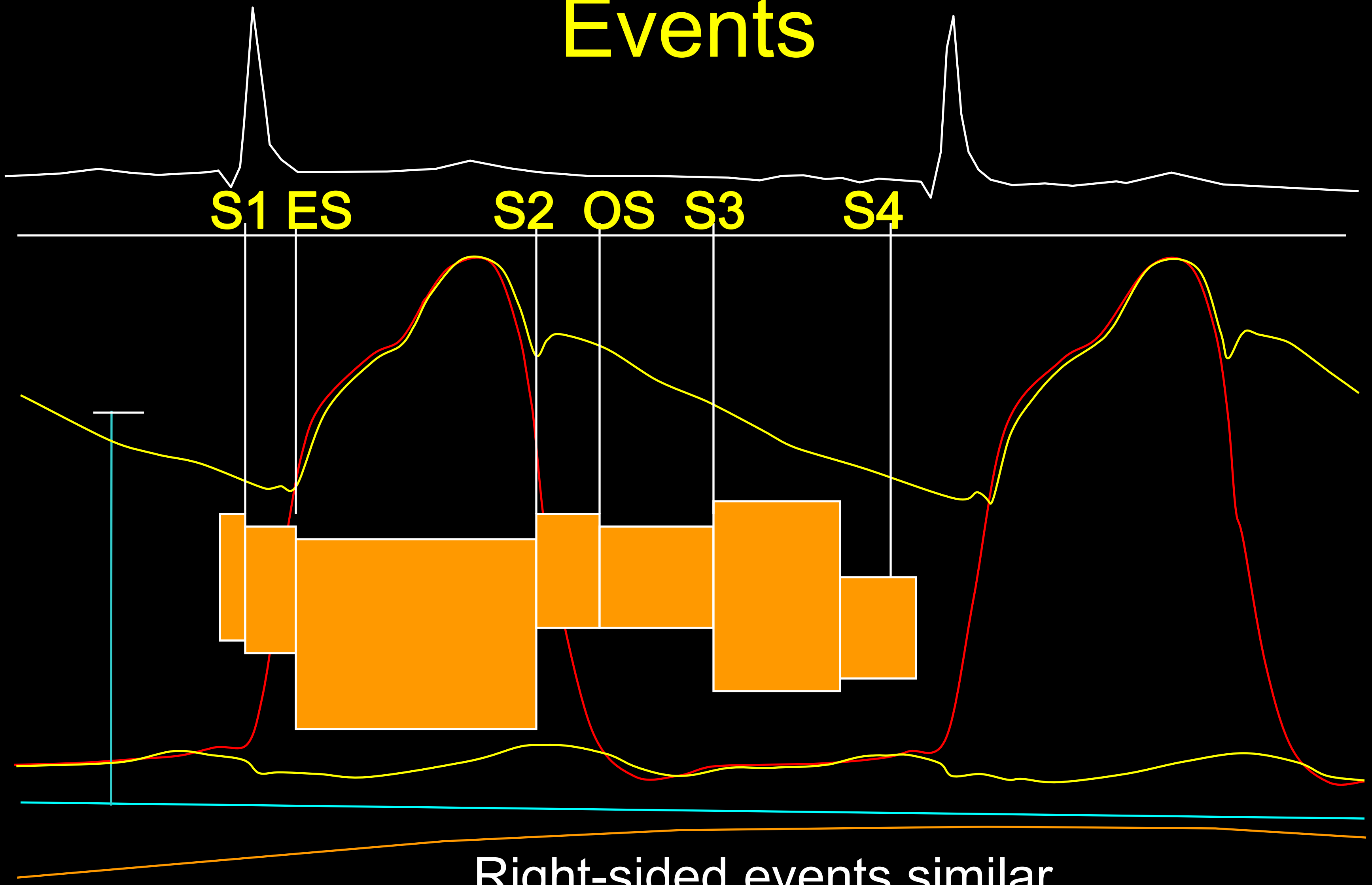
Begins with onset of pressure rise, ends with onset of QRS

The Cardiac Cycle

1. Electromechanical delay, Q-M1
2. Isovolumic contraction time
3. Ejection, systolic ejection period
4. Isovolumic relaxation time
5. Rapid filling
6. Diastasis
7. Atrial kick



The Cardiac Cycle and Auscultatory Events



Right-sided events similar

Assessing Pressure Tracings

1. Start with the ECG, note rhythm, rate and QRS width
2. Note the scales for pressure (note if there are 2 simultaneous pressures) and time (paper speed)
3. Identify the waveforms and obtain standard pressure measurements
4. Note respiratory effects
5. Reflect on the clinical significance of these
6. Observe the pressure waveforms for additional morphologic data and reflect on their clinical significance
7. Integrate all the information into the clinical context and reflect on patient management implications

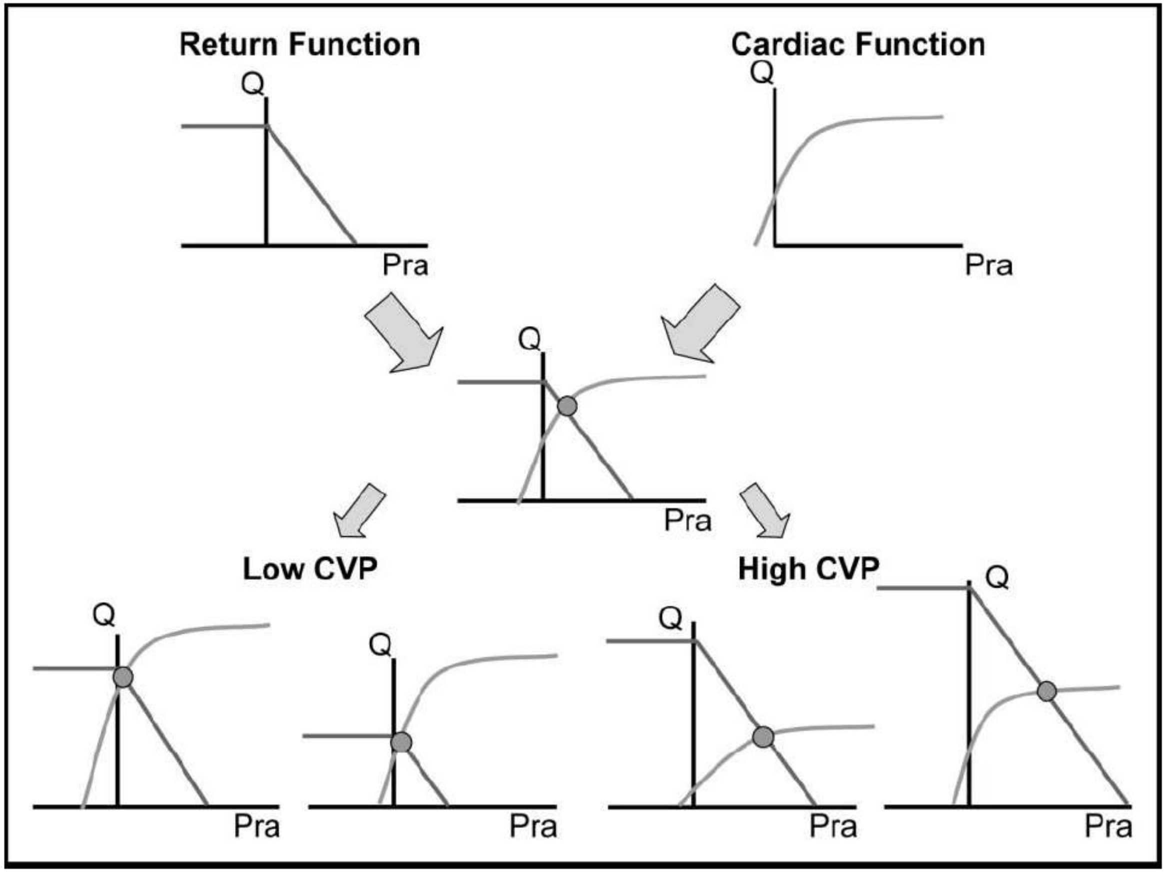
Basic Hemodynamics

- Flow
  - Return to the heart
  - Flow out of the heart
- Pressure
- Pressure/Flow = Resistance

Lower left, a low central venous pressure (CVP) can be associated with a high cardiac output and normal volume and return function or with normal cardiac function but volume and decreased return function. Lower right, a high CVP can be associated with normal return function but decreased cardiac function or normal cardiac function with high return function because of excess volume. Thus, a single value of CVP does not indicate volume status or cardiac function.

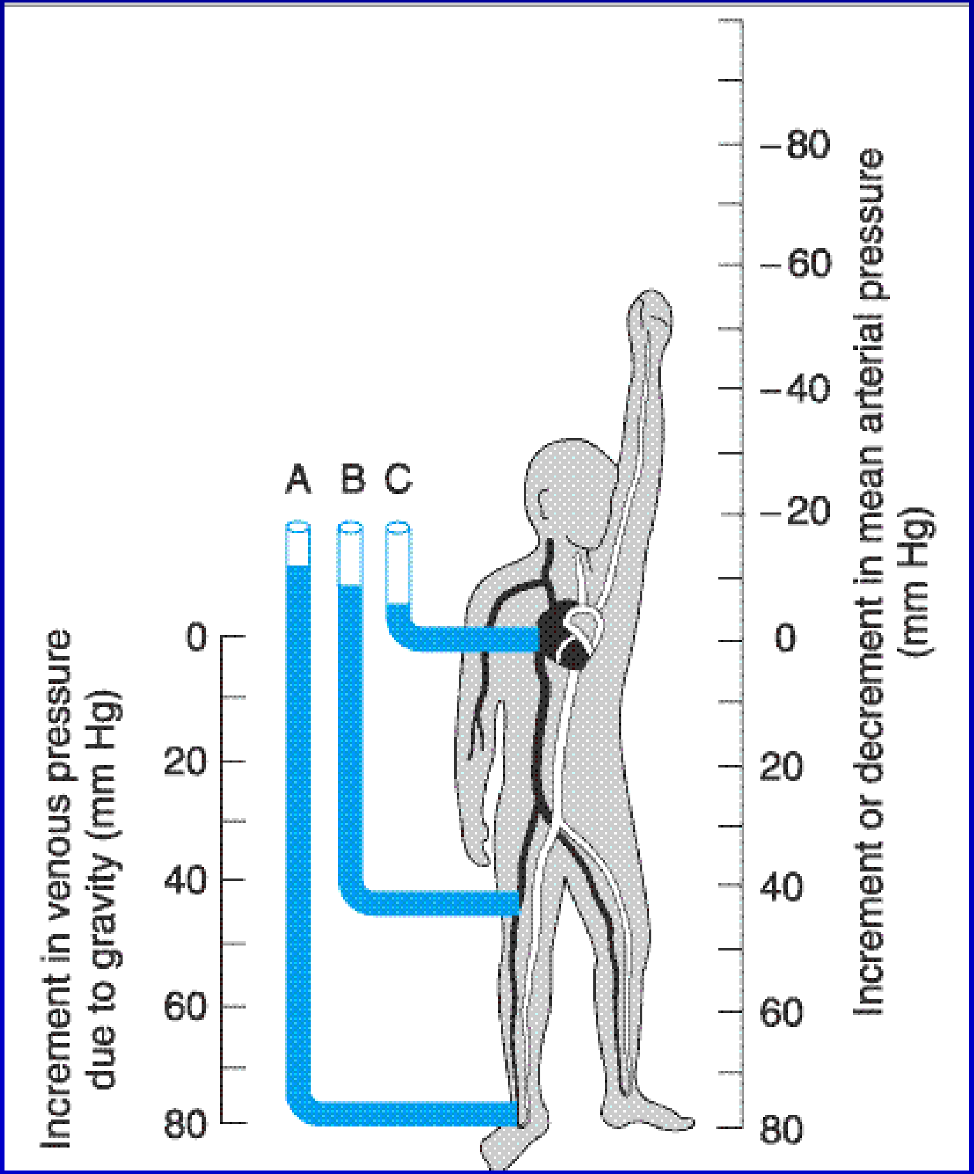
Inflow and Outflow

Figure 1. Interaction of the return function and cardiac function for the determination of right atrial pressure and cardiac output



Magder S. Curr Opin Crit Care. 2005;11:264-70.

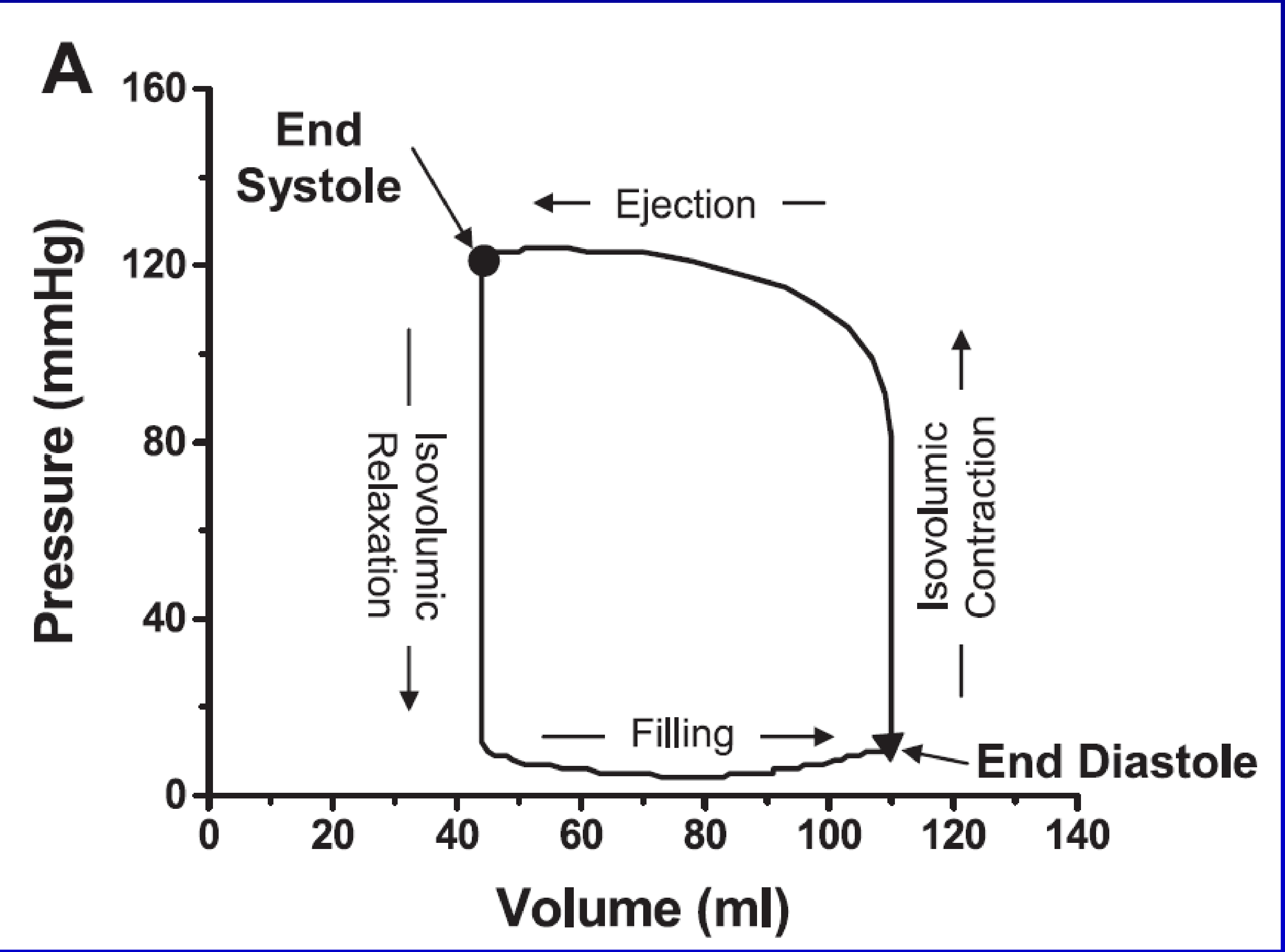
Venous Pressure



Effects of gravity on arterial and venous pressure. The scale on the right indicates the increment (or decrement) in mean pressure in a large artery at each level. The mean pressure in all large arteries is approximately 100 mm Hg when they are at the level of the left ventricle. The scale on the left indicates the increment in venous pressure at each level due to gravity. The manometers on the left of the figure indicate the height to which a column of blood in a tube would rise if connected to an ankle vein (A), the femoral vein (B), or the right atrium (C), with the subject in the standing position. The approximate pressures in these locations in the recumbent position—ie, when the ankle, thigh, and right atrium are at the same level—are A, 10 mm Hg; B, 7.5 mm Hg; and C, 4.6 mm Hg.

Ganong's Physiology, 2004 McGraw-Hill, Ch. 30

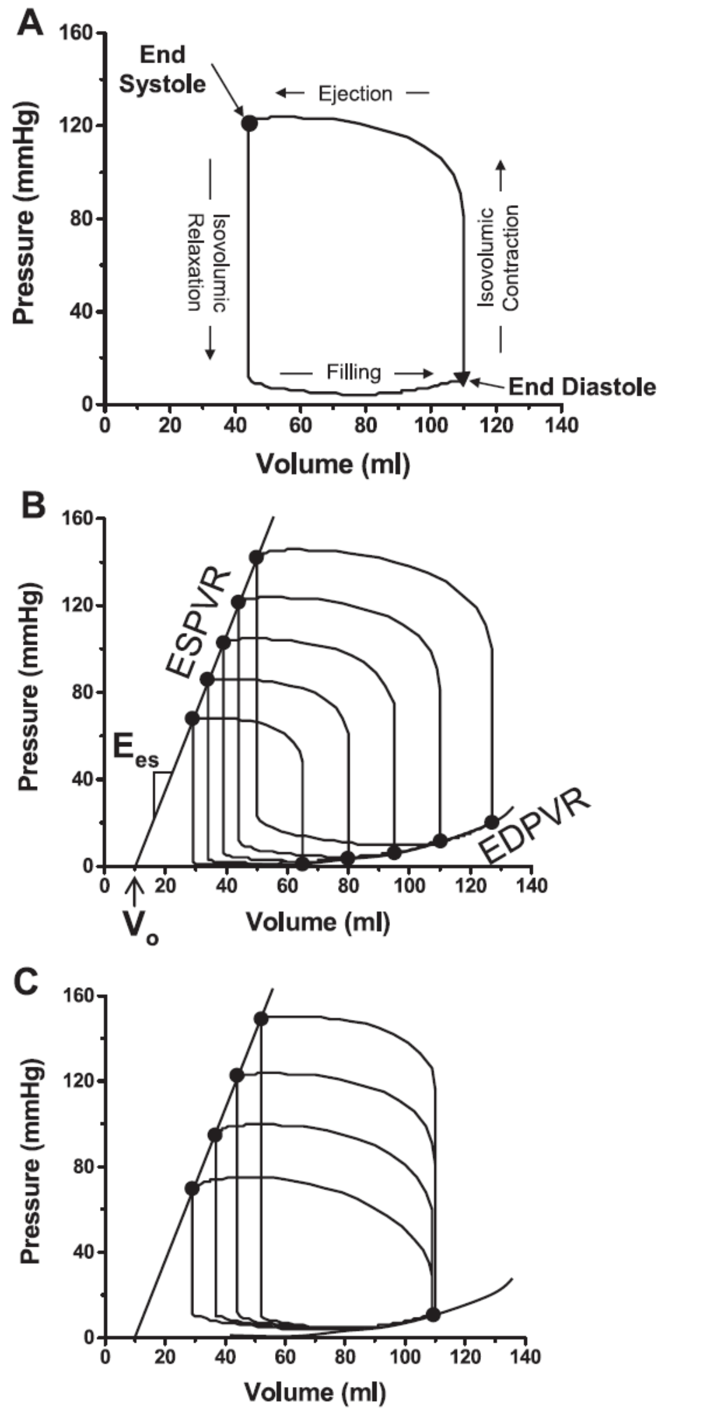
Pressure and Volume



Burkhoff D et al. AJP – Heart. 2005;289:501-512.

Pressure and Volume

Fig. 1. *A*: the 4 phases of the cardiac cycle are readily displayed on the pressure-volume loop, which is constructed by plotting instantaneous pressure vs. volume. This loop repeats with each cardiac cycle and shows how the heart transitions from its end-diastolic state to the end-systolic state and back. *B*: with a constant contractile state and afterload resistance, a progressive reduction in ventricular filling pressure causes the loops to shift toward lower volumes at both end systole and end diastole. When the resulting end-systolic pressure-volume points are connected, a reasonably linear end-systolic pressure-volume relationship (ESPVR) is obtained. The linear ESPVR is characterized by a slope (E_{es}) and a volume axis intercept (V_o). In contrast, the diastolic pressure-volume points define a nonlinear end-diastolic pressure-volume relationship (EDPVR). *C*: when afterload resistance is increased at a constant preload pressure, the loops get narrower and longer and, under idealized conditions, the end-systolic pressure-volume points fall on the same ESPVR as obtained with preload reduction.



Burkhoff D et al. AJP – Heart. 2005;289:501-5

Normal Values at BAMC

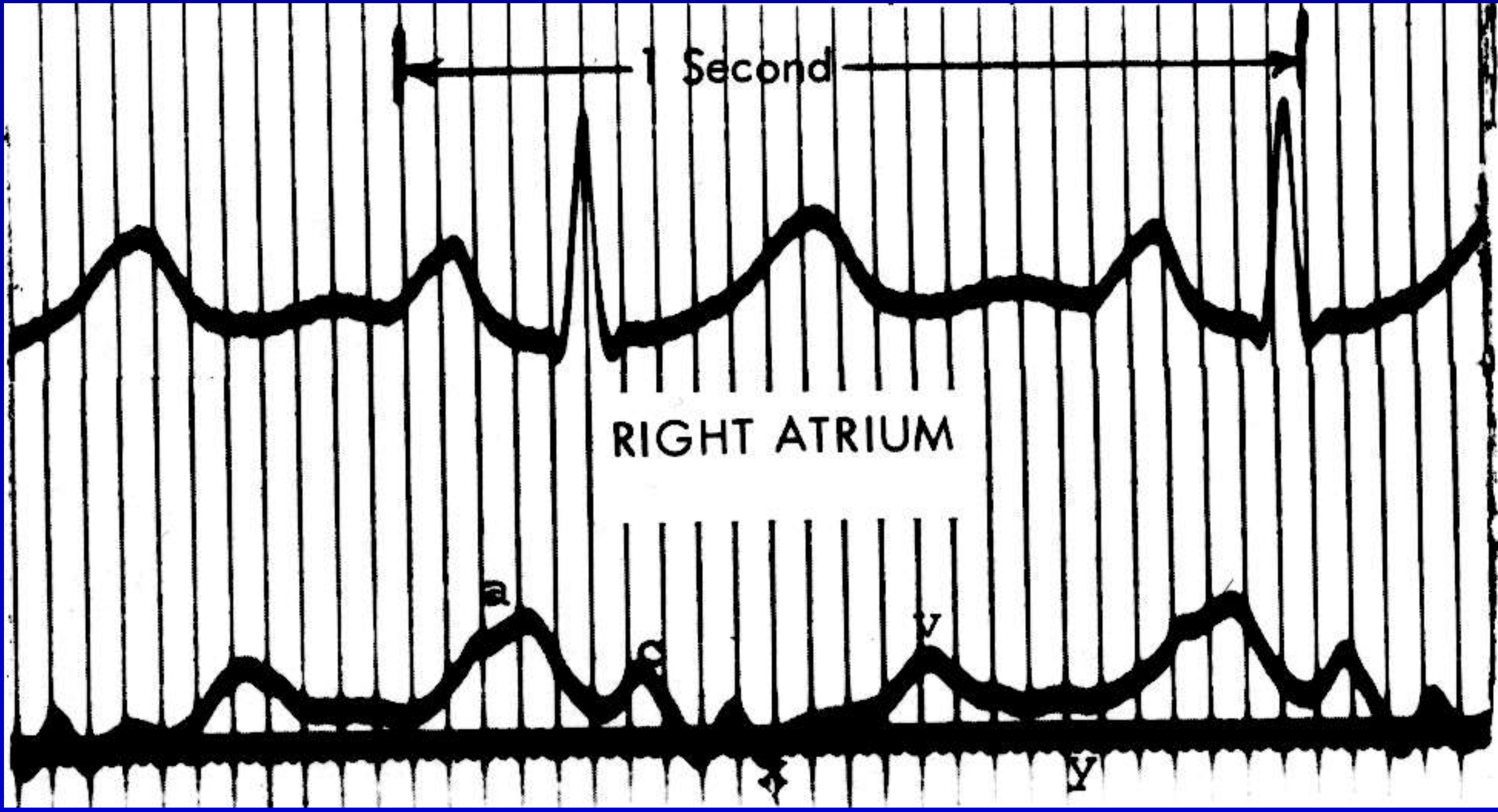
Location	Nml	Max	Resp Variation
RA, a	9	?12	2
RA, v	6	?12	2
RA, X nadir	3-4		
RA mean	6	8	2
LA, a	10	16	
LA, v	12		3-4
LA mean	8	12	
RV systolic	27	35	2-3
RVED	5	7	1-2
LV systolic	120	135	4-8
LVED	10	12	3-4
PA systolic	22	30	3-4
PA diastolic	12	15	3-4
PA mean	15-17	18 (20)	4-5

Normal Hemodynamic Values

	Pressure	Saturation
RA mean	0-5	65-80
RV Systolic	10-25	
PA Systolic	10-25	
PA mean	5-15	
LA mean	0-10	95-100
LV systolic	85-150	
LV end-diastolic	0-10	
Ao systolic	85-150	
Ao diastolic	60-90	
Ao mean	70-100	

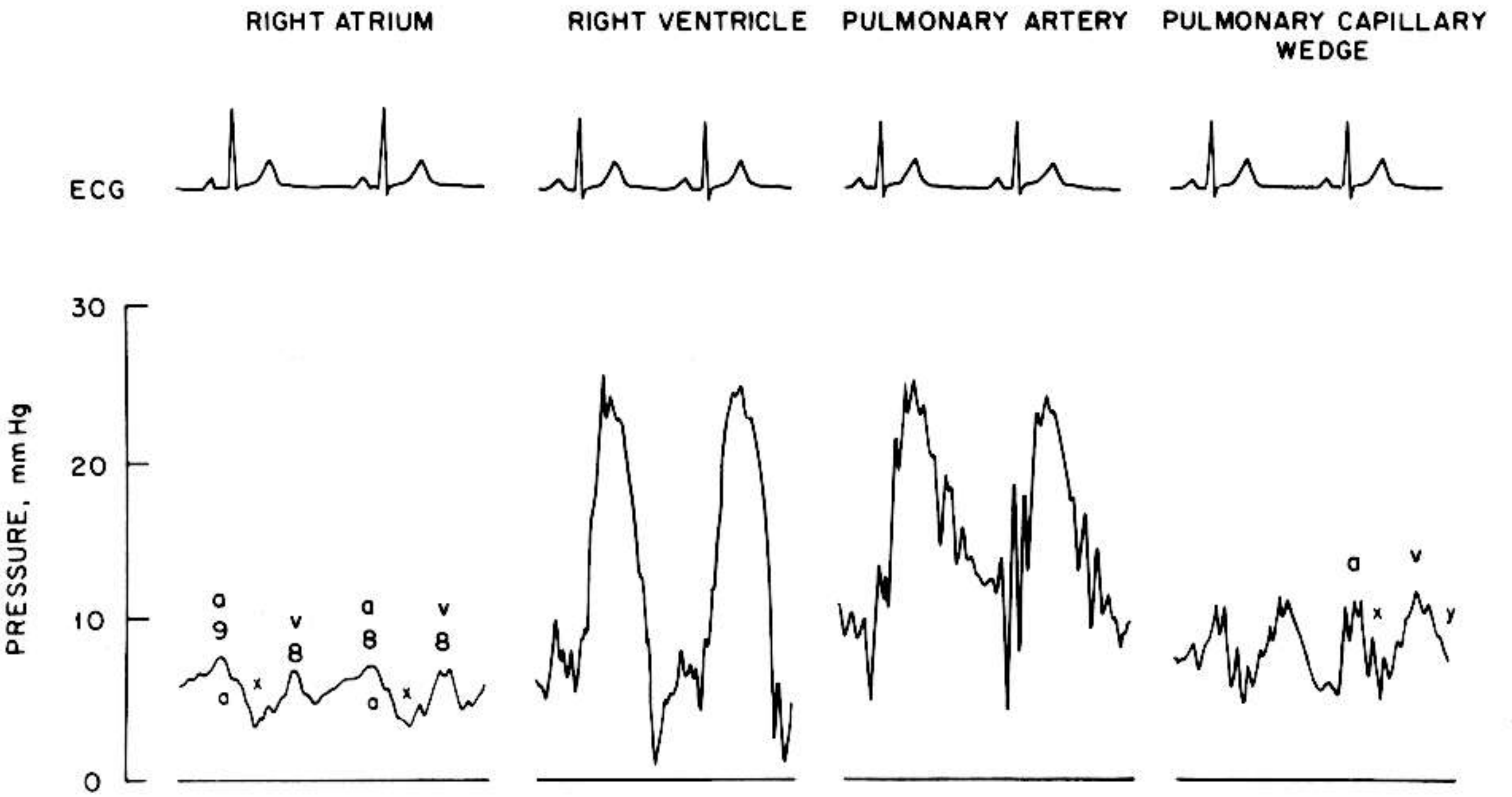
Criley and Ross, 1971

Normal RA Pressure Waveform



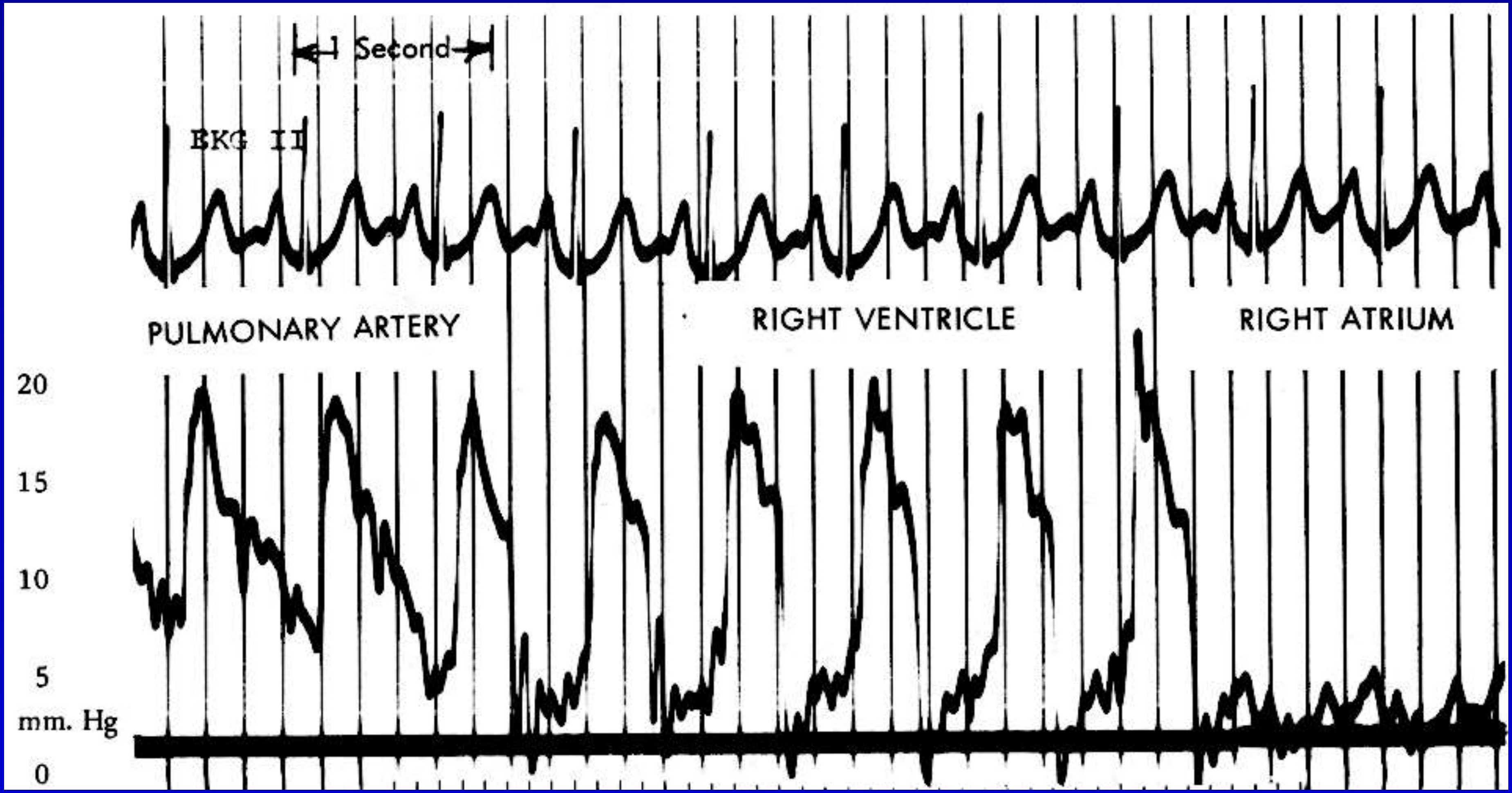
Criley JM and Ross RS, Tampa Tracings, 1971

Right Heart Pressures With Goodale-Lubin



Grossman, 5th ed, p.90

Normal Right Heart Waveforms



Criley JM and Ross RS, Tampa Tracings, 1971

Normal RA and RV Pressure Relationship

Notes:

RV pressure not normal (COPD).

RV waveform underdamped (white and black arrows)

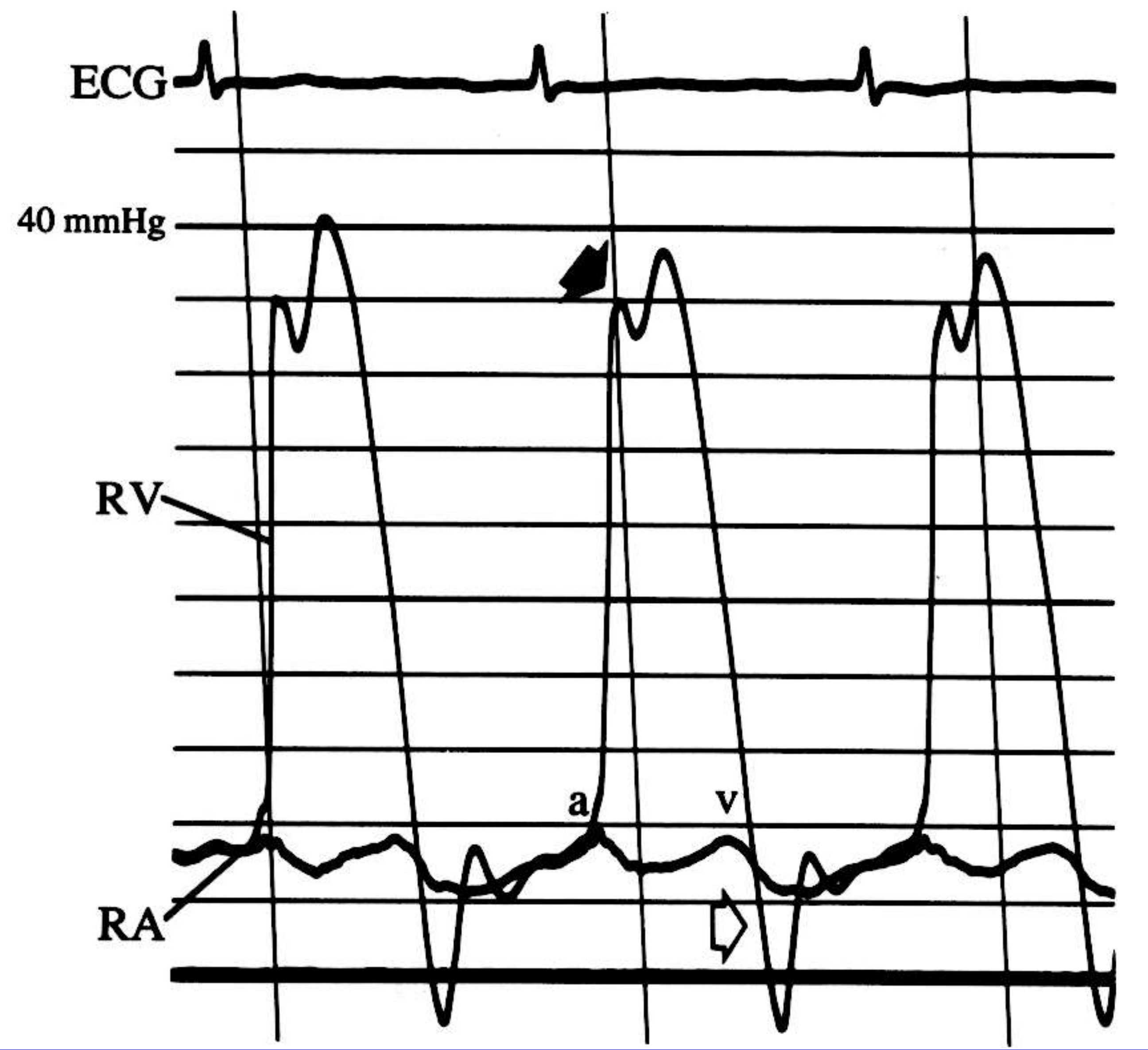
RA c wave inapparent.

a wave 7

v wave 7

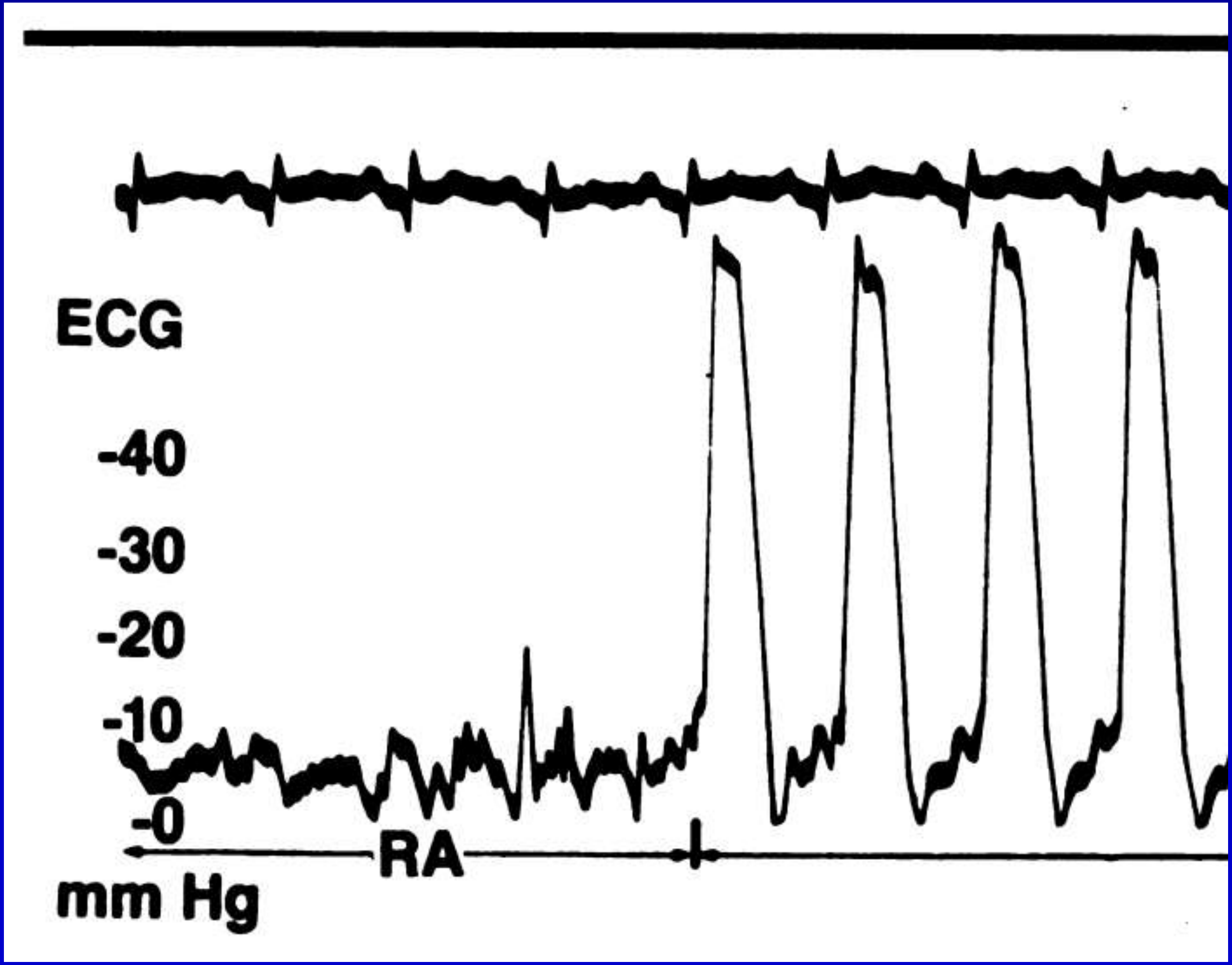
mean 6

nadir Y descent 4



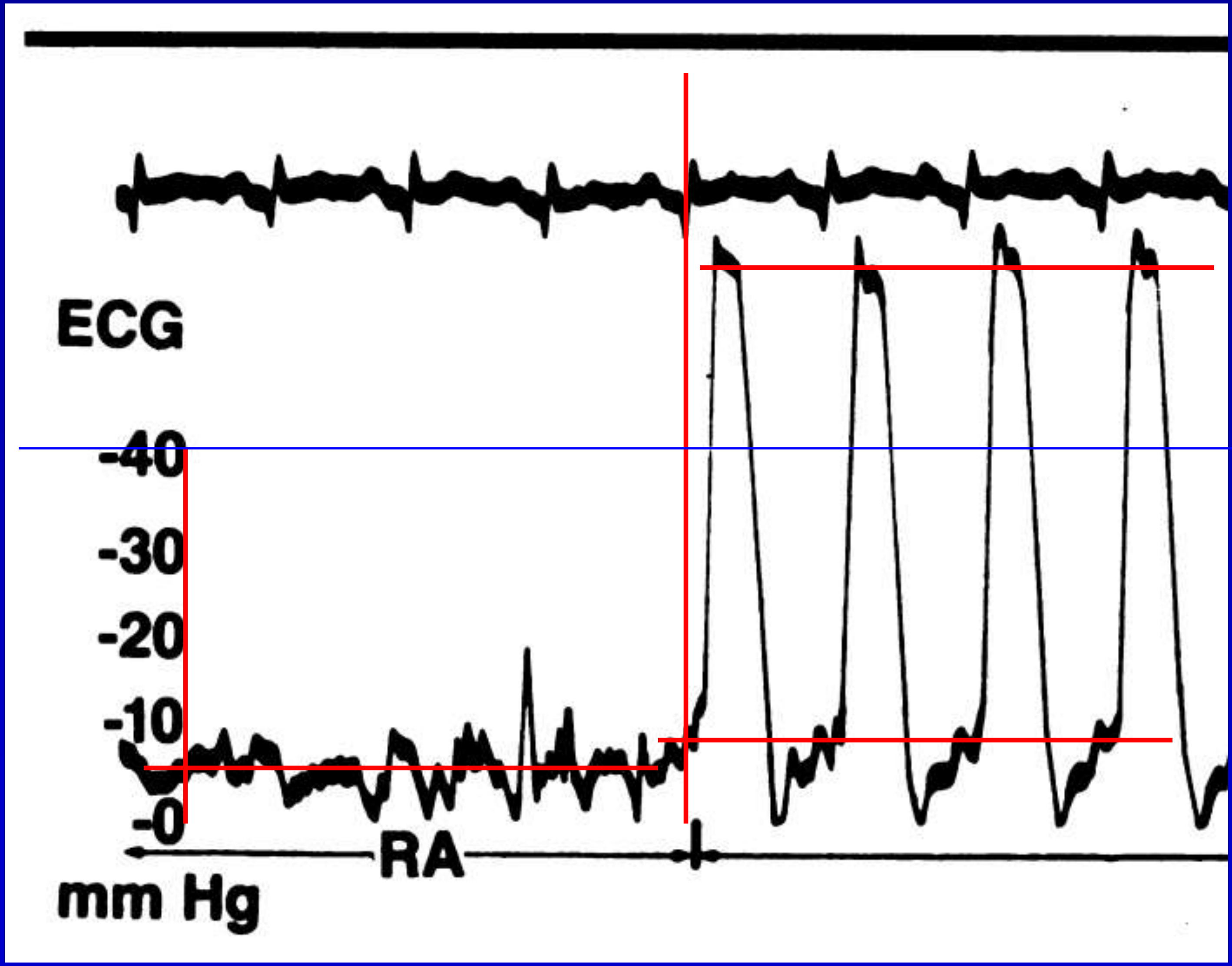
Kern, 1999, p. 102

Swan-Ganz Pressures Detail



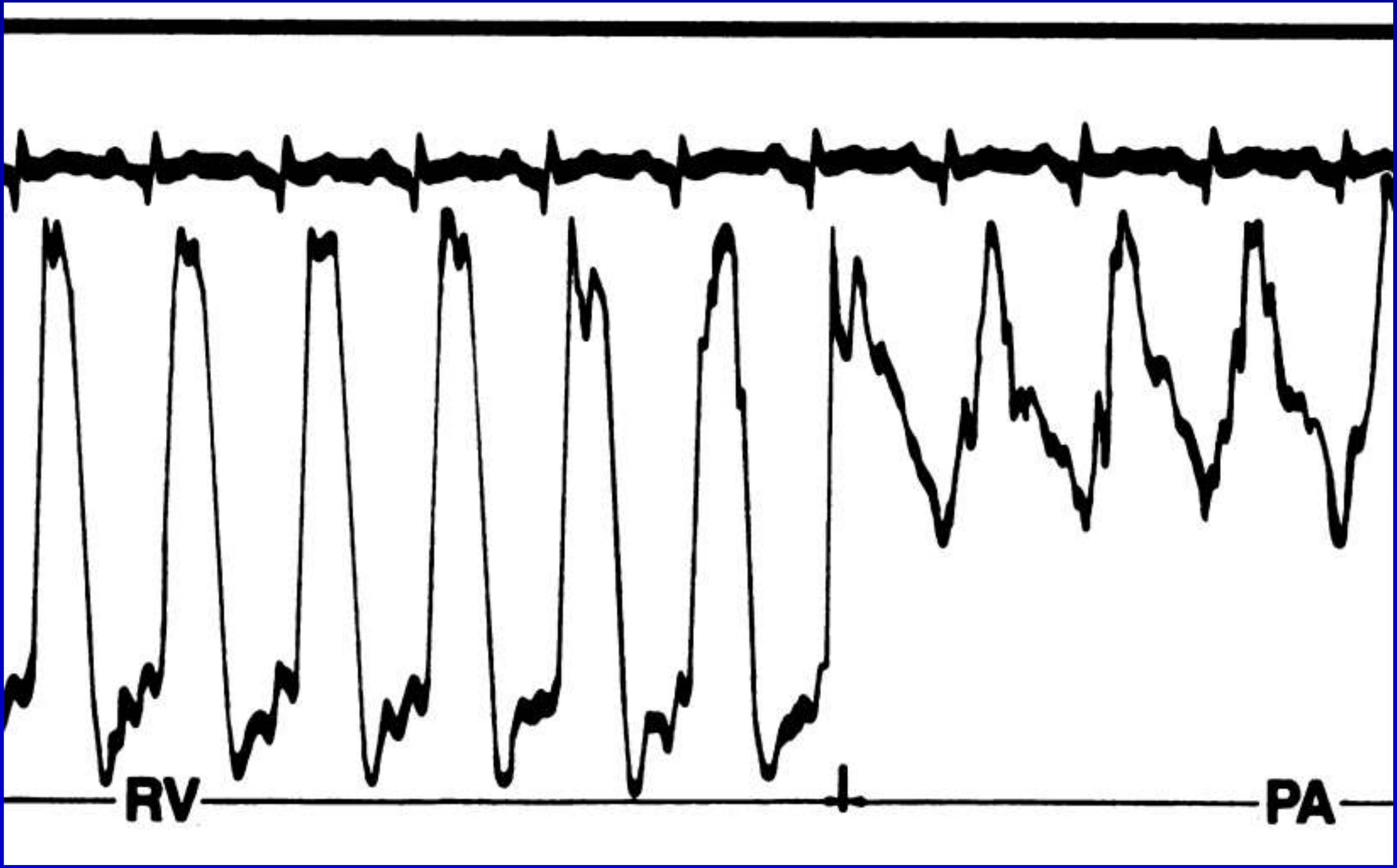
ACLS Textbook 12-19, 1994

Swan-Ganz Pressures Detail



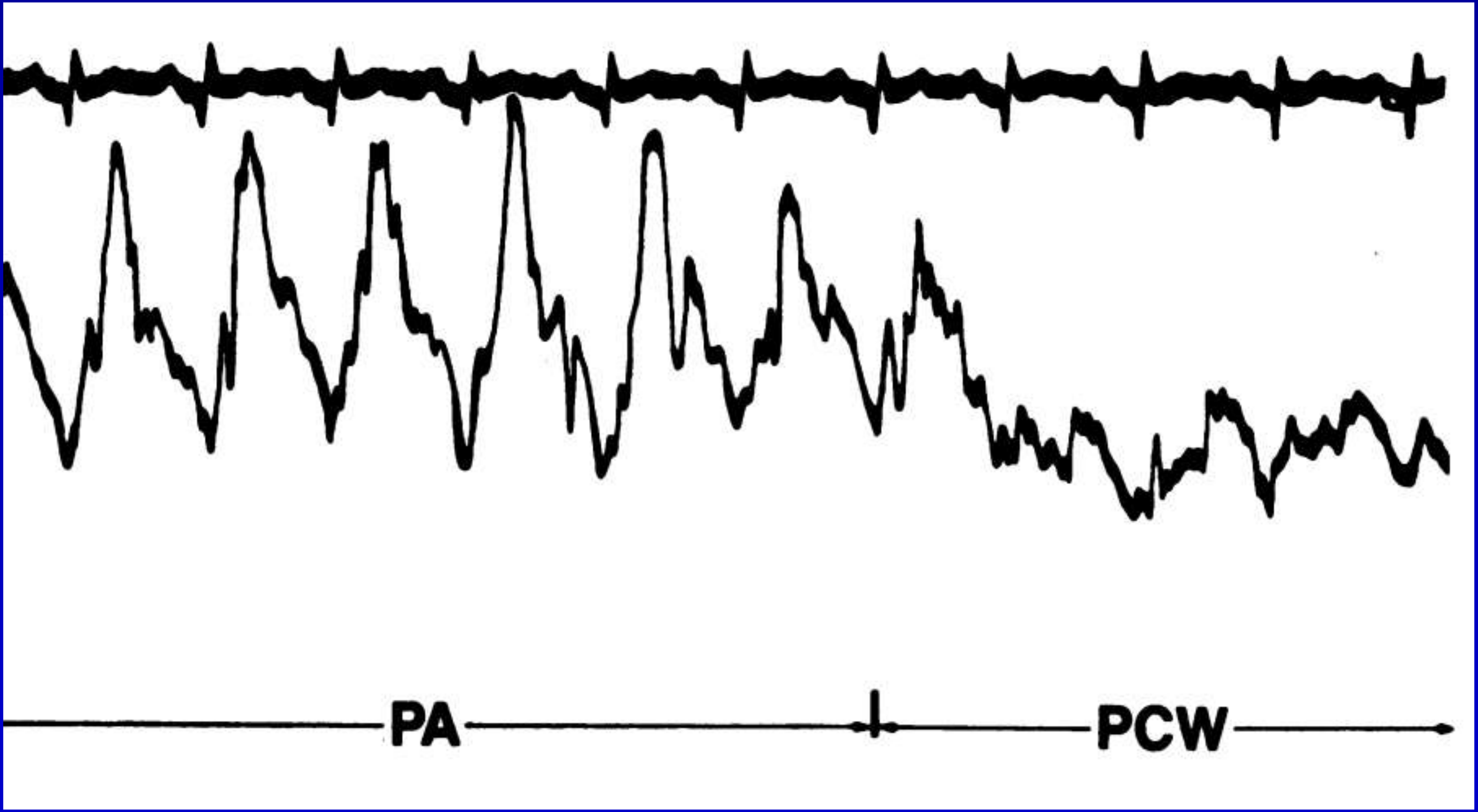
ACLS Textbook 12-19, 1994

Swan-Ganz Pressures Detail



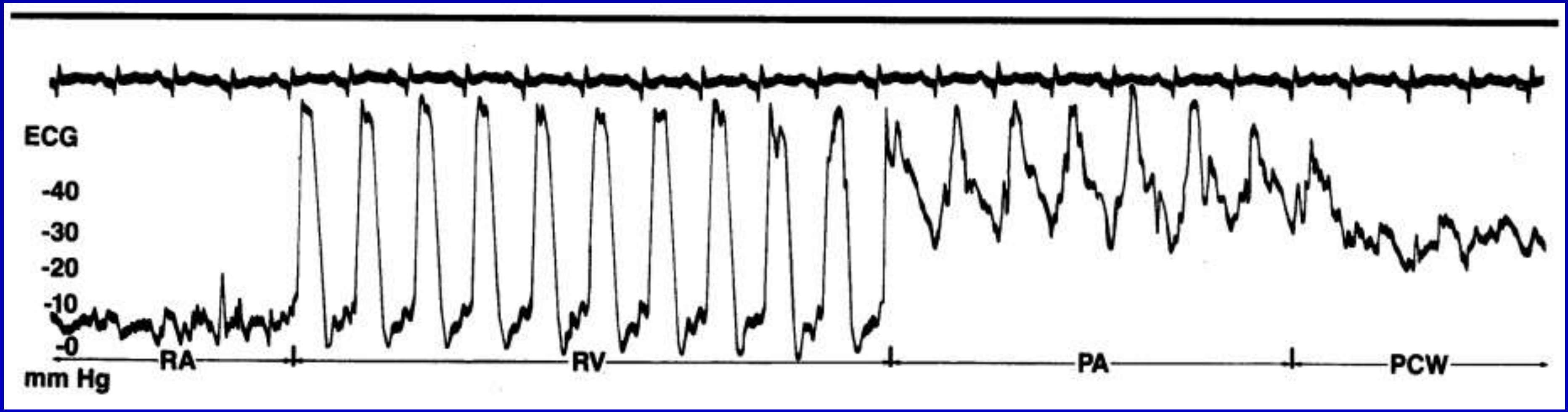
ACLS Textbook 12-19, 1994

Swan-Ganz Pressures Detail



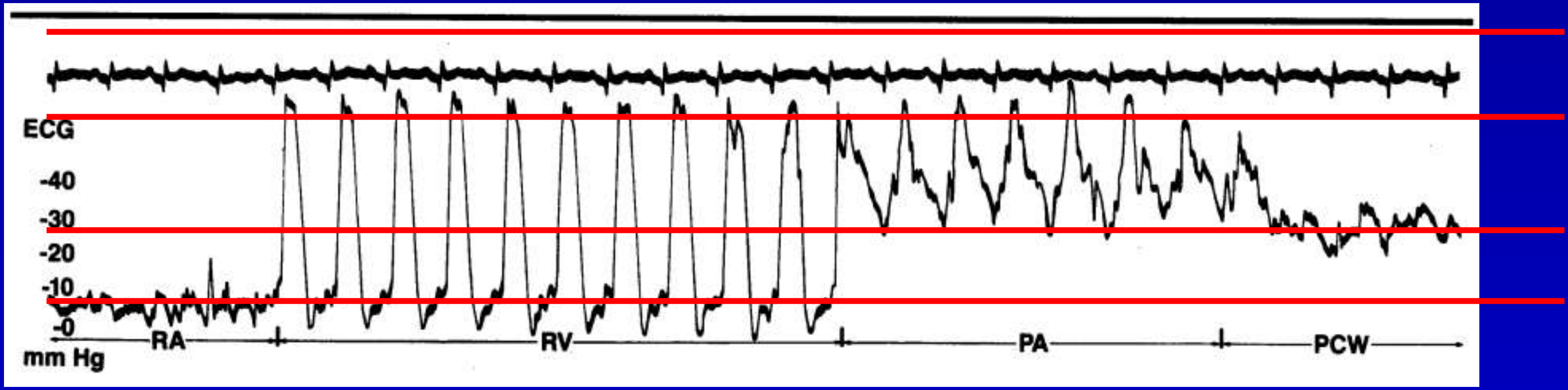
ACLS Textbook 12-19, 1994

Right heart pressures via Swan-Ganz catheter



ACLS Textbook 12-19, 1994

Right heart pressures via Swan-Ganz catheter



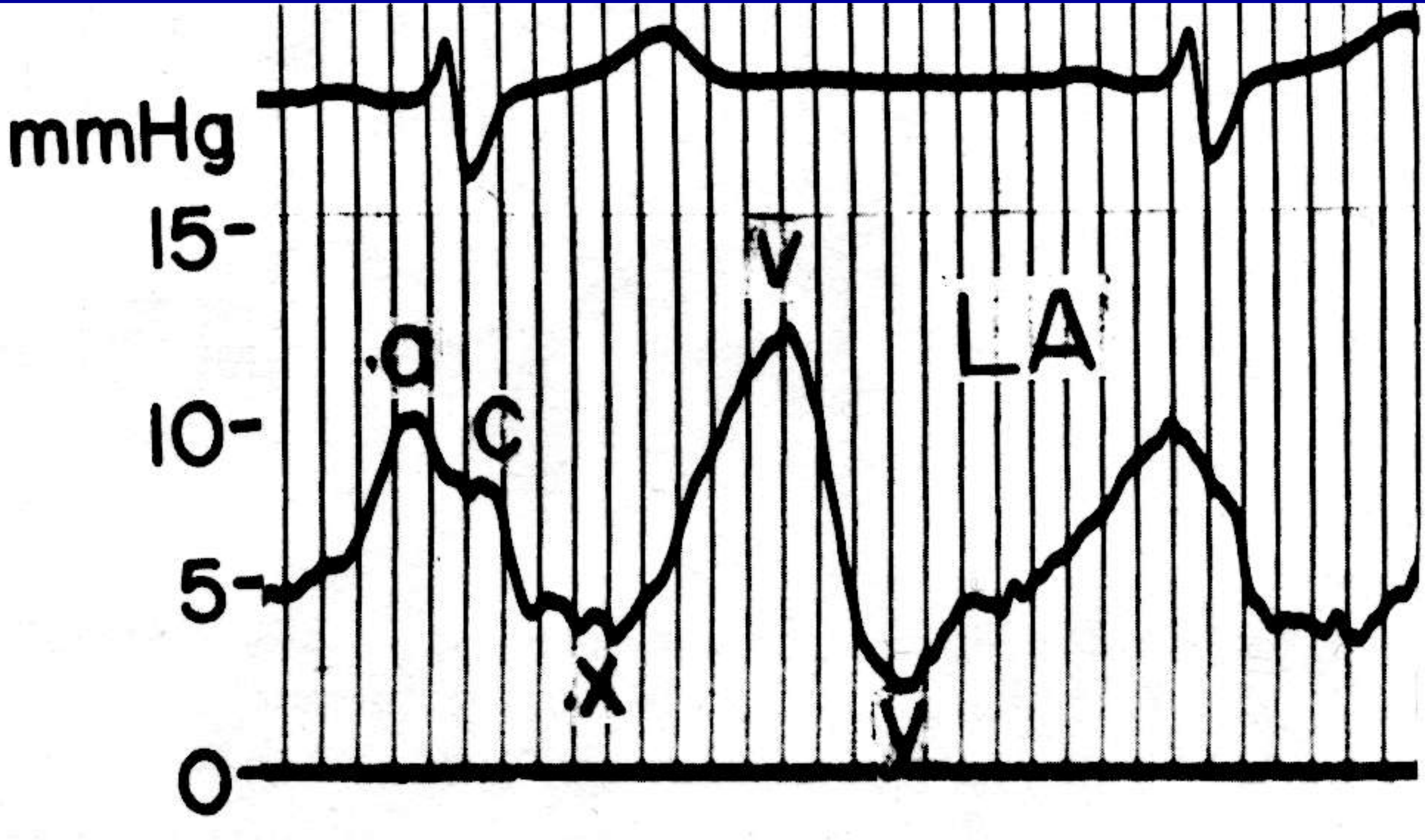
ACLS Textbook 12-19, 1994

Dysrhythmia and RA pressure

Kern, MJ, 1999, p. 103

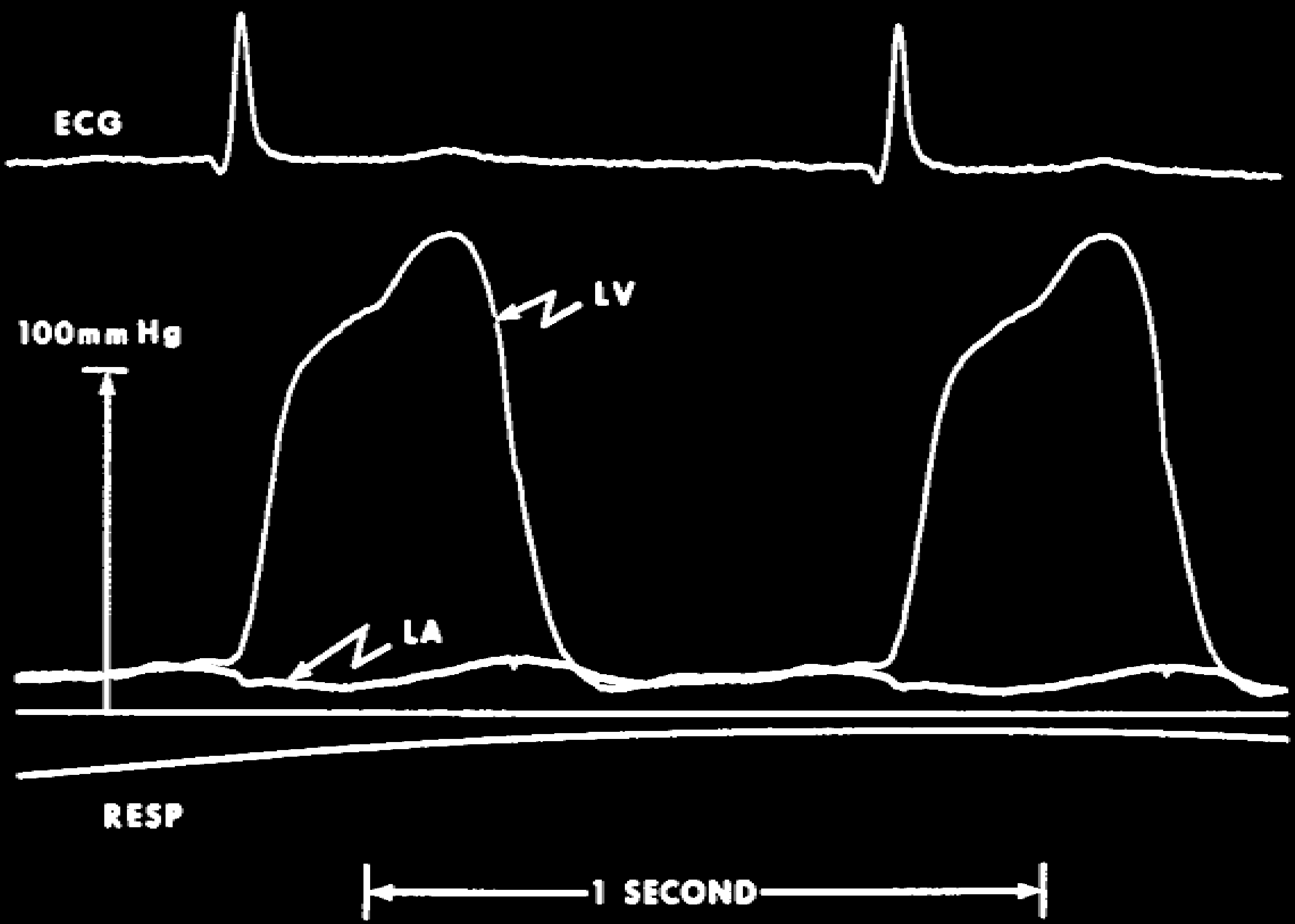
66 year-old man after MI

Normal LA Pressure Waveform

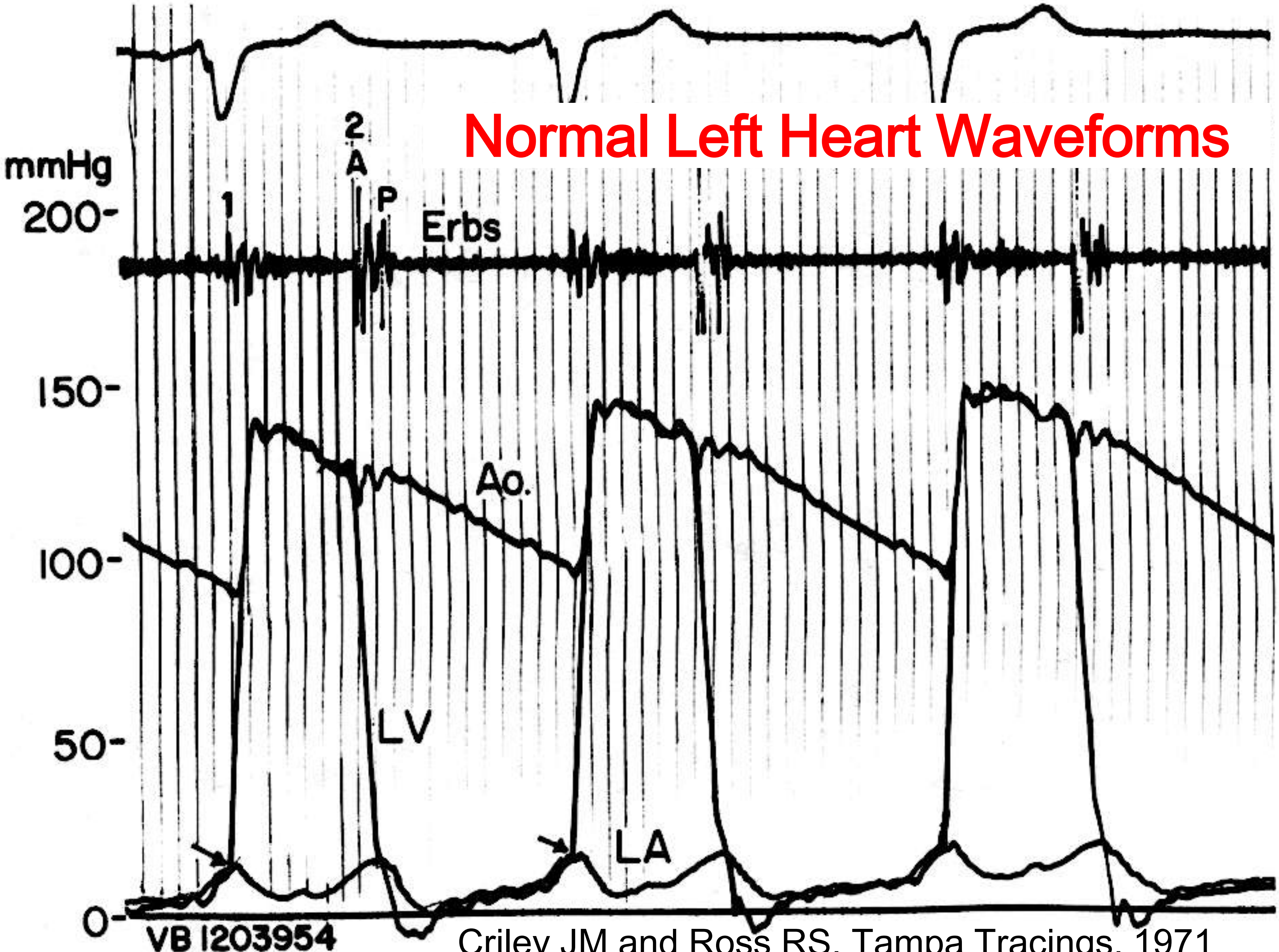


Criley JM and Ross RS, Tampa Tracings, 1971

Normal Left Ventricular – Left Atrial Relationship



Normal Left Heart Waveforms



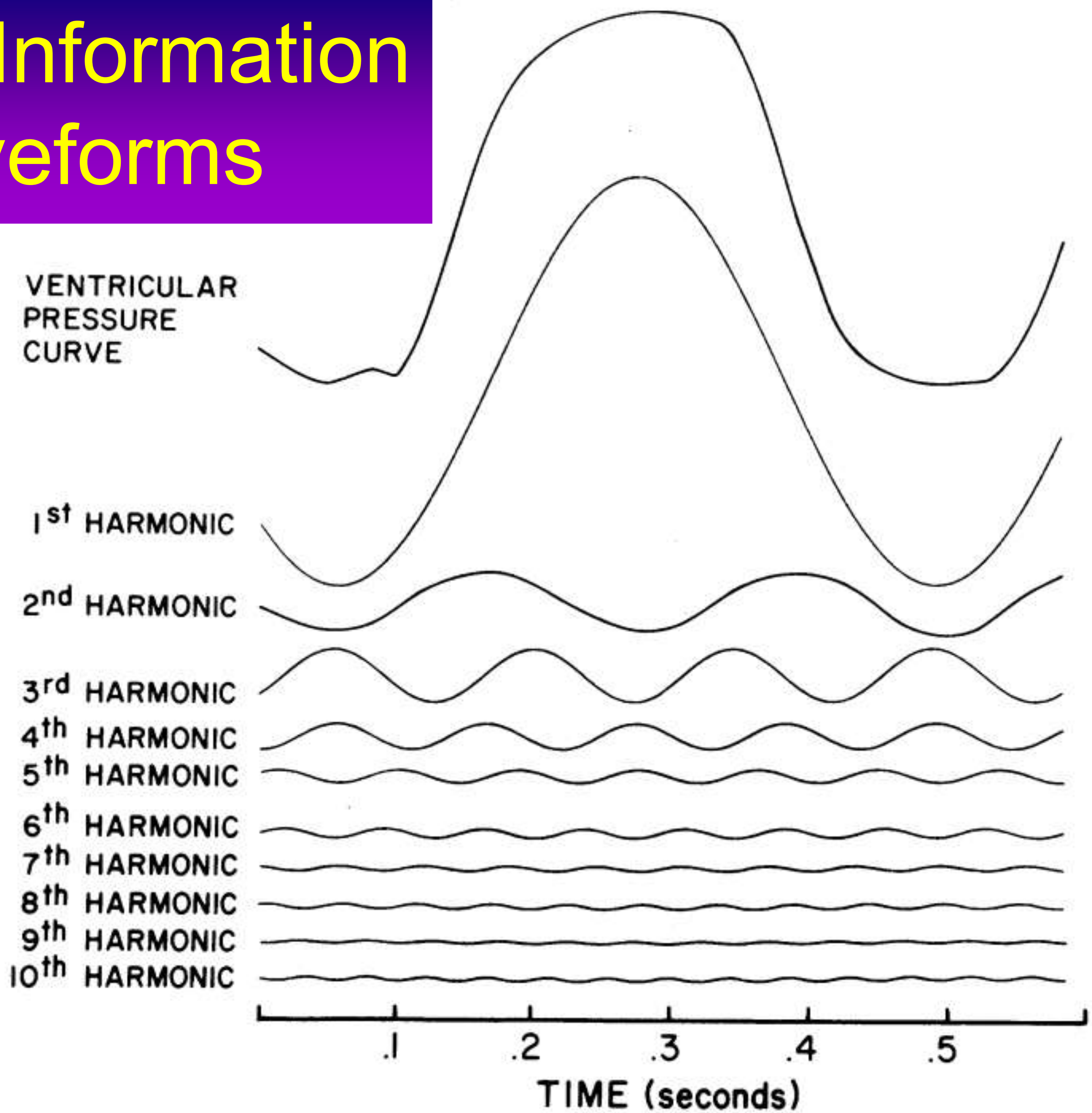
Criley JM and Ross RS, Tampa Tracings, 1971

Physical Principles in Pressure Measurement

- Harmonic information in waveforms
- Catheter-transducer system
  - Sensitivity
  - Frequency response
  - Damping
- Waveform reflection

Harmonic Information in Waveforms

Fourier analysis breaks down any repeating waveform into a series of sine and cosine waves, identifying the harmonic information

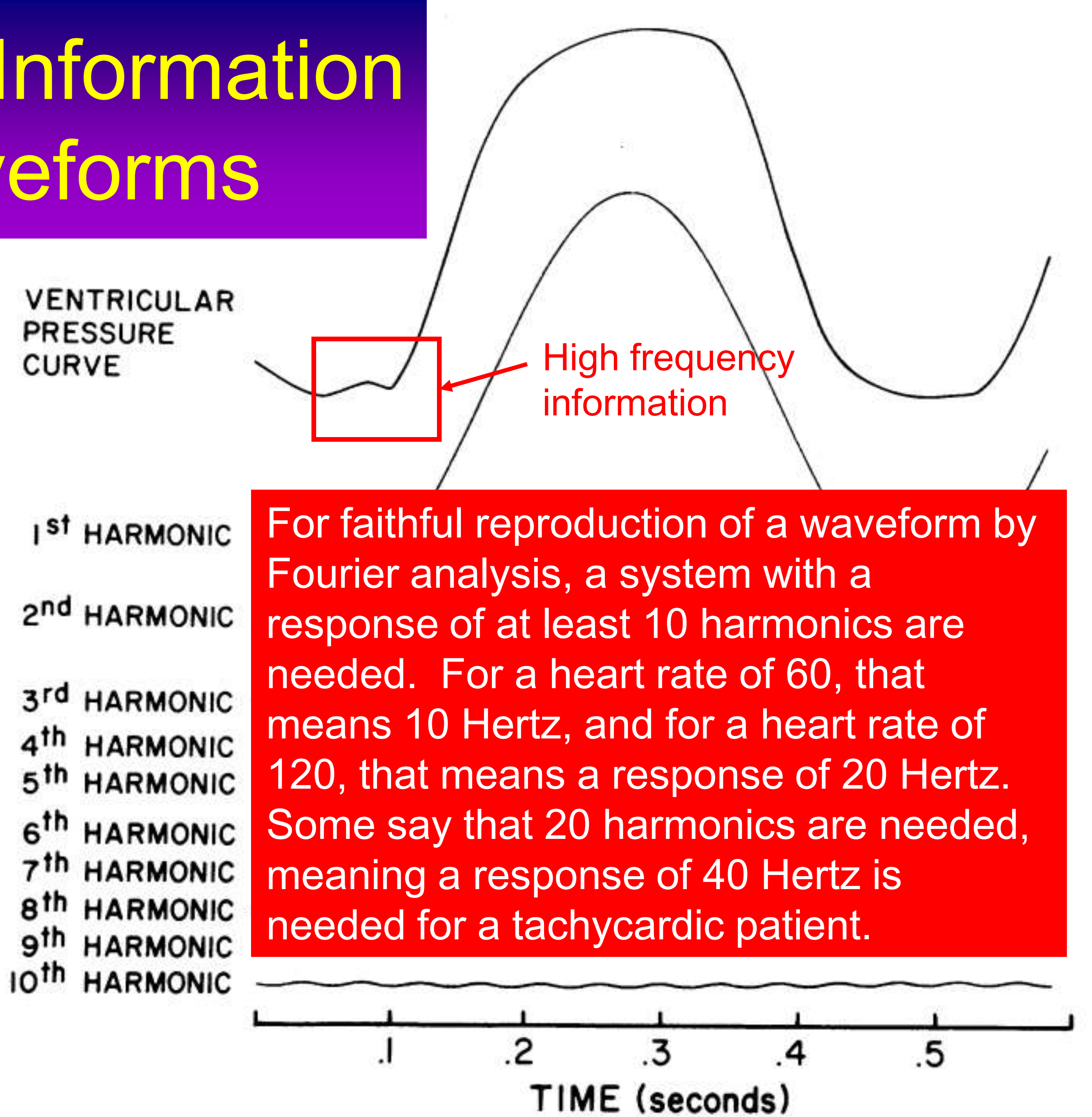


Grossman, 1996, p. 127

Harmonic Information in Waveforms

Fourier analysis breaks down any repeating waveform into a series of sine and cosine waves, identifying the harmonic information

Grossman, 1996, p. 127



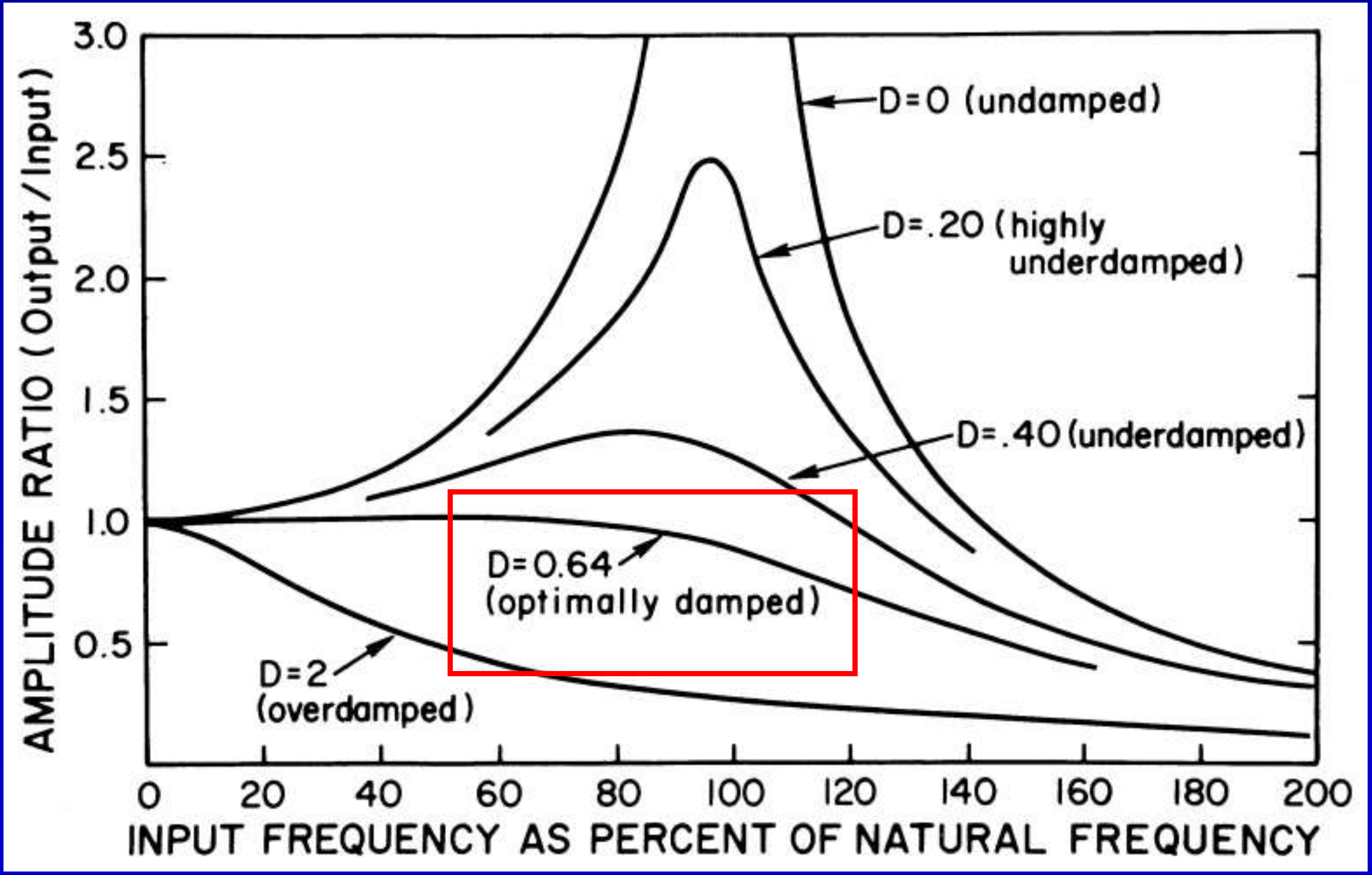
For faithful reproduction of a waveform by Fourier analysis, a system with a response of at least 10 harmonics are needed. For a heart rate of 60, that means 10 Hertz, and for a heart rate of 120, that means a response of 20 Hertz. Some say that 20 harmonics are needed, meaning a response of 40 Hertz is needed for a tachycardic patient.

Frequency Response of System

- System = catheter and transducer
- Fluid-filled systems are plagued by problems with frequency response
  - A system has a natural resonant frequency
  - Damping, especially underdamping
  - Delay in pulse transmission through fluid column

Pressure Measurement System

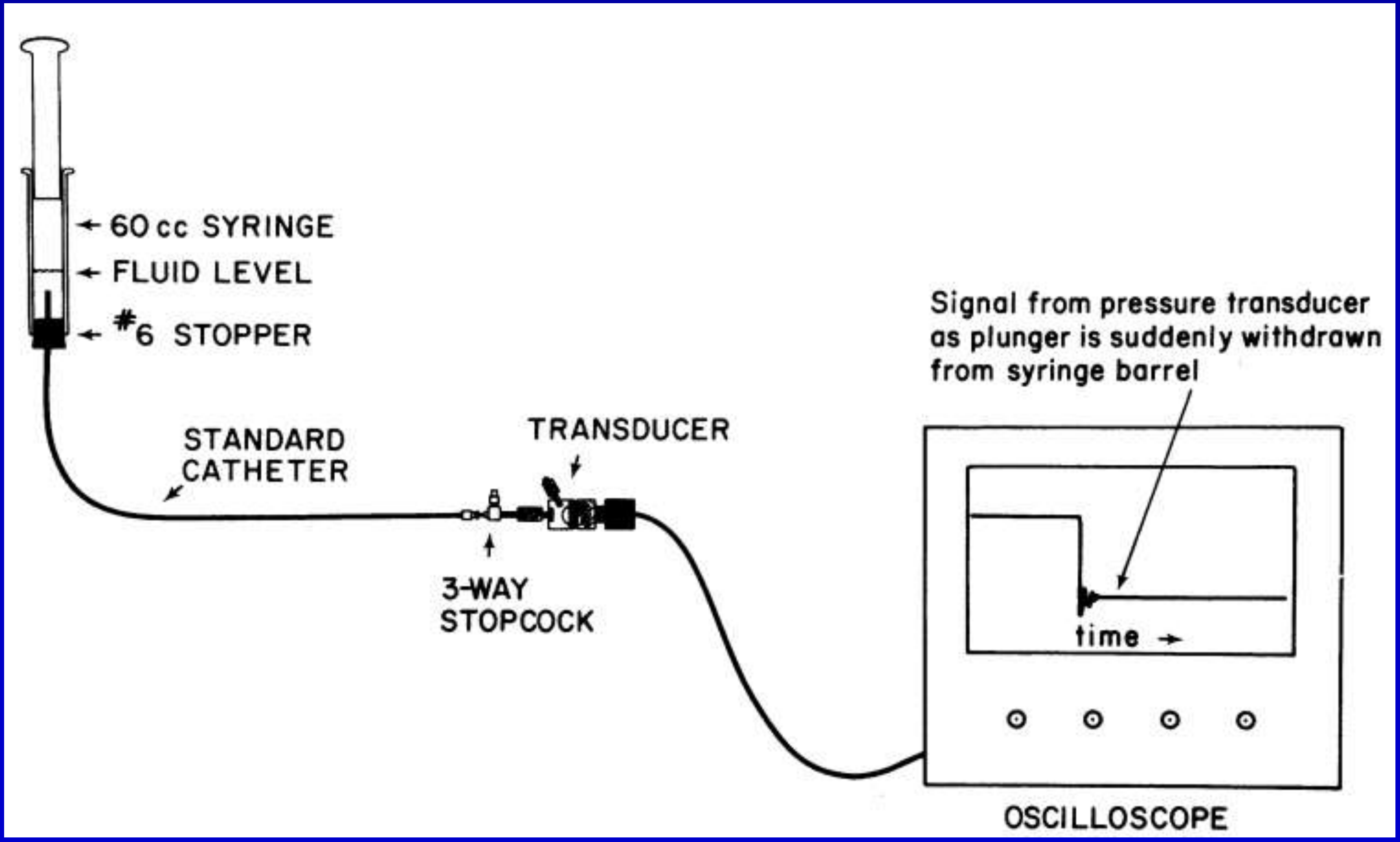
Response to Different Frequencies



Grossman, 1996, p. 128

Pressure Measurement System

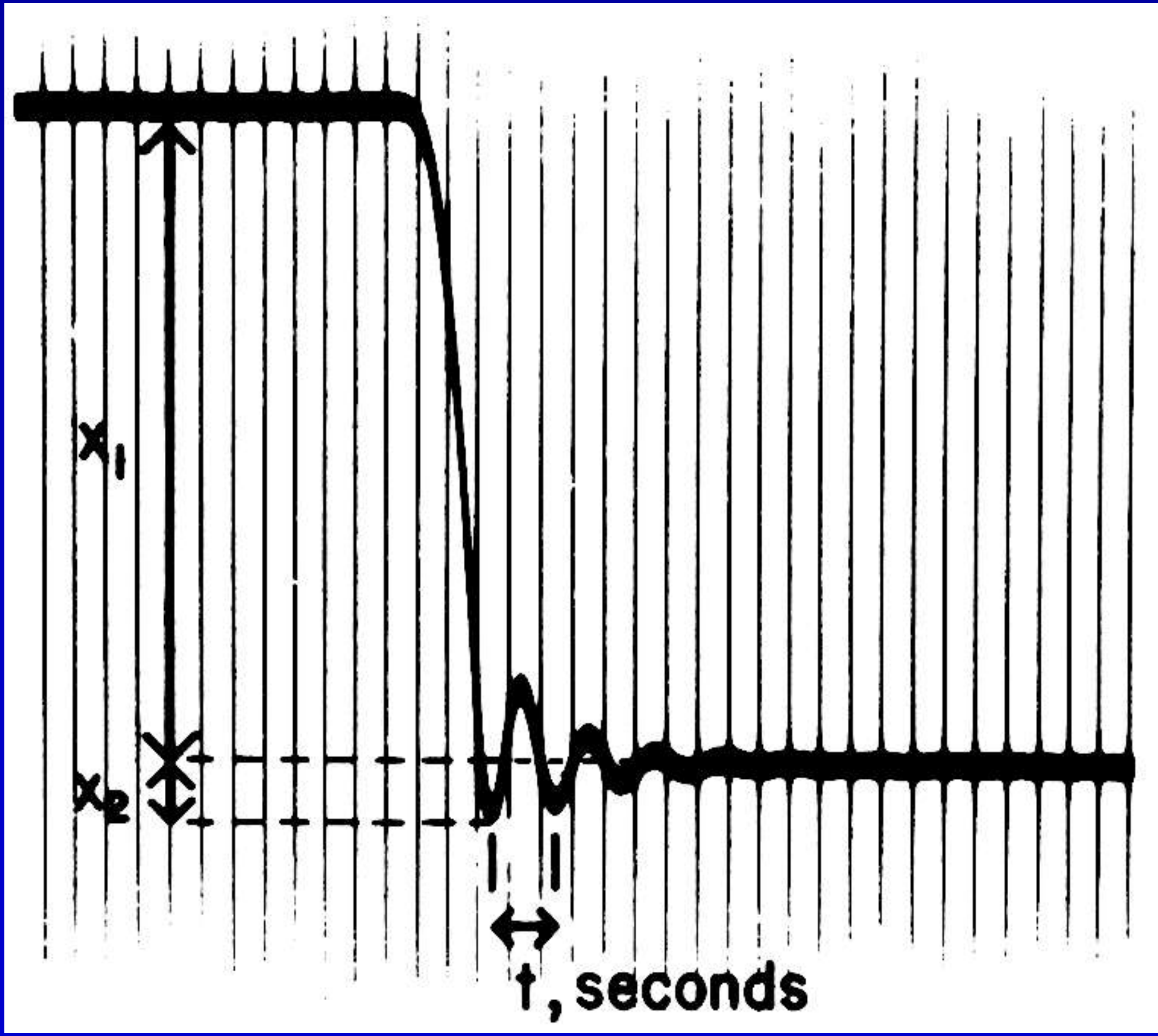
Technique of assessing frequency response with "Pop test"



Grossman, 1996, p. 131

Pressure Measurement System

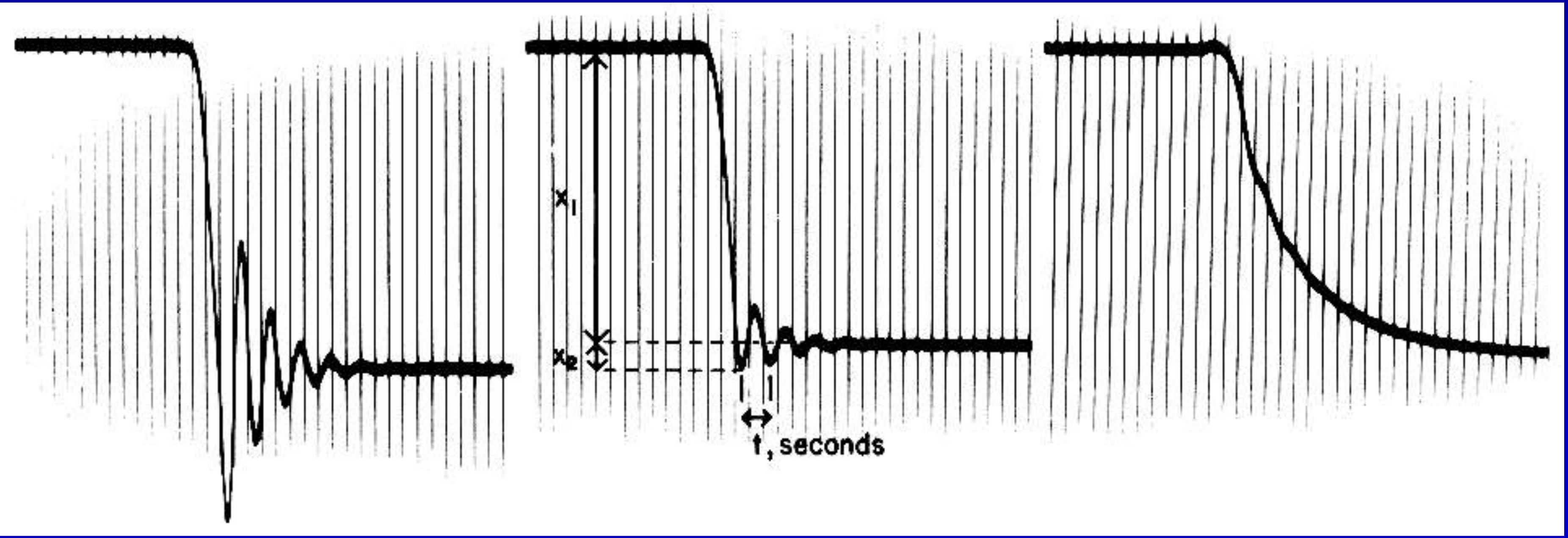
Analyzing frequency response



Grossman, 1996, p. 131

Pressure Measurement System

Analyzing frequency response



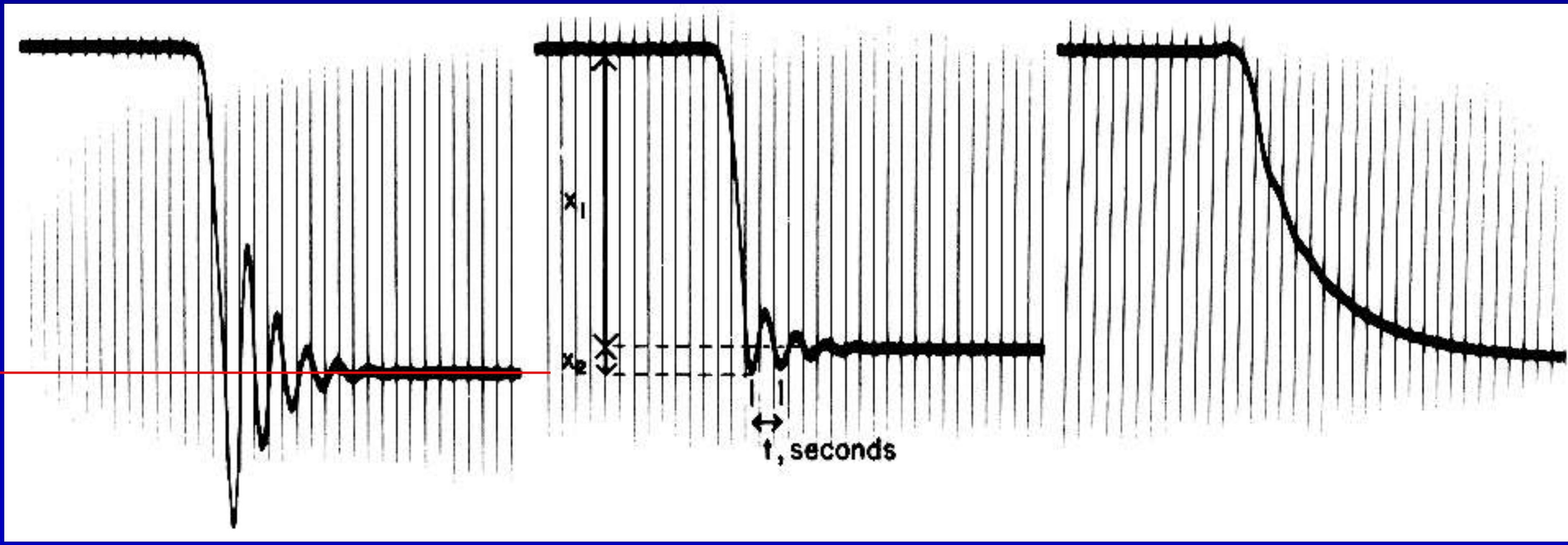
Underdamped **Nearly Optimally Damped** **Overdamped**

Progressively more damped tracings by introducing iodinated contrast into the catheter

Grossman, 1996, p. 131

Pressure Measurement System

Assessing frequency response



X2/x1 is percent overshoot
D is damping coefficient
N is undamped natural frequency
ND is damped natural frequency
Time lines are 20 msec

Grossman, 1996, p. 131

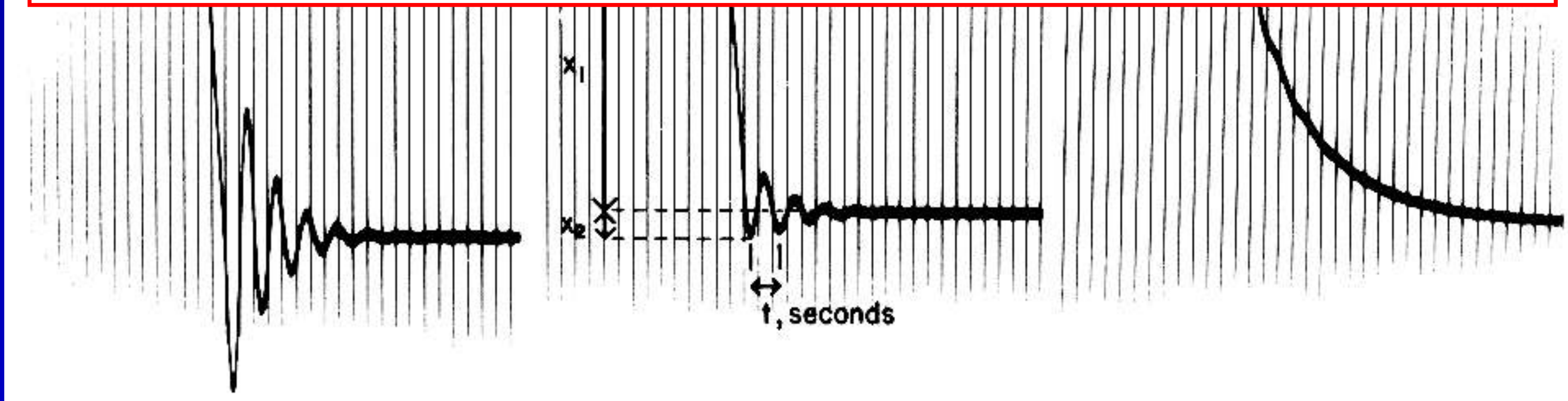
Pressure Measurement System

Assessing frequency response

In example B, t = 40 msec, $N_D = 1/t = 25$ cycles / second

$$D = \sqrt{\ln^2(x_2/x_1) / [\pi^2 + \ln^2(x_2/x_1)]} = .603$$

$$N = N_D / \sqrt{1-D^2} = 31.3 \text{ cycles / second}$$



In example A,
t = 40 msec,
ND = 25Hz,
D = 0.25,
N=25.8 Hz

X2/x1 is percent overshoot
D is damping coefficient
N is undamped natural frequency
ND is damped natural frequency

Grossman, 1996, p. 131

Example of Underdamped system

4F Right Judkins

$X2 = 29.5$

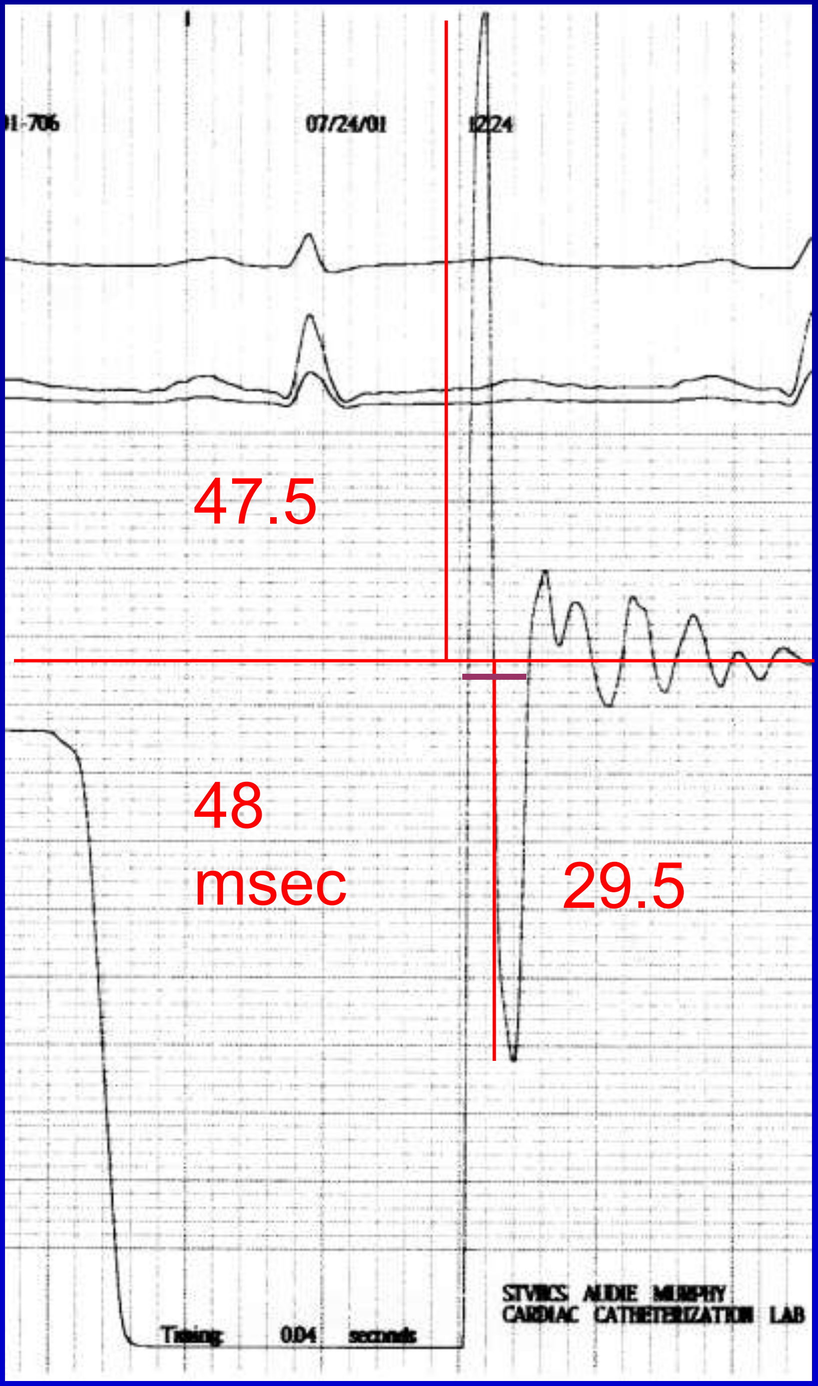
$X1 = 47.5$

$D = 0.15$

$T = 0.048$

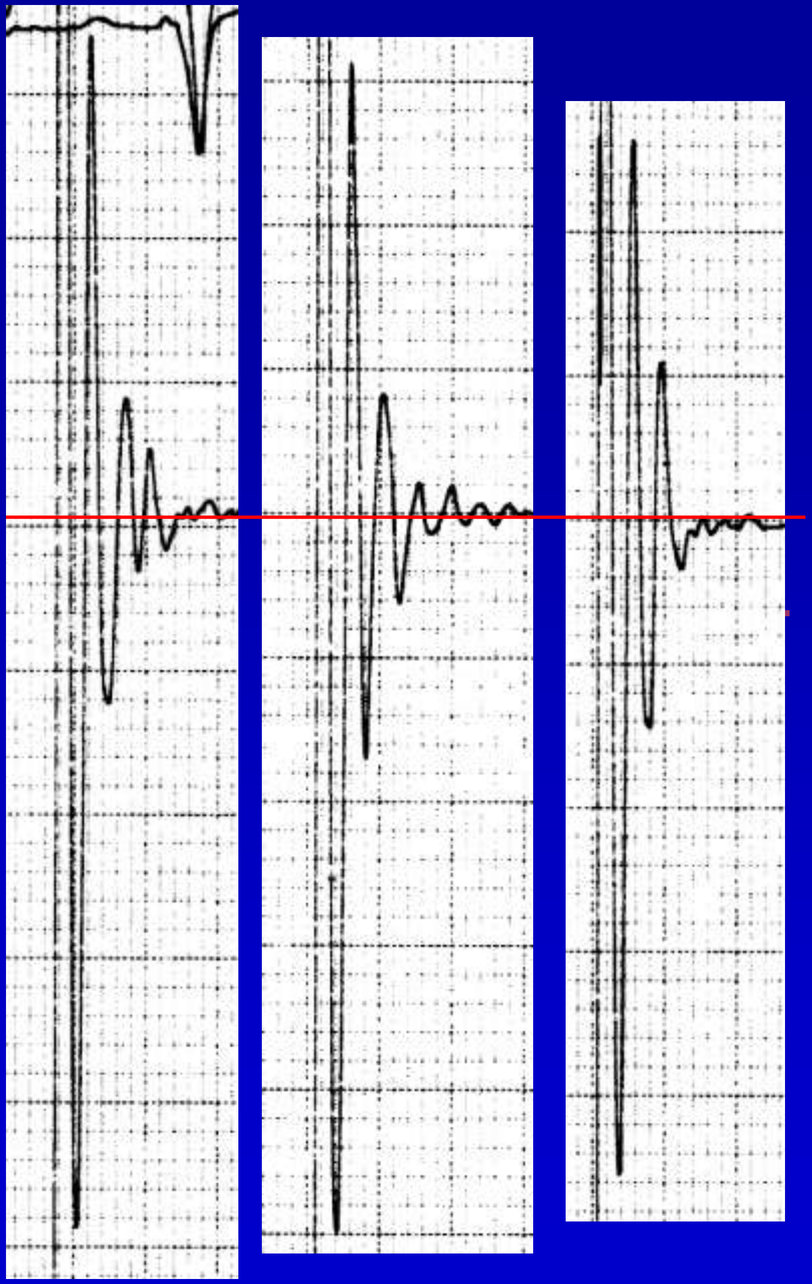
$ND = 21$

$N = 21$



Example of Underdamped System

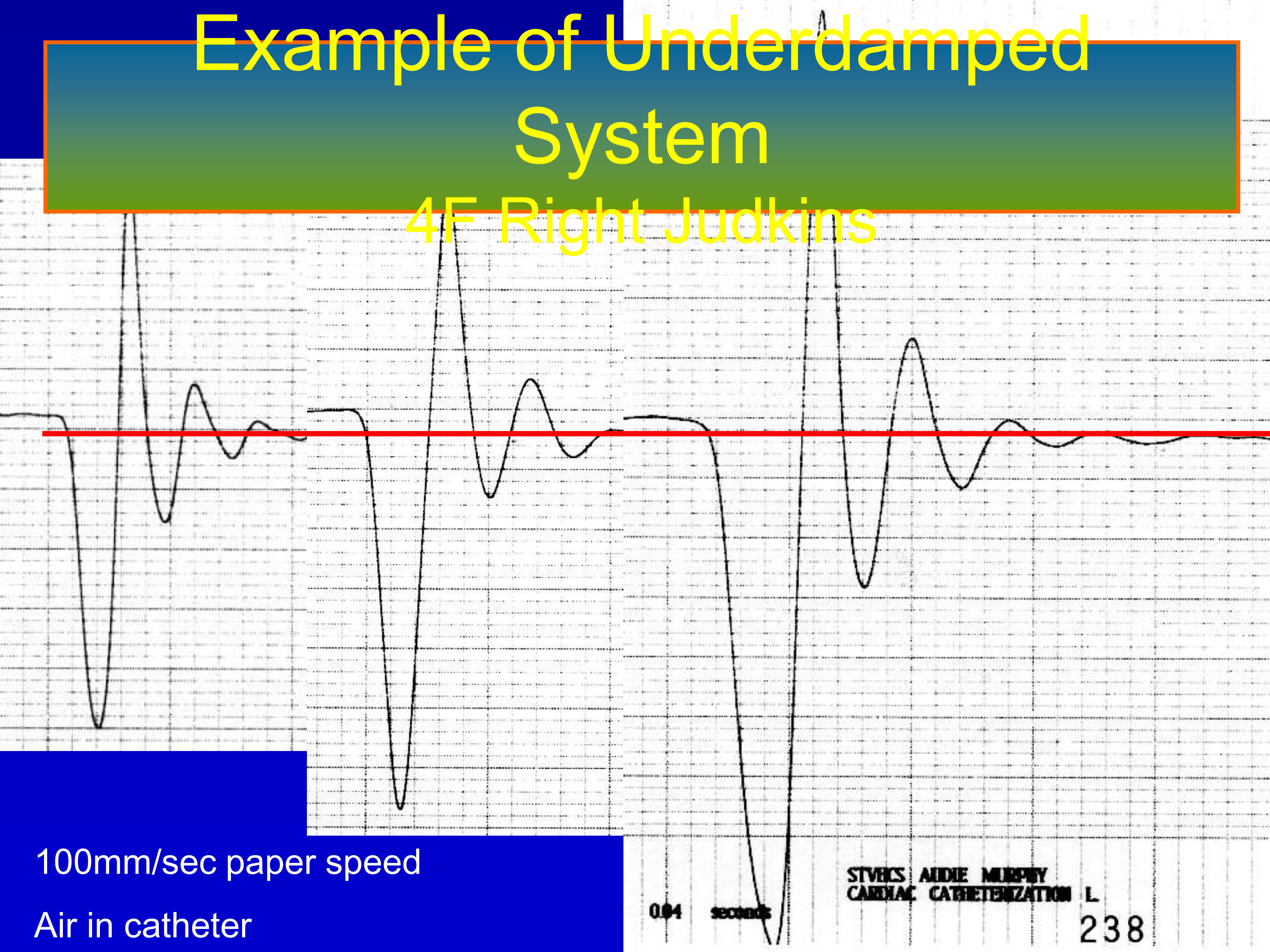
4F Right Judkins



25mm/sec paper speed

Example of Underdamped System

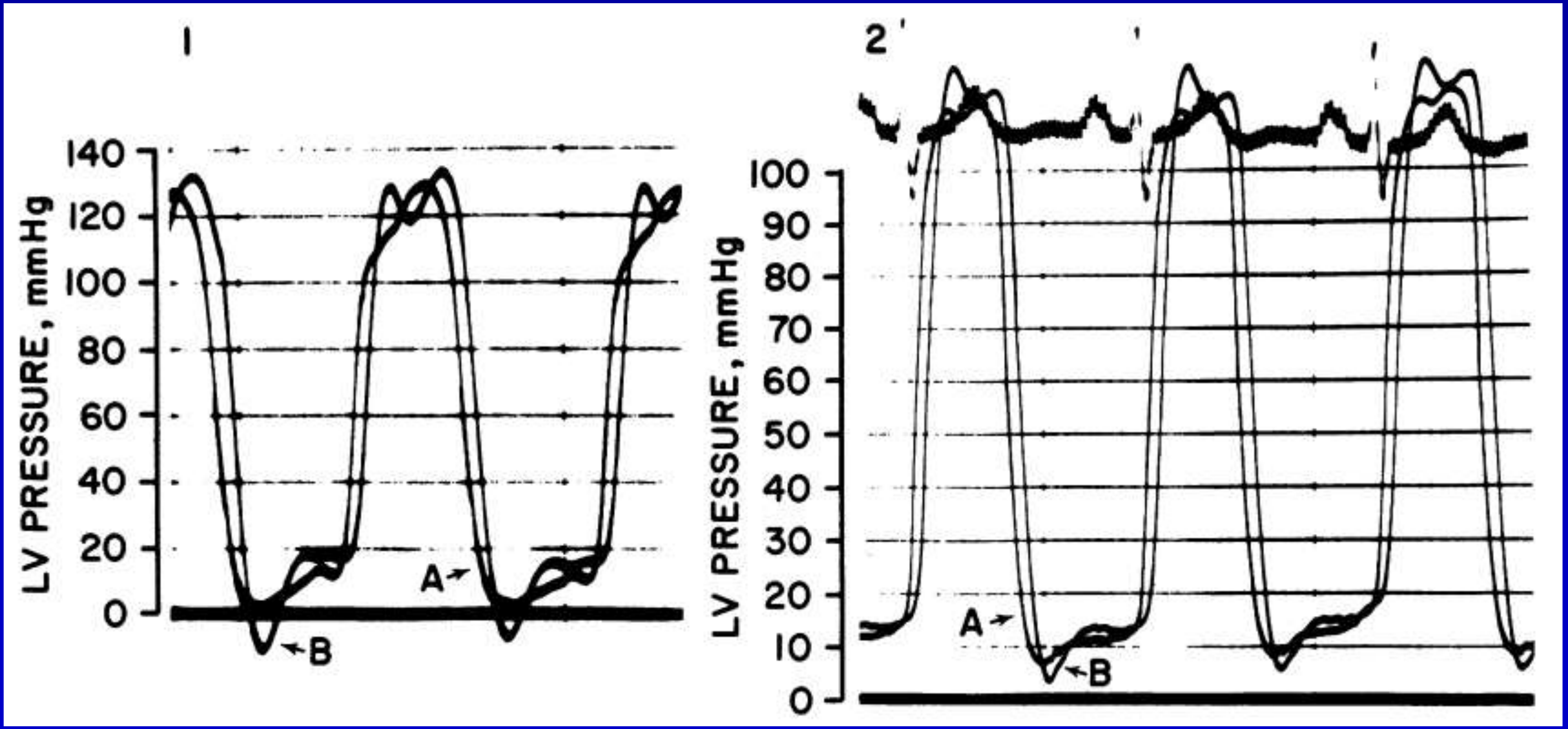
4F Right Judkins



100mm/sec paper speed

Air in catheter

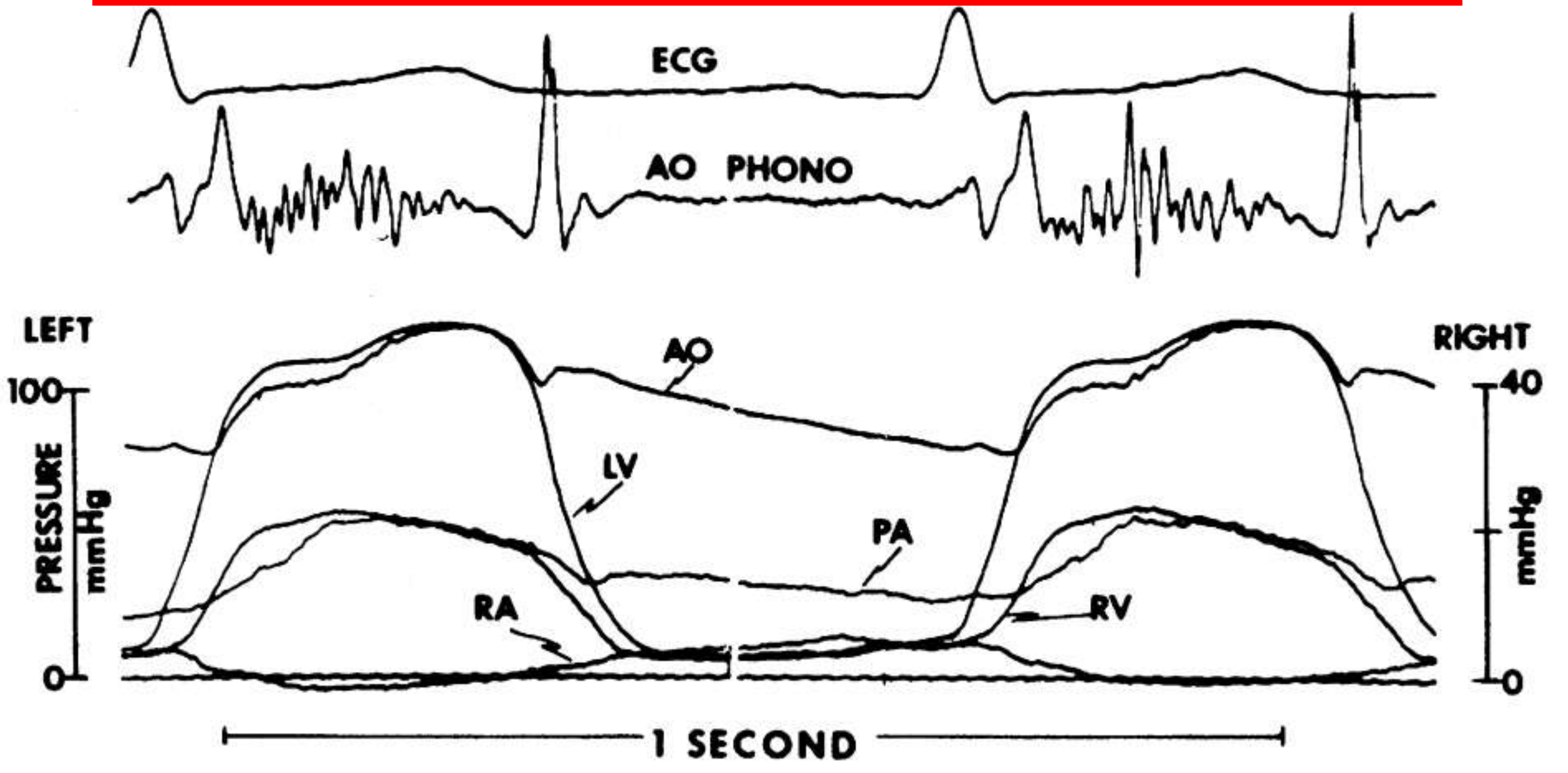
Comparison of Pressure Measurement Systems



A = micromanometer, B = fluid-filled system

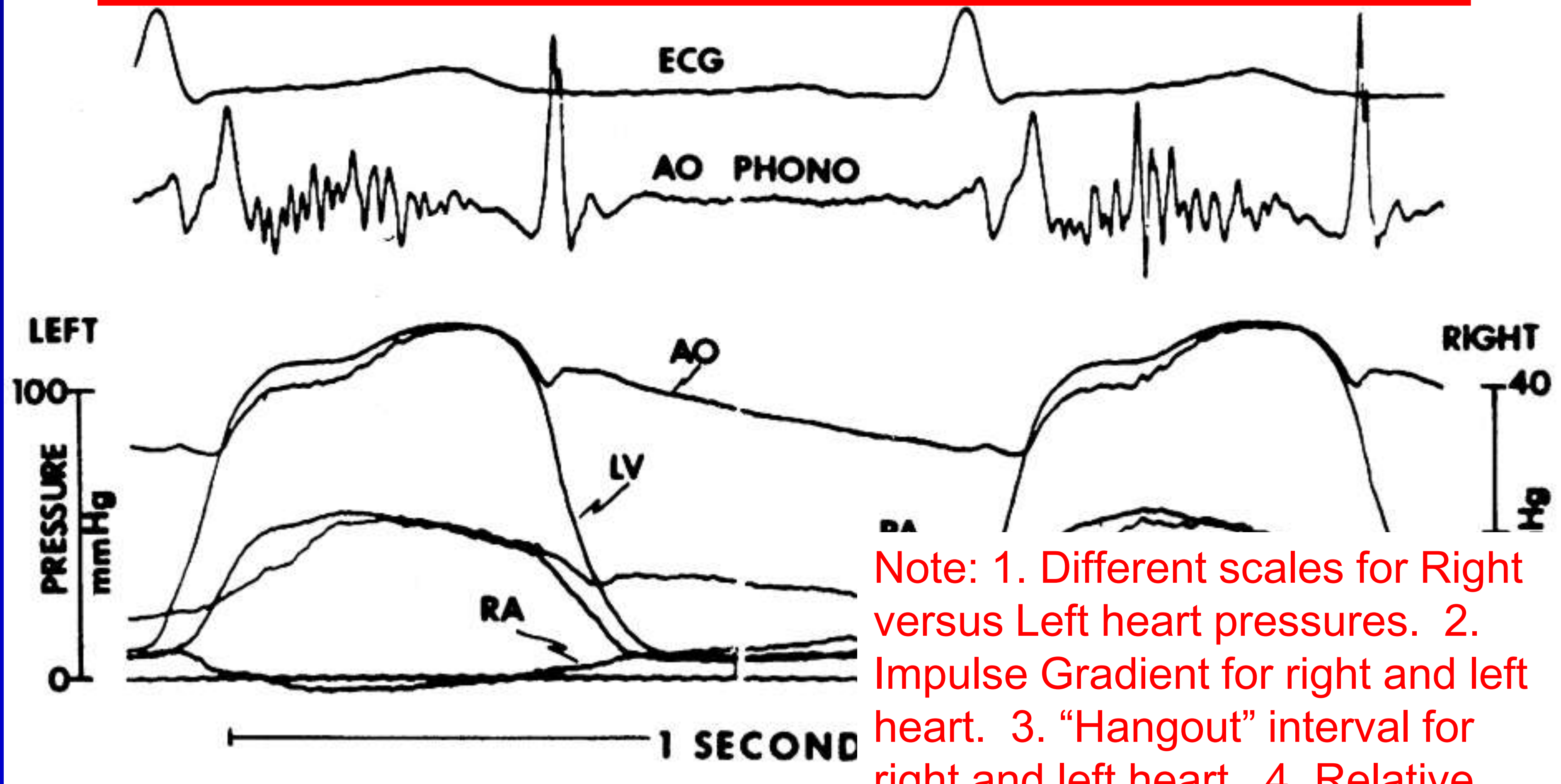
Grossman, 1996, p. 139

Normal Left and Right Heart Pressure Waveforms



Murgo, 1975, Circulation Supplement 46

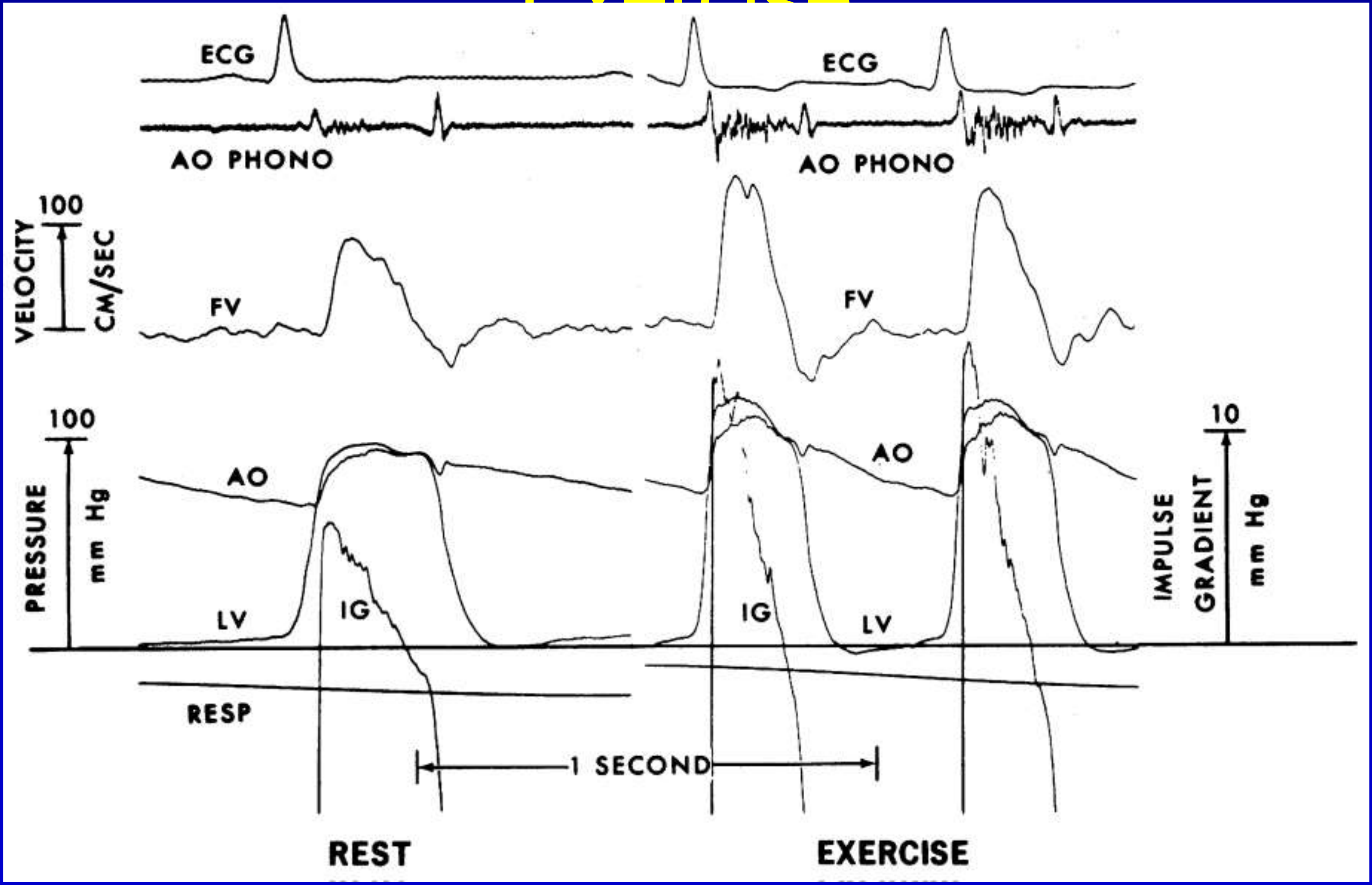
Normal Left and Right Heart Pressure Waveforms



Note: 1. Different scales for Right versus Left heart pressures. 2. Impulse Gradient for right and left heart. 3. "Hangout" interval for right and left heart. 4. Relative duration of ventricular systole. 5. Aortic wave reflection.

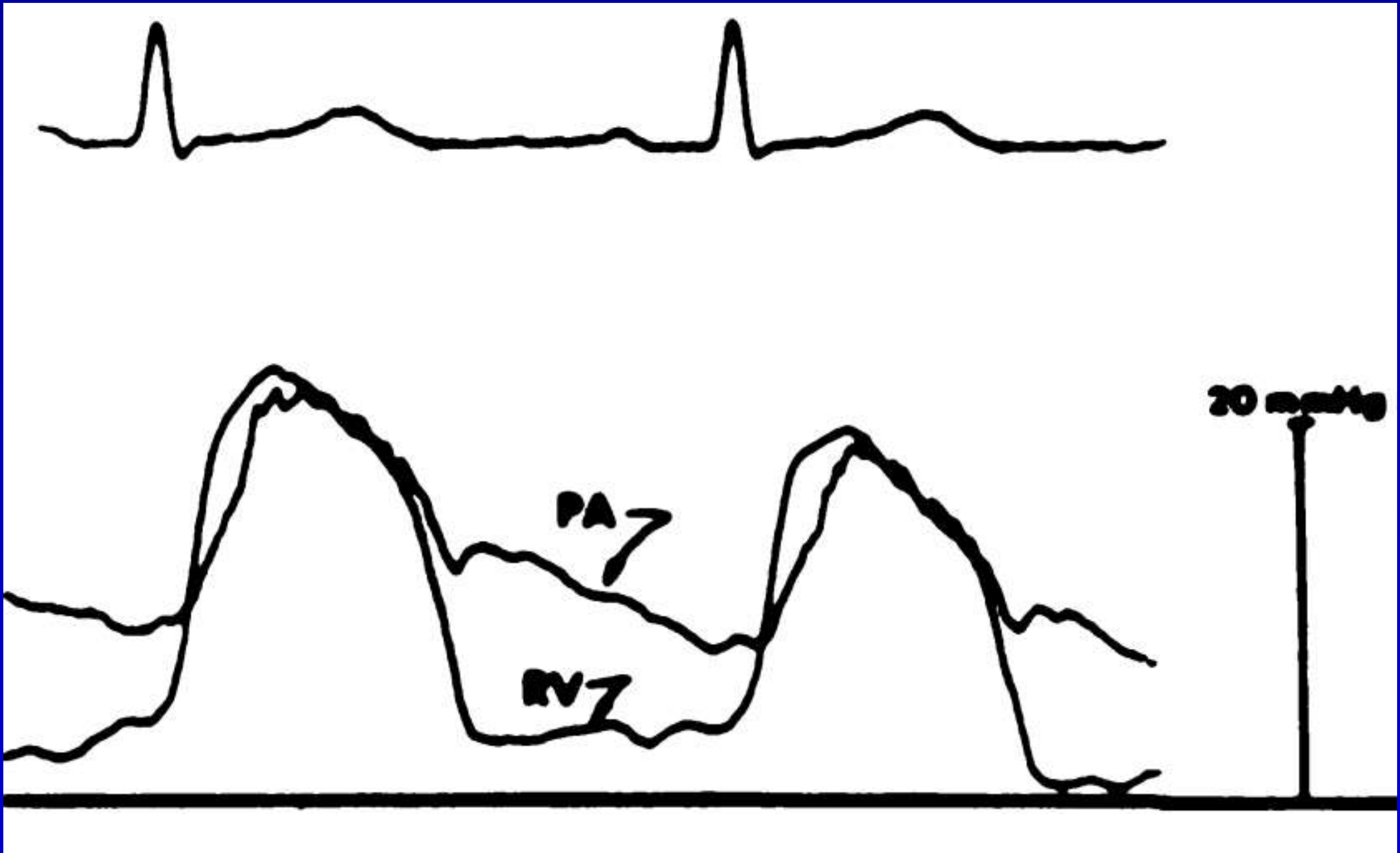
Murgo, 1975,
Circulation Supplement 46

Impulse Gradient, Rest and Exercise



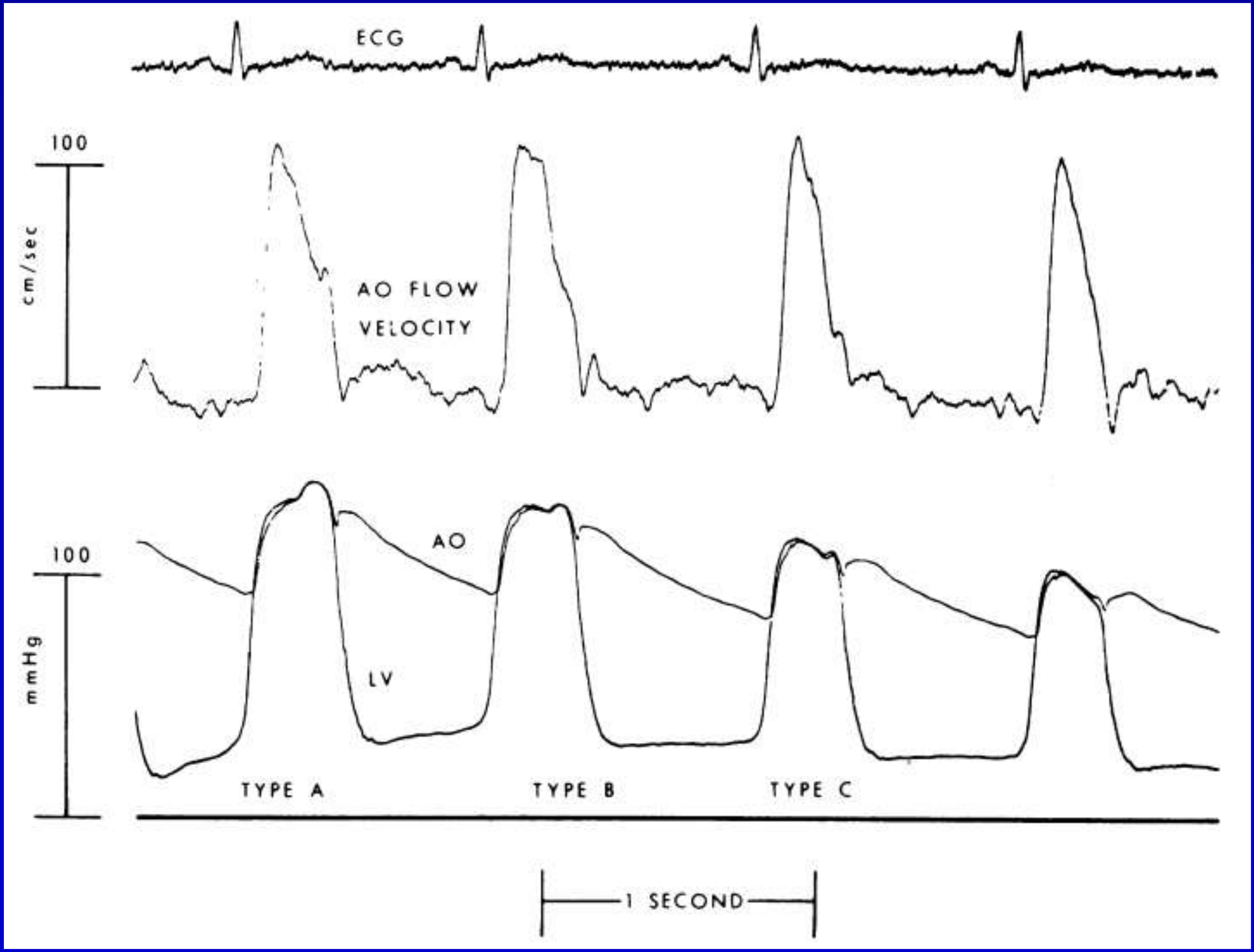
Murgo, 1975, Circulation Supplement 46

Resting RV and PA gradient



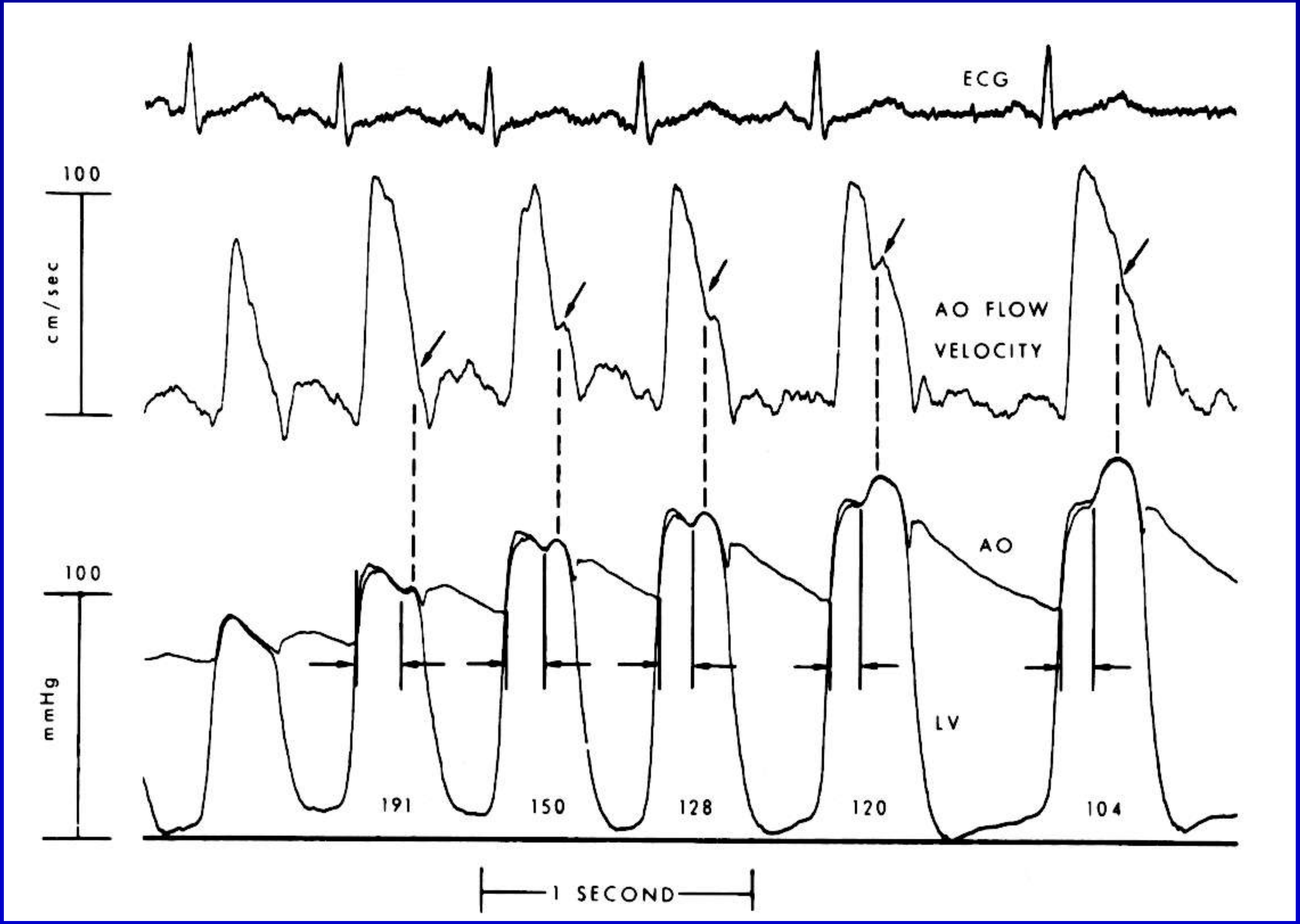
Murgo, 1975, Circulation Supplement 46

Valsalva Effect on Aortic Pressure Waveform



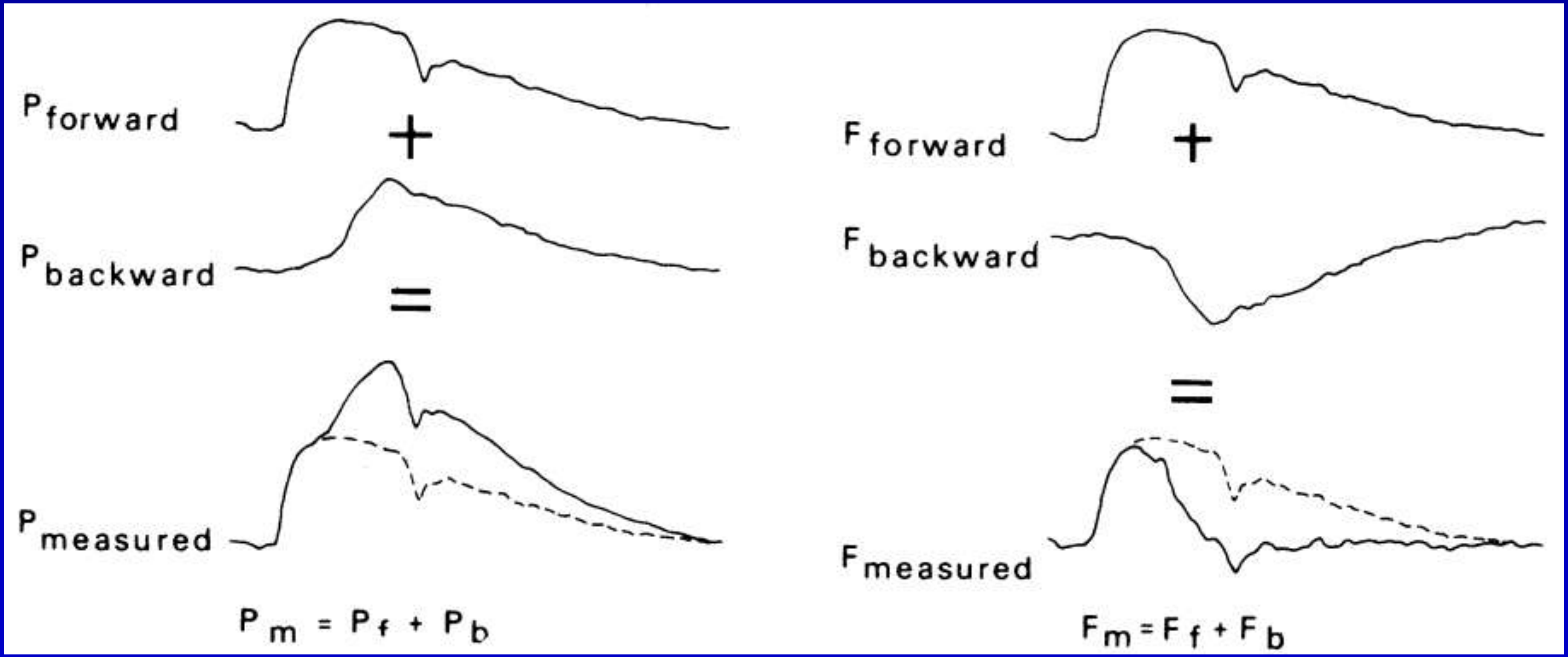
Murgo JP et al. Circulation 1981;63:122

Valsalva Release



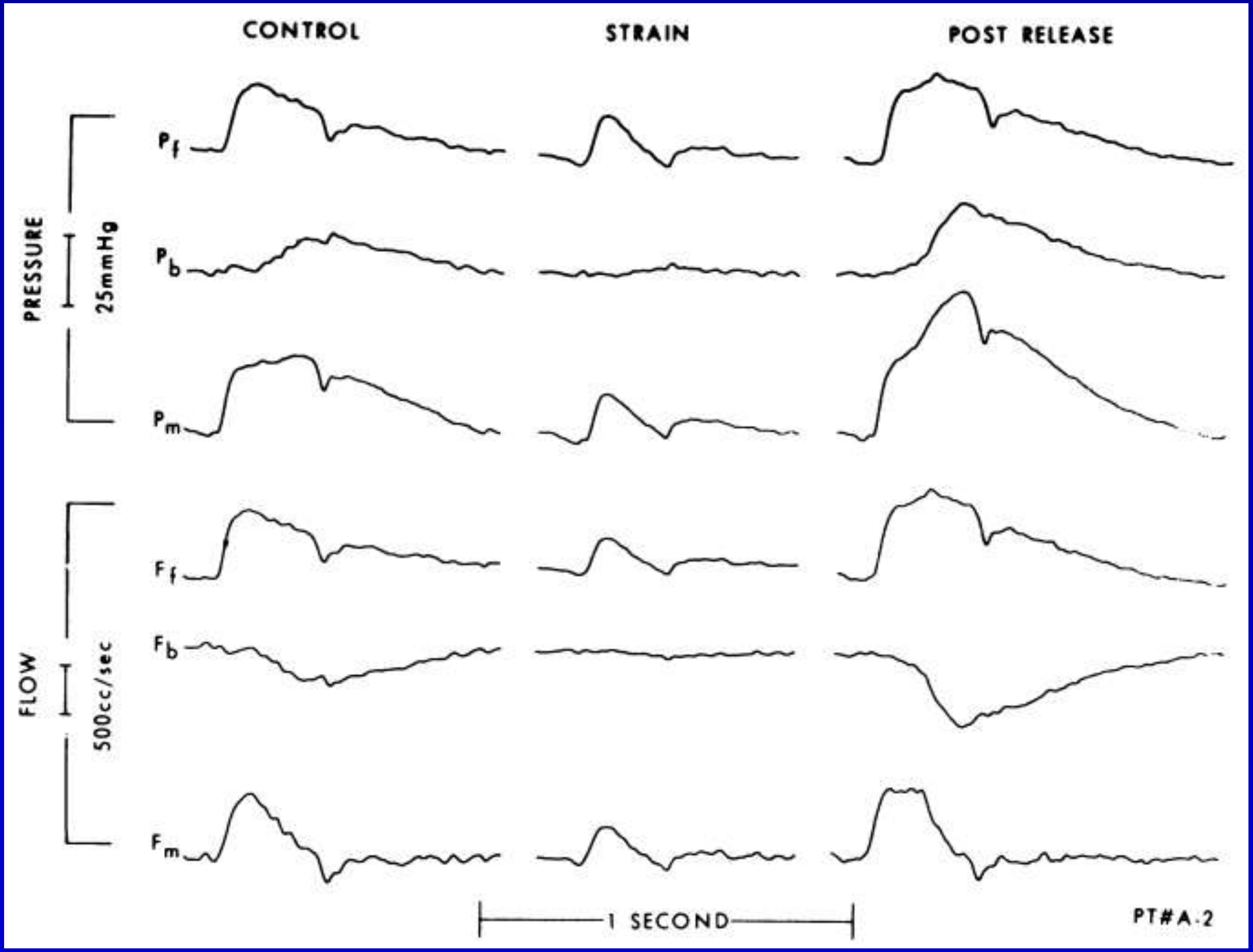
Murgo JP et al. Circulation

Reflected Wave



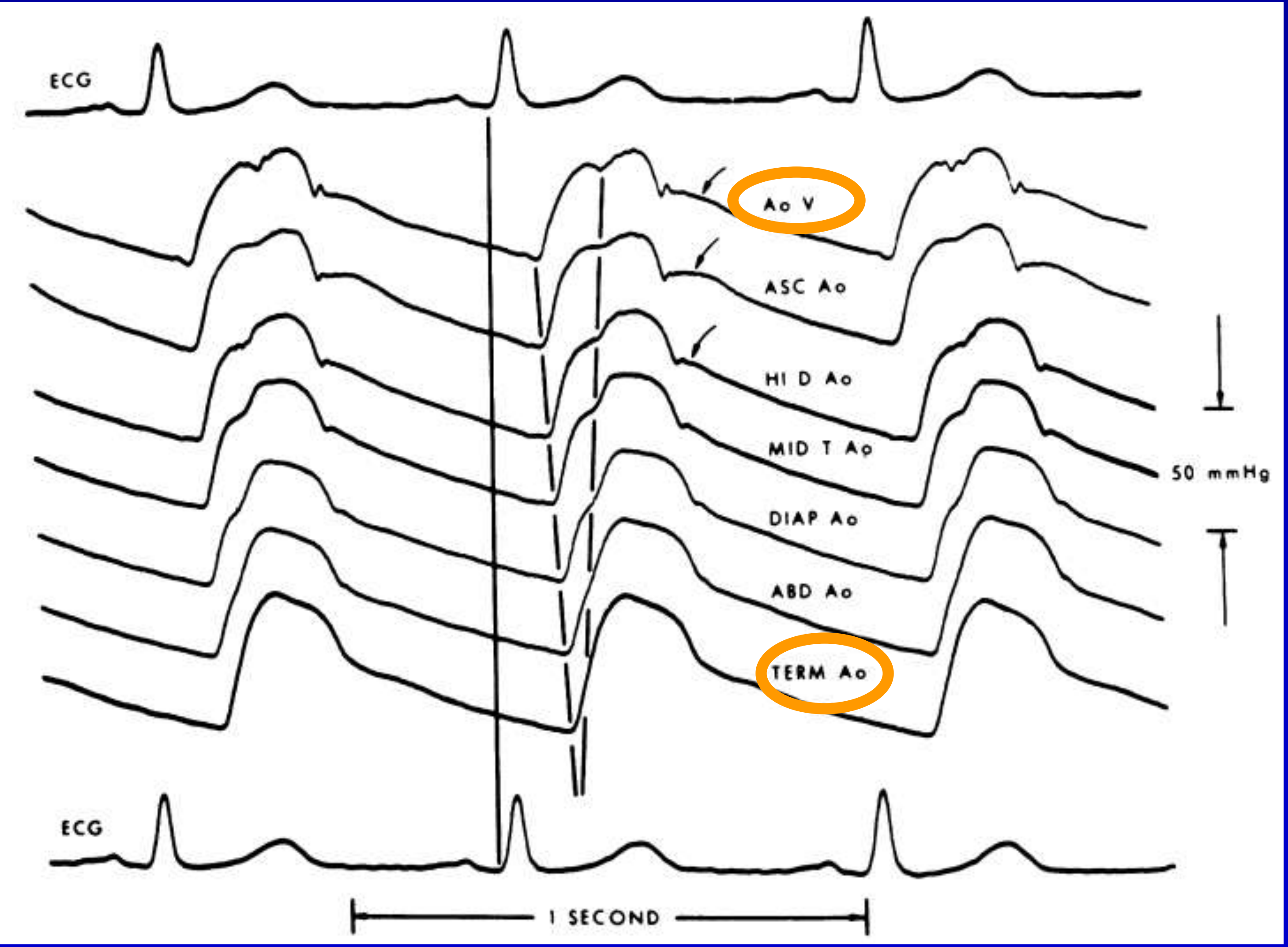
Murgo JP et al. <u>Circulation</u> 1981;<u>63</u>:122

Wave Reflection in Valsalva



Murgo JP et al. Circulation 1981;63:122

Wave Reflections in Aorta

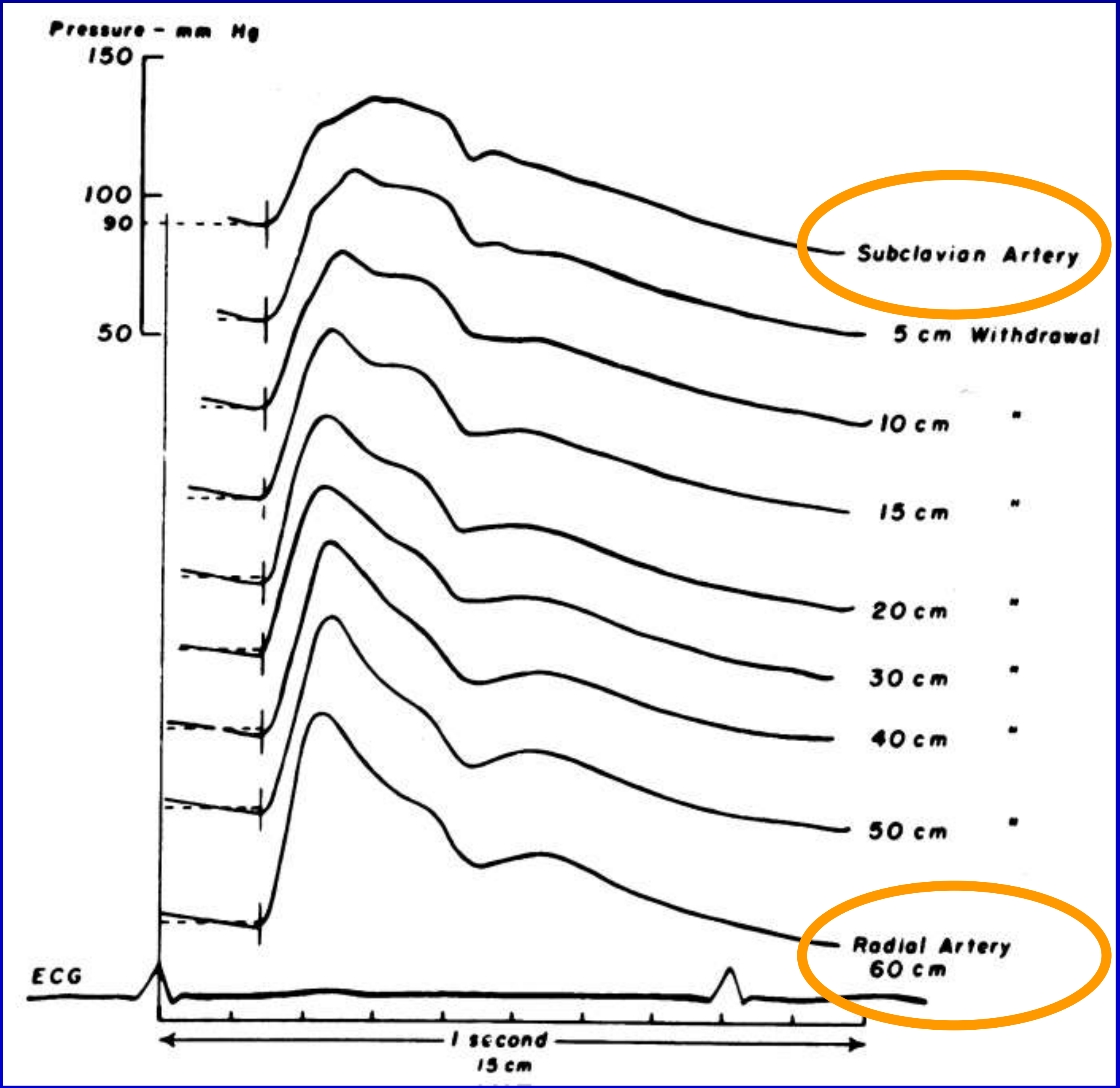


Murgo JP et al. Circulation 1980;62:105

Aortic Reflection

Healthy 30 year-old man: onset of pressure is aligned artificially

Marshall HW et al. in Grossman 1996, p.140



Factors Influencing Reflected Wave Size

Increase

- Vasoconstriction
- Heart failure
- Hypertension
- Aortic or ileofemoral obstruction
- Post-Valsalva release

Decrease

- Vasodilation
  - Physiologic (fever)
  - Pharmacologic (NTG, NTP)
- Hypovolemia
- Hypotension
- Valsalva strain phase

Grossman, 1996, p. 136

Normal Hemodynamic Values

- Cardiac index 2.8-4.2
- Stroke volume 30-65
- A-V O2 Difference, mL/L blood 30-48
- Brachial 90-140/60-90, mean 70-105
- LVED 5-12
- LA or PAW 5-12
- PA 15-28/5-16, mean 10-22
- RVED 0-8
- RA 0-8
- LV volume index (mL/m2) ED 50-90, ES 15-25
- SVR 900-1400
- PAR 45-120

Hurst, 10^{th} ed, p.66

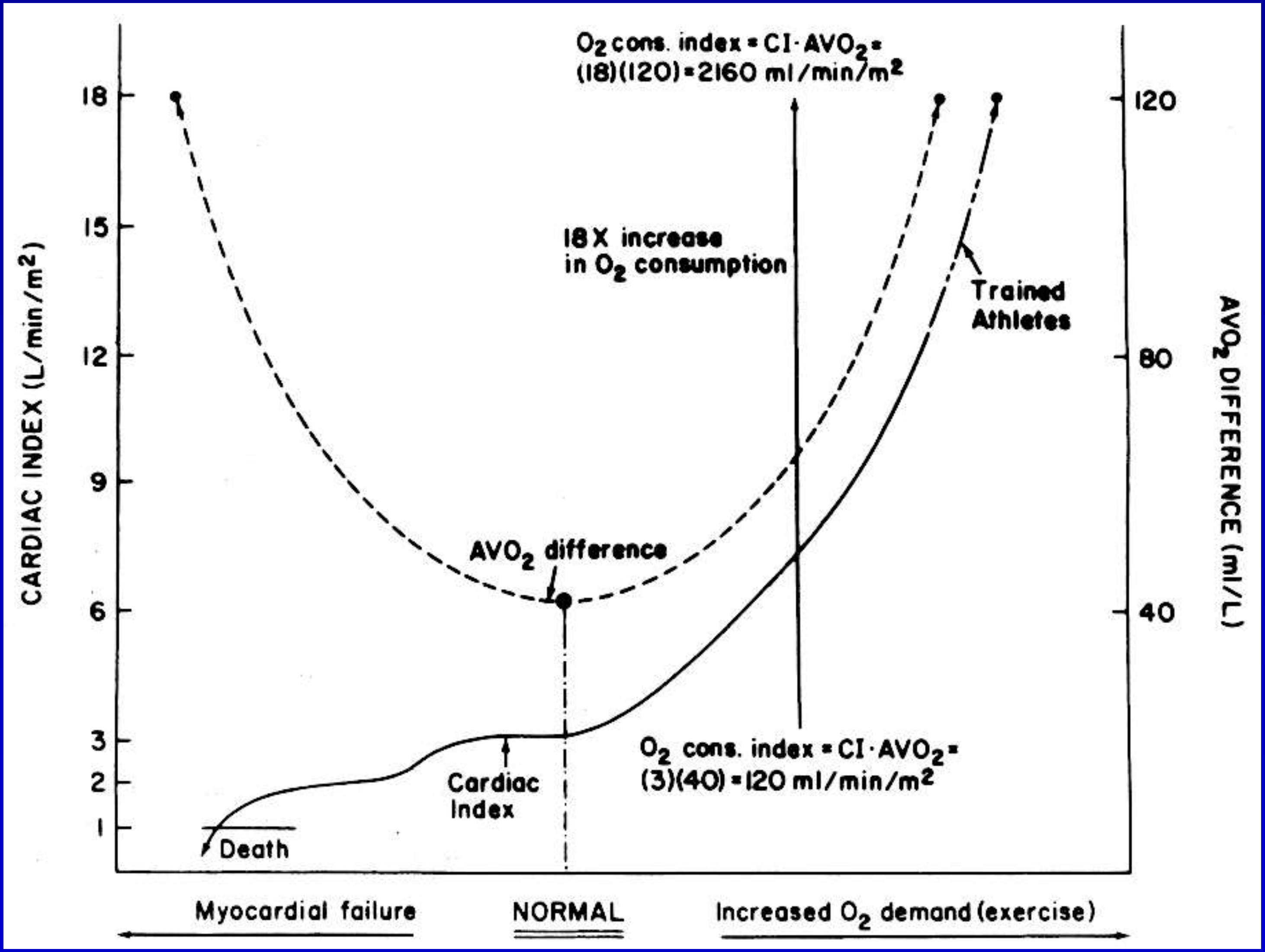
Techniques for Measuring Flow During Catheterization in Man

- Fick
- Thermodilution
- Angiography
- Indicator dilution
- Electromagnetic flow probe

Blood Flow: Cardiac Output

- Purpose: deliver oxygen and nutrients to body tissues and remove carbon dioxide and wastes
  - Extraction of oxygen by metabolizing tissues
  - Extraction creates an arteriovenous difference
- Adequacy depends on cardiac output relative to metabolic need
  - Extraction has reserve

Blood Flow: Cardiac Output



From Grossman, 1996, p. 160

Fick Principle

$$C.O. = \frac{O_2\ consumption}{A\text{–}V\ O_2\ difference}$$

- Note:

this calculation REQUIRES STEADY STATE!

- The volume of flow is directly related to the amount of substance removed or added to the flowing material, and inversely related to the resultant content difference in the flowing material.

Fick Principle

$$C.O. = \frac{O_2 \text{ consumption}}{A\text{–}V \ O_2 \text{ difference}}$$

- O_2 consumption
  - measured by expired air analysis using
    - Waters' hood or
    - Douglas bag, or merely
  - Usually 110-150 ml O_2/min/m^2
  - assumed to be 3.0 ml O_2/kg/min (0.86 MET)

Fick Principle

$$C.O. = \frac{O_2\ consumption}{A\text{–}V\ O_2\ difference}$$

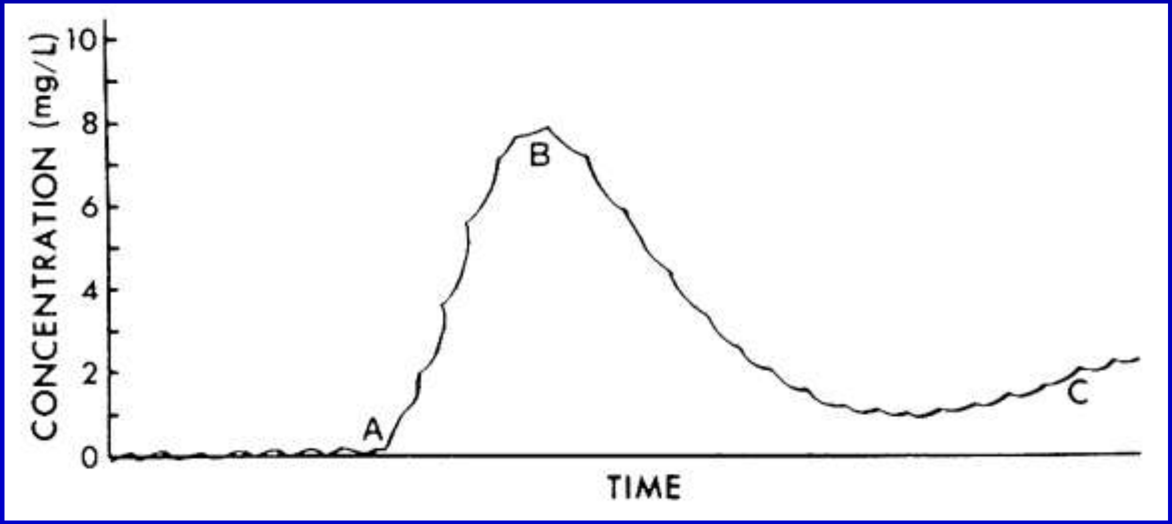
- A-V O_2 difference
  - Arterial minus mixed venous (mixed in RA and RV, so measured in PA)
  - Difference in O_2 content, not merely saturation
- A-V O_2 difference=(LVsat–PAsat)*10*1.36*(Hb)
- Using mere mixed venous saturation in the proper context is a good quick substitute for cardiac output and has advantages

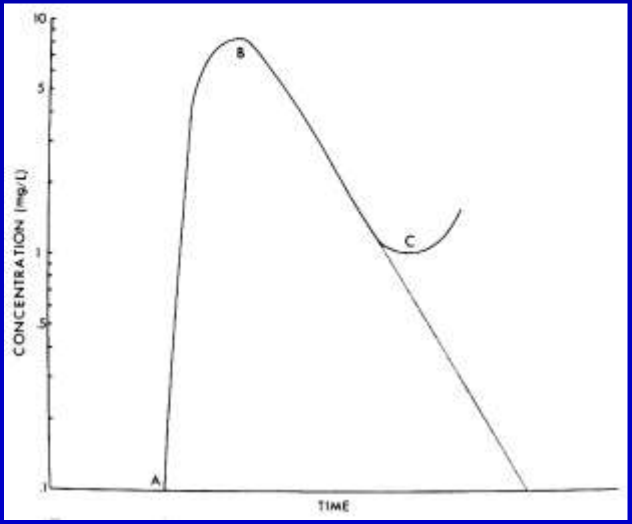
Fick Cardiac Output

- Errors: not steady state, error in expired air sample, error in respiration quotient, error in saturation measurement, error in collecting mixed venous sample
- More accurate at lower cardiac outputs
- Assuming oxygen consumption can introduce a 10% error, or even up to 25%

Thermodilution Cardiac Output

- An indicator dilution technique where the indicator is negative heat





From Grossman, 1996, p. 121.

Thermodilution Cardiac Output

- Errors with tricuspid regurgitation, with low-flow states with heat loss into surrounding structures
- Accuracy 5-10%

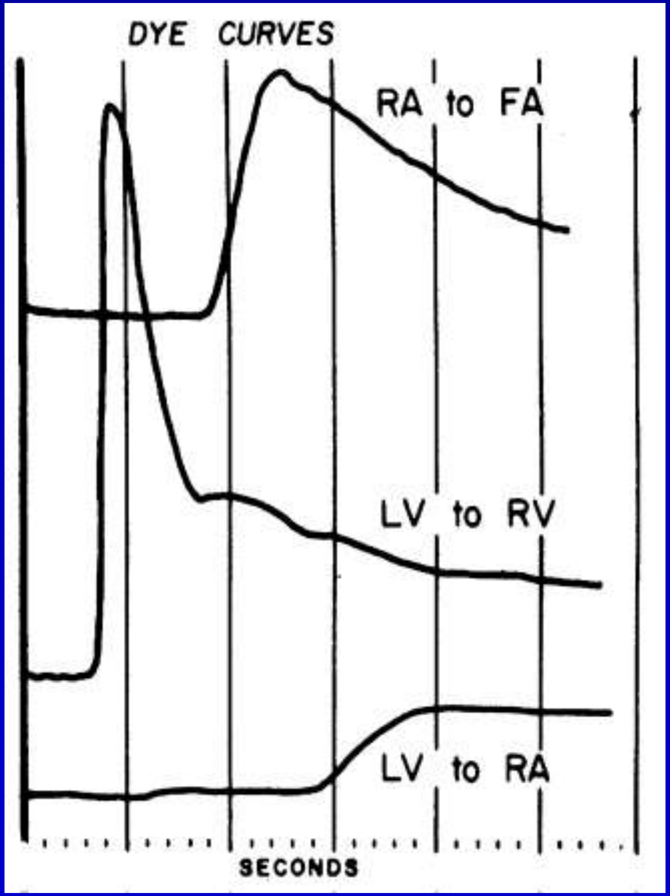
From Grossman, 1996, p. 121.

Dye Dilution Cardiac Output

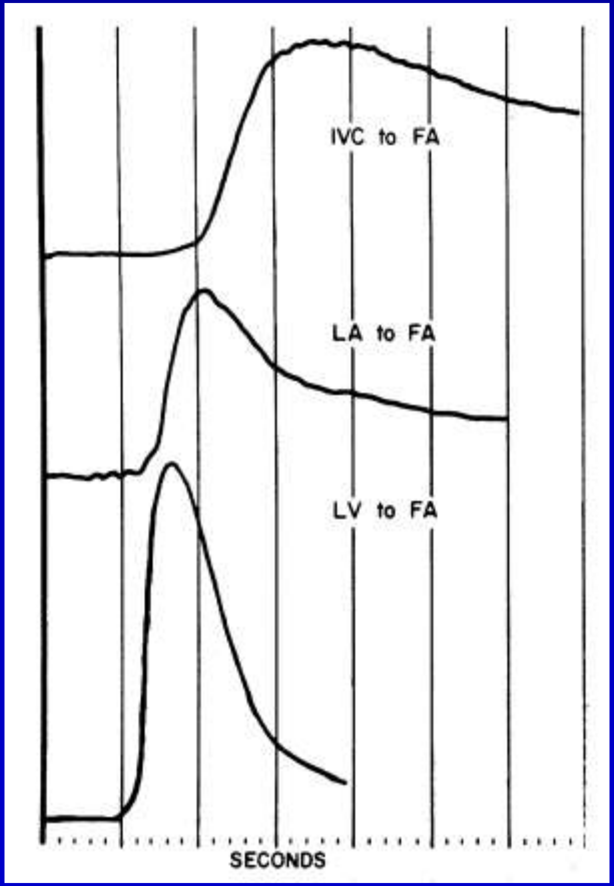
- Indocyanine green dye is classic indicator
- Inject into PA, sample in brachial artery
- Changes in dilution curve shape can detect abnormal circulation
- Early recirculation shows left to right shunt
- Early shoulder shows right to left shunt

From Grossman, 1996, p. 121.

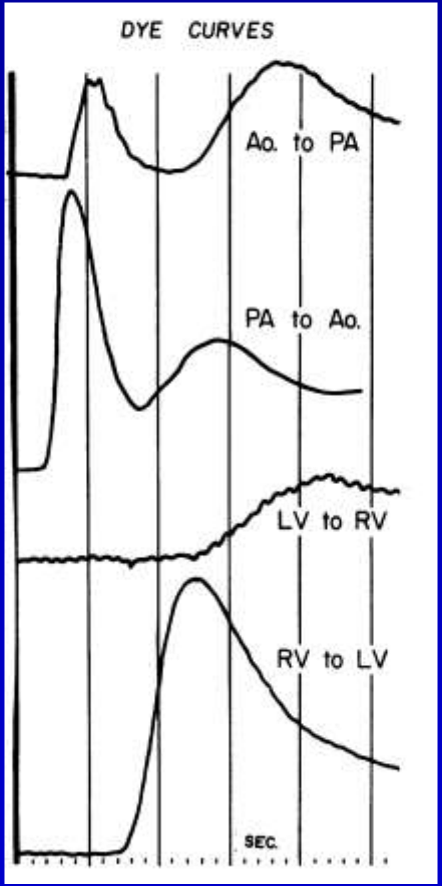
Dye Dilution Curves



VSD



ASD



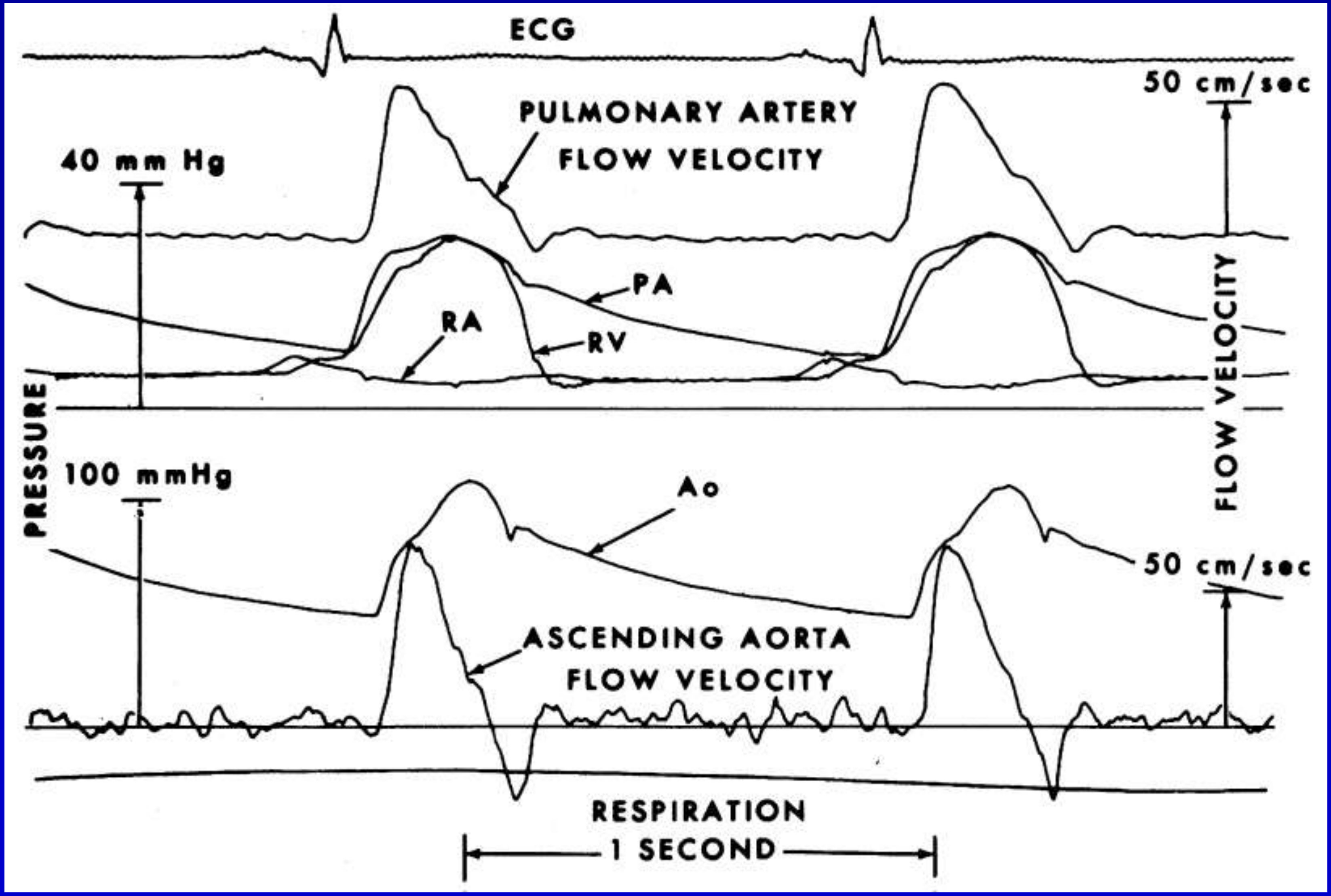
PDA

From Criley and Ross, 1971, pp 43-47.

Calculations from Catheterization Data

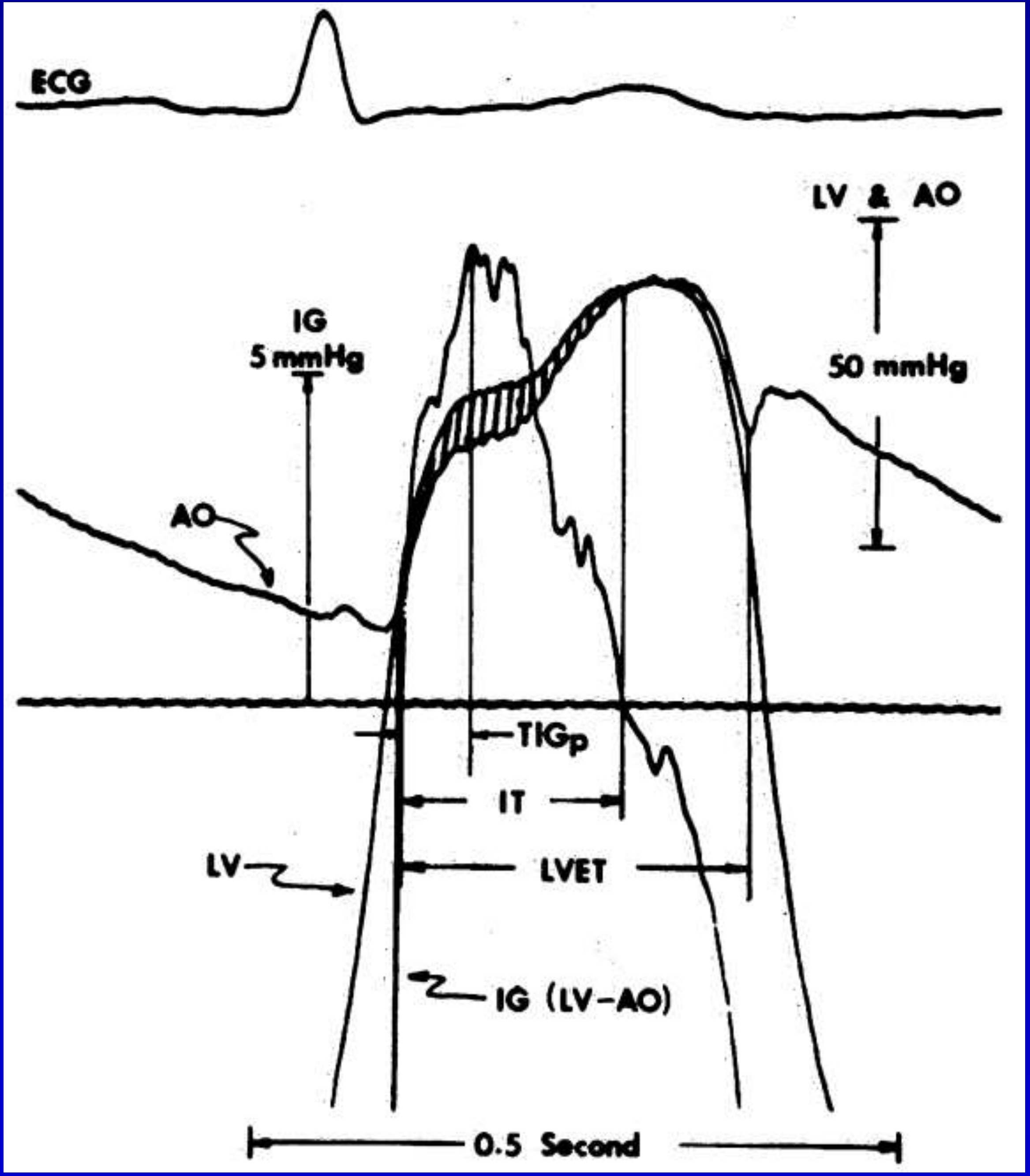
- Resistance is by “Ohm’s Law”
- E=I*R
- Pressure=Output*Resistance
- Resistance=Pressure/Output

Right and Left Heart Ejection Dynamics



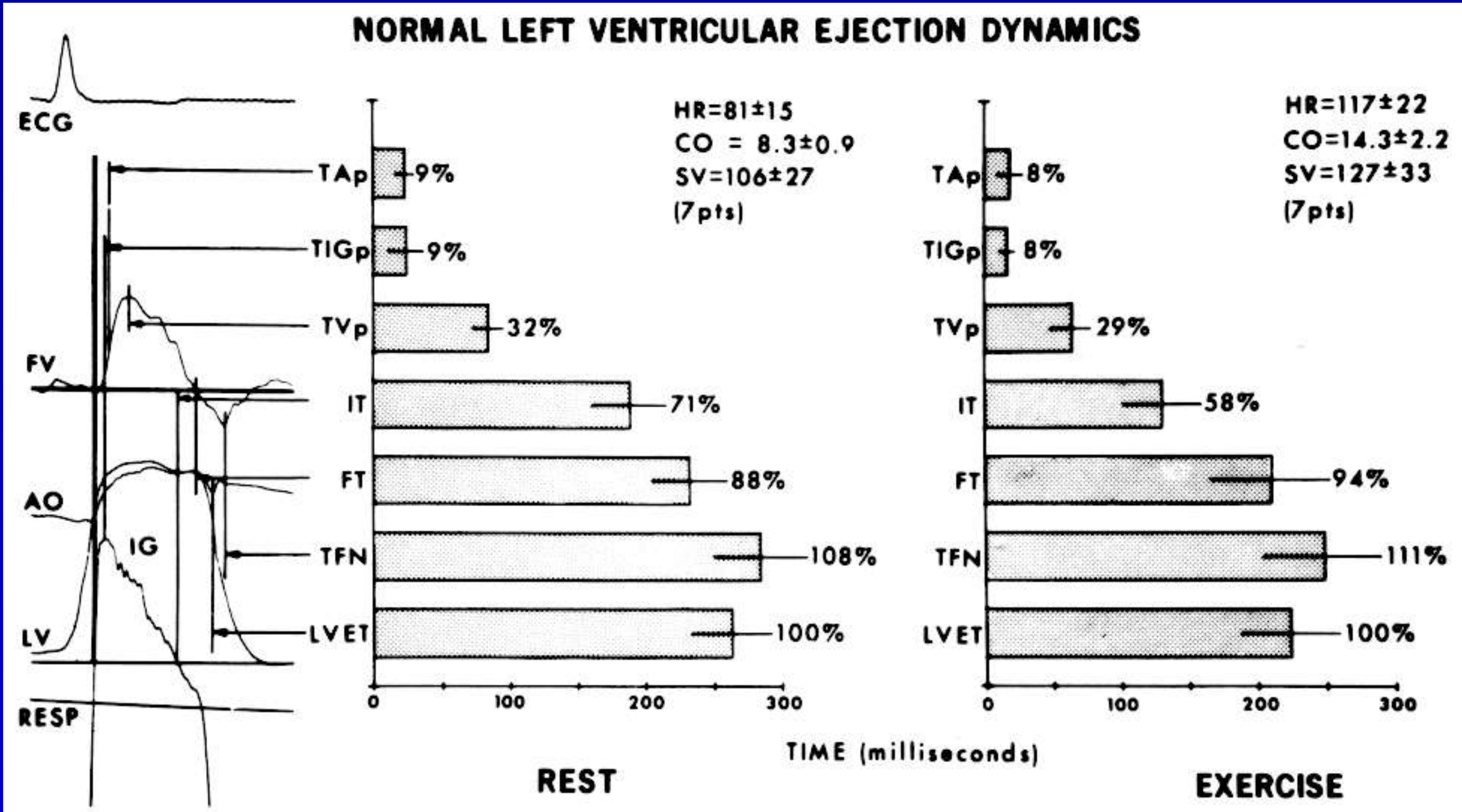
Murgo, 1975, Circulation Supplement 46

LV Ejection Profile



Murgo, 1975,
Circulation Supplement 46

Normal LV Ejection Dynamics



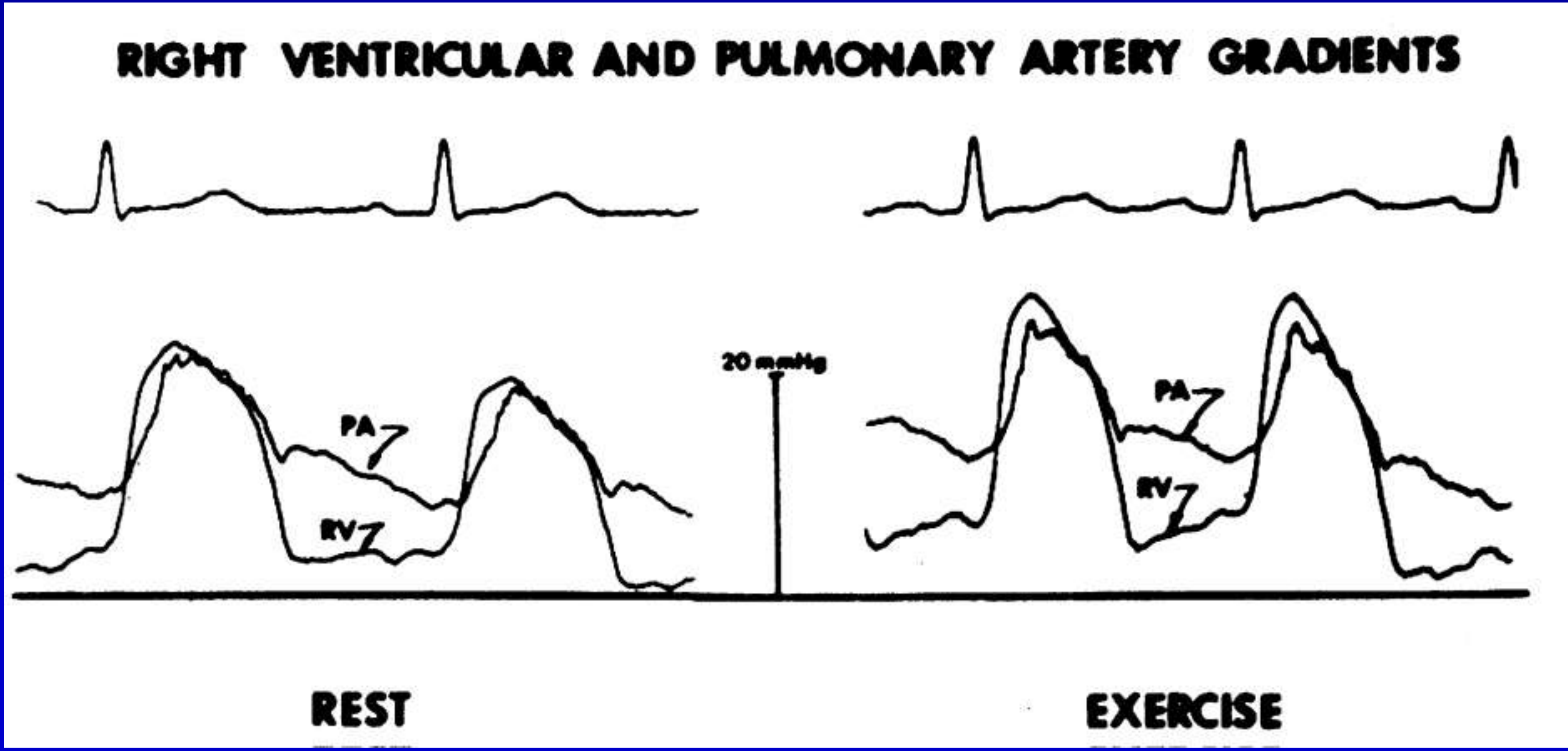
Murgo, 1975, Circulation Supplement 46

Pulmonary Hypertension

Murgo, 1975, Circulation Supplement 46

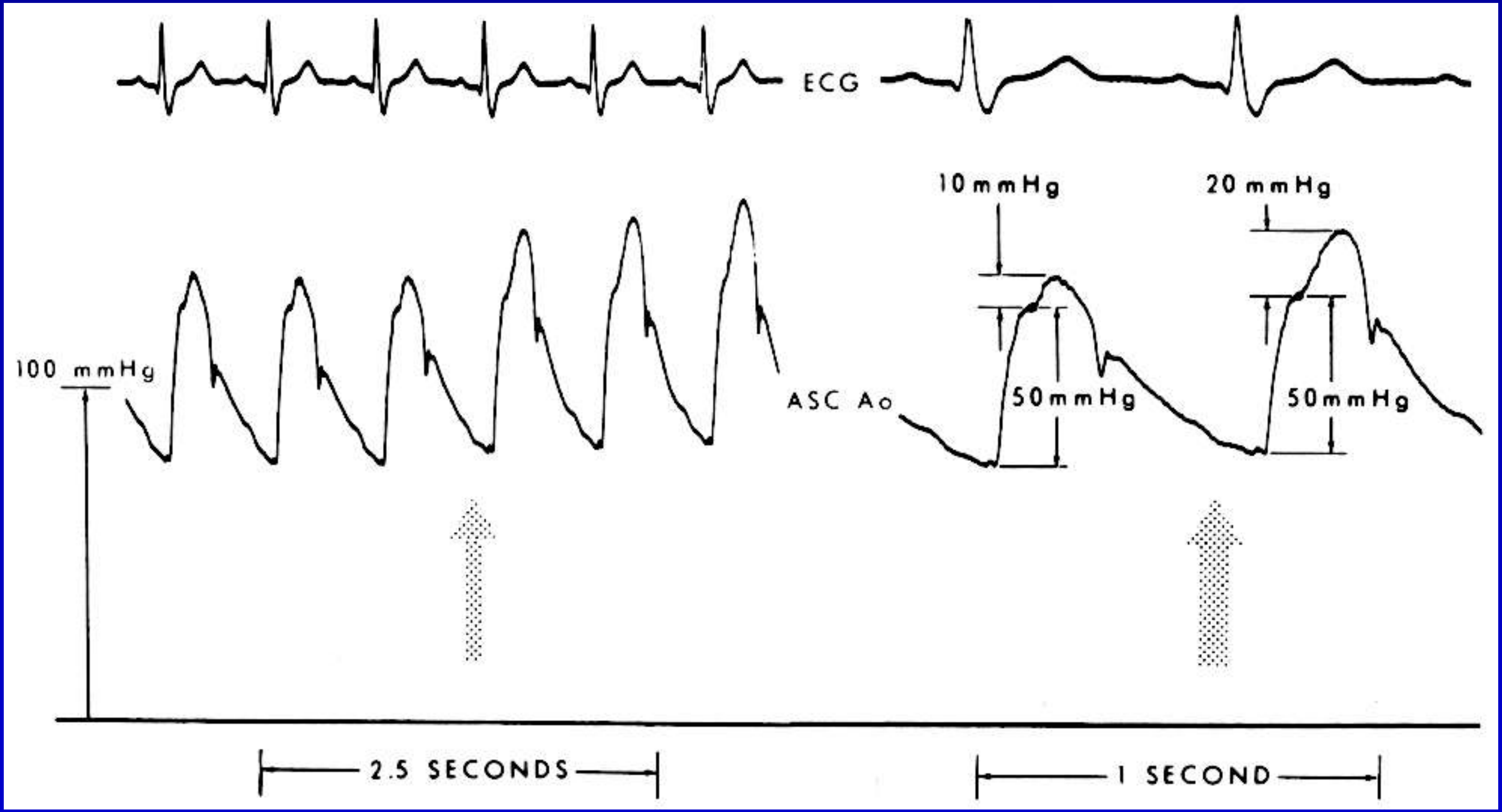
RV and PA Gradients

Rest and Exercise



Murgo, 1975, Circulation Supplement 46

Valsalva Release Effects on Aortic Pressure



Murgo JP et al. Circulation 1980;62:105

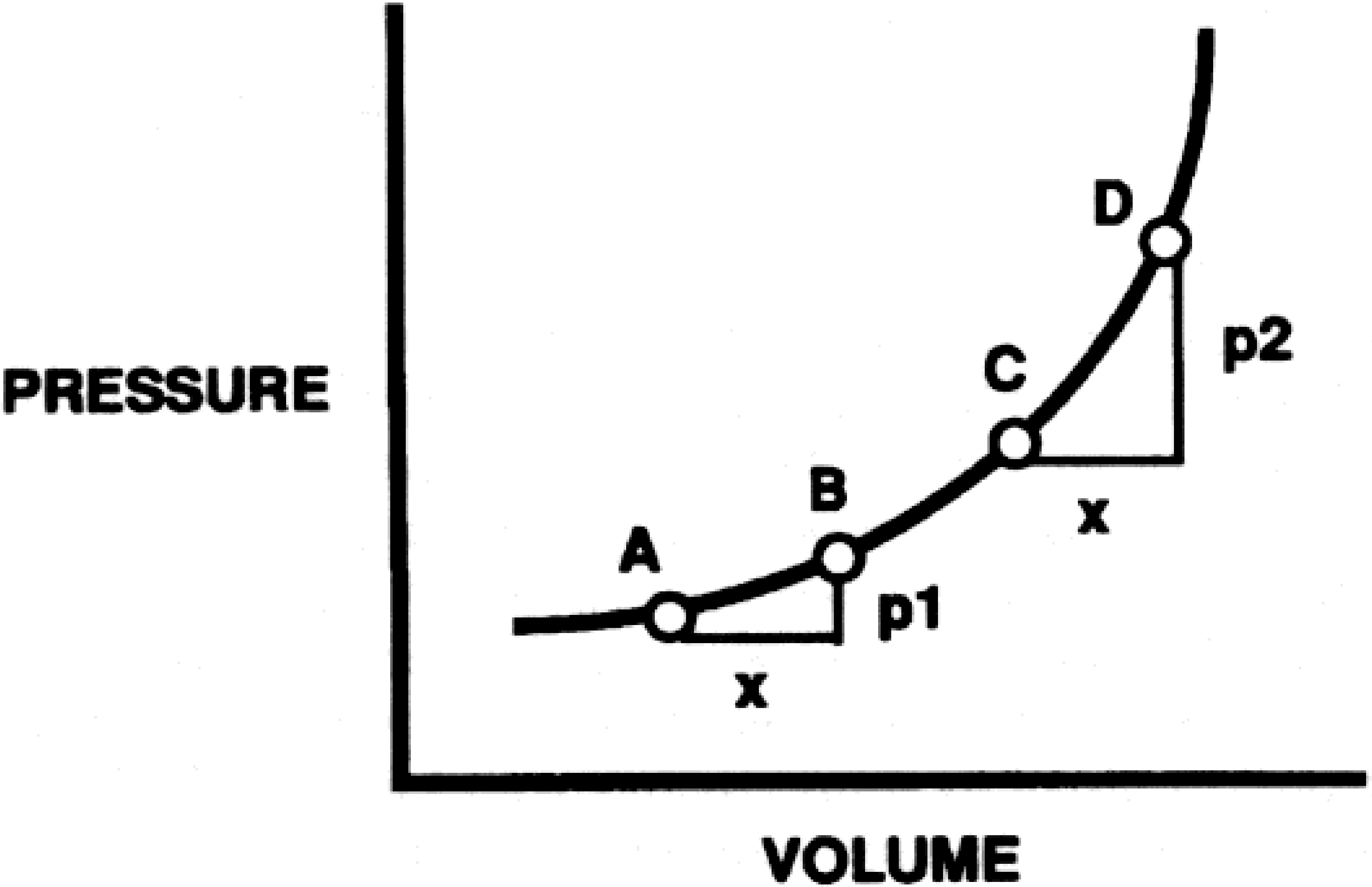
Technique of V Wave Measurement

- PCW pressure versus direct LA pressure
  - Delay 0.06 sec (Hurst, 10th ed, p.485)
  - Delay 50-70 msec (Grossman, 5th ed, p.156)
  - Delay 70 +/- 15 msec (Grossman, p.90, Lange, JACC ’89, 8F Goodale-Lubin, expect longer delay and more damping with smaller softer catheters)
  - Delay 140-200 msec (Kern, p.95)
  - Alignment is by placing peak of V wave just to left of (just before) the crossing of LV pressure
  - Y descent slope is less steep
  - LA pressure is overestimated by about 1.7 mmHg.

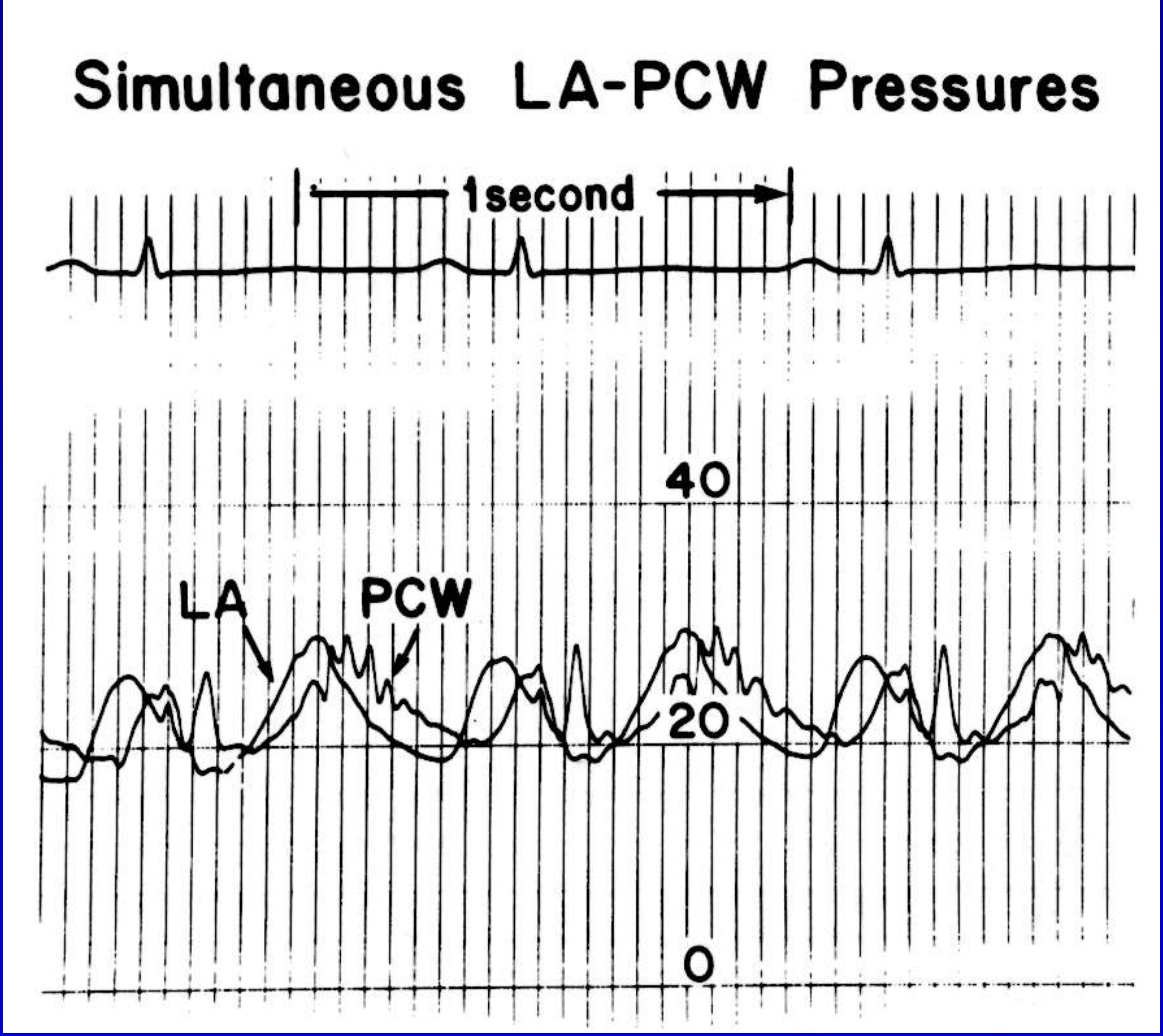
Assessing the LA V Wave

- V wave peak of twice mean pressure may be seen without significant MR
- V wave peak of three times mean pressure almost certainly indicates severe MR
- Normal V wave doesn’t exclude severe MR at all
- LV failure from any cause can give large V wave (distended LA becomes relatively noncompliant)
- High pulmonary blood flow can give large V wave (acute VSD) even >50mmHg

Hypothetical LA Diastolic P/V Curves

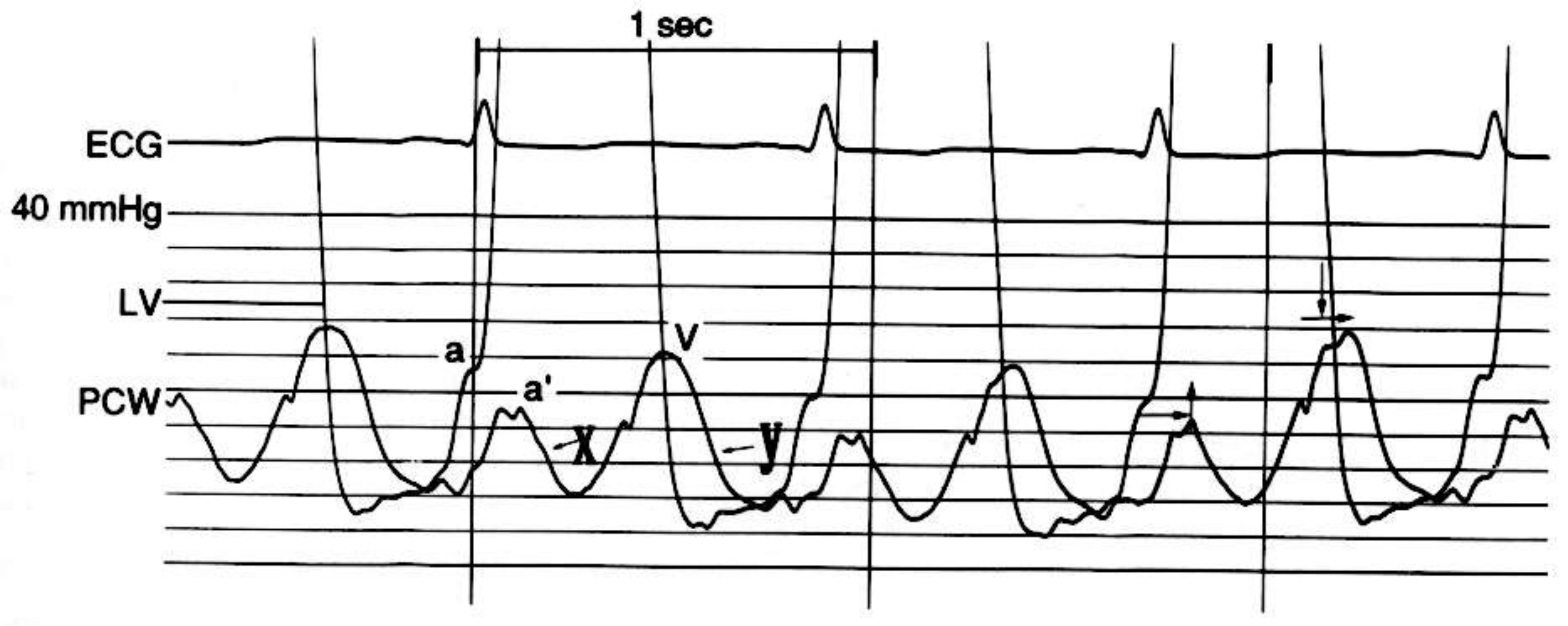


Tice, AJC, Jan 1995,



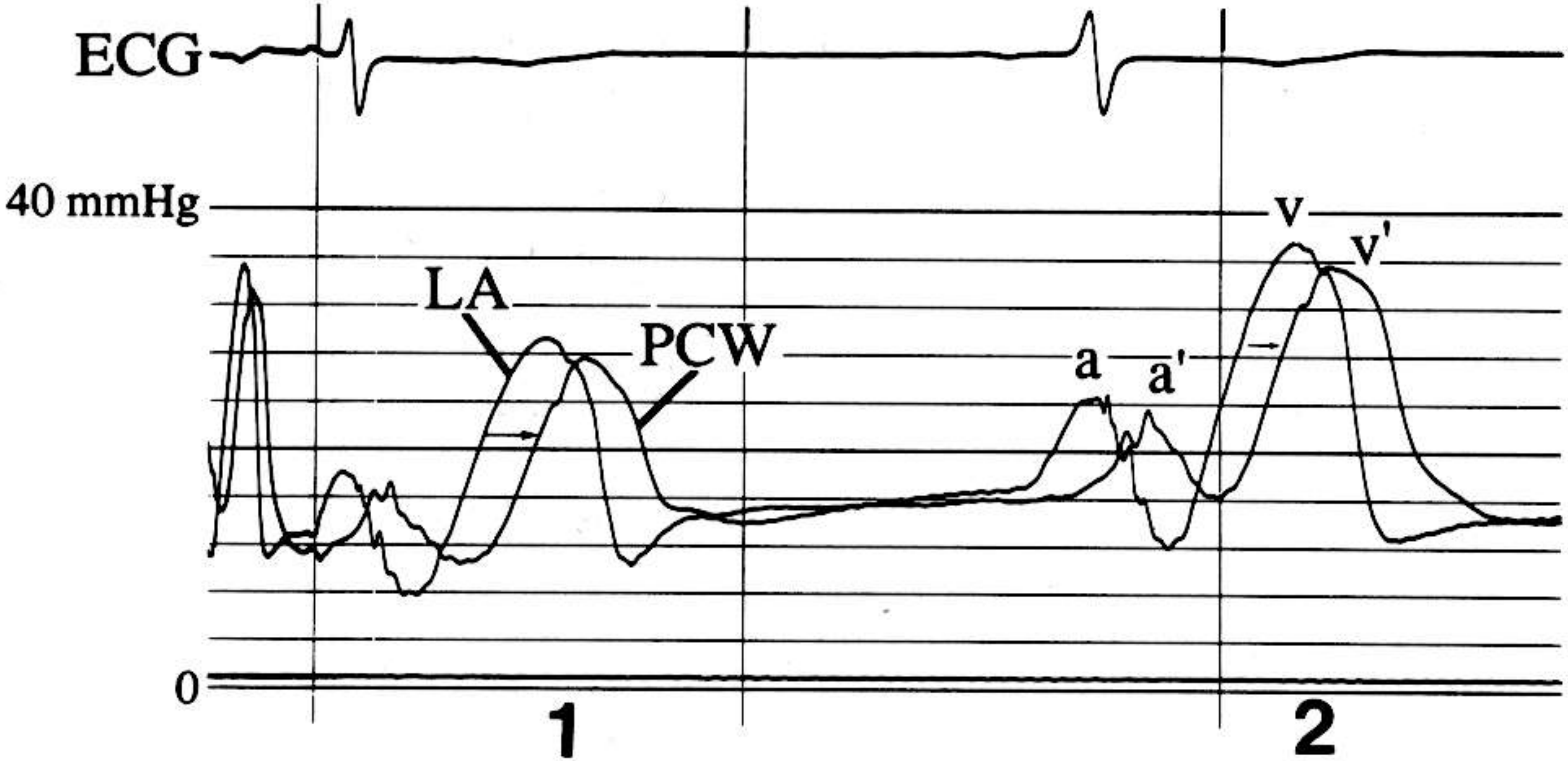
Grossman, 5th ed, p.91

Normal PCW Pressure

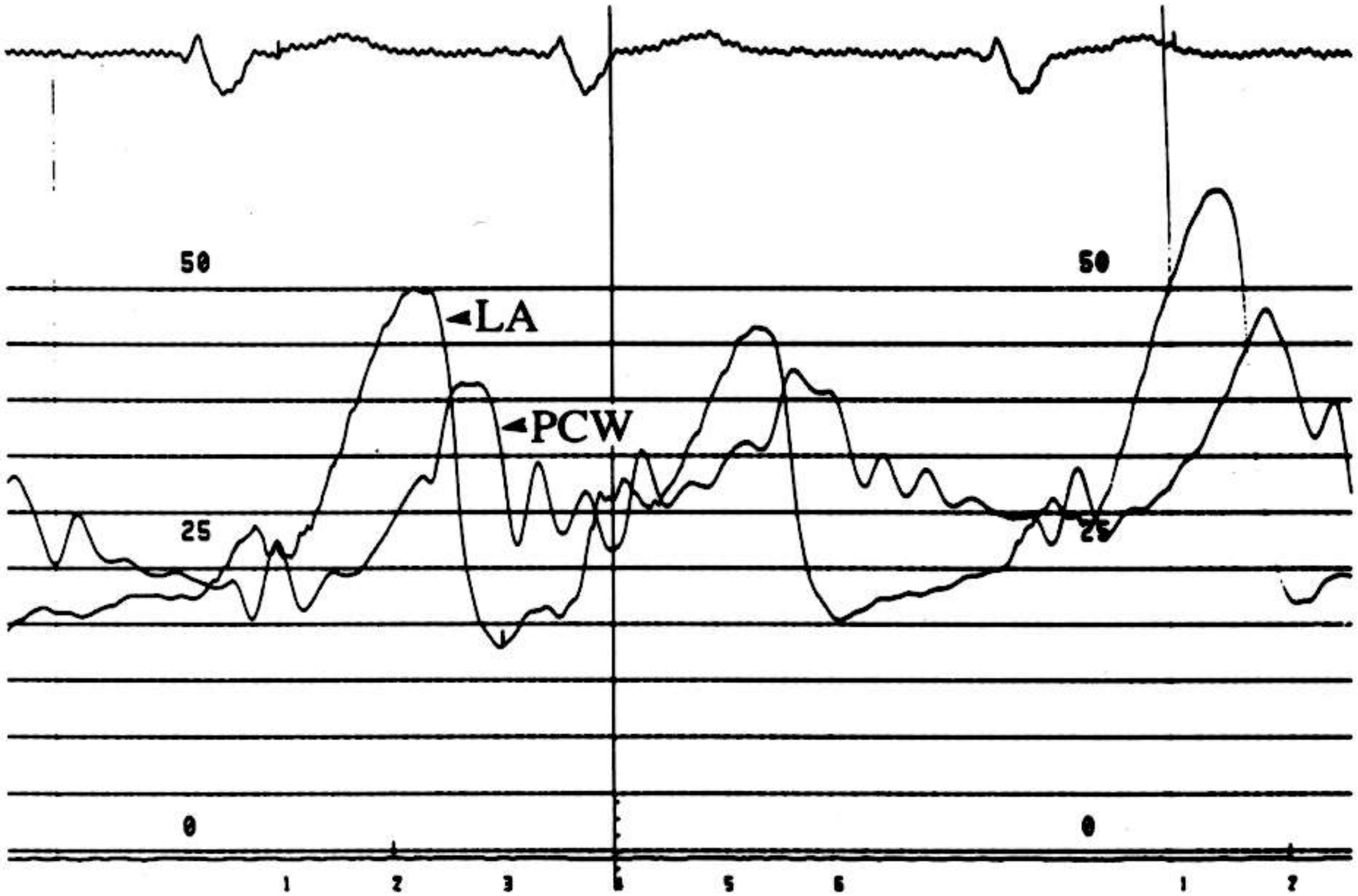


Kern, 1999, p. 95

Comparison of LA and PCW

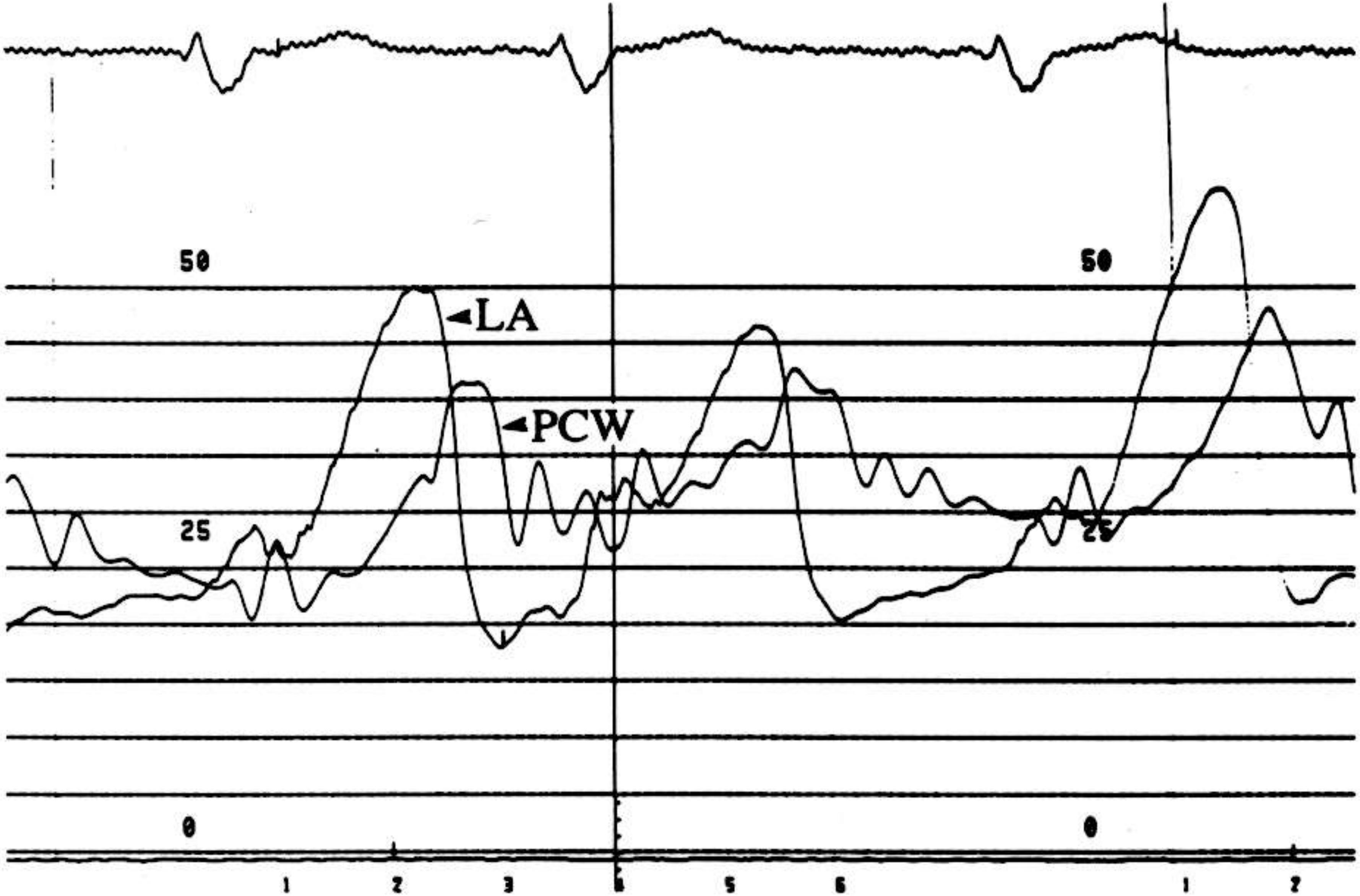


Kern, 1999, p. 95



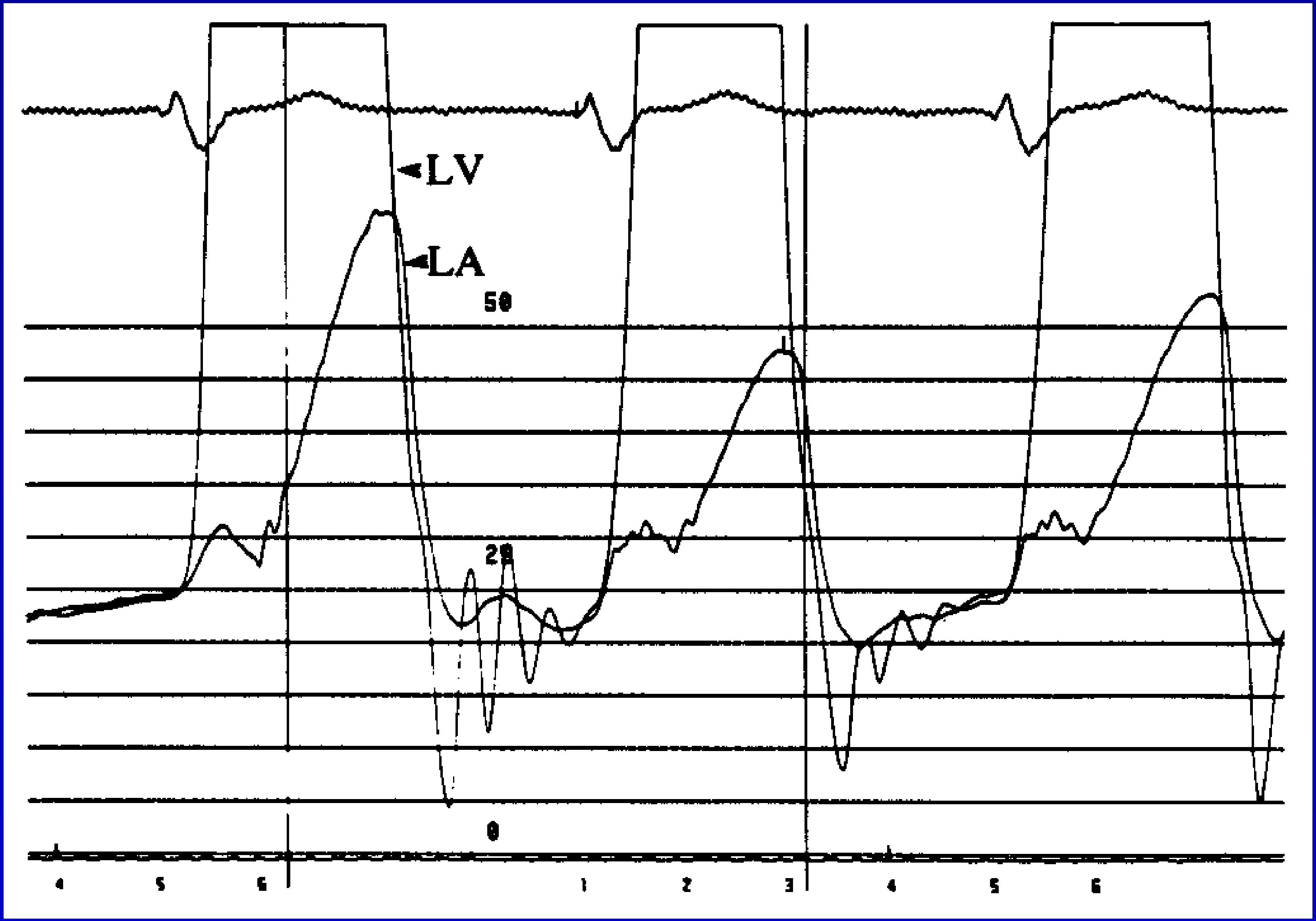
Simultaneous LA and PCW. Patient with MV Commisurotomy and MR and Progressive fatigue

Kern, 1999, p. 99



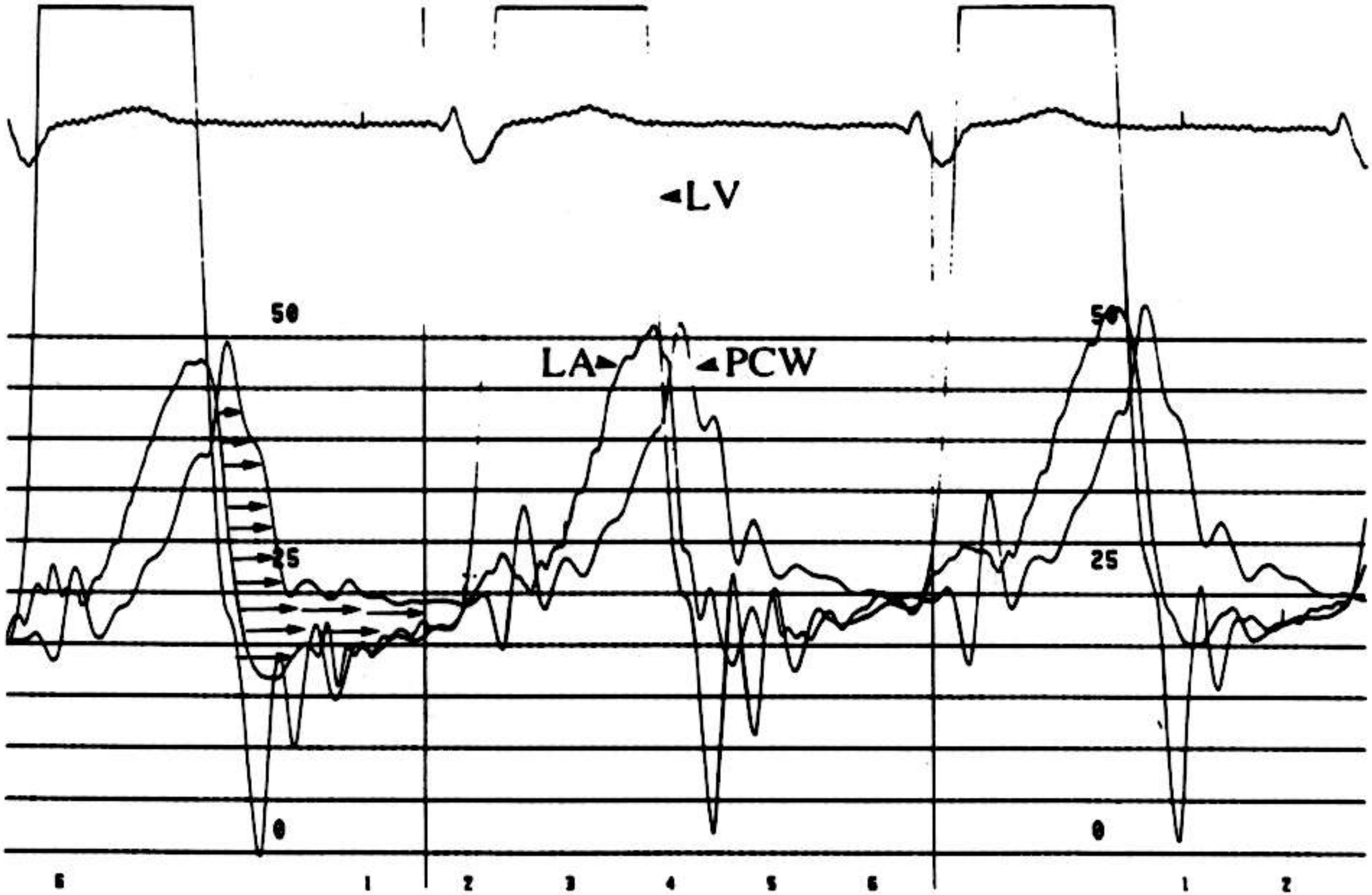
Note higher LA systolic and earlier occurrence and similar mean pressures, and slower PCW Y descent

Kern, 1999, p. 99



Simultaneous LA and LV. Same Patient with MV Commisurotomy and MR and Progressive fatigue. Is there MS?

Kern, 1999, p. 99



Arrows denote erroneous gradient if PCW used.

Kern, 1999, p. 99

Comparison of RA and LA V waves