

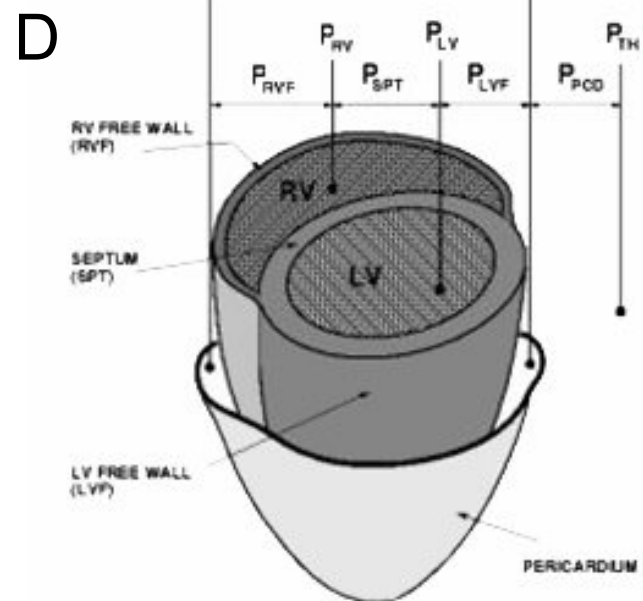
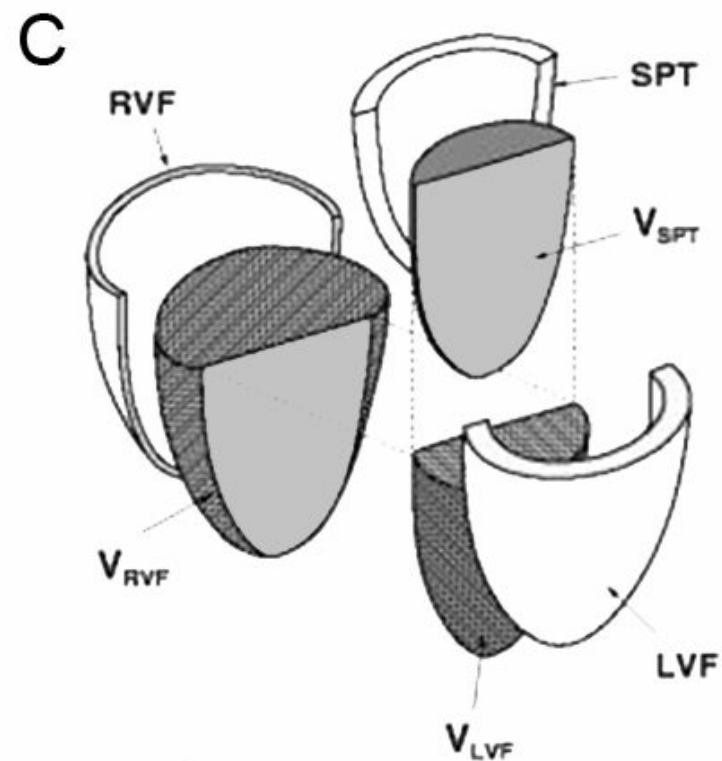
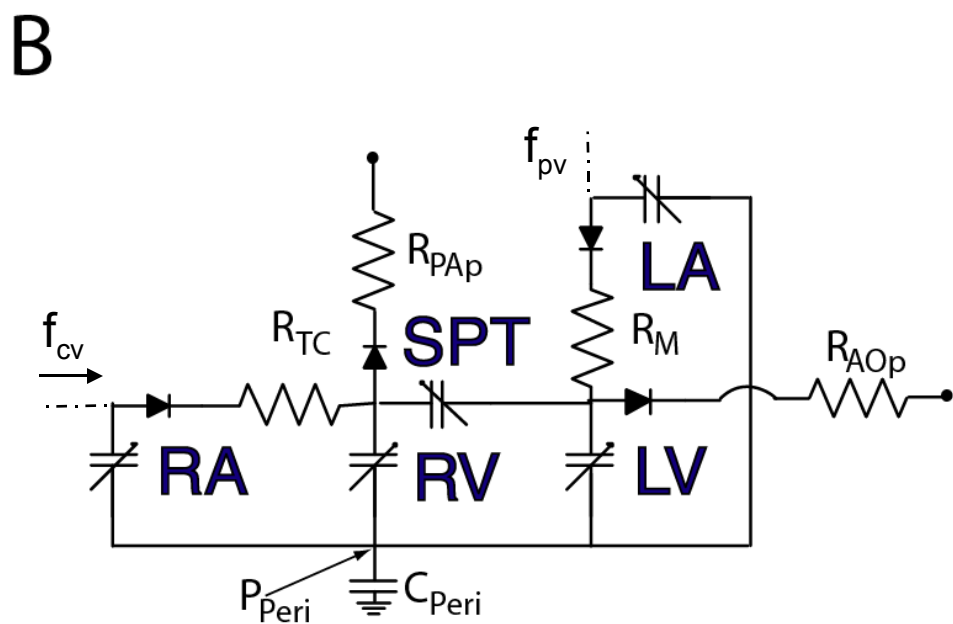
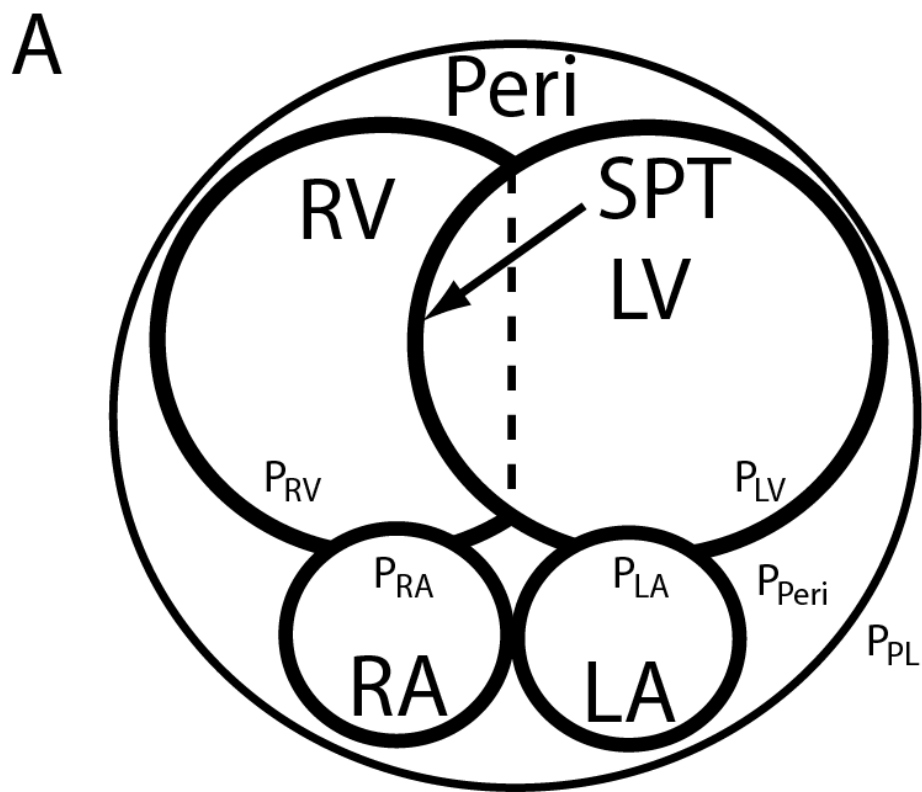
A Human Cardio-Respiratory Model

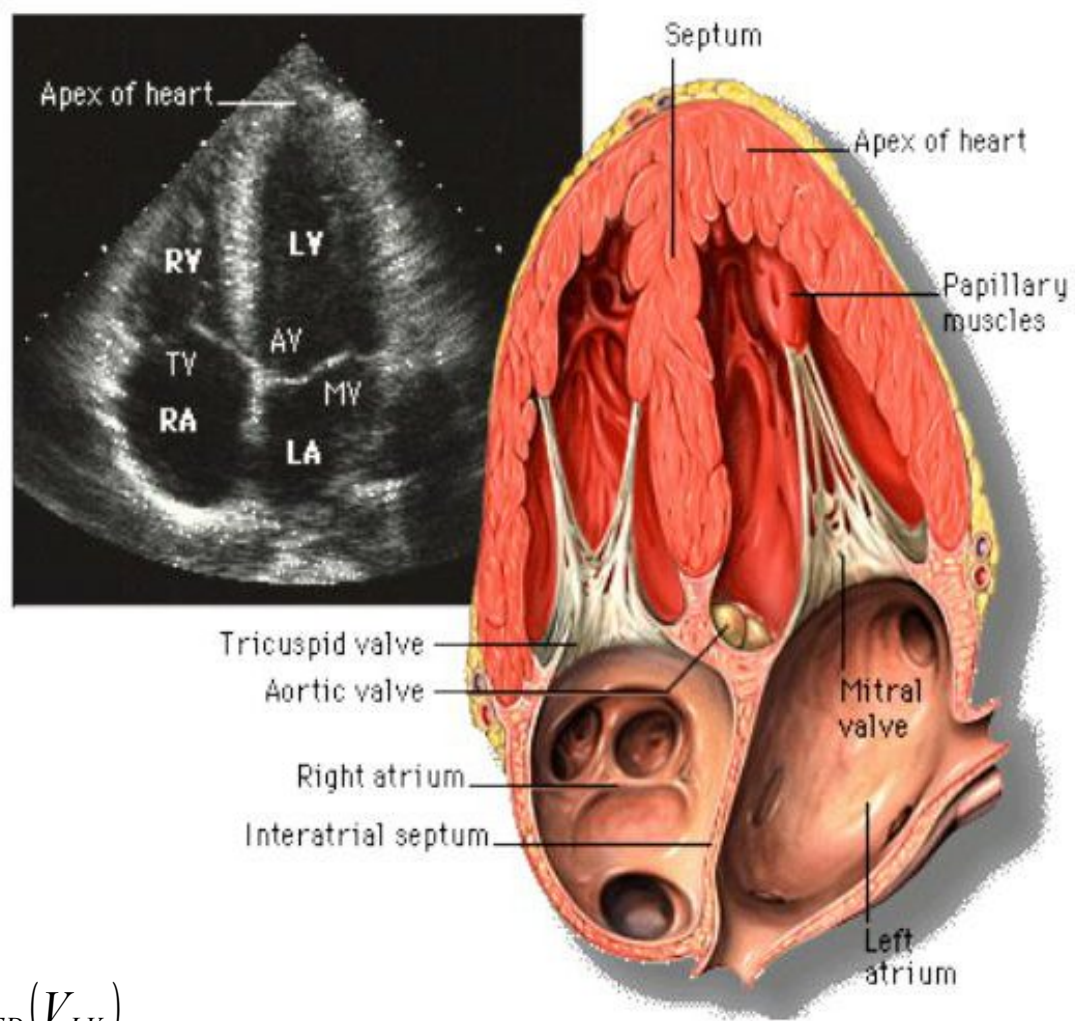
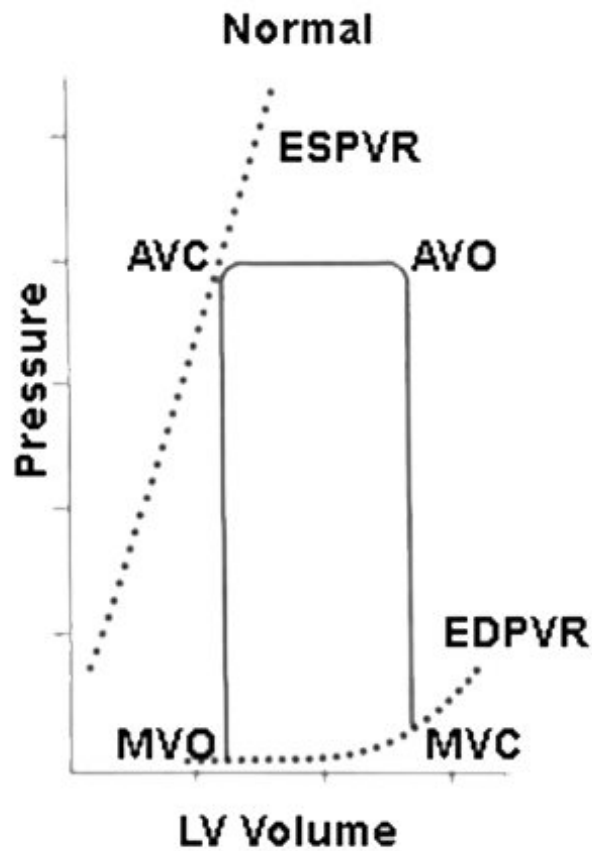
Application in Critical Care Medicine

Left Ventricular Diastolic Dysfunction (LVDD)

Major Components

- Cardiovascular System
 - Heart
 - Systemic and Pulmonary Circulations
- Respiratory System
 - Lung/Airway Mechanics
 - Gas Transport
- Neural Control
 - Baroreflex Control
 - ✓ Heart Rate
 - ✓ Myocardial Contractility
 - ✓ Vasomotor Tone
 - Chemoreflex Control
 - ✓ Ventilation
 - ✓ Effects of Chemical Control on Heart Rate





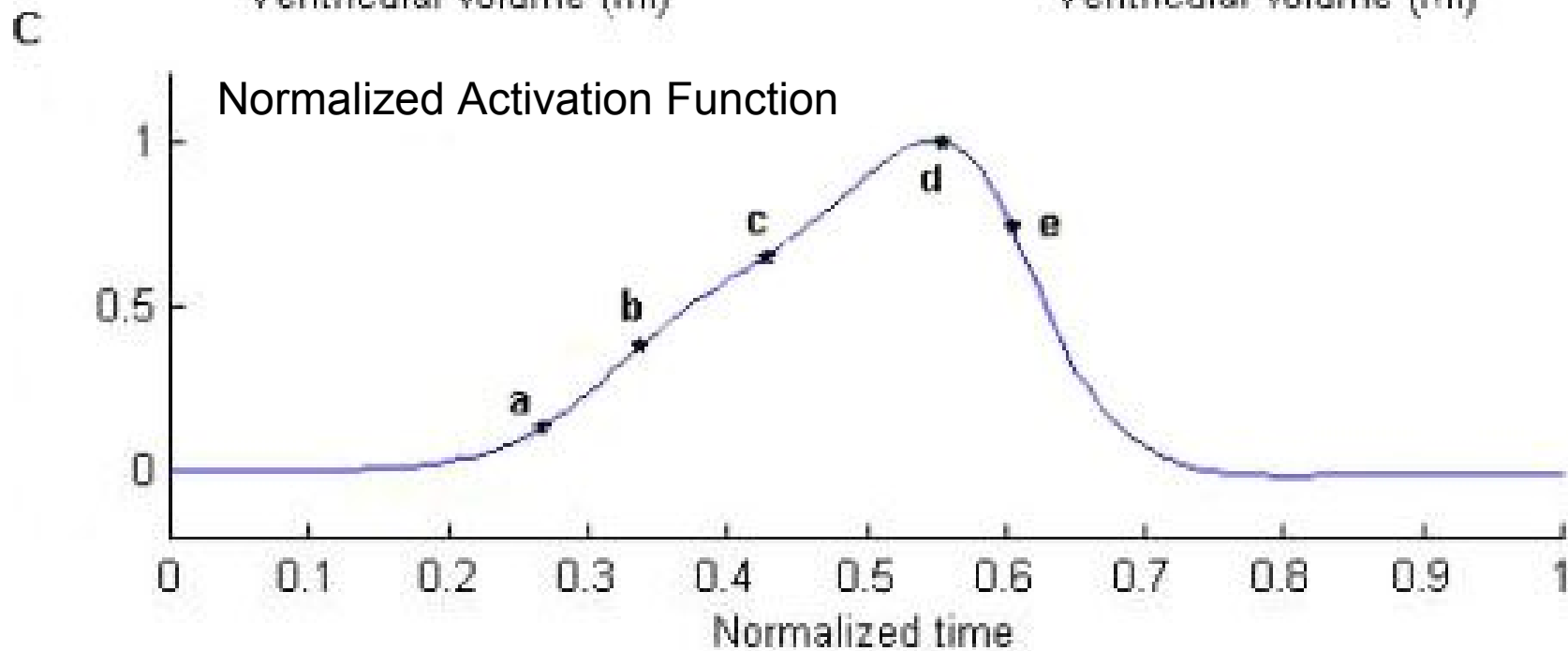
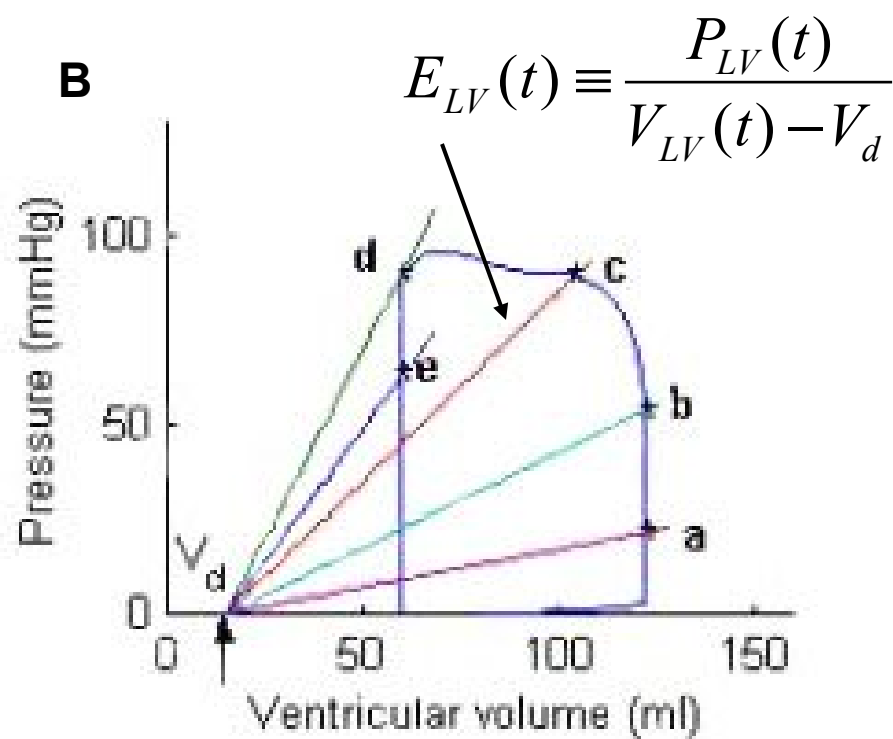
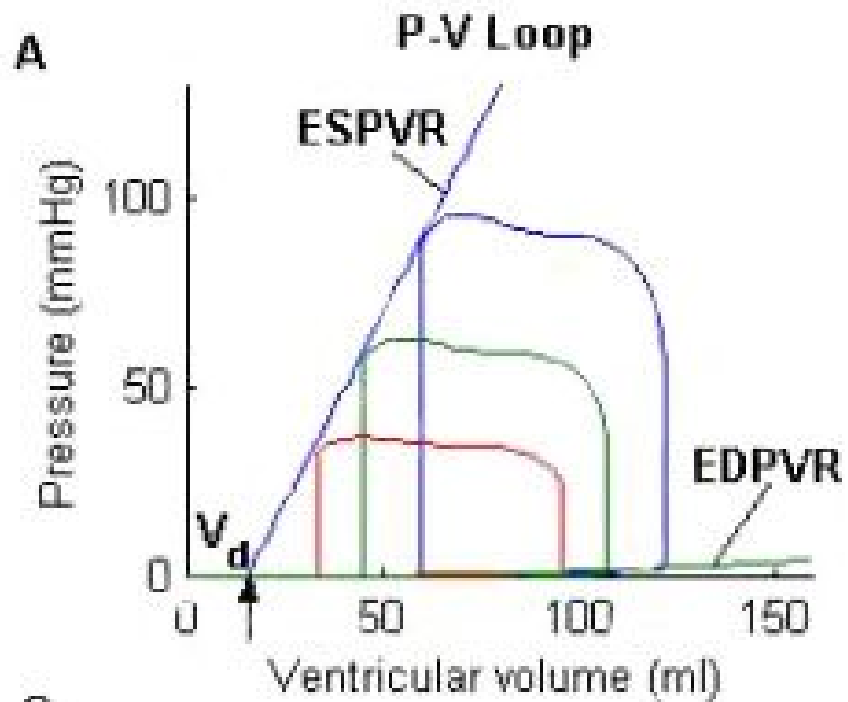
$$P_{LV}(V_{LV}, t) = e(t)P_{LVES}(V_{LV}) + [1 - e(t)]P_{LVED}(V_{LV})$$

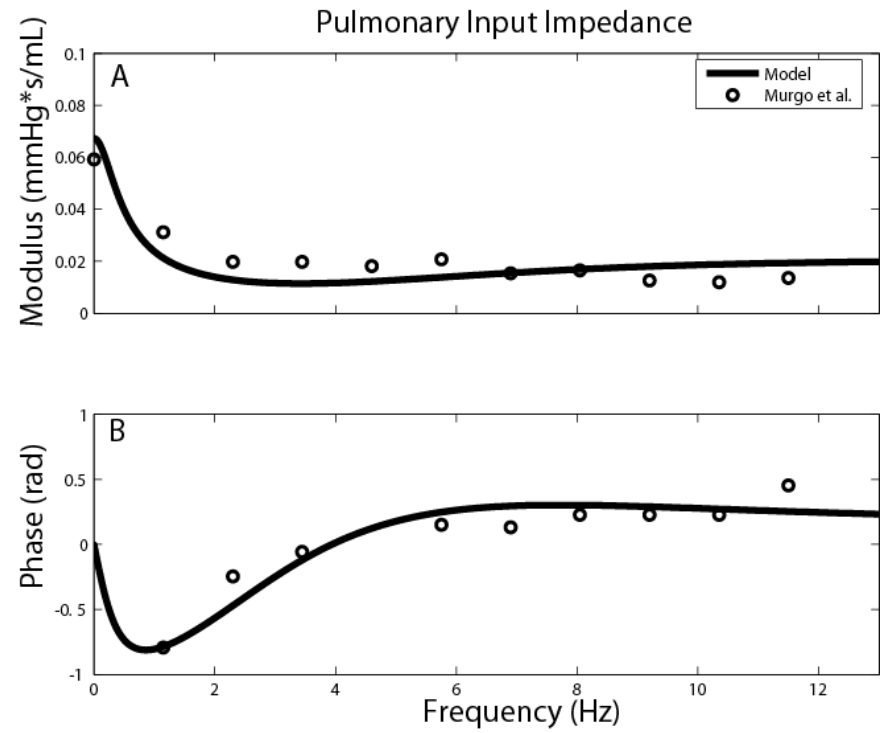
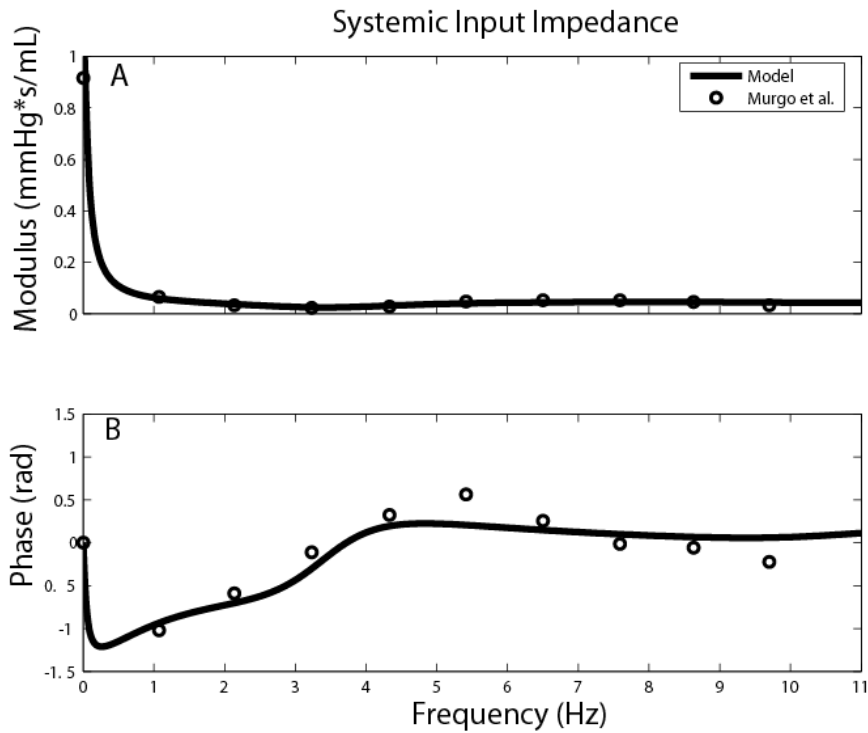
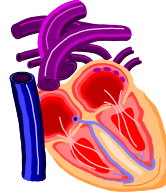
where:

$$P_{LVED} = P_o(e^{\lambda(V_{LV} - V_o)} - 1) \quad \text{EDPVR}$$

$$P_{LVES} = E_{ES}(V_{LV} - V_d) \quad \text{ESPVR}$$

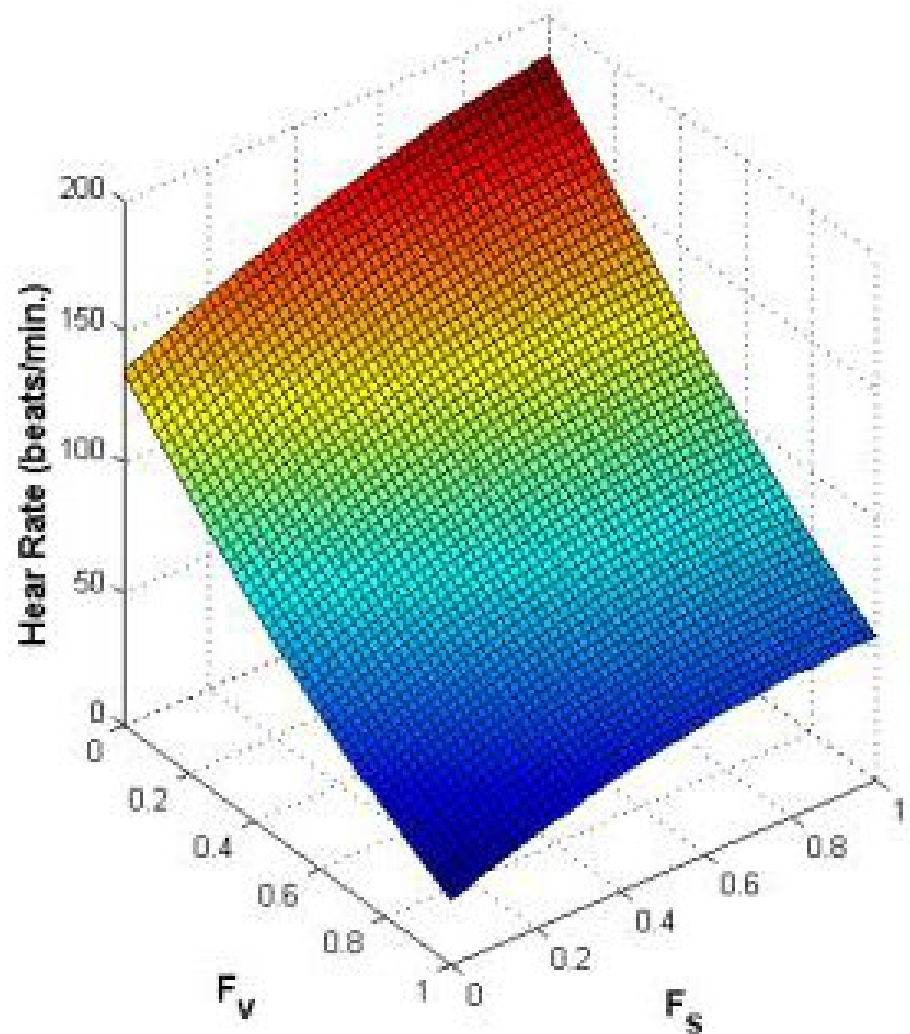
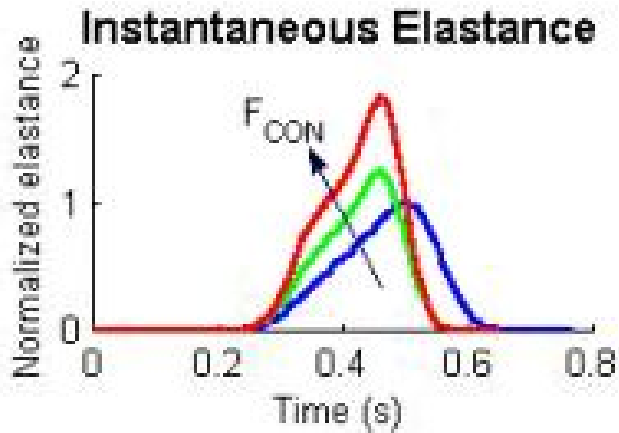
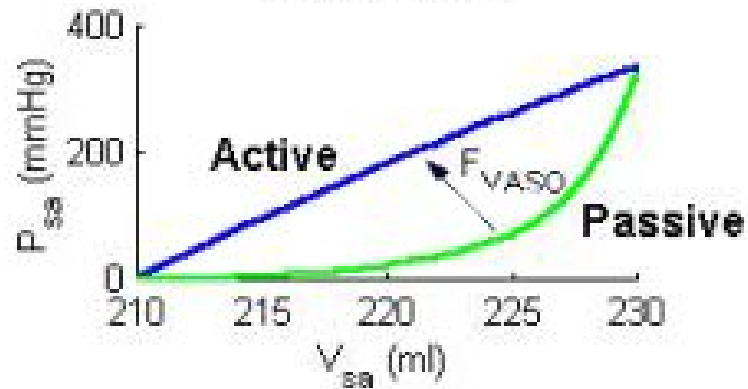
$$e(t) = \sum_{i=1}^N A_i \exp\left(-\frac{(t - C_i)^2}{2B_i^2}\right) \quad \text{electrochemical activation function}$$





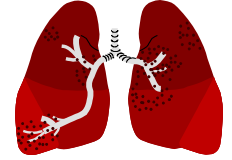
Input Impedance Characterization of the Systemic and Pulmonary Circulations

P-V curves

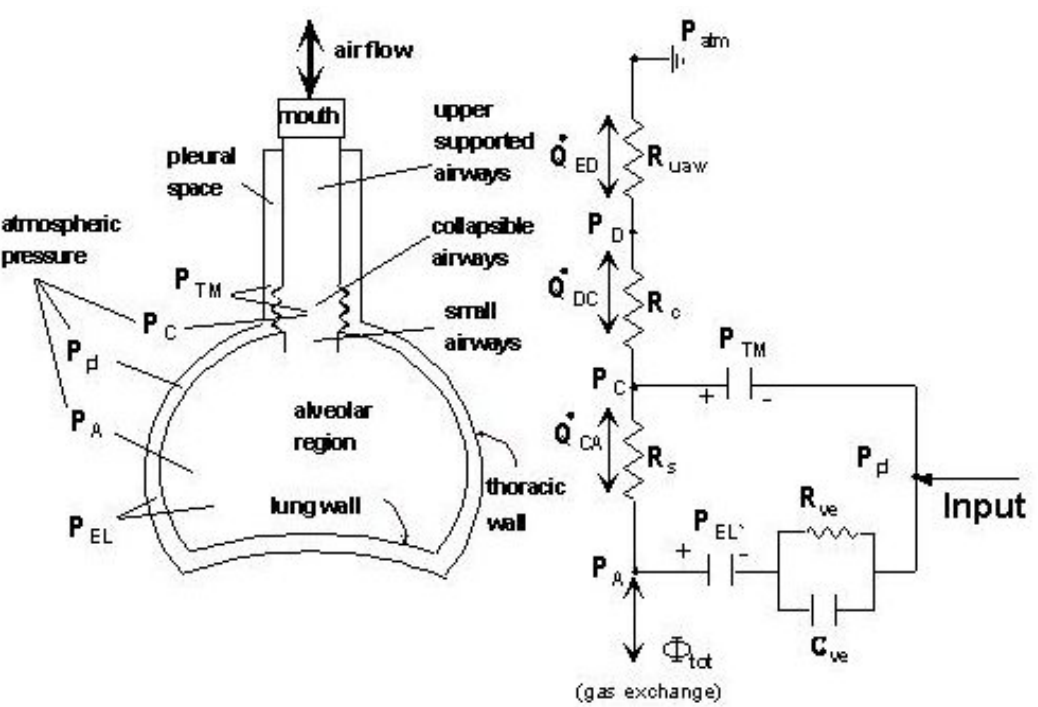
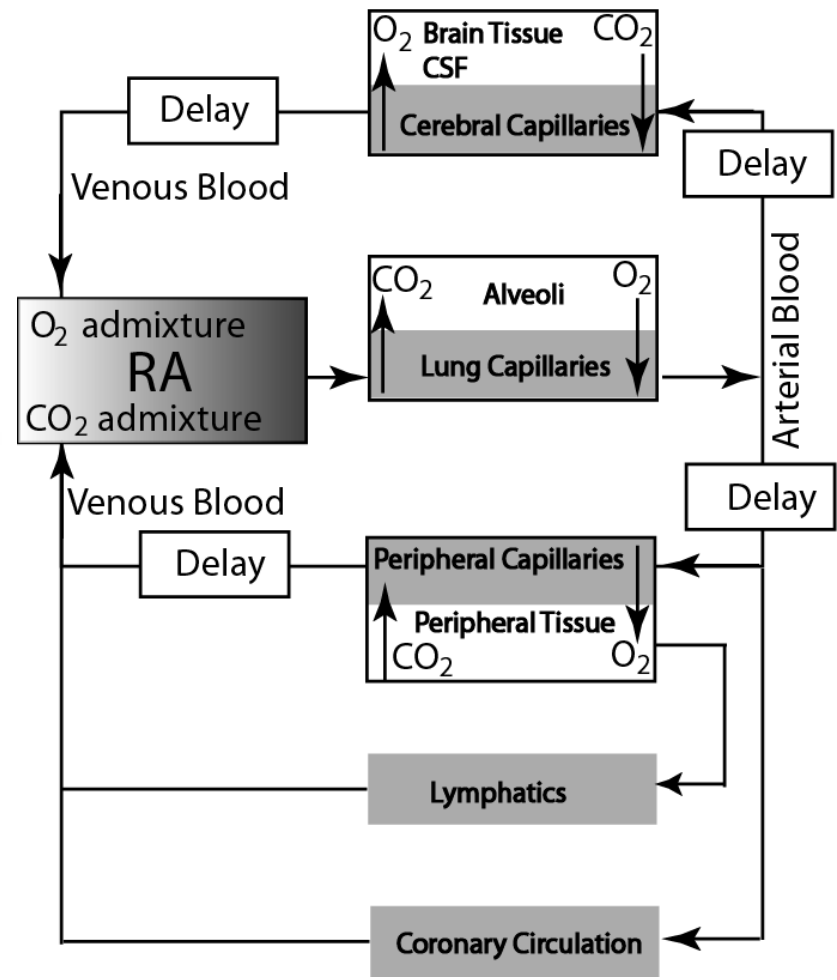


Nervous System Control of Heart Rate, Myocardial Contractility and Vasomotor Tone

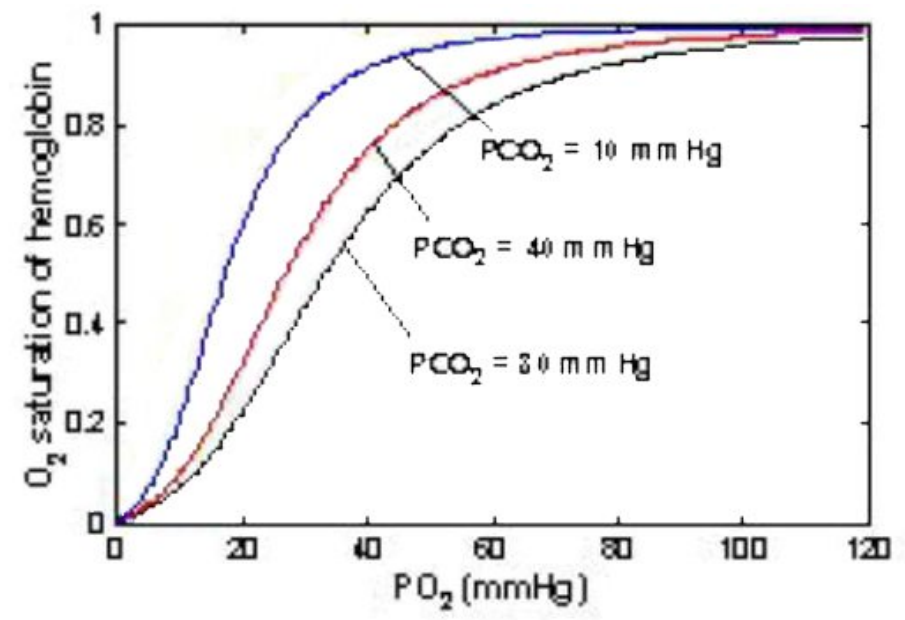
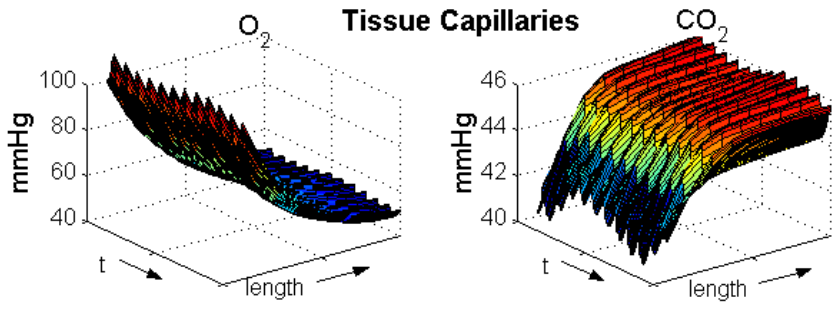
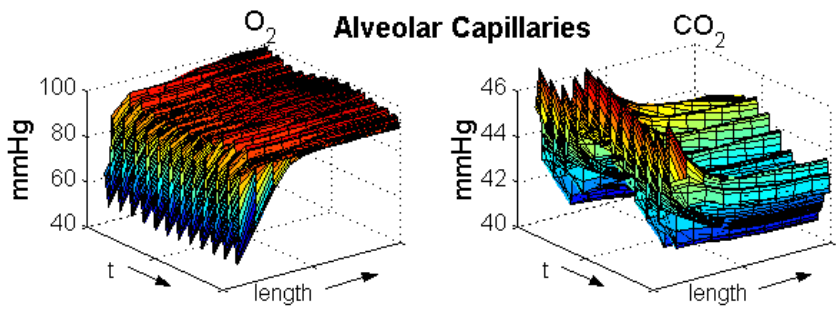
Lung and Airway Mechanics



Gas Transport Model

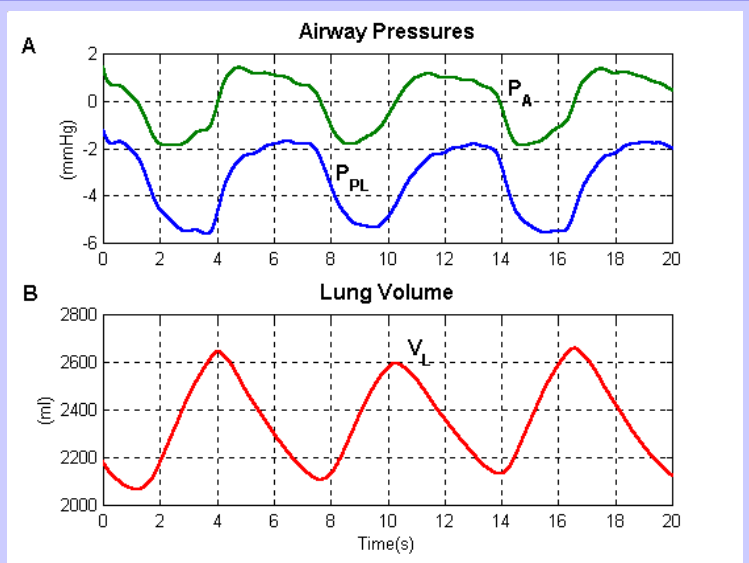
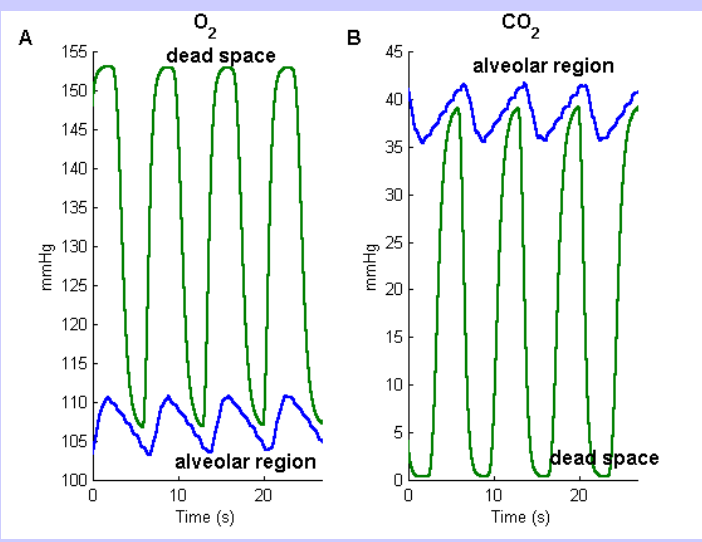


Equivalent Pneumatic Model of the Lung and Airways



Gaseous Exchange in the Lung and Tissues

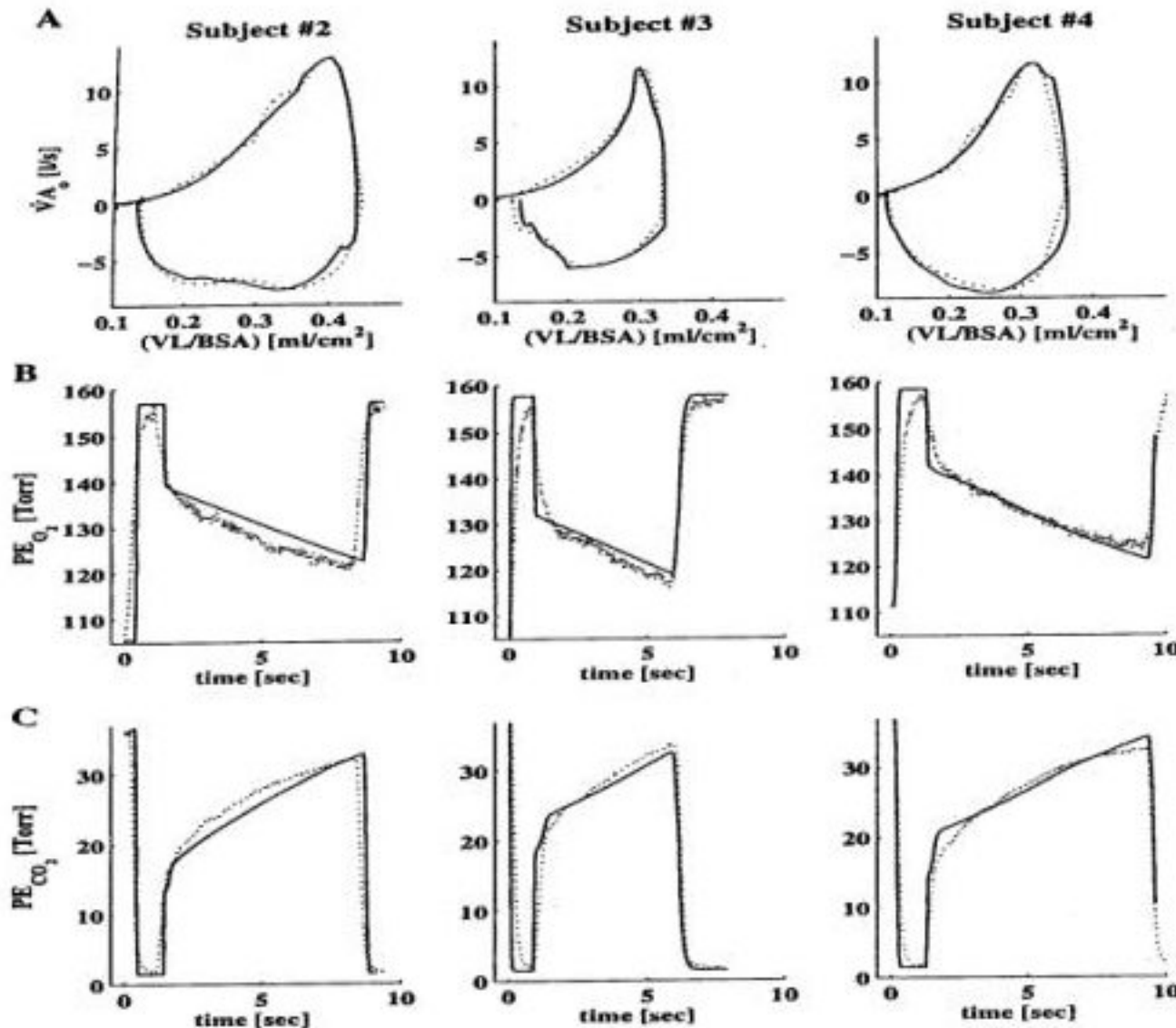
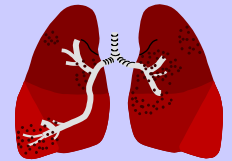
O_2 Dissociation Curve



Airway and Alveolar Gas Partial Pressures

Alveolar and Pleural Pressures & Lung Volume

ANALYSIS OF VENTILATION-CIRCULATION-METABOLISM



Lung-Airway
Mechanics

Oxygen Tension
at the Mouth

Carbon Dioxide
Tension at the
Mouth



Focus

The Cardiac Catheterization Laboratory

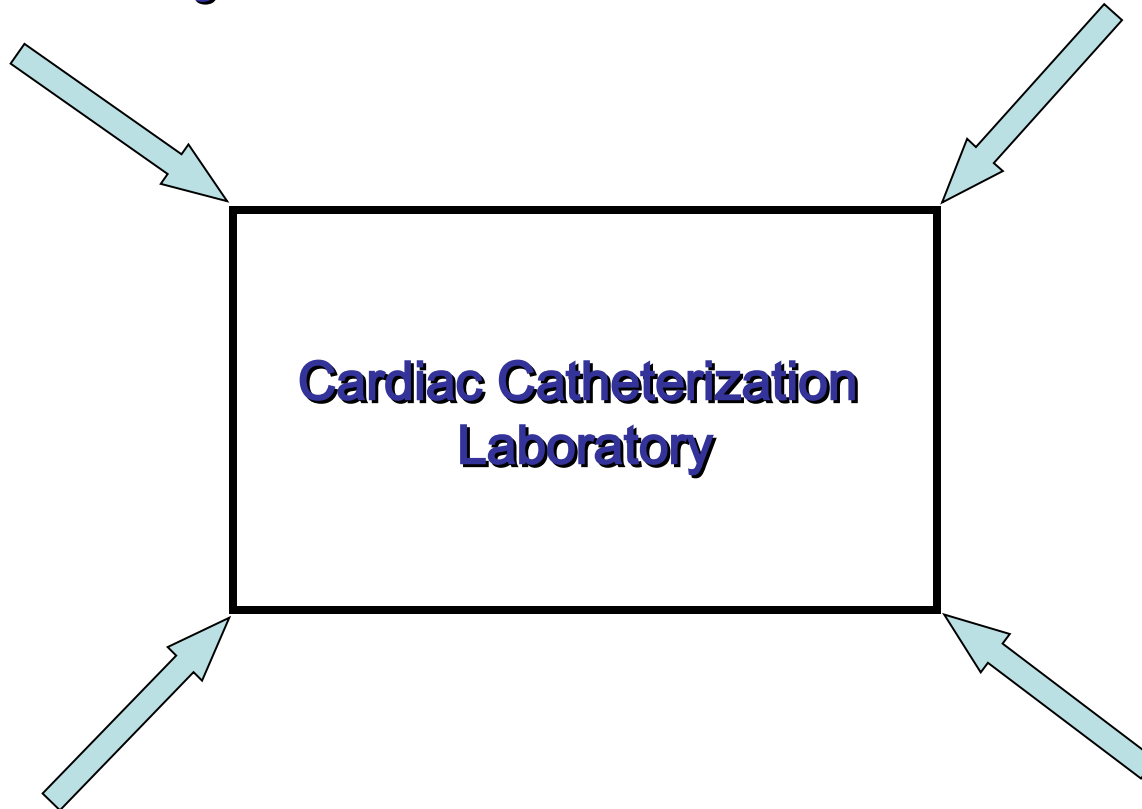
LVDD - Left Ventricular Diastolic Dysfunction

Pressure Measurements

- Left (and right) ventricular
- Aortic root and peripheral arterial
- Central venous and right atrial

Electrophysiological Measurements

- ECG
- Intracardiac catheter electrograms

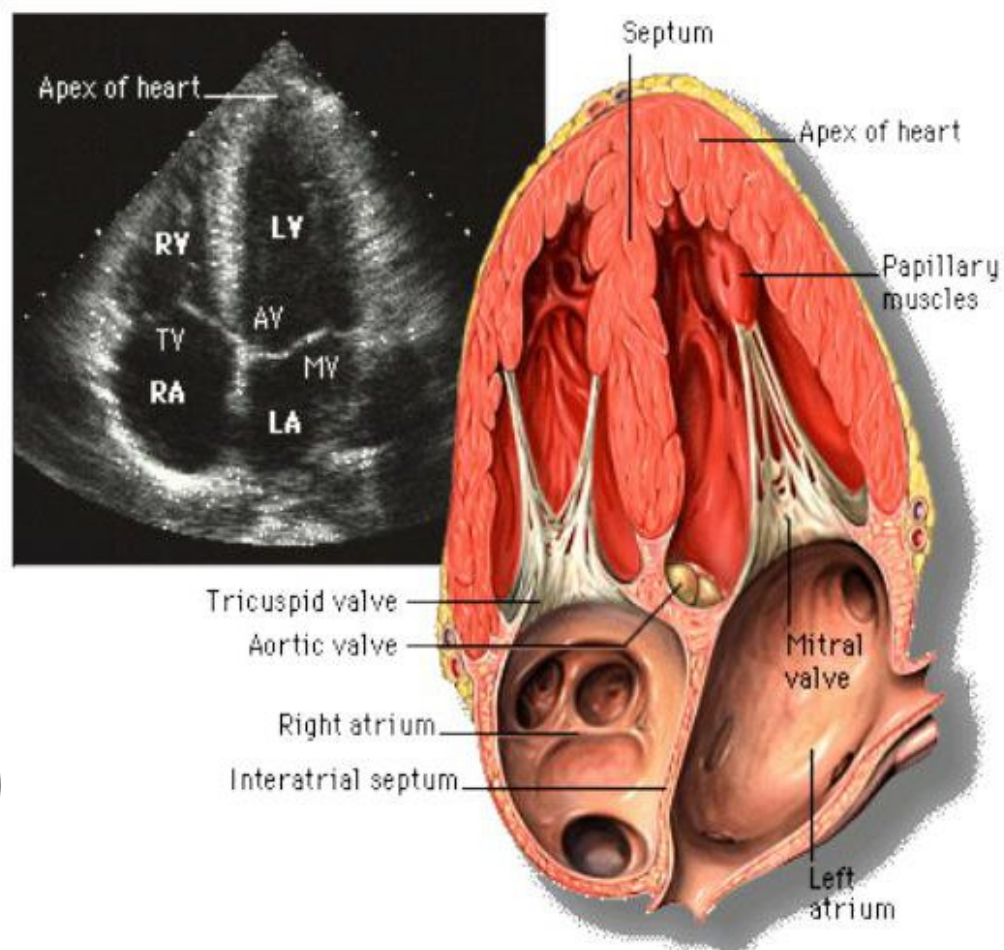
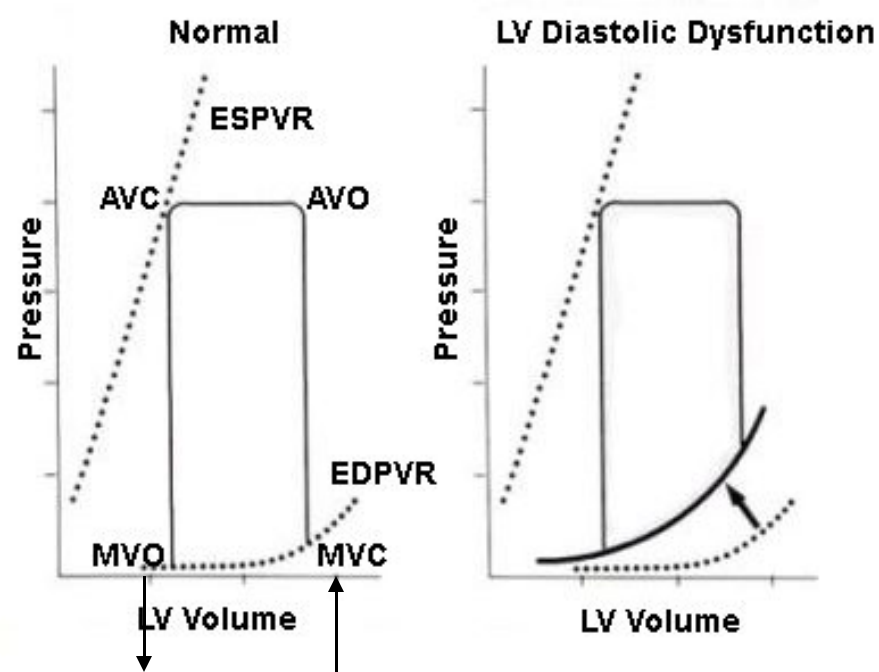


Echocardiographic Measurements

- Trans-Mitral and Tricuspid flow velocity
- Pulmonary vein flow velocity

Echocardiographic Imaging

- Intracardiac echocardiography via catheter (ICE)



$$P_{LV}(V_{LV}, t) = e(t)P_{LVES}(V_{LV}) + [1 - e(t)]P_{LVED}(V_{LV})$$

where:

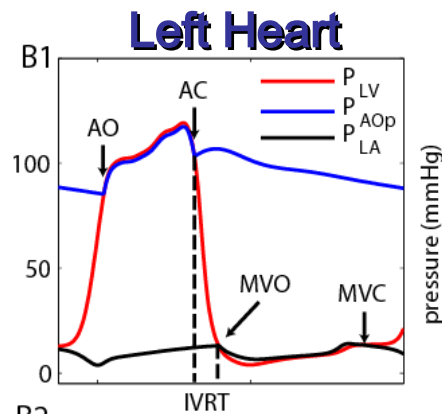
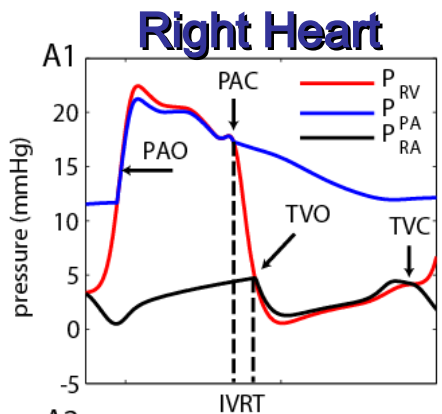
$$P_{LVED} = P_o(e^{\lambda(V_{LV} - V_o)} - 1) \quad \text{EDPVR}$$

$$P_{LVES} = E_{ES}(V_{LV} - V_d) \quad \text{ESPVR}$$

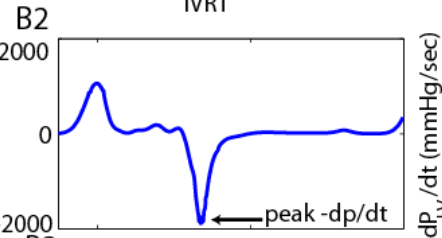
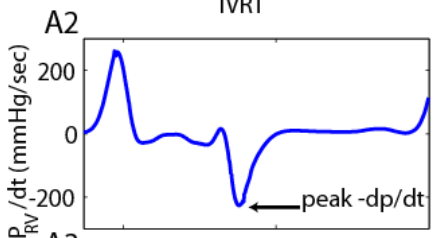
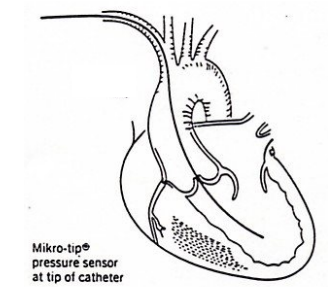
$$e(t) = \sum_{i=1}^N A_i \exp\left(-\frac{(t - C_i)^2}{2B_i^2}\right) \quad \text{electrochemical activation function}$$

Diagram of Left Ventricular P-V loops in normal patient and one with LV Diastolic Dysfunction (LVDD). Upper right: heart anatomy and 2D ultrasonic image of heart.

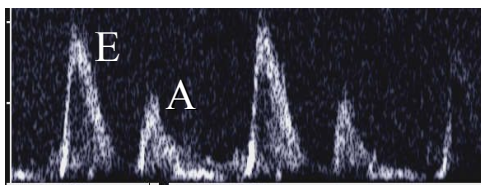
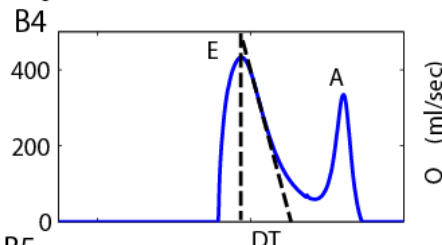
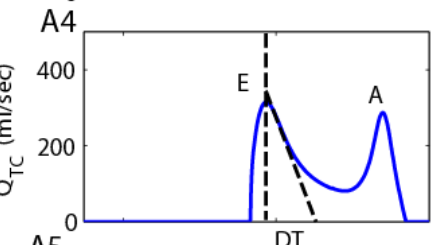
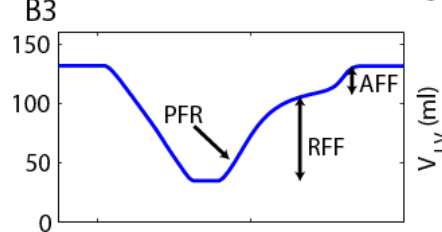
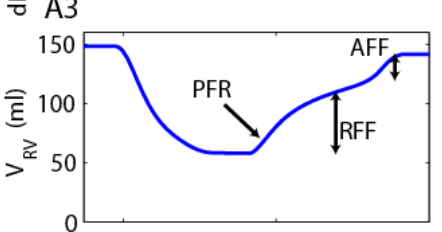
Model Generated Waveforms for Right and Left Heart of Normal Patient



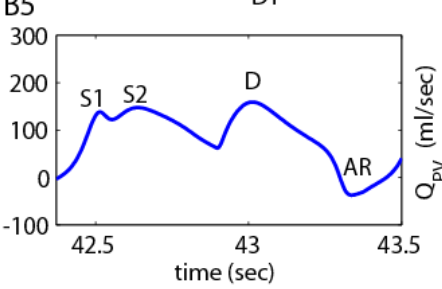
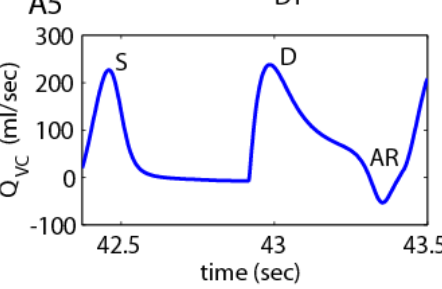
Pressure Waveforms



Waveform Derived from Echocardiographic Image Sequence



Doppler Flow Velocity Waveforms



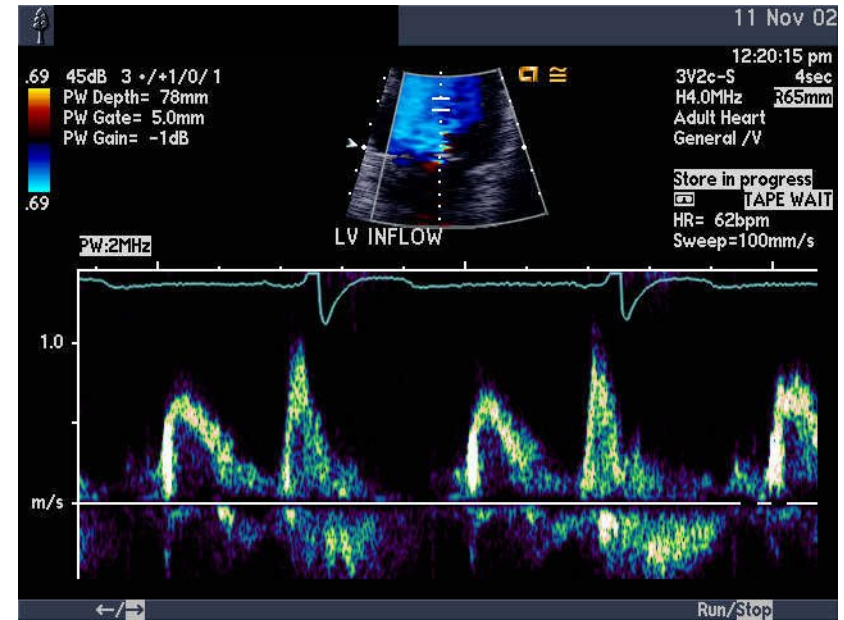
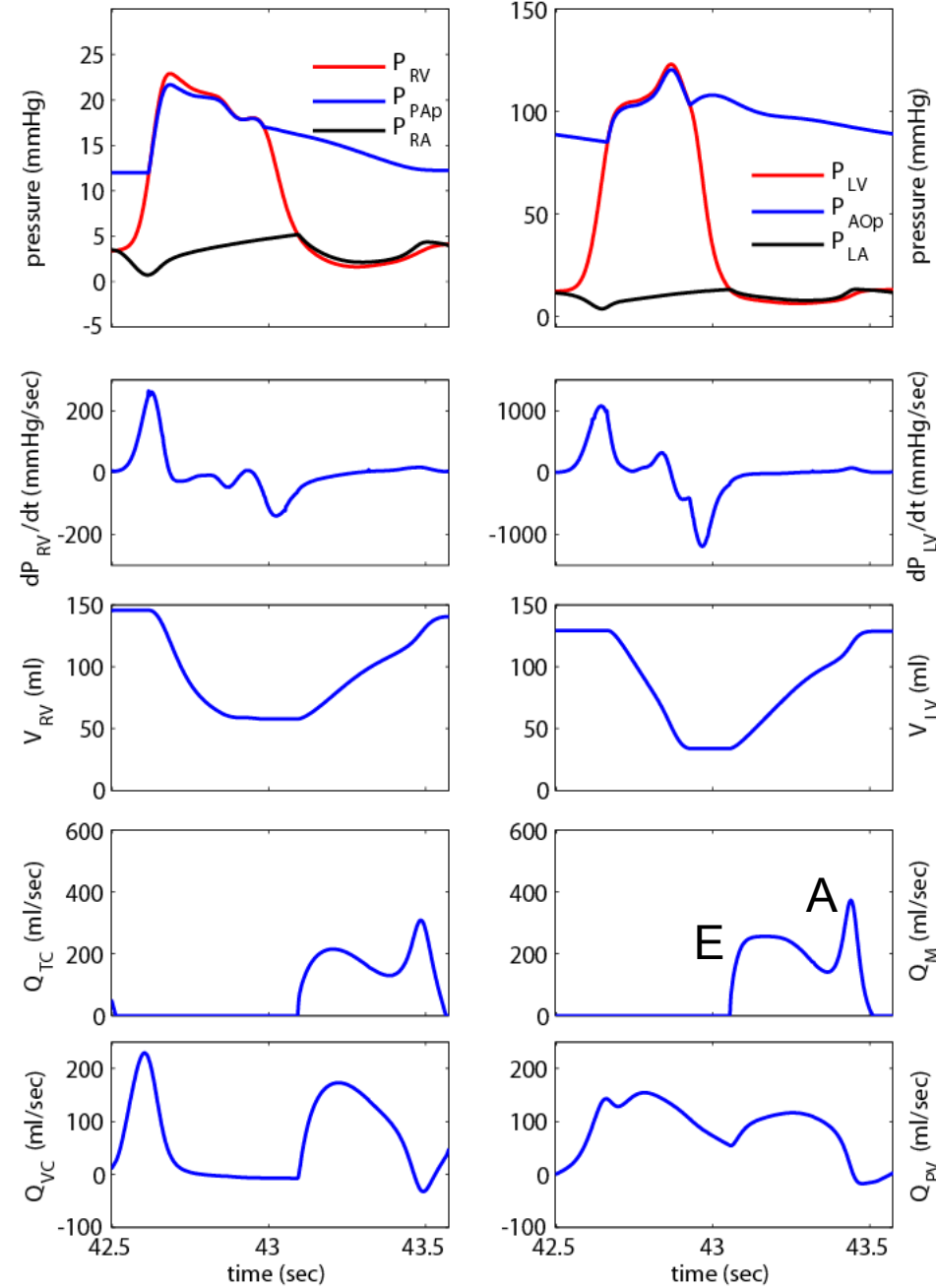
AFF = atrial filling fraction
 IVRT = isovolumic relaxation time
 PFR = peak filling rate
 RFF = rapid filling fraction

LVDD Diagnosis Using Doppler Flow Recordings

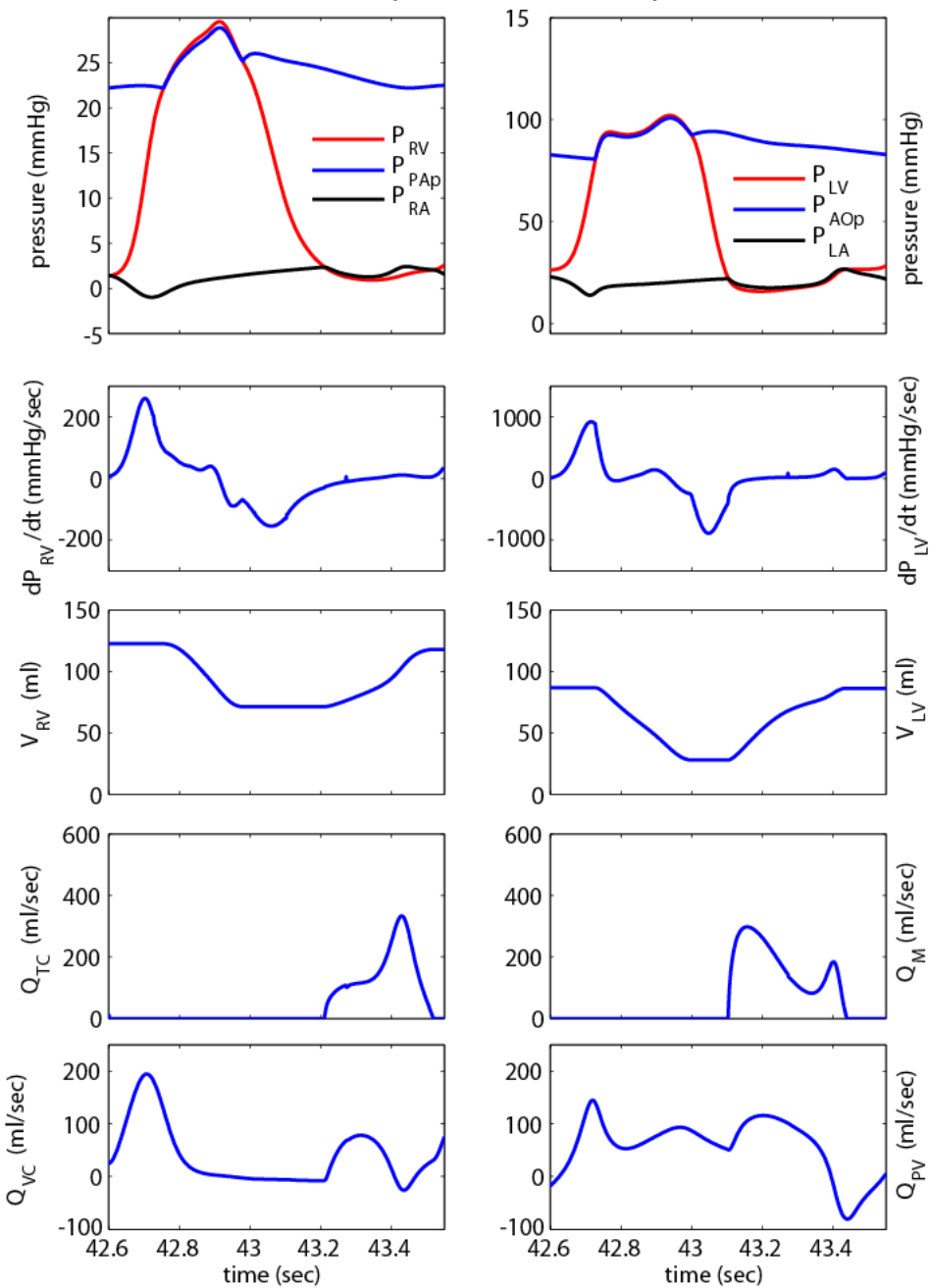
- Three flow velocity patterns of interest
 - Incomplete Relaxation (IR)
 - ✓ Evident in early rapid filling of LV
 - Restrictive
 - ✓ Evident in late diastole particularly with atrial contraction
 - High late diastolic pressure in LV
 - Pseudonormal
 - ✓ Mixed pattern
- Valve flow velocity recordings are related to the pressure drop across the valve
 - When the pressure gradient is small, so is the amplitude of the flow velocity recording

LVDD (Impaired Relaxation)

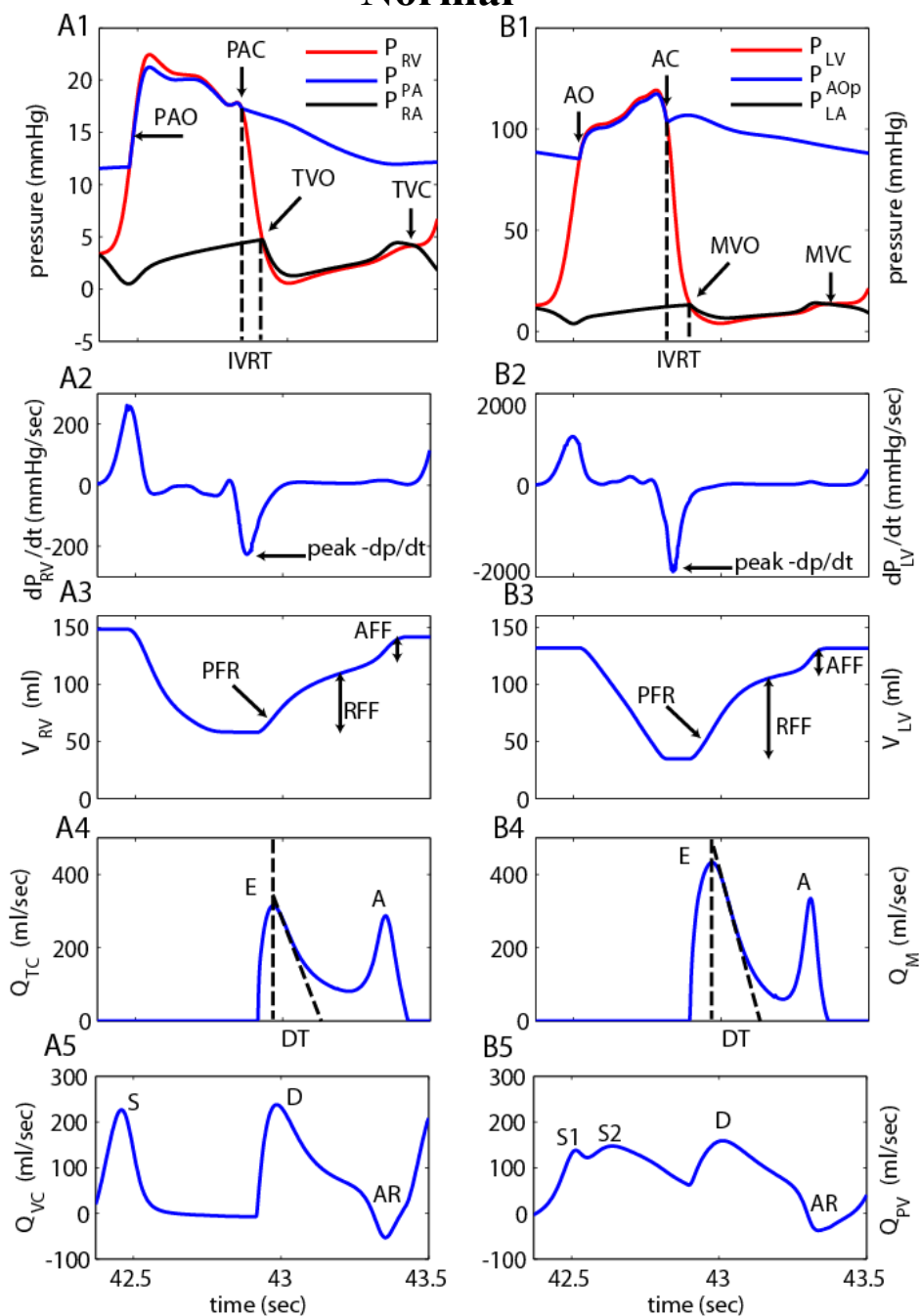
LVDD – Impaired Relaxation



LVDD (Pseudonormal)



Normal



Conclusions

- Adjustment of a relatively small number of parameters associated with the LV mechanics model, allows one to simulate many features of LV diastolic dysfunction (LVDD).
 - The stiffness parameter λ associated with the LV free wall and septum is very important in characterizing the restrictive features of LVDD inlet flow velocity patterns
 - For strong changes in isovolumic relaxation time (IVRT), parameters associated with the temporal decay of the ventricular activation function are also changed

$$e(t) = \sum_{i=1}^N A_i \exp\left(-\frac{(t - C_i)^2}{2B_i^2}\right)$$

- Thus, changes in these parameters allow one to produce good mimicry of the three well-recognized patterns of Doppler velocity signals in LVDD

