Accuracy of Stroke Volume Estimation from Blood Pressure Measurement

via Reservoir Pressure Concept and Three Element Windkessel Model

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Introduction

Cardiac and circulatory disease are the largest cause of death in the western world, and are the leading cause of ICU admission and mortality (WHO Global report)

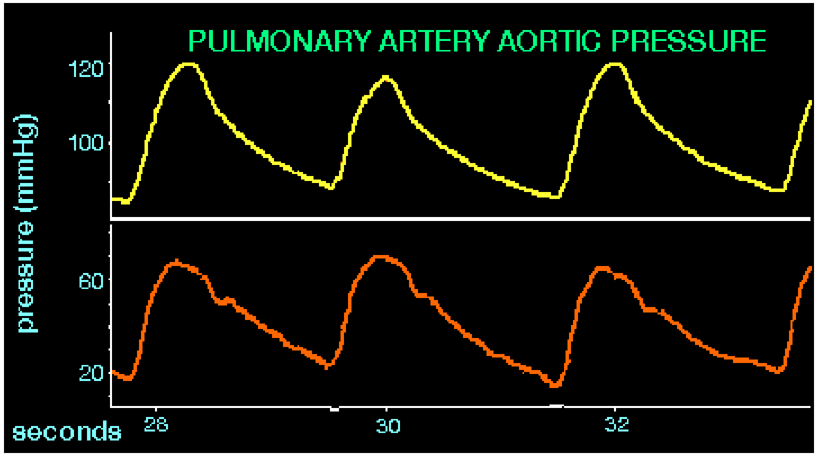
- Expected to increase with increasing elderly population
- 1 in every 3 deaths are related to cardiovascular disease
- Accounts for 30% of all ICU admissions (and mortality)

Patients with cardiovascular disease require hemodynamic monitors to obtain patient information for diagnosis and treatment

Hemodynamic Monitors

Pressure catheter

Blood pressure displayed on monitor



Blood Pressure Value?

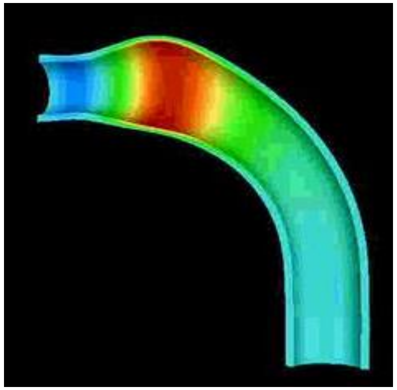
Main goal of cardiovascular support/treatment is to maintain adequate cellular perfusion and delivery of oxygen.

Pressure = Supply ?

Cardiovascular Physiology

Blood Vessels / Pressure / Flow

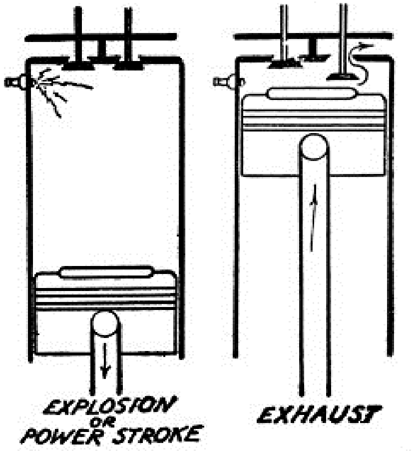
Pressure inside the artery depends not only on Volume, but also on Compliance. Flow through the artery depends on downstream Resistance



Pressure ≠ Supply

Stroke Volume

Amount of blood pumped from the heart each beat. Better metric to assess cardiovascular performance and perfusion.



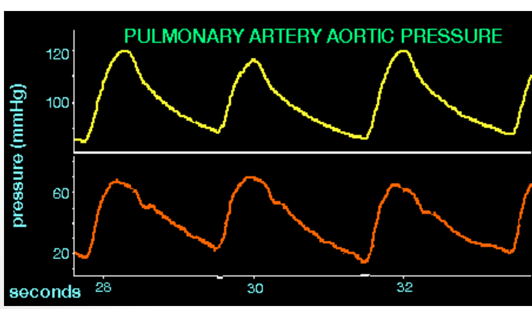
How to Measure SV?

Difficulties

- “Humans are horribly variable” (J.L Dickson et al)
- Direct measurements are highly invasive and clinically not feasible

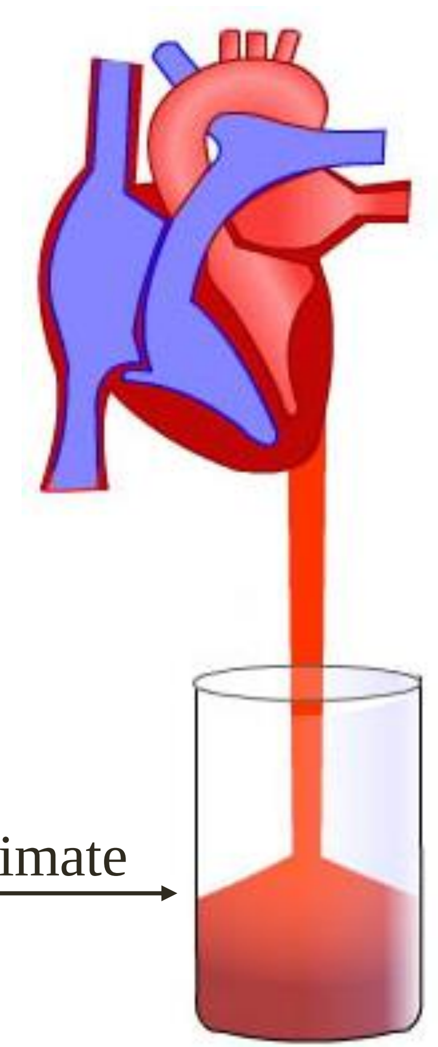
Method

A model-based analysis of blood pressure waveform to estimate Stroke Volume.



Analyse Pressure Contour

Estimate



Aortic Pressure Model

Reservoir pressure concept

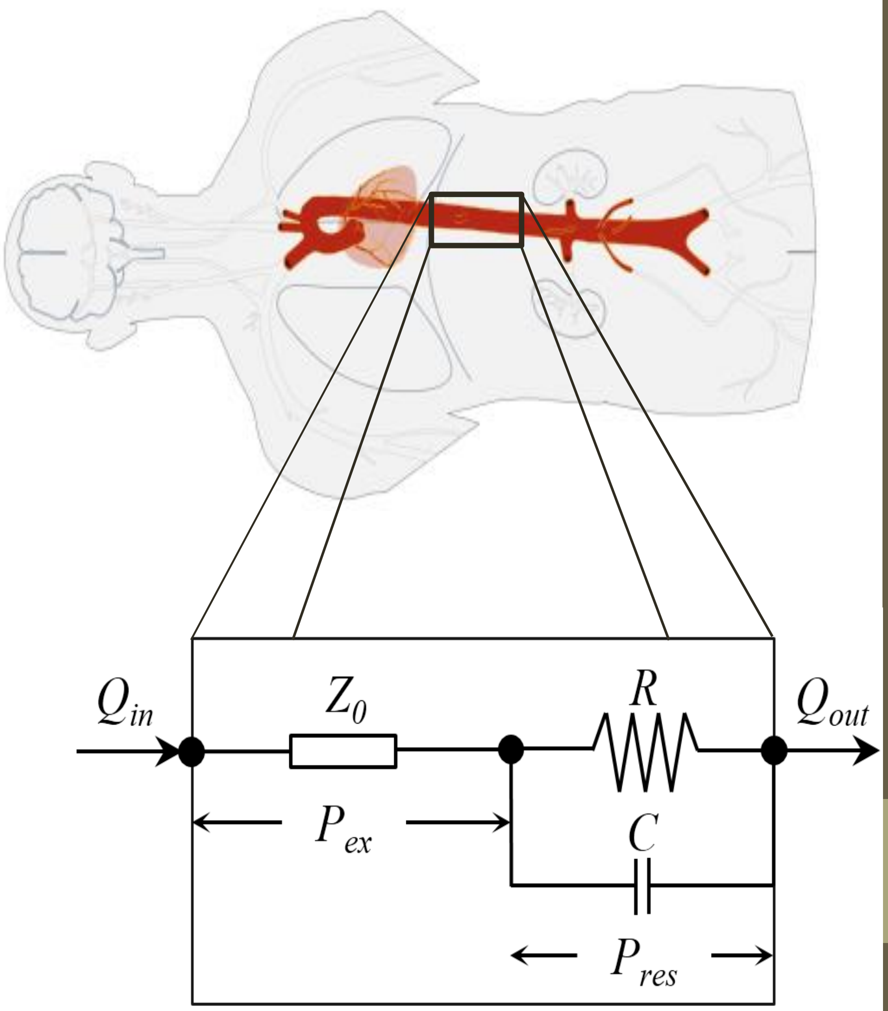
Aortic pressure (P_{ao}) can be represented as the sum of two pressure components

1. Reservoir pressure (P_{res}) accounts for the energy stored/released by the arterial wall
2. Excess pressure (P_{ex}) which is linearly proportional to Q_{in}

$$P_{ao}(t) = P_{res}(t) + P_{ex}(t)$$
$$P_{ex}(t) \propto Q_{in}(t)$$

Three Element Windkessel

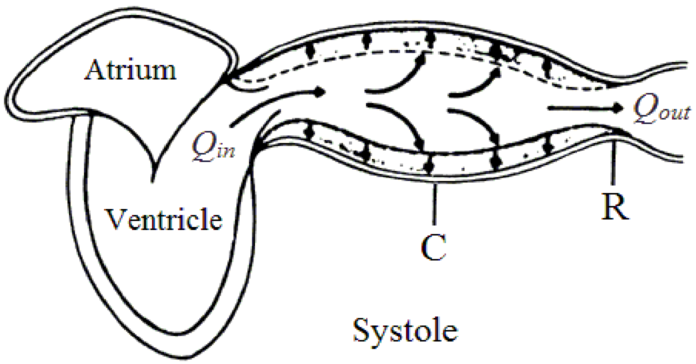
Z_0 - Characteristic impedance
R - Peripheral resistance
C - Aortic compliance



Model Element Relationships

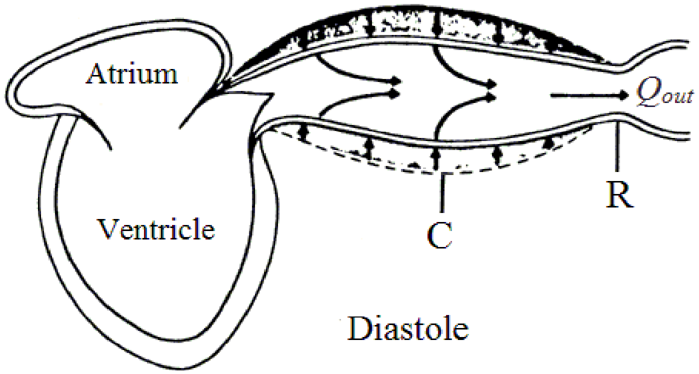
Reservoir Pressure

$$\frac{dP_{res}(t)}{dt} = \frac{Q_{in}(t) - Q_{out}(t)}{C}$$



Flow Leaving Aorta

$$Q_{out}(t) = \frac{P_{res}(t) - P_{msf}}{R}$$



Combine

$$\frac{dP_{res}(t)}{dt} = \frac{P_{ao}(t) - P_{res}(t)}{Z_0 C} - \frac{P_{res}(t) - P_{msf}}{RC}$$

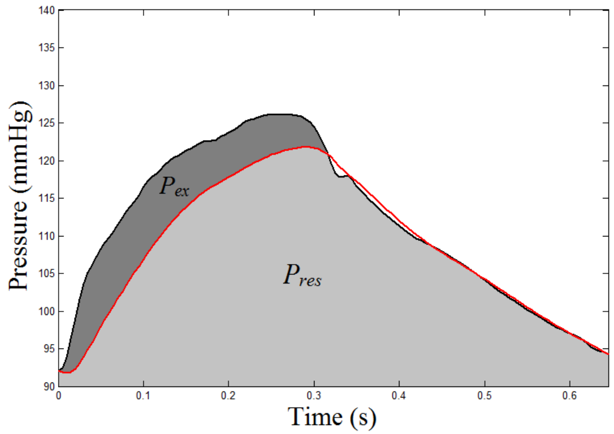
Stroke Volume Estimation

Three estimates of SV can be made

1 $$SV_R = \frac{1}{R_{subject}} \int^{one\ beat} (P_{res}(t) - P_{msf})dt$$

2 $$SV_c = \frac{C_{subject}}{RC_{identified}} \int^{one\ beat} (P_{res}(t) - P_{msf})dt$$

3 $$SV_{z0} = \frac{1}{Z_{0,subject}} \int^{one\ beat} P_{ex}(t)dt$$

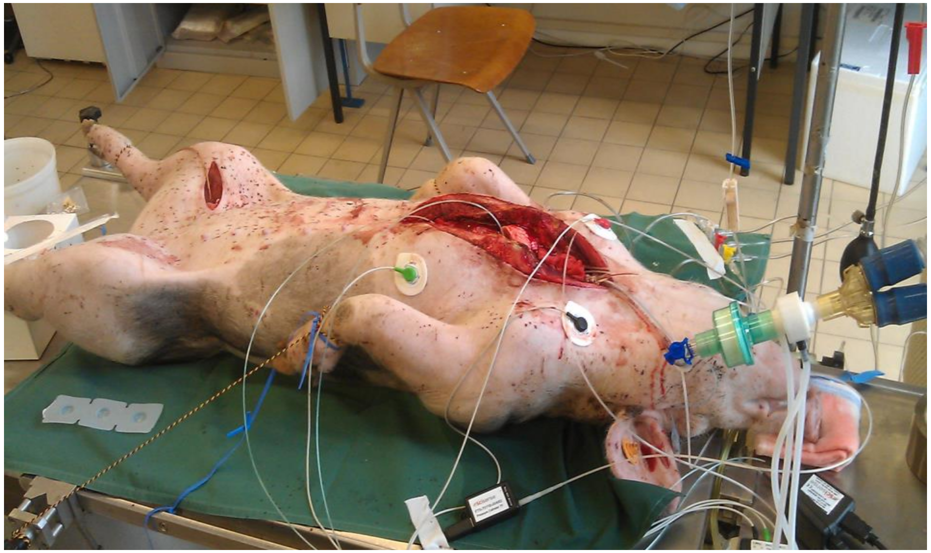


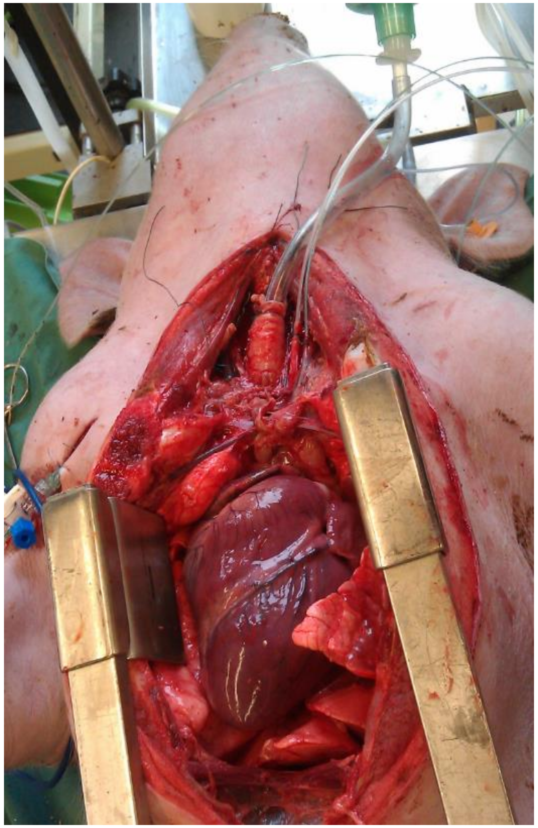
Subject-specific physiological parameters

$$[R, C, Z_0] = argmin_{[R,C,Z_0]}\left(\sum_{i=1}^{number\ of\ beats} abs(SV_{measured,i} - SV_{estimated,i})\right)$$

Experiment

To validate SV estimation via aortic pressure model, data from porcine experiment were used.





GIGA Cardiovascular Science

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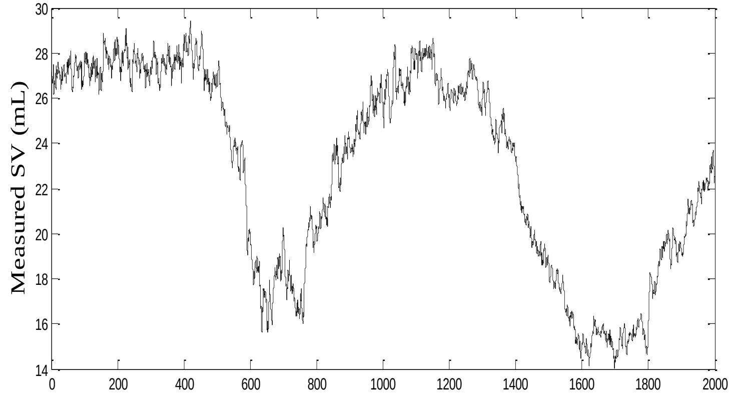
Stroke Volume Changes

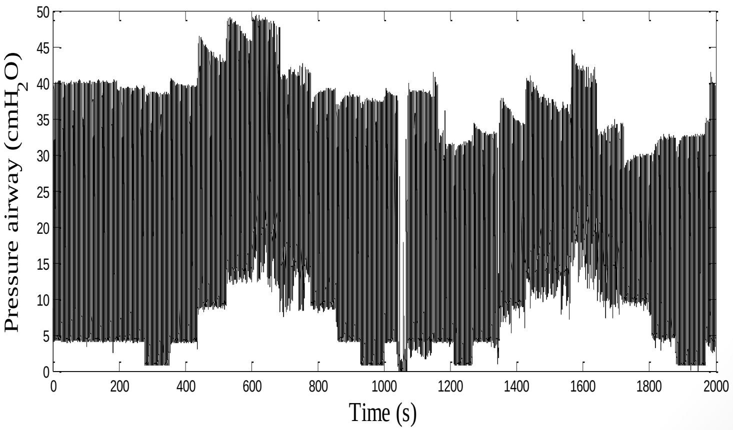
Mechanical ventilation settings

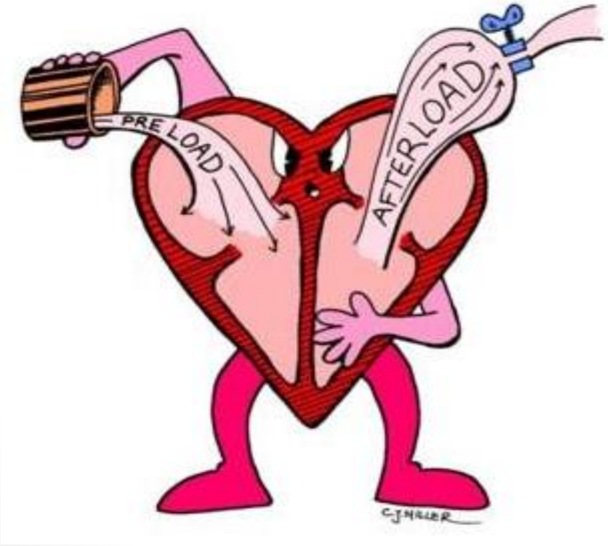
Step-wise changes in positive end expiratory pressure were made

Preload

Airway pressure increase and decrease changes the amount of blood flowing into the ventricle during diastole.



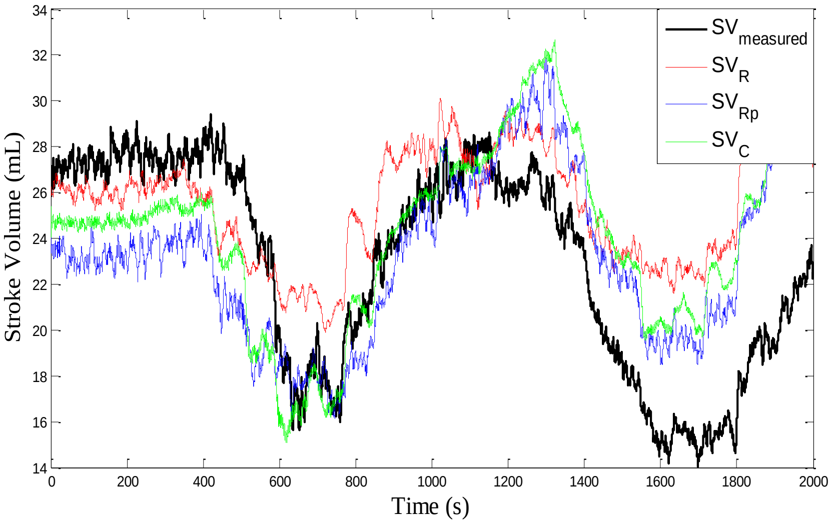




Results

Pig-specific physiological parameters

Pig No	R (mmHg.s/ml)	C (ml/mmHg)	Z_0 (mmHg.s/ml)
Pig 1	1.2104	0.6363	0.0825
Pig 2	2.1353	0.3837	0.1333
Pig 3	0.7008	0.9930	0.0395



Stroke Volume Accuracy

Pig No	Bland-Altman results (ml)		
	ΔSV R	ΔSV C	ΔSV Z_0
Pig 1	0.9 [-11.4, 13.3]	-1.1 [-15.5, 8.1]	0.6 [-10.6, 12.3]
Pig 2	3.9 [-6.5, 8.7]	1.0 [-7.7, 5.1]	2.7 [-5.6, 8.6]
Pig 3	-2 [-7.2, 12.5]	-0.4 [-12.8,10.8]	0.2 [-11.0, 15.0]
All Pigs	2.0 [-10.5,12.9]	0.6 [-13.3, 8.0]	1.5 [-9.9, 12.0]
Overall Average:			
1.4 [-11.3, 12.2]			

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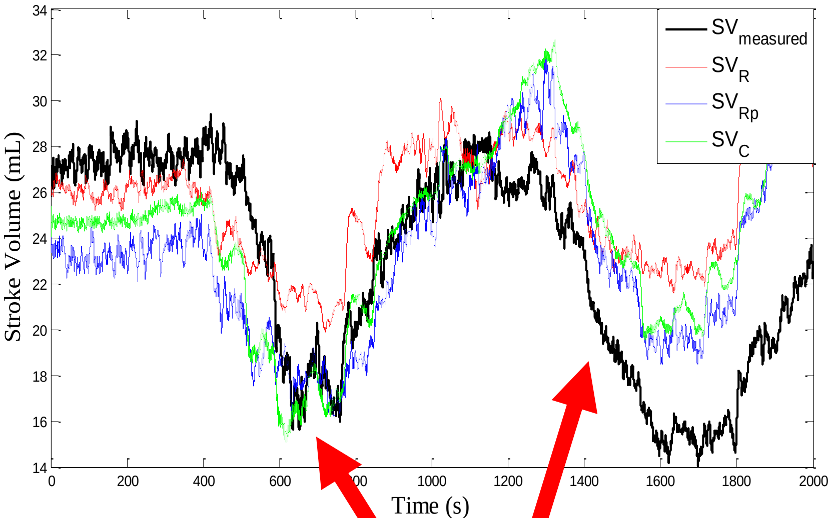

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Trend Accuracy

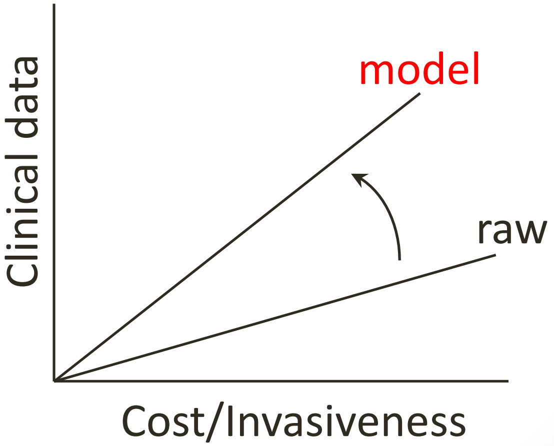
Pig No	Correlation Value (R value)		
	R	C	Z_0
Pig 1	0.68	0.60	0.45
Pig 2	0.65	0.86	0.68
Pig 3	0.66	0.85	0.67
Overall	0.66	0.77	0.60

Clinical Benefit

- Patients cardiovascular performance can be analysed more accurately than just Mean Arterial Pressure (MAP)

- Stroke volume trend can be used to guide treatment selection and to titrate therapy
  - Fluid resuscitation
  - Use of inotrope and vasoactive drugs

- Does not require specialised equipment and/or personnel



Limitation & Future Work

- Change in physiological parameters (R, C, Z_0)
  - Multiple pressure measurements
  - Could one of the three estimate be more reliable measure depending on the patient condition
  - Are changes in value/contour of separated pressure waveform related to changes in parameters

- Aortic pressure measurements (Highly Invasive?)
  - How much information can be retrieved from radial arterial pressure

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This work was supported by EU FP7 IRSES (FP7-PEOPLE-2012-IRSES) program, project title: eTime - Engineering Technology-based Innovation in Medicine, Grant No. 318943.

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Questions?

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Parameter Identification

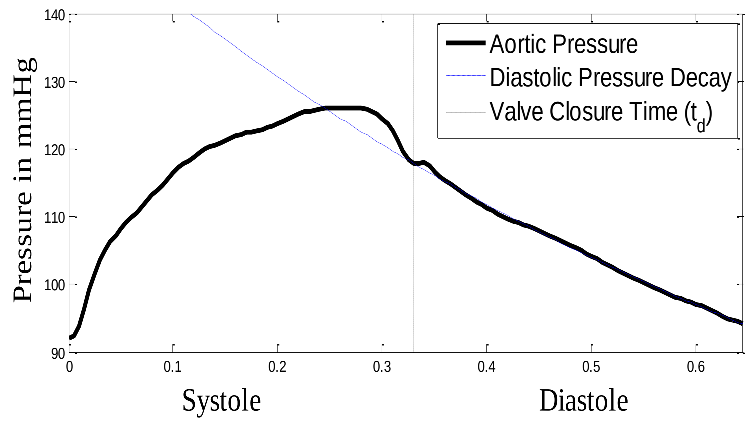
RC & P_{msf}

Diastolic Condition: $P_{res}(t) = P_{ao}(t)$

$Since\ \ Q_{in} = 0$

Diastolic Reservoir

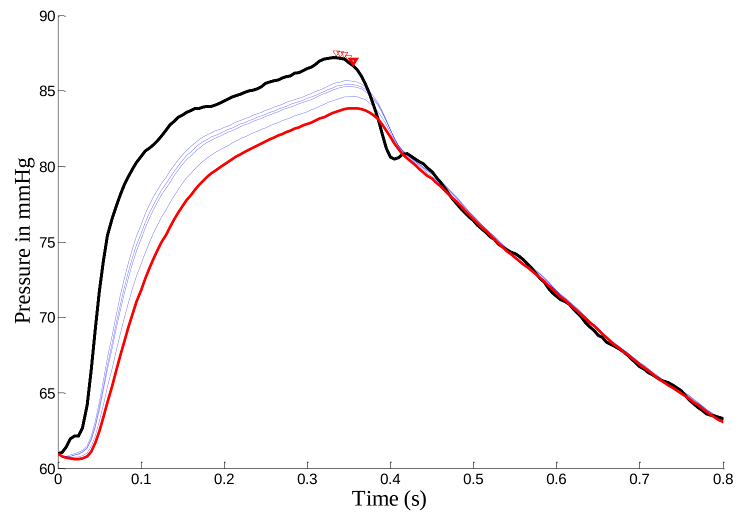
$$P_{res}(t) = \left(P_{ao}(t_d) - P_{msf}\right)e^{-\frac{(t-t_d)}{RC}} + P_{msf}$$



Z_0C

Equilibrium Condition: $\dfrac{dP_{res}(\tau)}{dt} = 0$

$$P_{res}(\tau) = \frac{RCP_{ao}(\tau) + Z_0CP_{msf}}{Z_0C + RC}$$



ODE

$$\frac{dP_{res}(t)}{dt} = \frac{P_{ao}(t) - P_{res}(t)}{Z_0C} - \frac{P_{res}(t) - P_{msf}}{RC}$$