2013年先進電機電子科技研討會—
生物、醫學與電子科技的交流

電導心導管量測系統分析

Chia-Ling Wei（魏嘉玲）, Associate Professor
Department of Electrical Engineering,
National Cheng Kung University, Tainan, Taiwan

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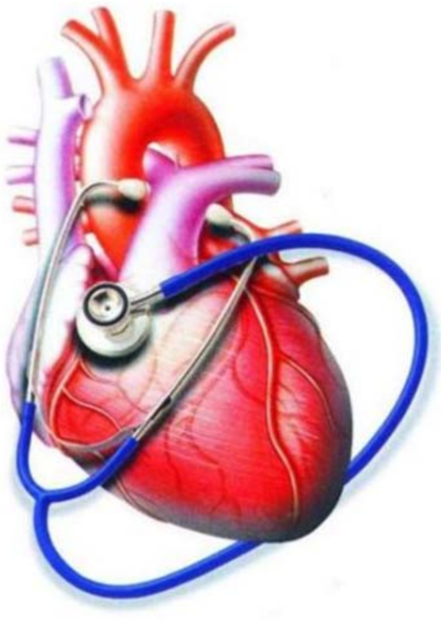
Outline

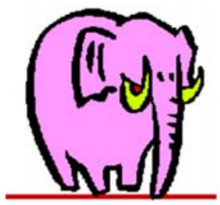
- Motivation
- Cardiology and Pressure-Volume Loop
- Introduction of Conductance Catheter Measurement System
- Issues of Conductance Catheter Measurement System
- Improvements and Achievement
- Conclusion

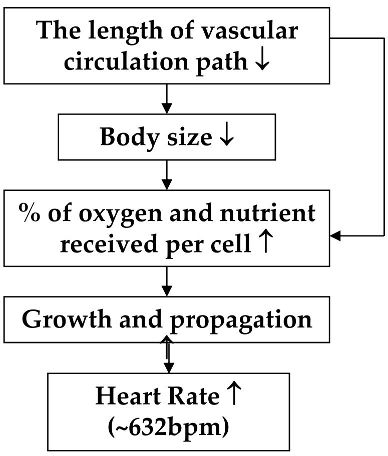
Motivation

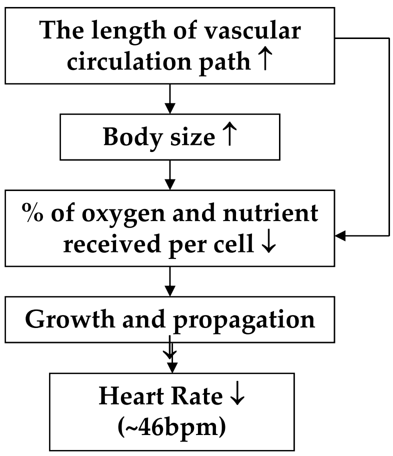
- Heart disease
  - More than 5,000,000 each year (USA)
  - One of the top ten death reasons (Taiwan)
- Heart-related Research
  - Gene
  - Medicine
- Animal Experiments
  - A method to quantitatively evaluate the performance of a heart is needed.



Heart in Different Animals

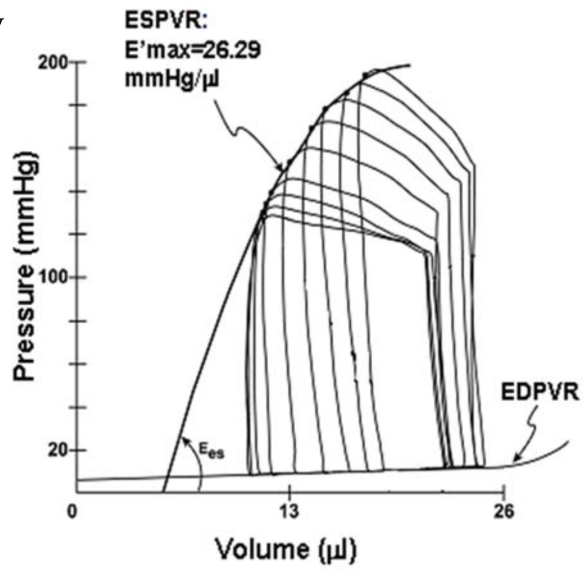






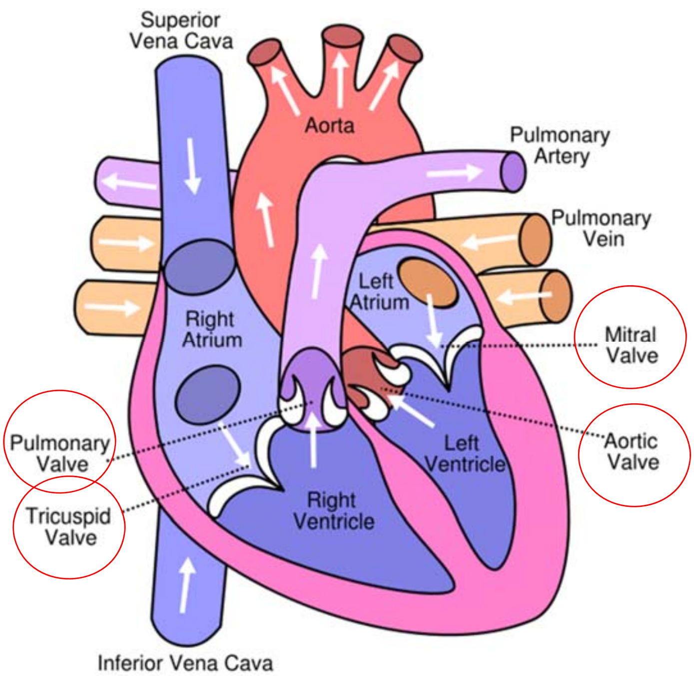
Pressure-Volume Loops

- Pressure-volume loop analysis
  - Hemodynamic characterization of LV function
  - Myocardial physiologic function
- Baseline
  - Stroke volume
  - EDV & ESV
  - End-diastolic pressure
  - End-systolic pressure
- Dynamic
  - Preload
  - Afterload

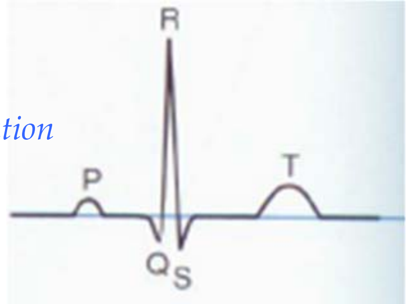


Cardiac Anatomy

- Left and Right Atrium (LA & RA)
- Left and Right Ventricle (LV & RV)
- Aortic valve
- Pulmonary valve
- Mitral valve
  - bicuspid valve (二尖辦膜)
- Tricuspid valve (三尖辦膜)



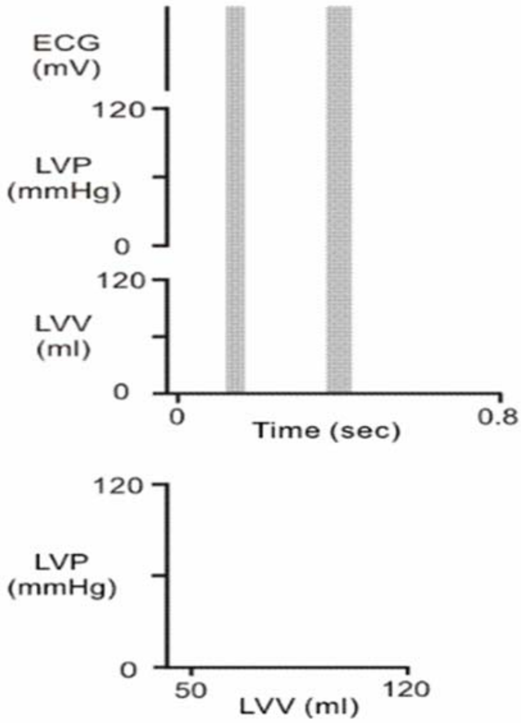
Electrical Behavior of Cardiac Cells



- The *P wave* is produced by *atrial depolarization*
- The *QRS complex* primarily by *ventricular depolarization*
- The *T wave* by *ventricular repolarization*
  - The atrial repolarization is masked by QRS complex
- P-R interval is caused by conduction delay in the AV node
- S-T segment is related to the average duration of the plateau regions of individual ventricular cells
- A small additional U wave is sometimes recorded, which is due to slow repolarization of ventricular papillary(乳突肌) muscles.

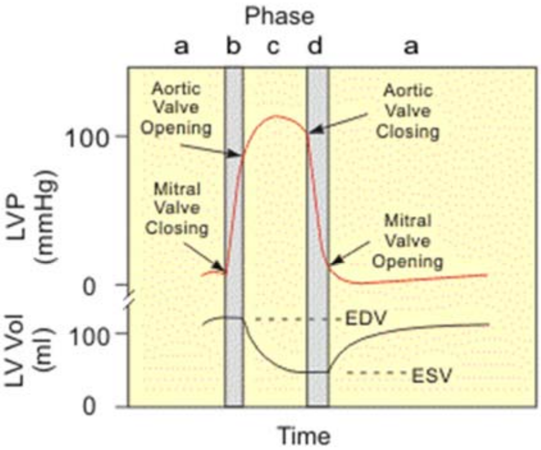
Pressure-Volume Loop

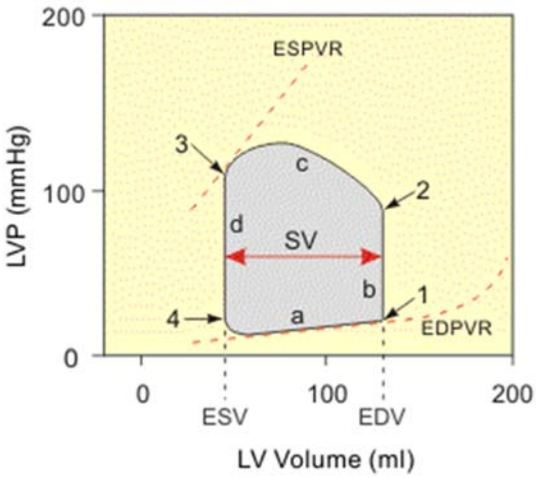
- LV pressure-volume (PV) loops
  - pressure and volume information in the cardiac cycle diagram.
  - SV
    - the width of the loop
  - Ventricular stroke work
    - the area within the loop



Pressure-Volume Loop

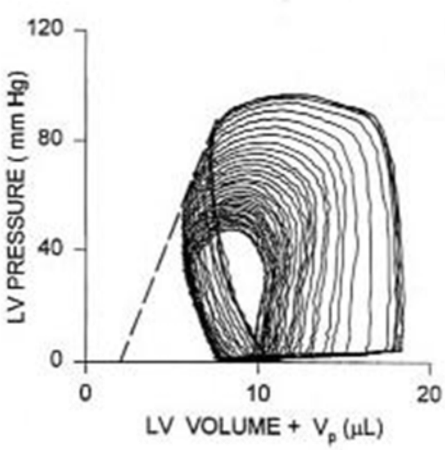
- Phase a: ventricular filling (diastole)
- Phase b: isovolumetric contraction
- Phase c: ventricular ejection (systole)
- Phase d: isovolumetric relaxation



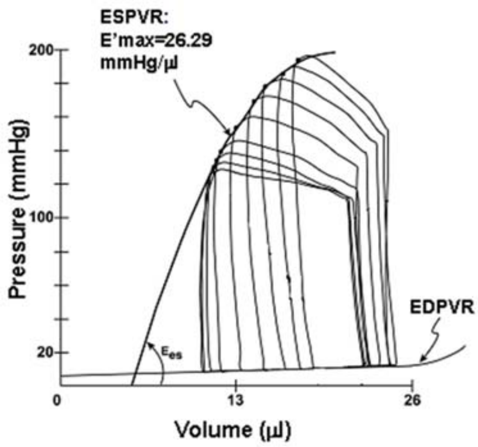


Measurement of ESPVR and EDPVR

- ESPVR and EDPVR
  - dynamically changing preload and afterload



Decreasing preload

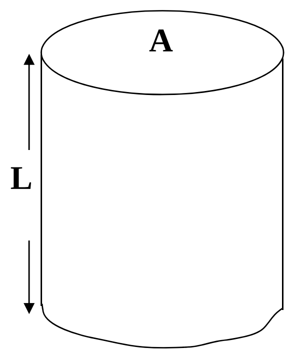


Increasing afterload

Transgenic Mice

- Transgenic mice
  - Similar to human genes
  - Short generation
  - Cheap
- Issue of measuring mouse LV volume
  - Too small: LV ~ 15~80 μl (0.015~0.08 cc)
  - Too fast: up to 600 bpm
- Conductance catheter measurement (1984)
  - G=1/R
  - proportional to volume

The Relationship between Volume and Conductance



- Volume *Vol*

$$Vol = A \cdot L$$

- Conductance *G*

$$G = \frac{1}{R} = \frac{A}{\rho L} \Rightarrow A = \rho G L$$

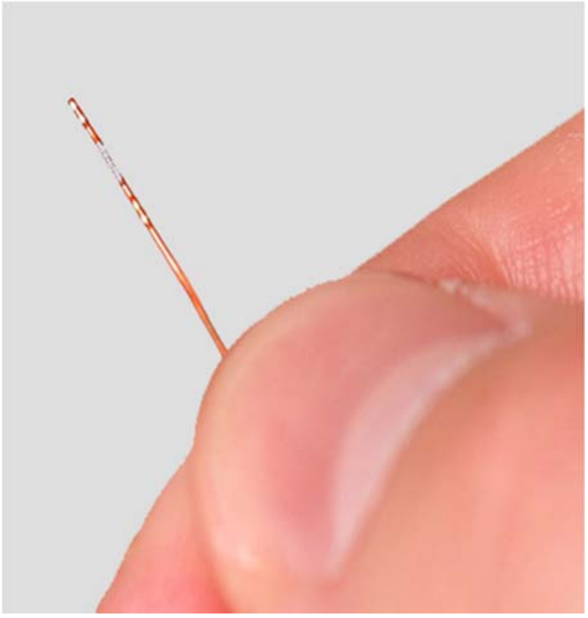
- The relationship between Volume and Conductance

$$Vol = (\rho G L) \cdot L = \rho L^2 G$$

- Linear relationship

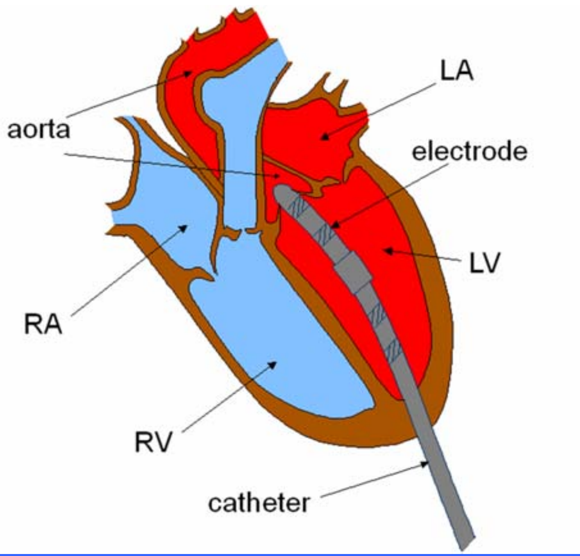
Conductance Catheter

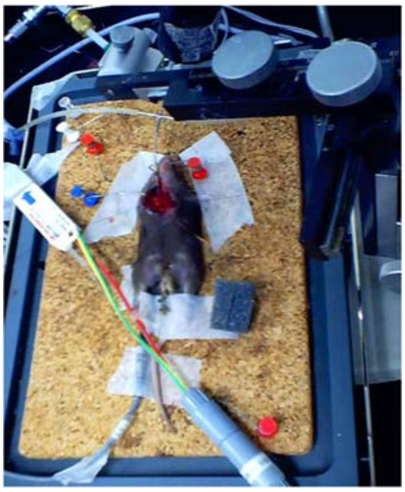
- Millar Instruments, Houston, Texas, USA.
- Conductance catheter (SPR-719)



Placement of Conductance Catheter

- A four-electrode conductance catheter
  - typically used in mice and rats
  - More electrodes for larger animals





Inferior *Vena Caval* Occlusion

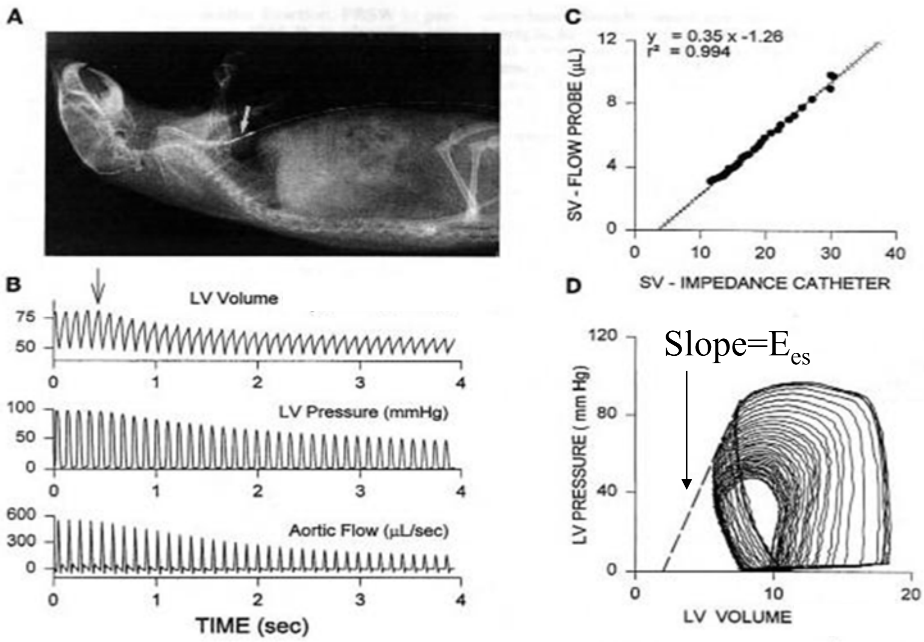
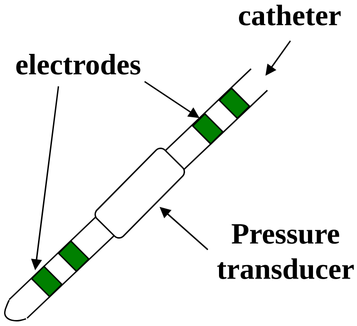
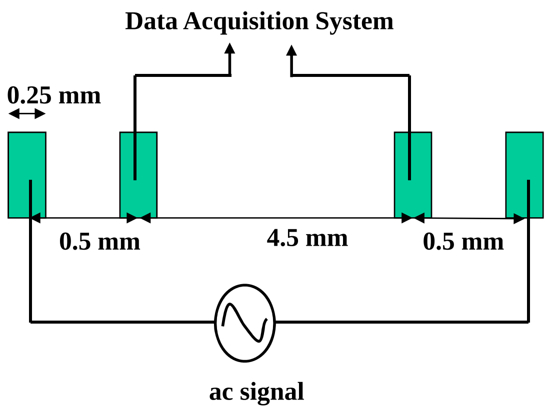


Illustration of Conductance Catheter Principle

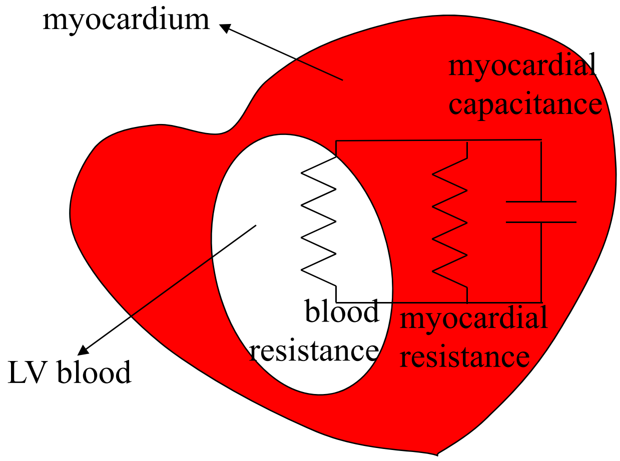
- Inject an ac current: I
- Sensed the voltage: V
- Conductance G = I/V





How to Convert Conductance to Volume?

- Both LV blood and myocardium are conductive.
  - Only the blood conductance is desired
  - Remove the myocardial contribution



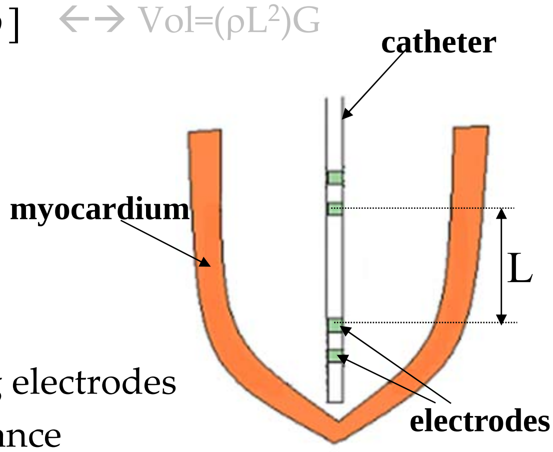
Baan's Conductance-to-Volume Conversion Equation

- The conductance-to-volume conversion equation

$$Vol(t) = \frac{1}{\alpha}\rho L^2[G_{meas}(t) - Gp] \quad \leftarrow\rightarrow \quad Vol=(\rho L^2)G$$

where

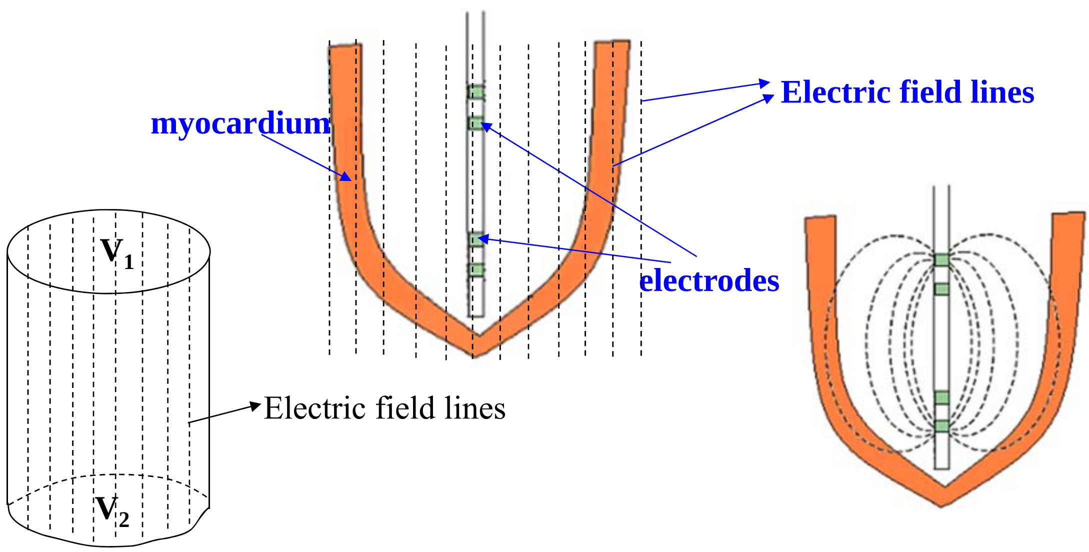
Vol(t): volume
α: calibration factor
ρ: blood resistivity
L: distance between sensing electrodes
$G_{meas}(t)$: measured conductance
Gp : myocardial conductance



Accuracy of Conductance Catheter System

- Accuracy is mainly limited by three factors:
  - Assumption of a linear conductance-volume relationship
  - Deviation of the catheter position inside the LV
  - Estimation of myocardial contribution

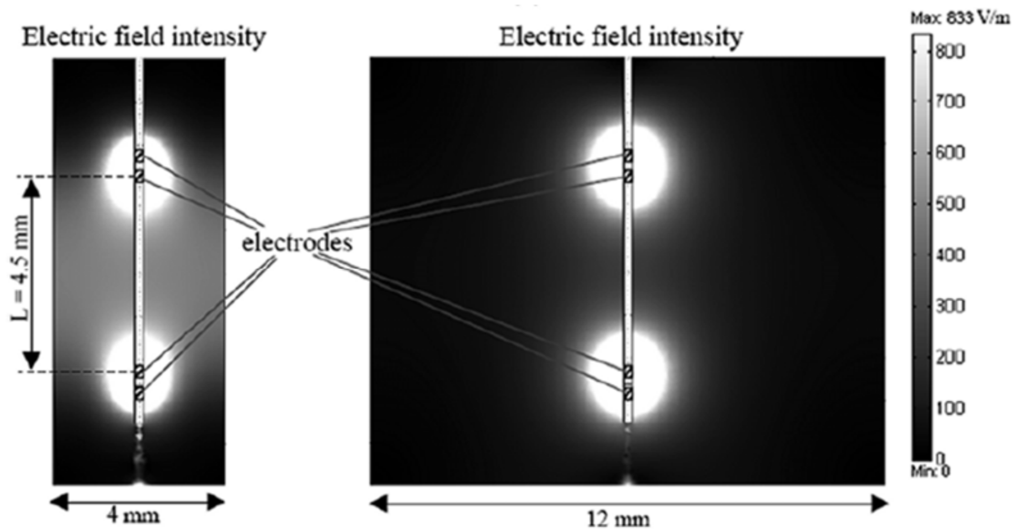
Distribution of Electric field



- Inhomogeneous → nonlinear conductance-volume relationship

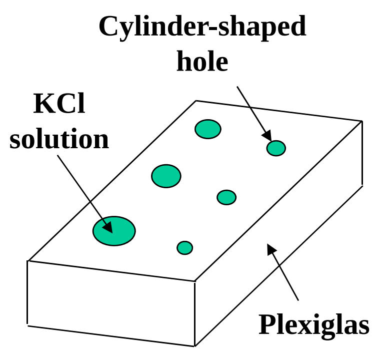
Inhomogeneous Electrical Field: Conductance-Catheter Case

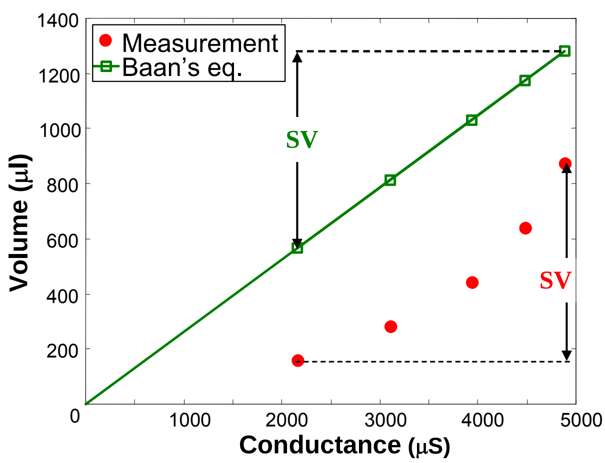
- The electric field generated by LV catheter electrodes is not uniform.



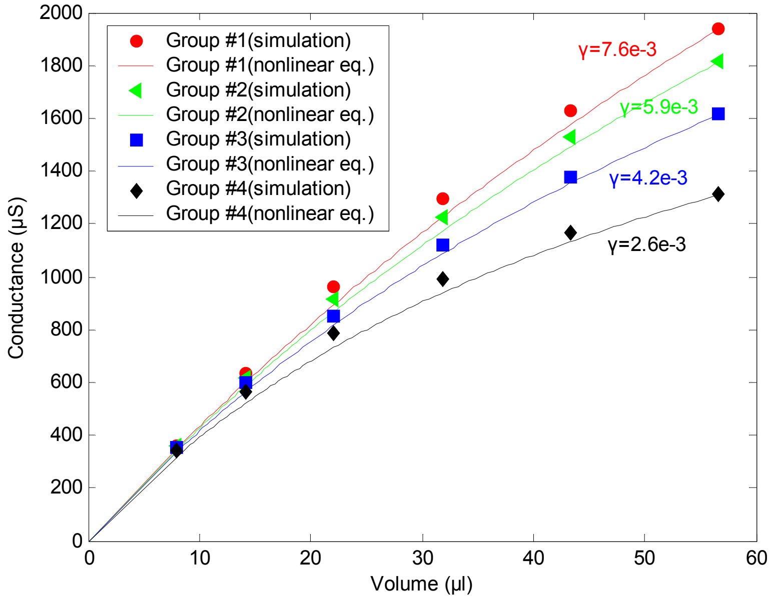
Nonlinear Conductance-Volume Relationship

- Nonlinear relationship
- Baan's equation overestimates volumes





Conductance-Volume Relationship v.s. Catheter Position

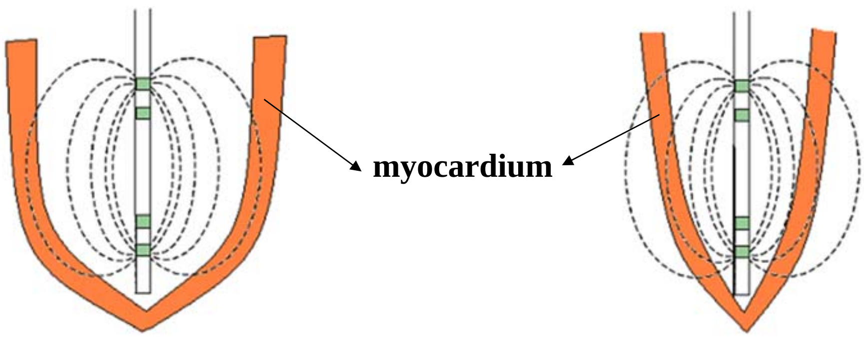


Assumptions of Constant Myocardial Contribution

- The conductance catheter technique has long been said to have constant parallel conductance or current leakage into the myocardial wall throughout the cardiac cycle.
  - Previous studies only determine a single steady state value for the parallel myocardial contribution to conductance
    - Constant myocardial contribution
      $Vol(t)=(1/\alpha)(\rho L^2)(\ Gi(t)-Gp)$
      Not a function of time

Time-Varying Myocardial Contribution

- The fraction of total current reaching the myocardium varies between end-systole and end-diastole because the myocardium changes distance from the source electrodes
  - Time-varying myocardial contribution



Improvements & Achievements

Nonlinear Approximation Equation

$$\alpha(g_b) = 1 - \frac{g_b}{\gamma}$$

$$\text{Vol} = \frac{1}{\alpha(g_b)}\rho L^2 g_b = \frac{\gamma}{\gamma - g_b}\rho L^2 g_b$$

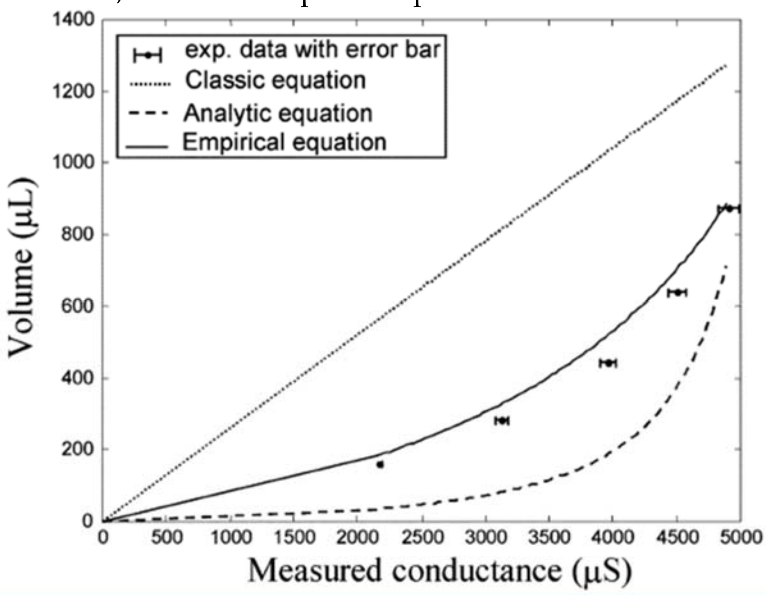
- Use the SV to calibrate the system as Baan's equation, and then the empirical factor γ can be determined by

$$\gamma = \frac{-b \pm \sqrt{b^2 - 4ac}}{2a}$$

$$a = \text{SV} - \rho L^2(g_{b-\text{ED}} - g_{b-\text{ES}})$$
$$b = -\text{SV} \cdot (g_{b-\text{ED}} + g_{b-\text{ES}})$$
$$c = \text{SV} \cdot g_{b-\text{ED}} \cdot g_{b-\text{ES}}.$$

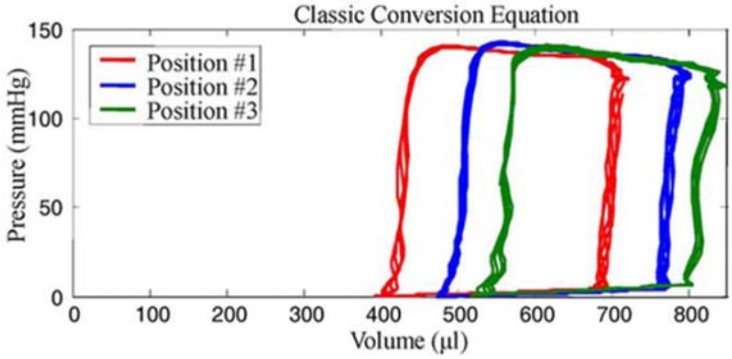
Rat LV-Sized Volume Range

- A rat catheter (SPR-838, Millar Instruments) was used.
  - Baan's equation overestimates the volumes and the analytic equation underestimates the volume, while the empirical equation estimation is closest to the true volume.

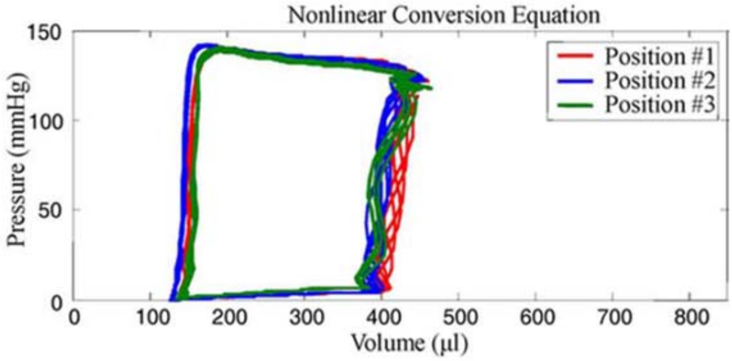


In Vivo Rat Experiment

- Baan's Equation

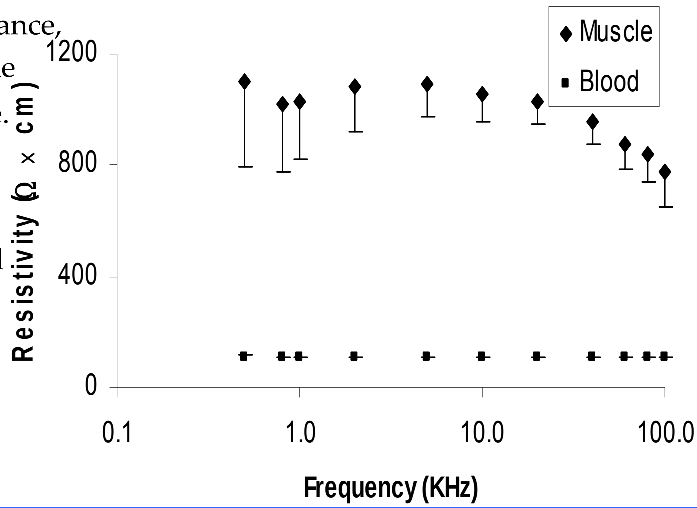


- Wei's Equation



Electrical Property of Myocardium

- For frequencies below 100 kHz, blood has been shown to be pure resistive, while myocardium has both resistive and capacitive properties.
  - The capacitive property of myocardium makes the "apparent" myocardial resistivity decrease with increasing frequency.
  - Instead of myocardial conductance, it is more appropriate to use the term of myocardial admittance.
  - The distinguished capacitive property of myocardium can be used to separate myocardial contribution from blood conductance.



Myocardial Conductance and Capacitance

- In electromagnetism, the myocardial conductance g_m and myocardial capacitance C_m can be represented as

$$g_m = \frac{I}{V} = \frac{\oint_A J \cdot dA}{-\int_L E \cdot dl} = \frac{\oint_A \sigma_m E \cdot dA}{-\int_L E \cdot dl}$$

$$C_m = \frac{Q}{V} = \frac{\oint_A \varepsilon_m E \cdot dA}{-\int_L E \cdot dl}$$

where σ_m is myocardial conductivity, ε_m is myocardial permittivity, E is electric field, J is current density, I is current, Q is charge, A is the area of the surface enclosing the source electrode, and L is the path length for potential calculation.

Myocardial Conductance and Capacitance

- Assumed that both σ_m and ε_m are isotropic constants in the myocardium:

$$g_m = \sigma_m \frac{\oint_A E \cdot dA}{-\int_L E \cdot dl}$$

$$C_m = \varepsilon_m \frac{\oint_A E \cdot dA}{-\int_L E \cdot dl}$$

Hence, the well-known conductance-capacitance analogy is yielded:

$$\frac{C_m}{g_m} = \frac{\varepsilon_m}{\sigma_m}$$

- Either myocardial conductance g_m or myocardial capacitance C_m is once determined, the other one can be calculated by the analogy.

Admittance Measurement Technique

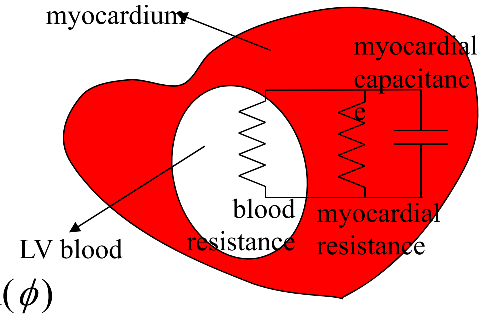
- ❑ The admittance measurement consists of magnitude measurement and phase measurement.
- ❑ Magnitude ($|Y_{meas}|$)+ phase (ϕ) measurements ➔ admittance (Y_{meas})

$$Re\{Y_{meas}\} = |Y_{meas}|\cos(\phi) = g_b + g_m$$

$$Im\{Y_{meas}\} = |Y_{meas}|\sin(\phi) = 2\pi f C_m$$

- ♦ Myocardial capacitance C_m

$$C_m = \frac{|Y_{meas}| \cdot \sin(\phi)}{2\pi f}$$

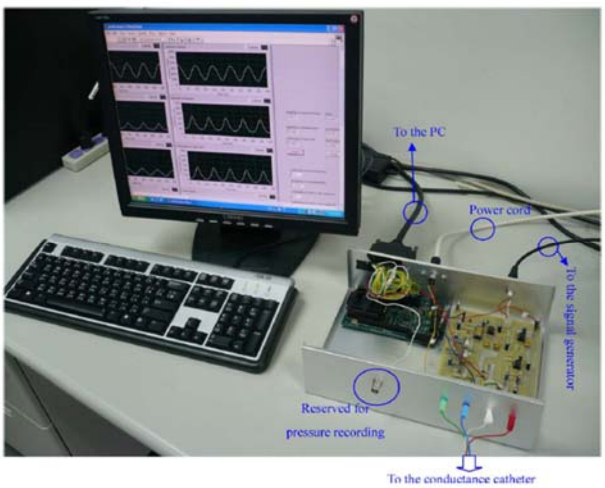


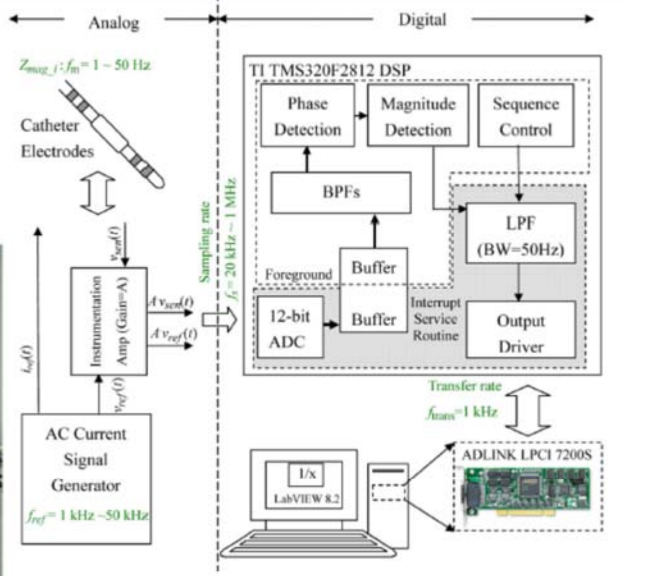
- ♦ The myocardial conductance g_m

$$g_m = \frac{\sigma_m}{\varepsilon_m} C_m = \frac{\sigma_m |Y_{meas}| \sin(\phi)}{2\pi f \varepsilon_m}$$

DSP-Based Admittance Measurement System

- ❑ Real-time measurement
- ❑ Single frequency





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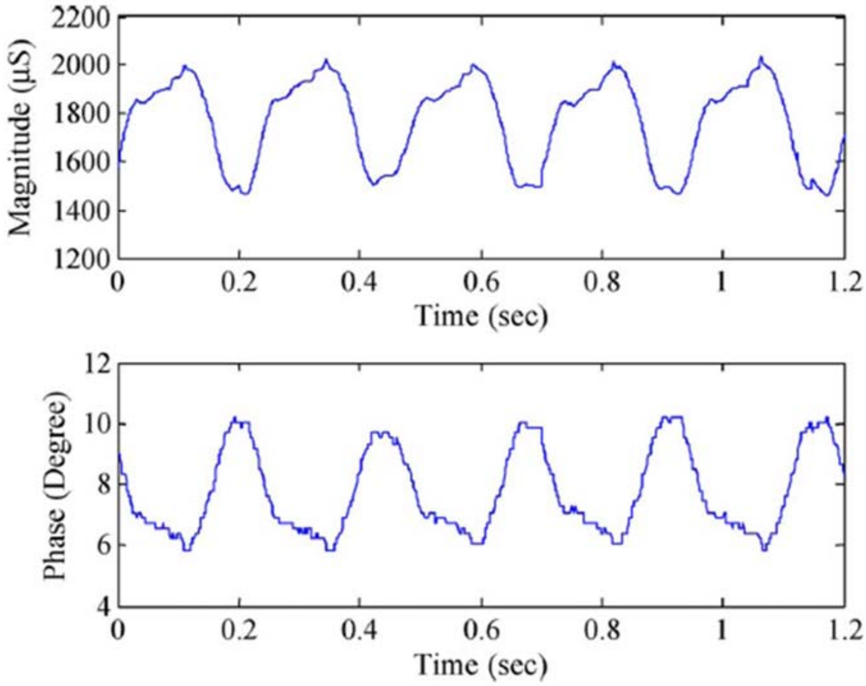
In Vivo Measured Waveform



Commercial PV Loop Measurement Systems

- Commercial conductance catheter measurement systems are available.
  - Millar Instruments, Houston, Texas, USA
    - Baan's Equation
  - Scisense, London, Ontario, Canada
    - Baan's Equation
    - Wei's Equation

Conclusion

- There are still many issues about the conductance catheter system.
  - Multidiscipline research
    - (Cardiac dynamics, Electromagnetism, Electronics, Digital image processing, Digital signal processing, *in vivo* & *in vitro* experiments, etc.)
  - Interesting

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