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A Non-Linear Autoregressive Model of Pulmonary Mechanics

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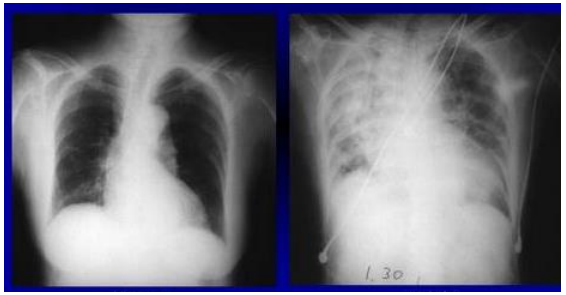
Motivation

- Acute respiratory distress syndrome (ARDS) severity varies between patients
- Optimal ventilator settings for each patient will be different



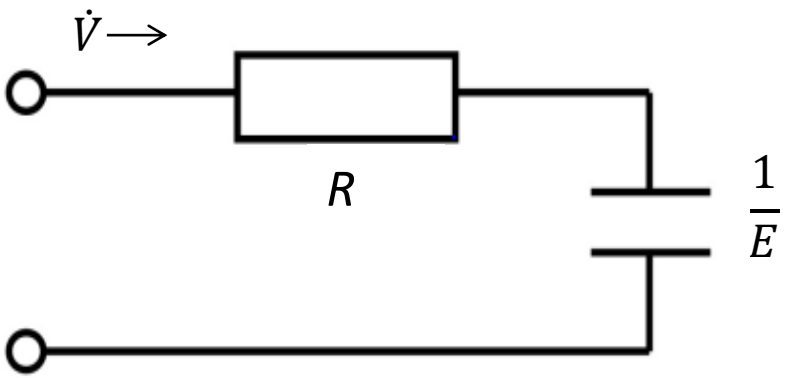
Normal lungs ARDS lungs

- Mathematical models that capture patient-specific information can enable personalised mechanical ventilation
- It is difficult to find a model that captures all important dynamics while still being simple enough to be useable in the ICU
- A new nonlinear autoregressive model (NARX) aims to fit airway pressure better than current models

First Order Model

- A simple model with single resistance and elastance terms

$$P(t) = EV(t) + R\dot{V}(t) + P_0$$



Nonlinear Autoregressive Modelling

- A grey box approach

$$X(t) = \sum_{i} a_i X(t_{-i}) + \sum_{j}\sum_{i} b_{j,i}\theta_j(t_{1-i}) \; + \sum_{i} c_i f(X(t_{1-i}))$$

where: X = measured output
a, b, c = coefficients to be identified
θ = known input
j = number of known inputs
i = length of inputs

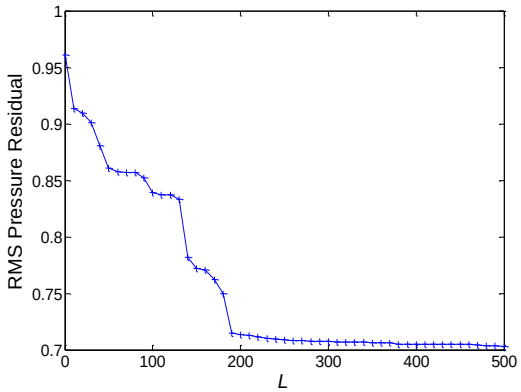
NARX Model

$$P_{aw}(t) = \sum_{i=1}^{M} a_i \theta_{i,d}\left(P_{aw}(t)\right)V(t) + \sum_{j=0}^{L} b_j \dot{V}\left(t_{-j}\right) + P_0(t)$$

NARX Model

$$P_{aw}(t) = \sum_{i=1}^{M} a_i \theta_{i,d}\left(P_{aw}(t)\right)V(t) + \boxed{\sum_{j=0}^{L} b_j \dot{V}\left(t_{-j}\right)} + P_0(t)$$

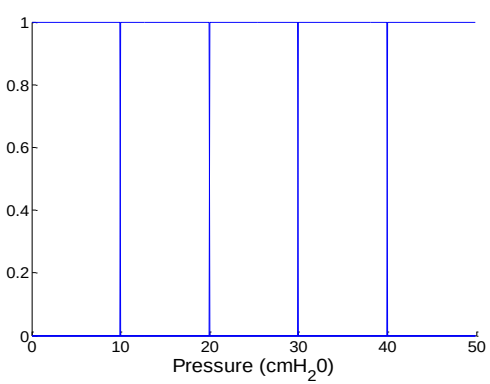
- *L* number of *b* coefficients
- *L* was chosen as 350
- These terms represent the effects of airway resistance to flow and changes in flow



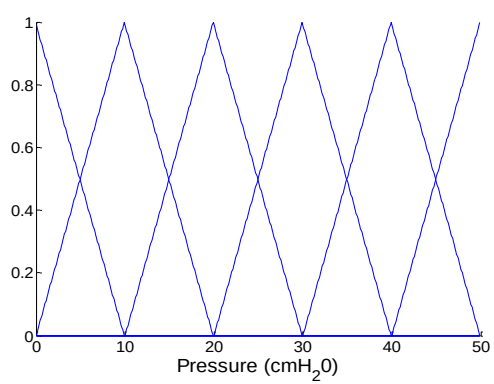
NARX Model

$$P_{aw}(t) = \boxed{\sum_{i=1}^{M} a_i \theta_{i,d}\big(P_{aw}(t)\big)V(t)} + \sum_{j=0}^{L} b_j \dot{V}(t_{-j}) + P_0(t)$$

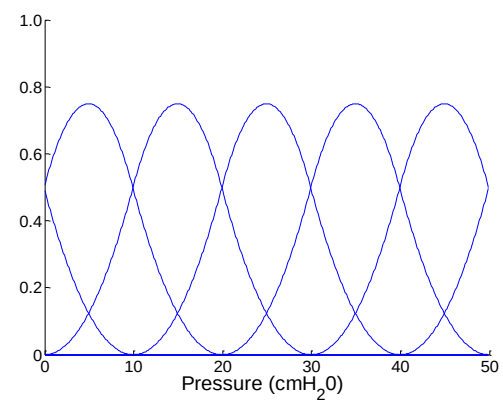
- M is the number of basis-functions to be used
- $\theta_{i,d}\big(P_{aw}(t)\big)$ is the basis function value for a given pressure measurement.
- M = 5, d = 1



d = 0



d = 1



d = 2

NARX Model

$$P_{aw}(t) = \sum_{i=1}^{M} a_i \emptyset_{i,d}\big(P_{aw}(t)\big)V(t) + \sum_{j=0}^{L} b_j \dot{V}\big(t_{-j}\big) + P_0(t)$$

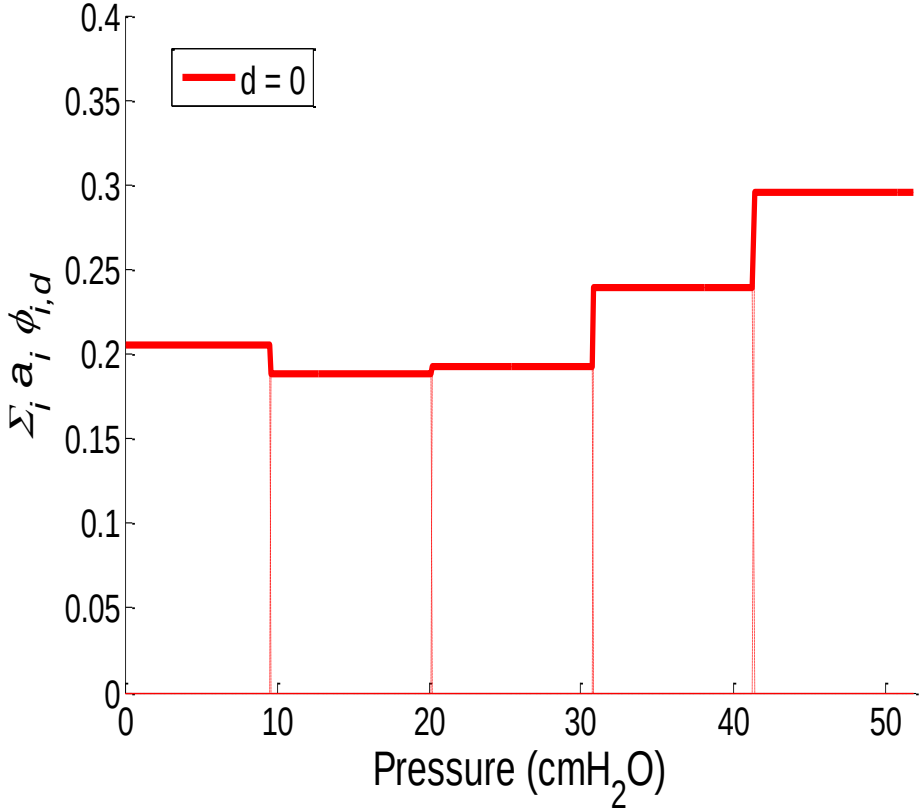
$$\mathbf{Ax} = \mathbf{b}$$

$$\mathbf{A} = \begin{bmatrix} \emptyset_{1,d}(P_{aw}(t_0))V(t_0) & \dots & \emptyset_{M,d}(P_{aw}(t_0))V(t_0) & \dot{V}(t_0) & \dots & \dot{V}(t_{-L}) \\ \emptyset_{1,d}(P_{aw}(t_1))V(t_1) & \dots & \emptyset_{M,d}(P_{aw}(t_1))V(t_1) & \dot{V}(t_1) & \dots & \dot{V}(t_{L-j-2}) \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ \emptyset_{1,d}(P_{aw}(t_N))V(t_N) & \dots & \emptyset_{M,d}(P_{aw}(t_N))V(t_N) & \dot{V}(t_N) & \dots & \dot{V}(t_{N-L}) \end{bmatrix}$$

$$\mathbf{b} = \begin{bmatrix} P_{aw}(t_0) - P_0(t_0) \\ P_{aw}(t_1) - P_0(t_1) \\ \vdots \\ P_{aw}(t_N) - P_0(t_N) \end{bmatrix}; \qquad \text{and } \mathbf{x} = \begin{bmatrix} a_1 \\ \vdots \\ a_M \\ b_1 \\ \vdots \\ b_L \end{bmatrix}$$

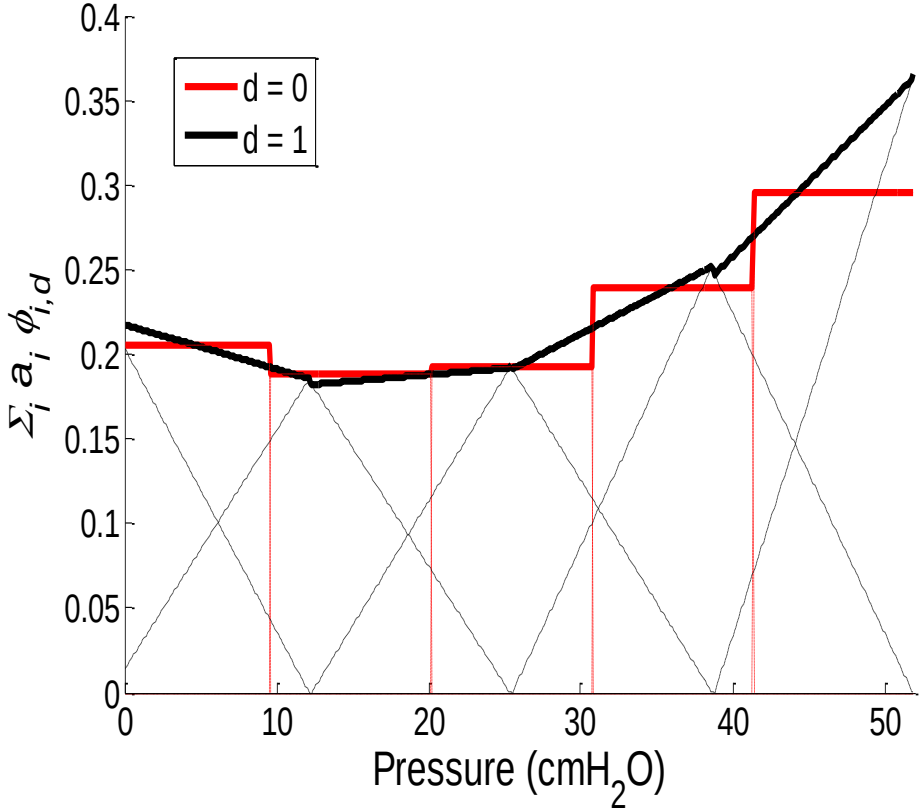
NARX Model

- $M = 5$



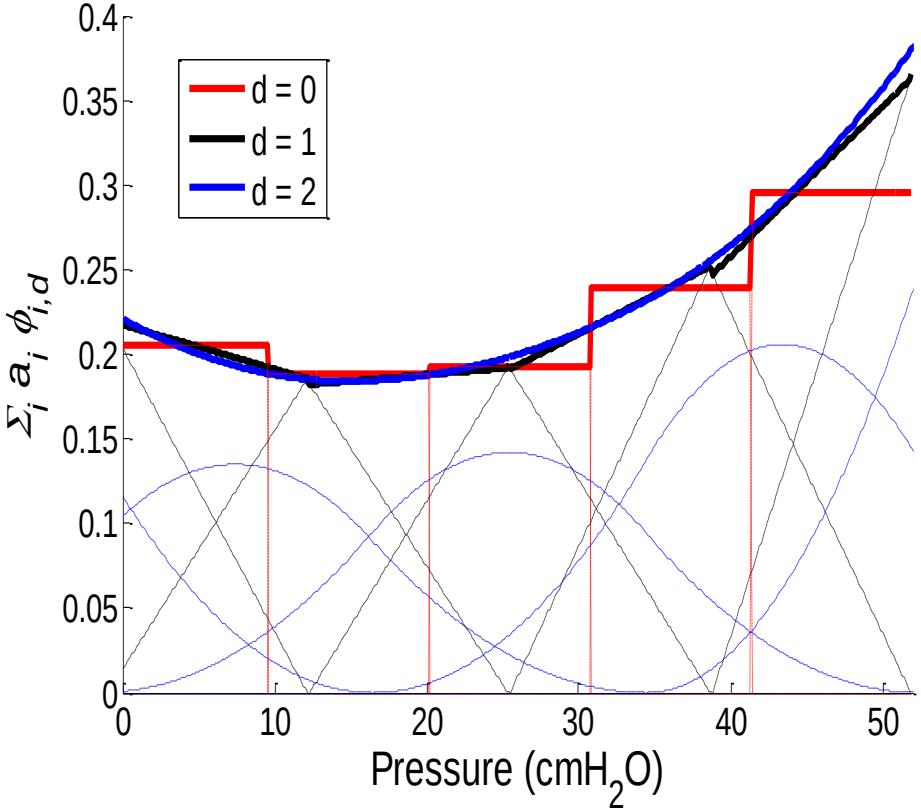
NARX Model

- $M = 5$



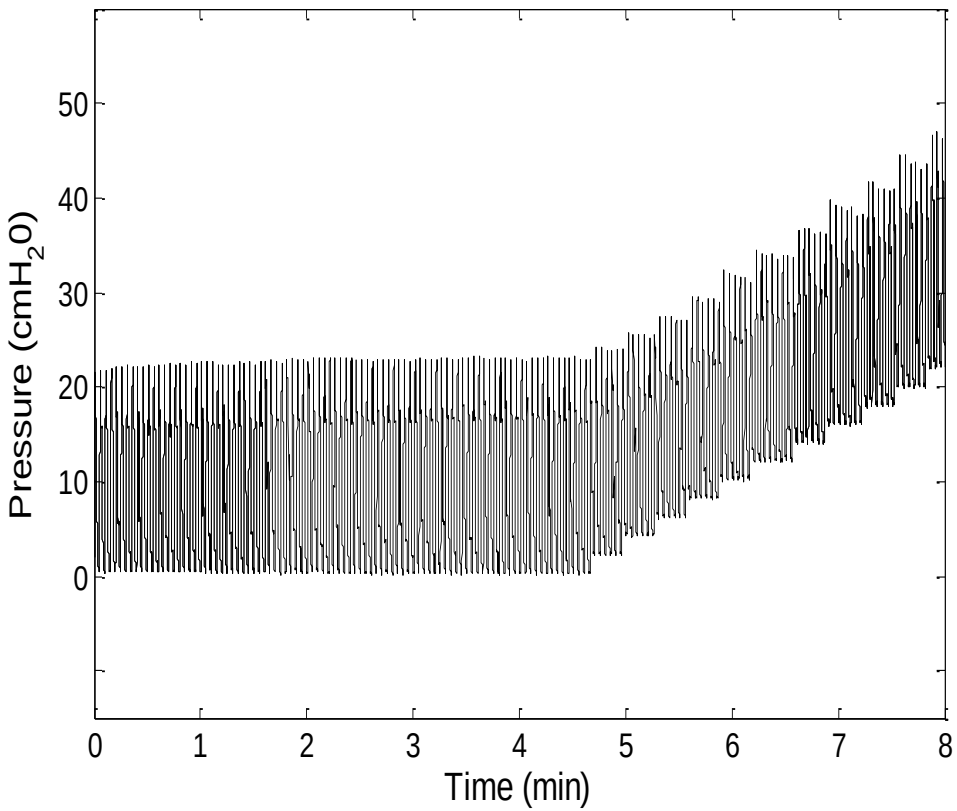
NARX Model

- $M = 5$
- First and second order basis functions capture a similar curve
- Five zero order functions cannot capture the same curve



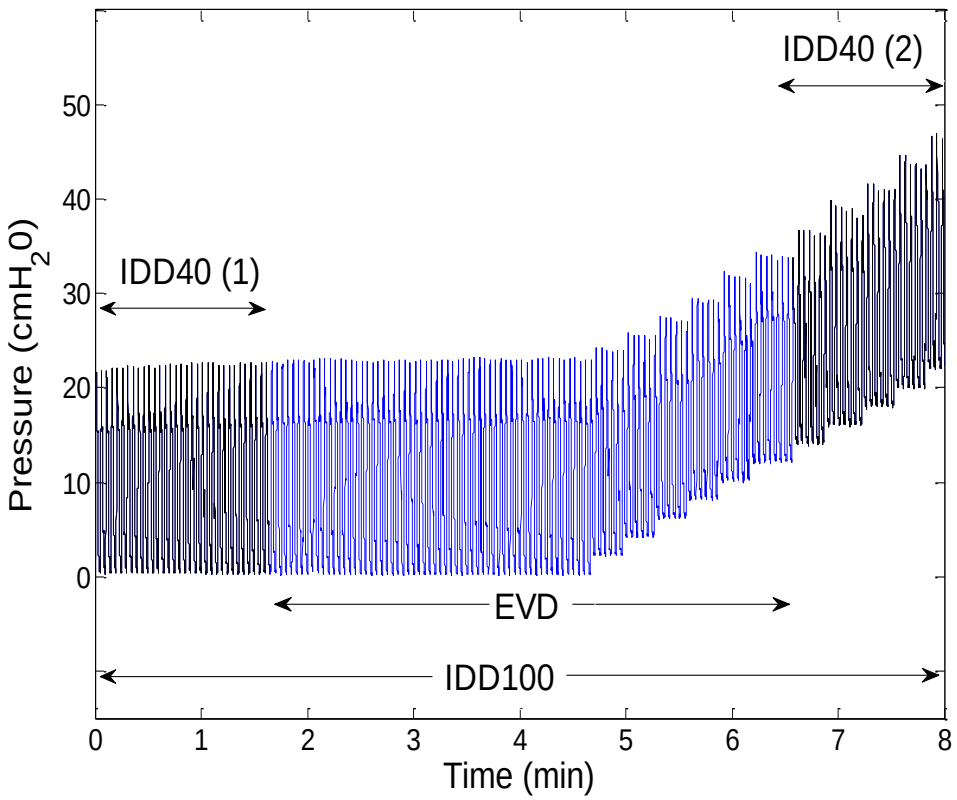
Data

- 25 patients with ARDS
- Approx. 5 minutes of ZEEP and 5 minutes of PEEP increasing by 2 cmH_2O every 10 breaths
- Model was identified on the entire data set

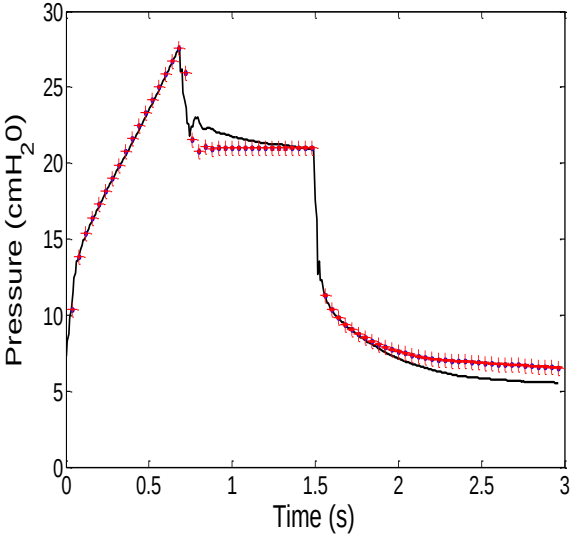


Data

- 25 patients with ARDS
- Approx. 5 minutes of ZEEP and 5 minutes of PEEP increasing by 2 cmH_2O every 10 breaths
- Model was identified on the entire data set
- Interpolation: Model was identified on 40% of each data set
- The first order model was compared with the NARX

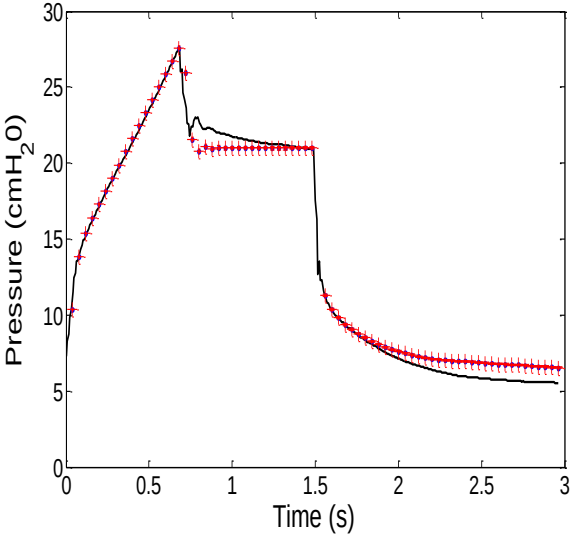


Results

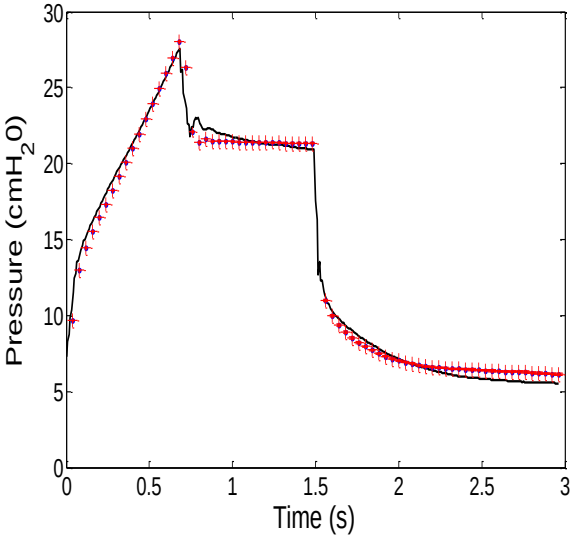


First Order Model

Results

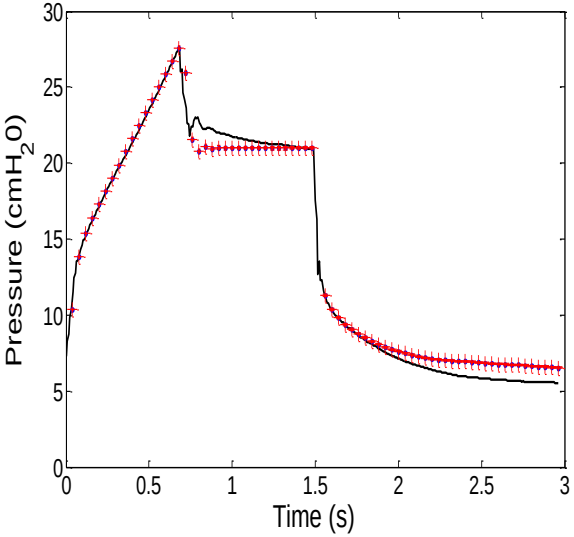


First Order Model

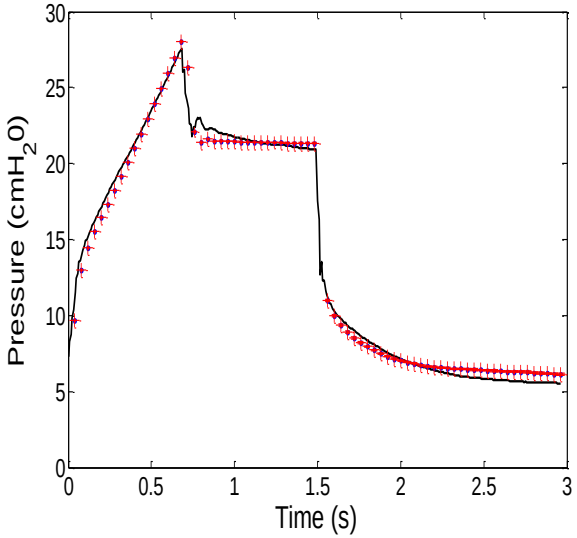


NARX Model, L = 1

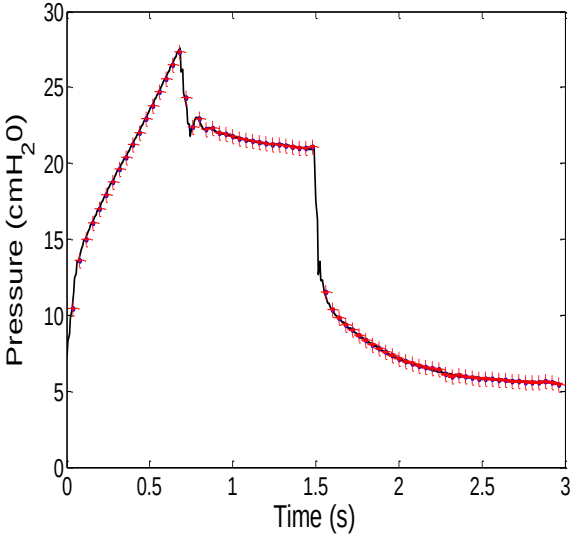
Results



First Order Model



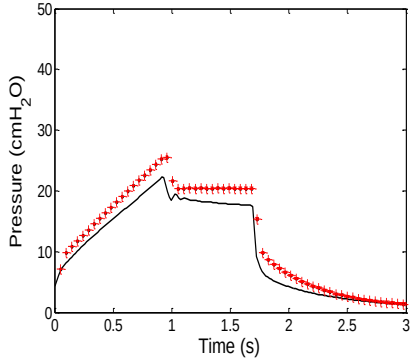
NARX Model, L = 1



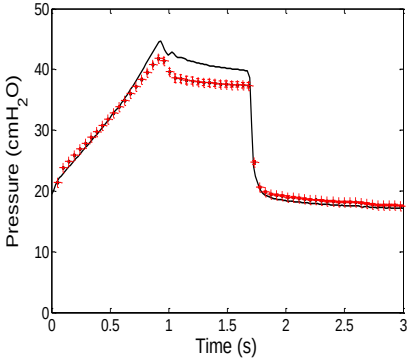
NARX Model, L = 350

Interpolation Results

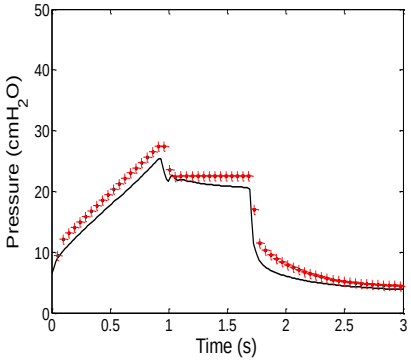
First Order Model



$IDD40_1$

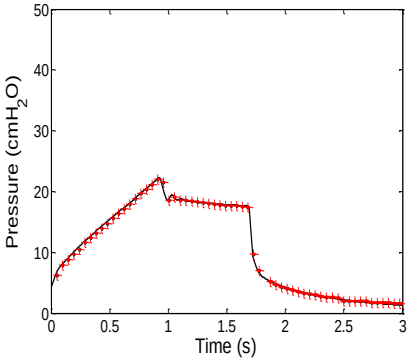


$IDD40_2$

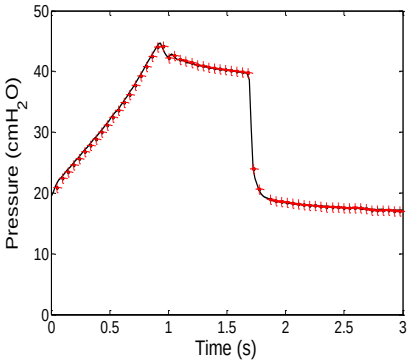


EVD

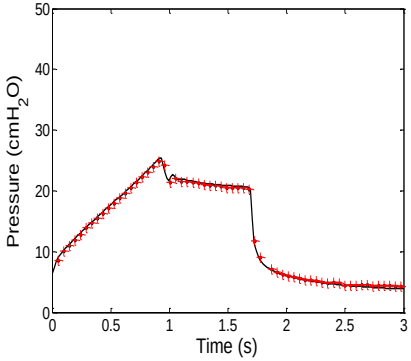
NARX Model



$IDD40_1$



$IDD40_2$

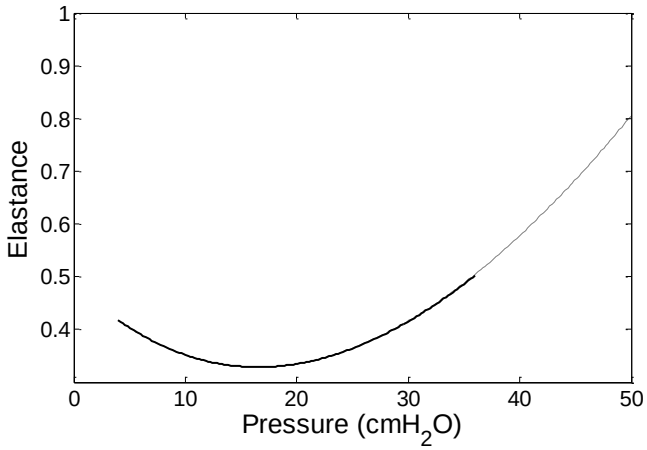


EVD

- 60% of the data was not needed to identify an accurate NARX model

Next Steps

- Extrapolation: By extending the elastance curve beyond known pressures, we can predict behaviour at higher PEEP

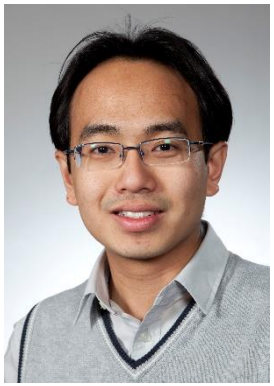


Conclusions

- Basis functions were incorporated into a nonlinear autoregressive model
- The NARX model fits to airway pressure during a recruitment manoeuvre better than the FOM
- The model is able to capture pressure dependent elastance
- It is identifiable in real time, requiring only flow and pressure measurements
- The results should be verified by testing with a larger sample size and different ventilation modes

Thanks

- Thanks to my Co-authors Paul Docherty, Yeong-Shiong Chiew, Knut Möller, and J. Geoffrey Chase



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