

Study of ventricular interaction during pulmonary embolism using clinical identification in a minimum cardiovascular system model

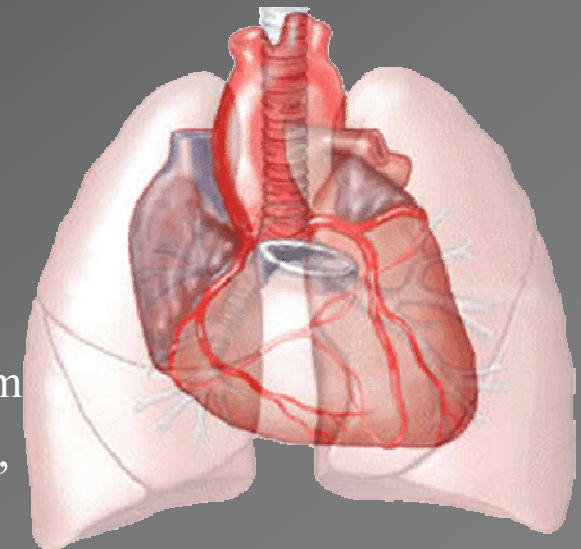
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❑ **General problem:** Cardiovascular disturbances are difficult to diagnose and treat

❑ Large range of possible dysfunctions

❑ Reflex actions can mask the symptoms

————→ Conflicting clinical data

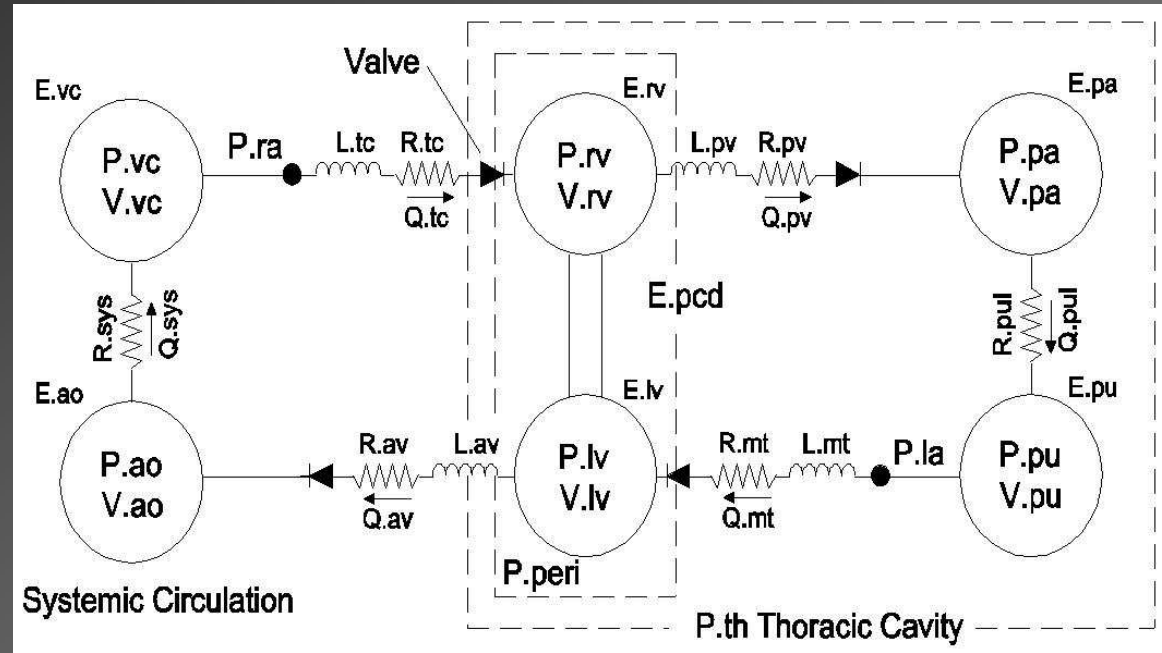
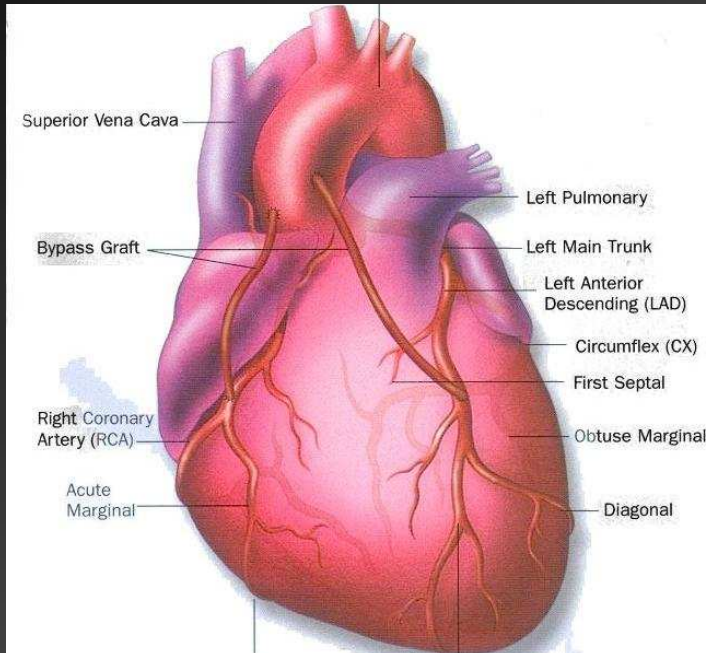
————→ Medical professionals often rely on experience and intuition to optimize the hemodynamics in the critically ill

❑ **Solution:** physiological, identifiable and validated computer model

❑ Minimal Model + Patient-Specific Parameter ID process

❑ Identification must use common ICU measurements

❑ **Application:** evolution of induced pulmonary embolism in porcine data

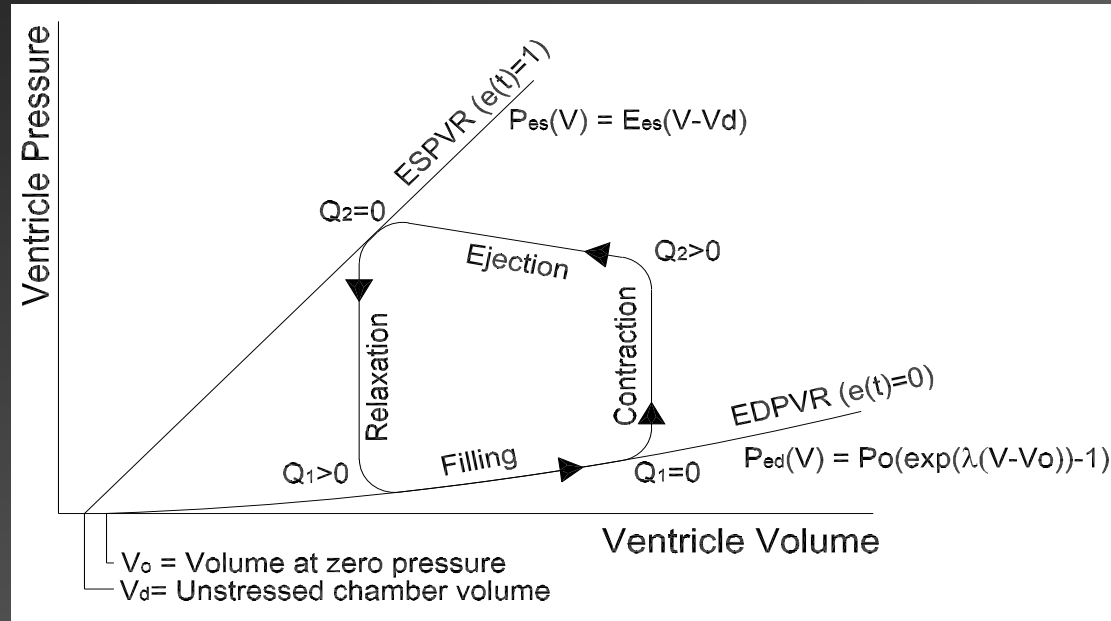


Minimal cardiovascular model:

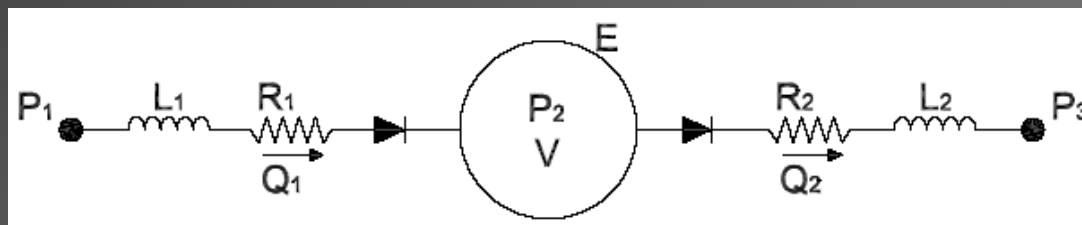
- Physiologically validated
- Capable of capturing patients dynamics commonly seen in the Intensive Care Unit (ICU)
- Using a small number of physiological variables

→ Suitable for rapid diagnostic feedback

P-V diagram



One chamber model



$$\dot{V} = Q_1 - Q_2$$

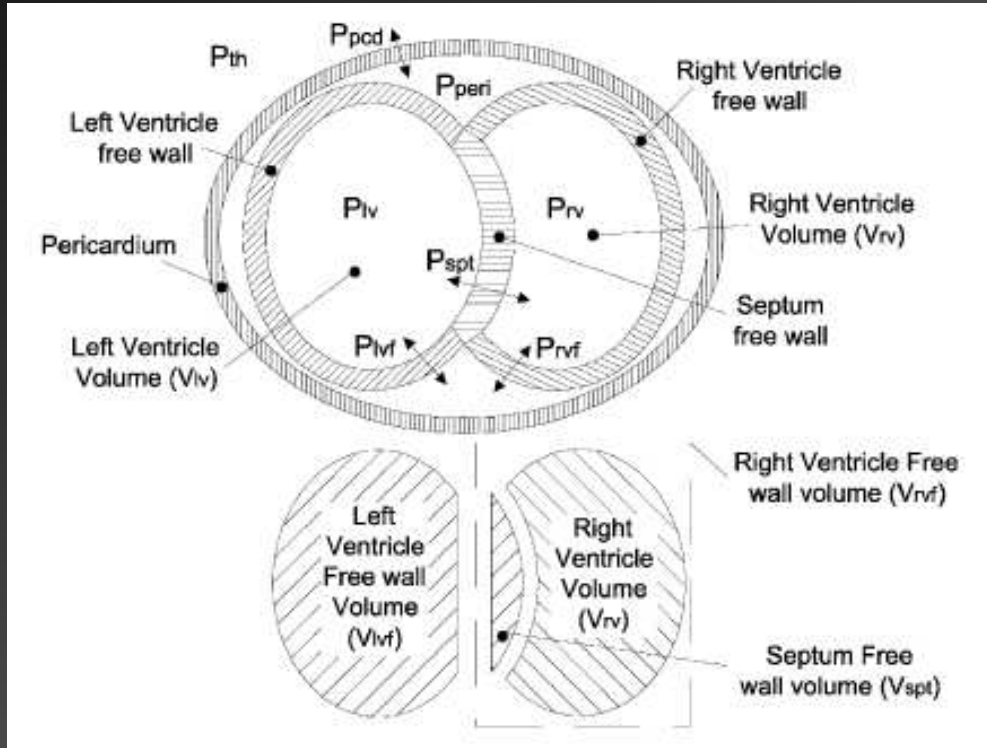
$$\dot{Q}_1 = \frac{P_1 - P_2 - Q_1 R_1}{L_1}$$

$$\dot{Q}_2 = \frac{P_2 - P_3 - Q_2 R_2}{L_2}$$

$$P_2 = e(t)E_{es}(V-V_d) + (1-e(t))P_0(e^{\lambda(V-V_0)} - 1),$$

$$e(t) = e^{-80\left(t - \frac{\text{period}}{2}\right)^2}$$

Ventricular interaction (VI)



- Direct ventricular interaction (VI) has a significant impact on cardiovascular dynamics.
- It is caused by both the septum and the pericardium.
- V_{lvf} , V_{rvf} and V_{spt} are not physical volumes, but are defined to capture the deflection of the cardiac free walls relative to the ventricle volumes.



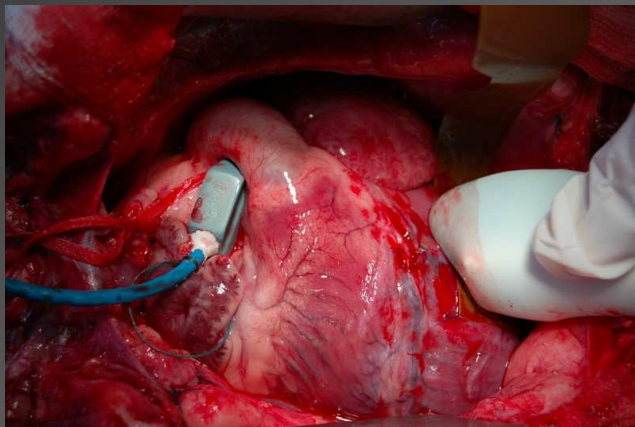
$$\begin{aligned}
 & e(t)E_{es,spt}(V_{spt} - V_{d,spt}) + (1 - e(t))P_{0,spt}(e^{\lambda_{spt}(V_{spt} - V_{0,spt})} - 1) \\
 & = e(t)E_{es,lvf}(V_{lv} - V_{spt}) + (1 - e(t))P_{0,lvf}(e^{\lambda_{lvf}(V_{lv} - V_{0,spt})} - 1) \\
 & \quad - e(t)E_{es,rvf}(V_{rv} + V_{spt}) - (1 - e(t))P_{0,rvf}(e^{\lambda_{rvf}(V_{rv} + V_{0,spt})} - 1)
 \end{aligned}$$

Time-varying septal P-V relationship

Experimental trials: pulmonary embolism



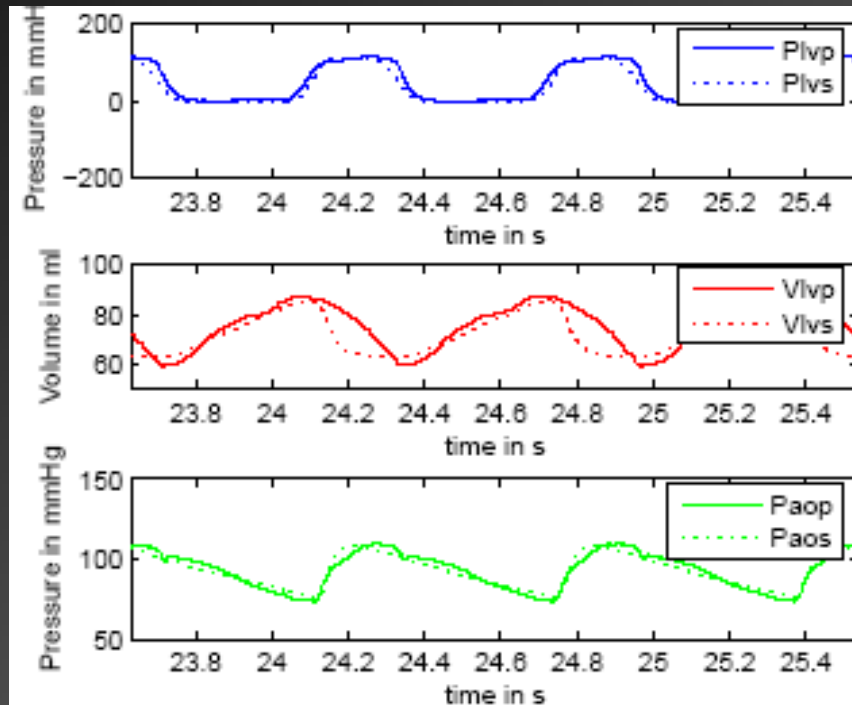
Open-chest surgery



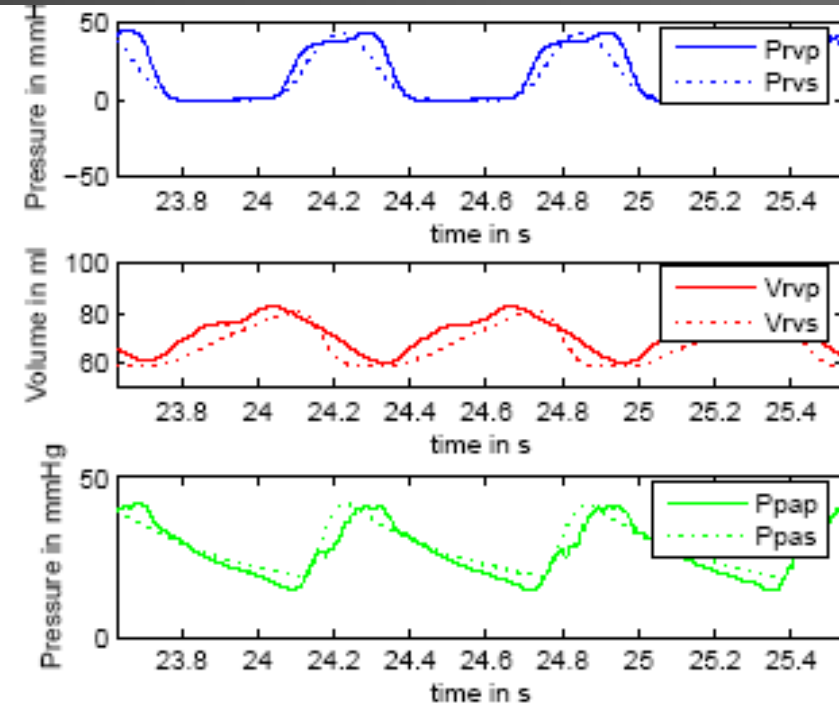
- **Pulmonary embolization** induced in pigs with autologous blood clots.
- **Clots** injected every two hours with decreasing concentrations.
- **Aortic pressure** and **pulmonary artery pressure** measured using micromanometer-tipped catheters (Sentron pressure-measuring catheter; Cordis, Miami, FL)
- **Pressures and volume of both ventricles** measured with 7F, 12 electrodes (8-mm interelectrode distance) conductance micromanometer tipped catheters (CD Leycom, Zoetermeer, The Netherlands)
- **Hemodynamics variables** are recorded every 30 min.
- Data from **6 pigs** used in this study.

- ❑ Transforms typically non-linear and non convex ID problem into linear and convex problem
- ❑ Limited data and minimal computation
 → **Very suitable for clinical applications**
- ❑ Available experimental data: P_{ao} , P_{pa} , P_{lv} , P_{rv} , V_{lv} , V_{rv}
- ❑ System of linear equations for the full CVS model
- ❑ Parameters identified for each period of experimental data (30 min.)

Left Ventricle (30 min)



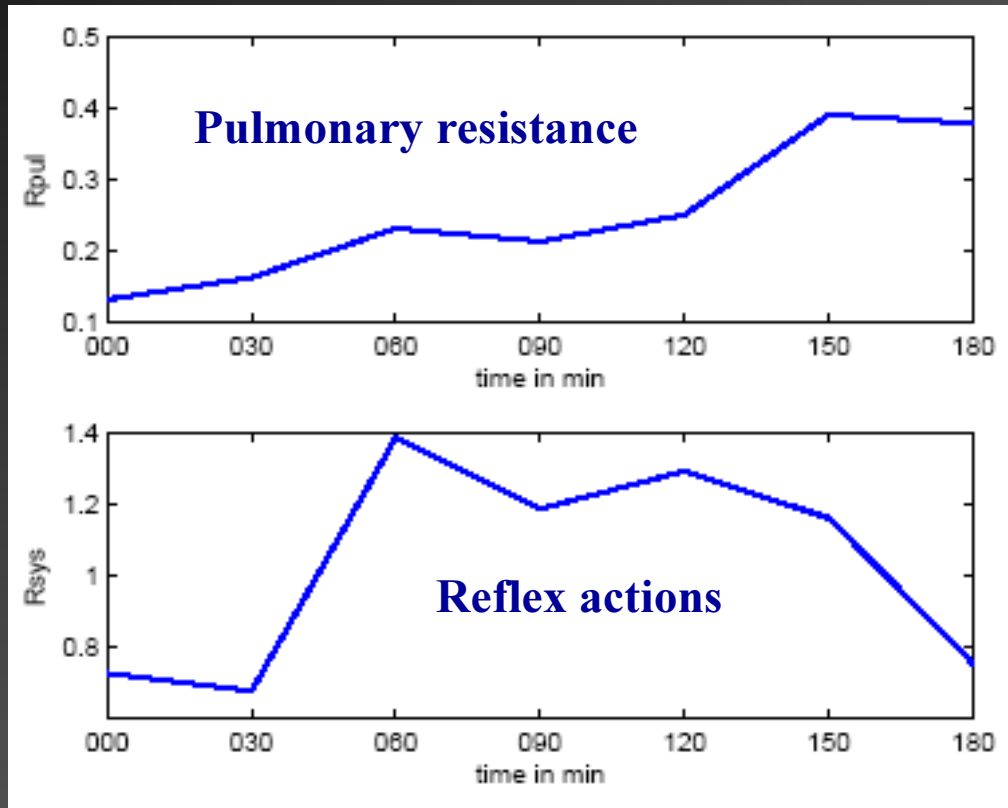
Right Ventricle (30 min)



Errors ~5%

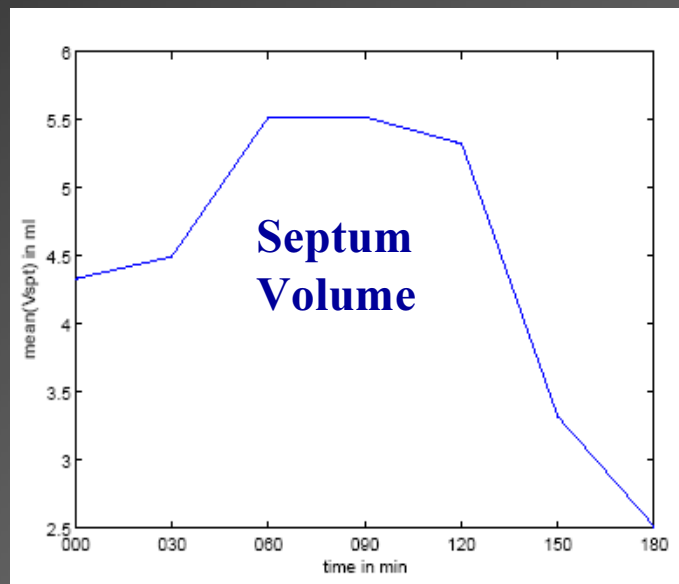
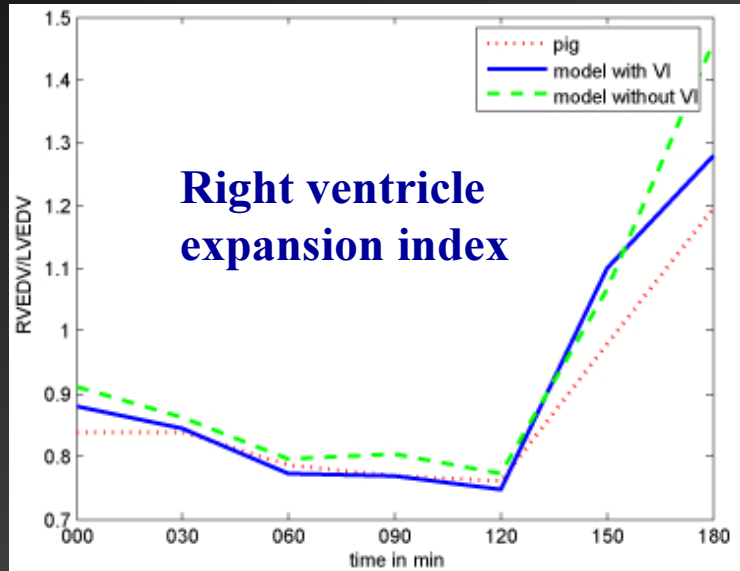
- Dashed lines: model output – solid lines: experimental data
- Use only: Pao, Ppa, min/max(Vlv, Vrv) to ID all parameters

Results over time (pig 2)



□ As the pulmonary embolism grows, the R_{pul} increases

□ R_{sys} also increases as a reflex response to raise blood pressure and divert more blood to the heart



- RVEDV/LVEDV increases resulting from the expansion of the RV due to the increased afterload.

- Without VI ($V_{spt}=0$) the model overpredicts the RV expansion.

- Main problem about VI: difficult to measure experimentally and very little data are available in the literature.

→ Whether or not the dynamic of VI is important for diagnosis in the ICU remains to be shown in future human clinical trials.

- VI changes are captured: decreasing septal volume resulting from the compression of the LV by the overfilled RV.

Hemodynamic parameters: summary

Pig	% increase R_{pul}	% increase R_{sys}	% increase E_{eslvf}	% increase E_{esrvf}	% increase V_{spt}
1	261.44	40.66	29.10	154.60	9.13
2	89.98	49.34	74.78	20.56	40.15
3 ¹	24.23	27.16	0.81	9.74	8.37
4	166.85	39.21	19.06	56.44	19.84
5	103.63	21.16	71.51	80.07	27.64
6	99.52	53.90	11.00	14.64	14.00



(reflex)



¹ Limited data for this pig and insufficient time for the parameters to change significantly

Conclusions

- **Minimal cardiac model** → simulate time varying disease states
 - Accurately captures physiological trends and magnitudes
 - Accurately captures a wide range of dynamics
 - Very Fast simulation methods available
- **Integral-based parameter ID** → patient specific models
 - Error on max/min pressures/volumes < 5%
 - Identification needs a minimal number of common measurements
 - Rapid ID = Rapid diagnostic feedback
- **Pulmonary embolism:**
 - Hemodynamics successfully captured over time
 - Physiological responses to pulmonary embolism also captured
- **Future Work = septic shock currently in progress**