Wave potential: a unified model of arterial waves, reservoir phenomena and their interaction

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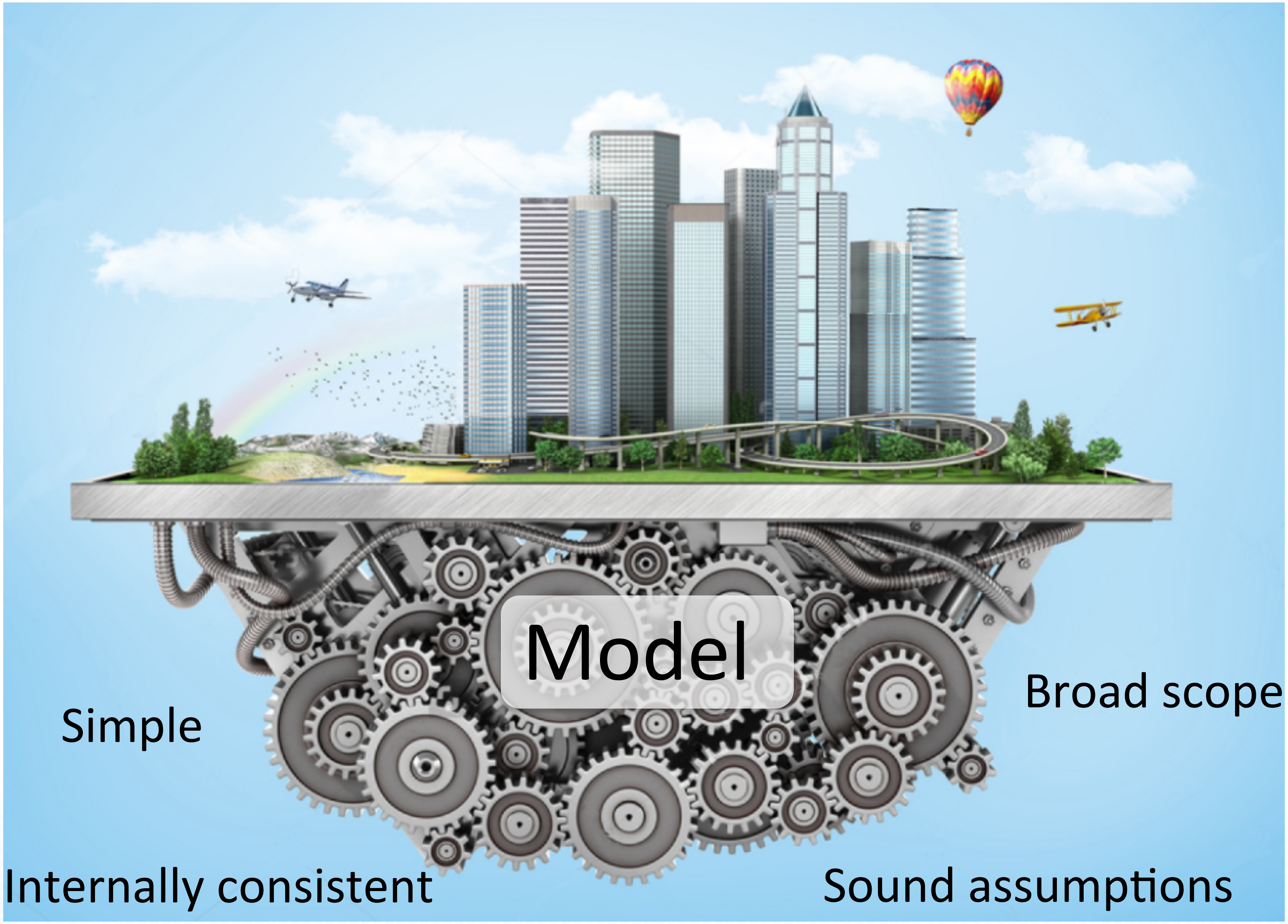
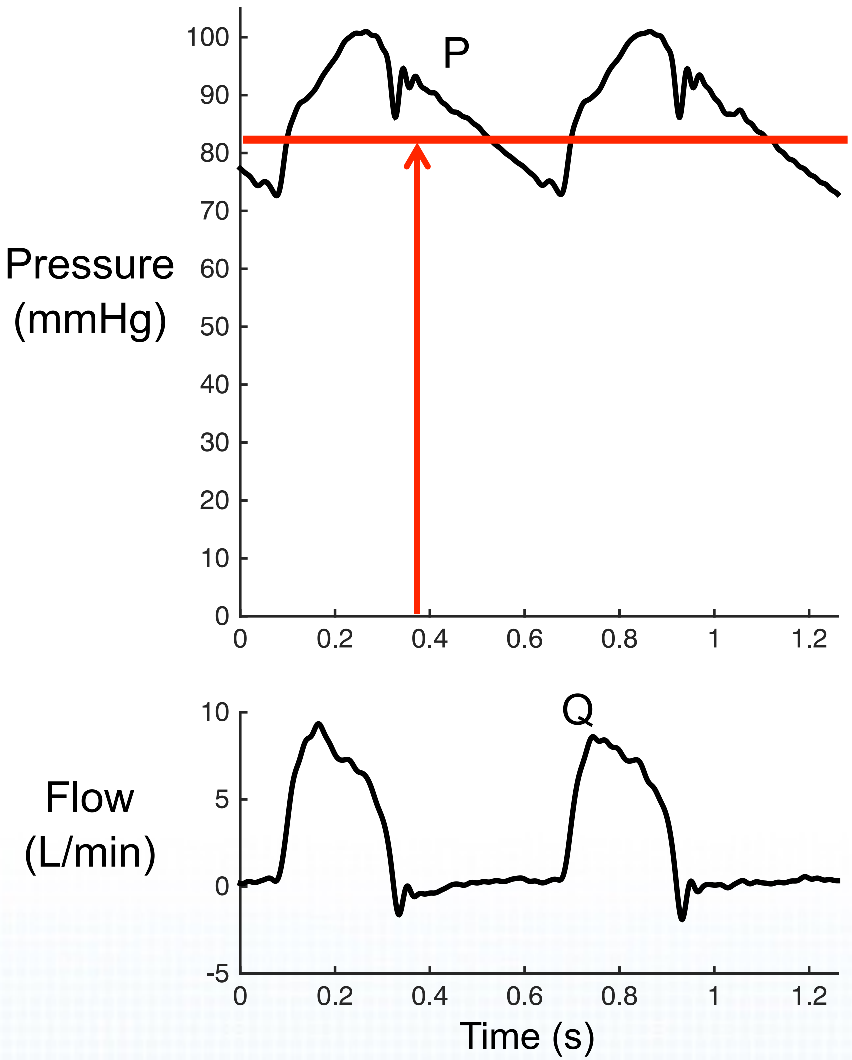
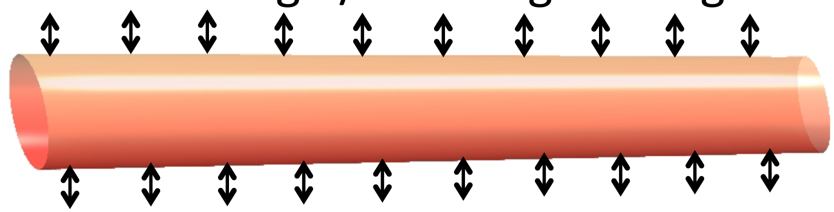

Model
Simple
Broad scope
Internally consistent
Sound assumptions

Wanted: a unified model of haemodynamics

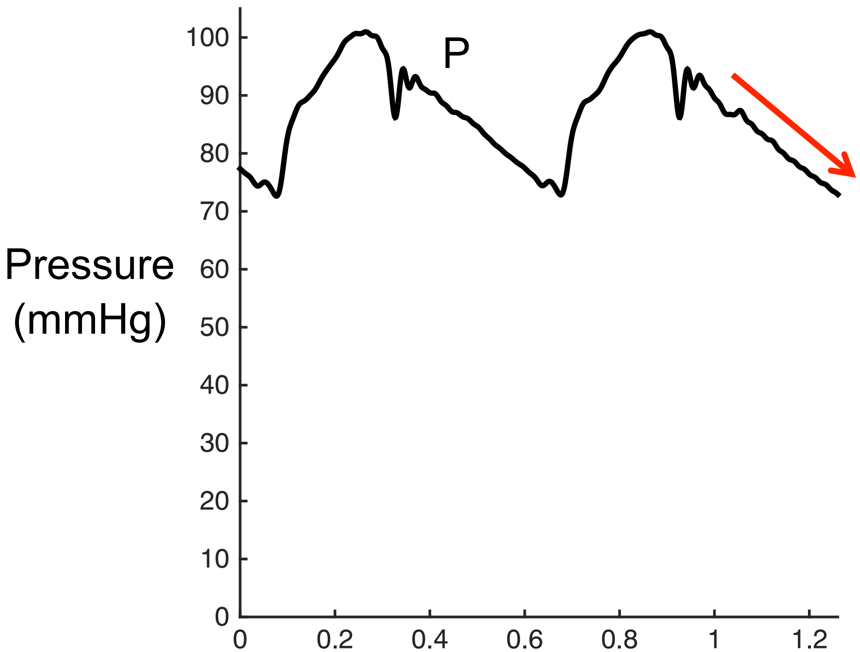


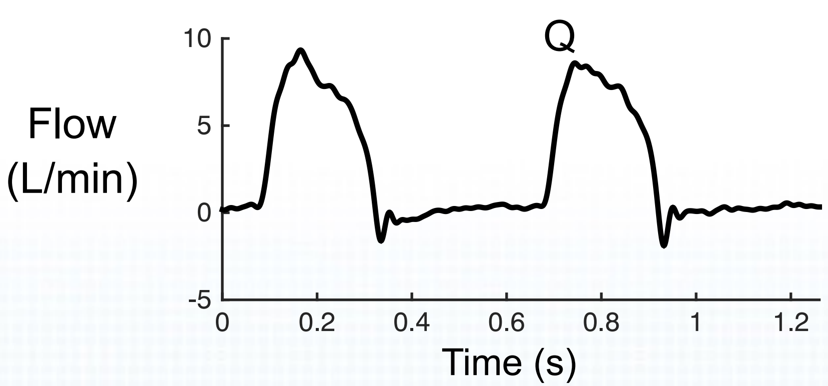
Mean pressure

Volume storage / discharge in large arteries



Wanted: a unified model of haemodynamics





Mean pressure

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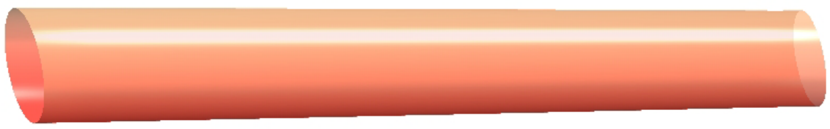
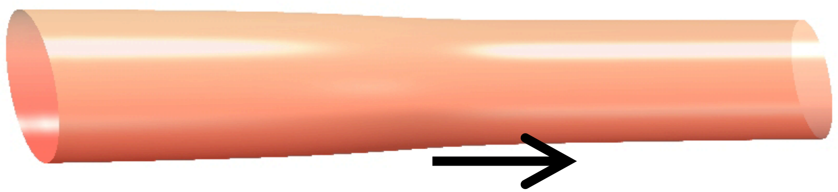


Exponential diastolic P decay

Pulse propagation (PWV) and reflection



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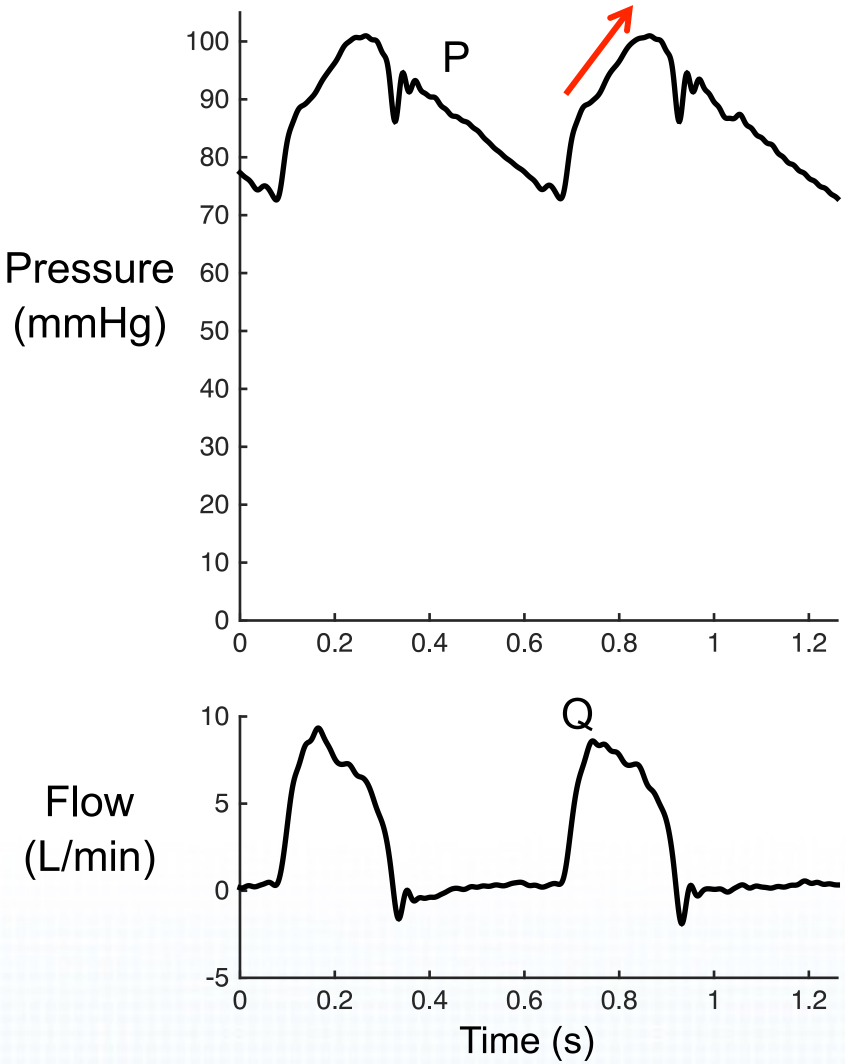

Mean pressure

Volume storage / discharge in large arteries

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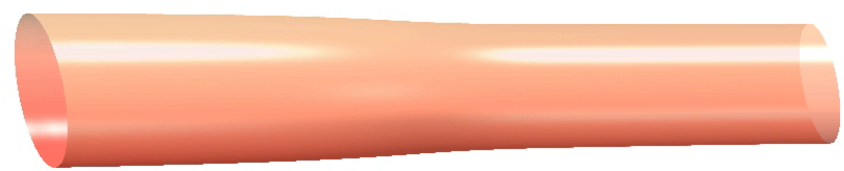
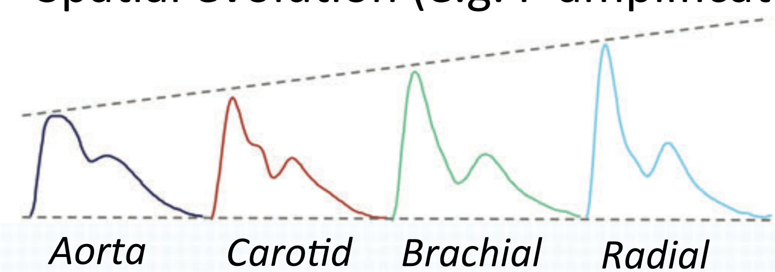


P/Q pulse features

- Systolic P augmentation
- Spatial evolution (e.g. P amplification)



Wanted: a unified model of haemodynamics

	Windkessel	Wave Model
Mean Pressure	✓	✗
Volume storage	✓	✗
Exponential P decay	✓	??
Pulse propagation	✗	✓
P Augmentation	✗	✓
P Amplification	✗	✓

↓

Assumes infinite wave speed

Reservoir-Wave Model

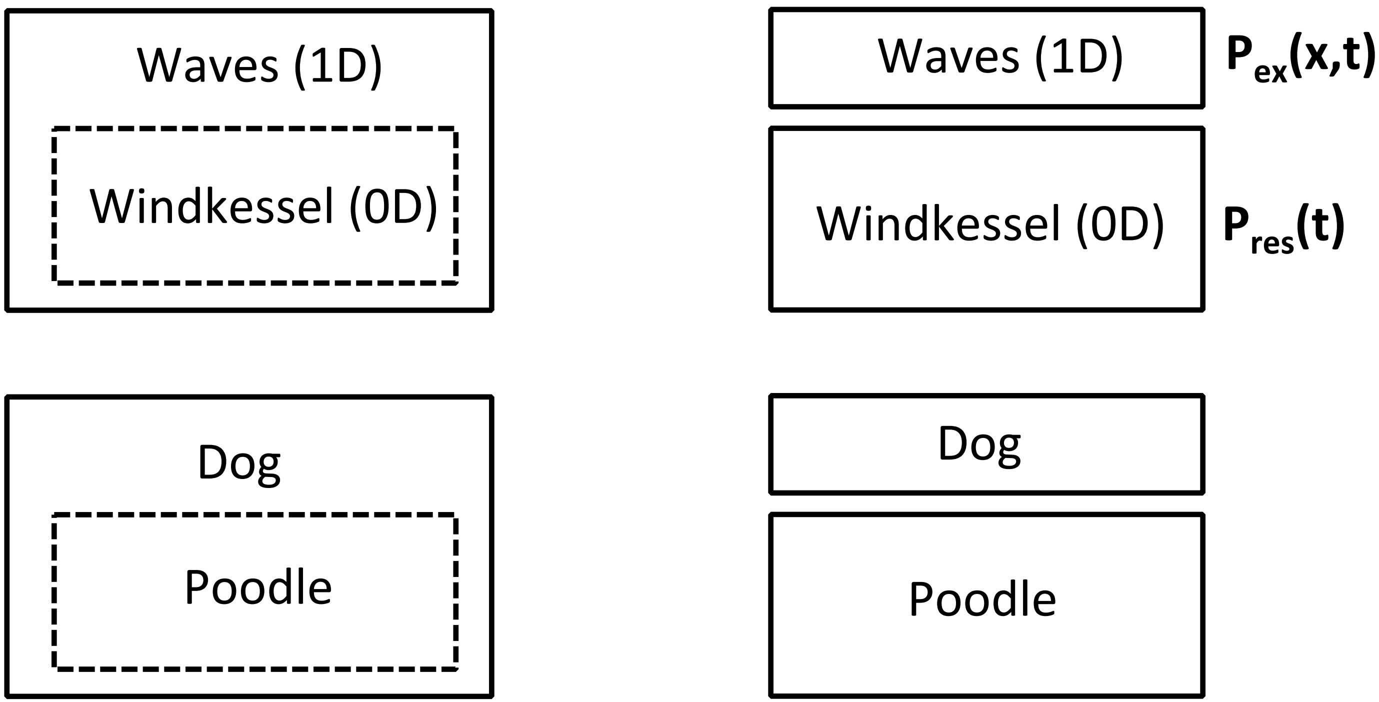
$$P(x,t) = P_{res}(t) + P_{ex}(x,t)$$

	Windkessel	Wave Model	Reservoir-Wave
Mean Pressure	✓	✗	✓
Volume storage	✓	✗	✓
Exponential P decay	✓	??	✓
Pulse propagation	✗	✓	✓
P Augmentation	✗	✓	✓
P Amplification	✗	✓	✓

Wang JJ, O'Brien AB, Shrive NG, Parker KH, and Tyberg JV. Time-domain representation of ventricular-arterial coupling as a windkessel and wave system. *Am J Physiol Heart Circ Physiol* 284: H1358-H1368, 2003.

Reservoir-Wave Model

Mathematical difficulty for the goal of separating 0D & 1D effects



Mynard JP et al. ***Journal of Hypertension***. 30:734-43, 2012
Mynard JP. ***IEEE Engineering in Medicine and Biology Society***, Osaka, Japan, 2013, p. 213-216.
Mynard JP and Smolich JJ**. *International Journal of Cardiology.*** 176:1009-1012, 2014.
Mynard JP, Smolich JJ, Avolio A. ***Journal of Hypertension***. 33:461-4, 2015.
Segers P et al. ***Journal of Hypertension.*** 33:554-563, 2015.

Reservoir-Wave Model

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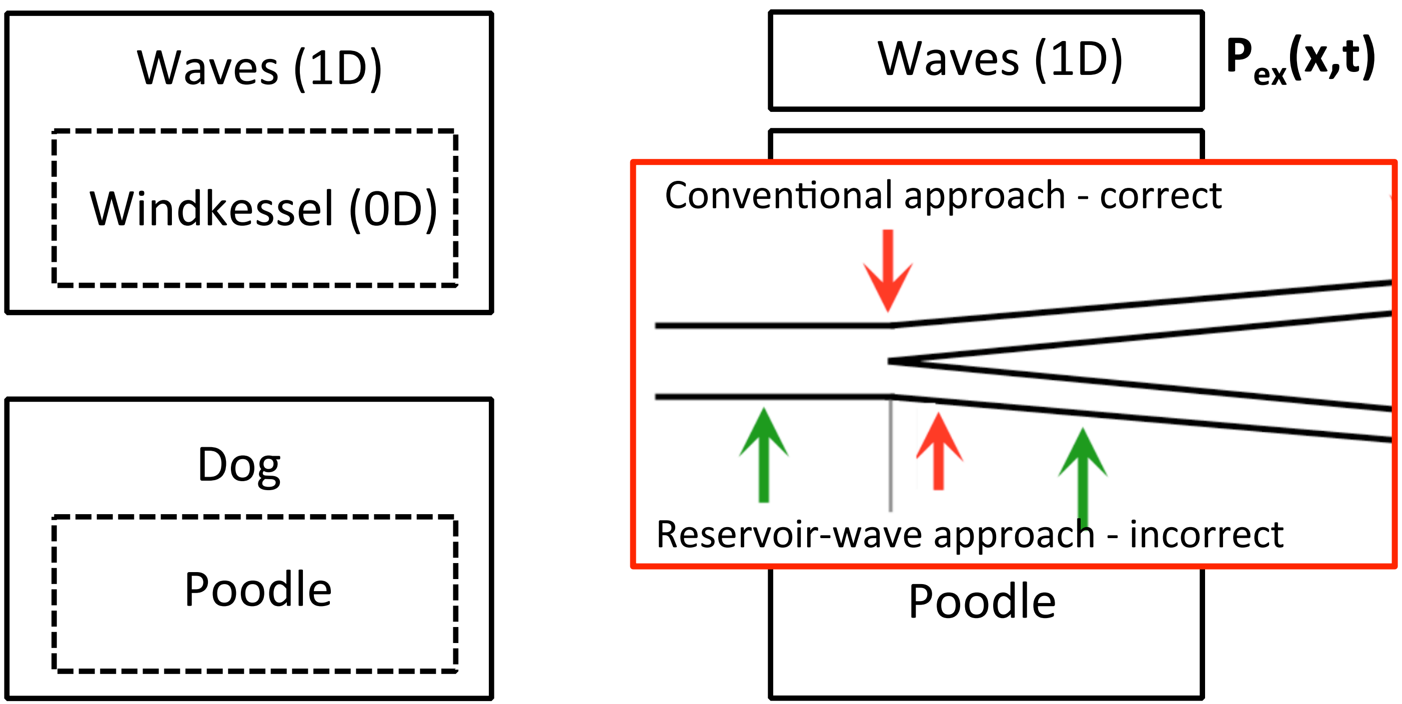

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Murdoch Childrens Research Institute
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Wanted: a unified model of haemodynamics

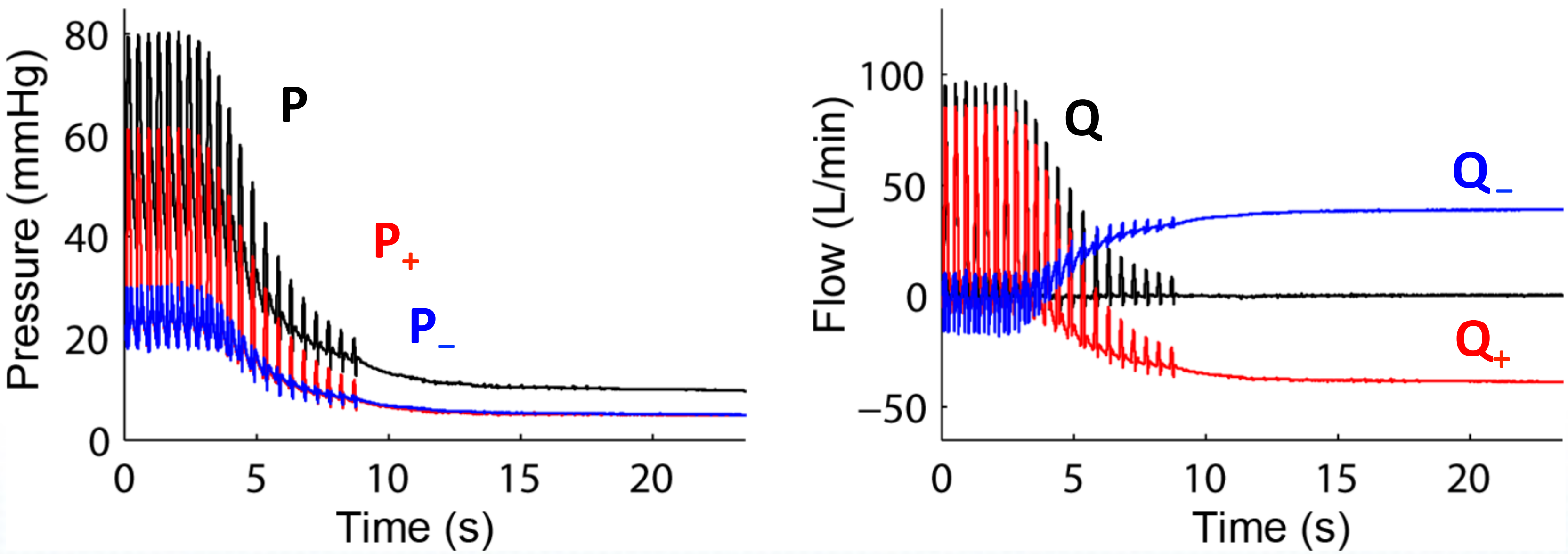
	Windkessel	Wave Model V1	Wave Model V2
Mean Pressure	✓	✗	💡
Volume storage	✓	✗	💡
Exponential P decay	✓	✗	💡
Pulse propagation	✗	✓	✓
P Augmentation	✗	✓	✓
P Amplification	✗	✓	✓

Conventional wave separation

With extended asystole (e.g. death), wave components do not fall to zero

- absolute values of $P_{\pm}$ and $Q_{\pm}$ are *arbitrary* (arbitrary constants c_P and c_Q)

$$P_{\pm} = \frac{1}{2}\left(P \pm Z_c Q\right) + c_P \qquad Q_{\pm} = \frac{1}{2}\left(Q \pm \frac{1}{Z_c} P\right) + c_Q$$

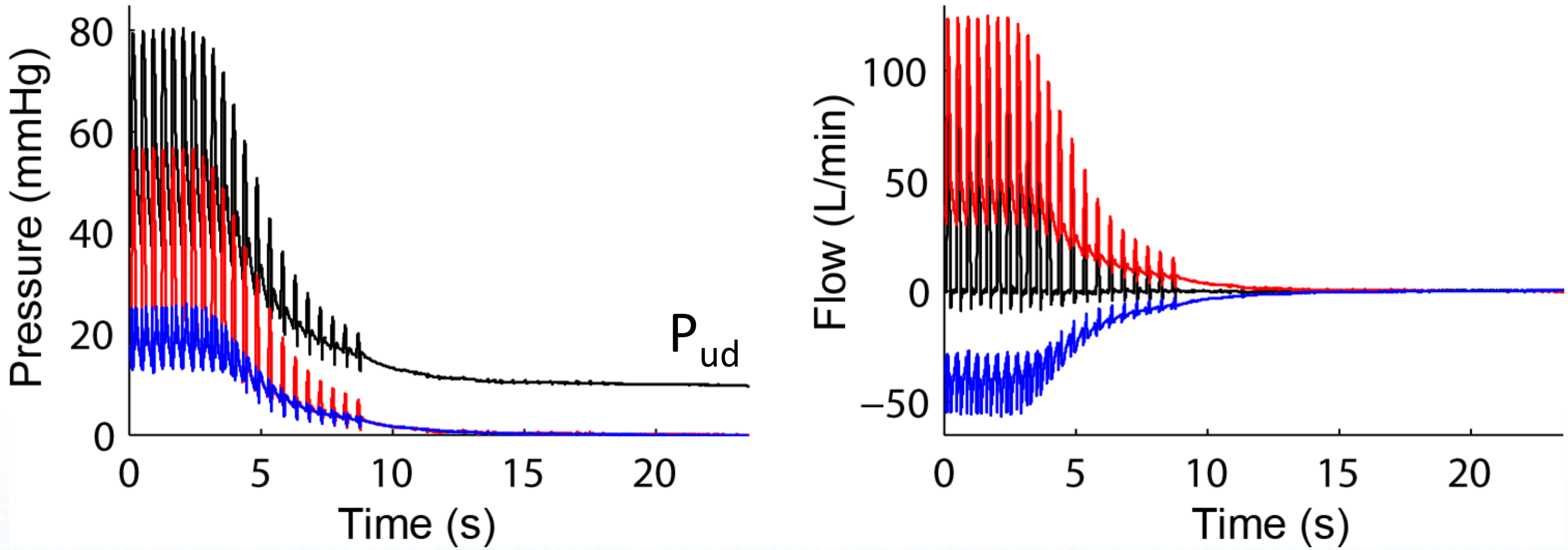


Mynard JP and Smolich JJ. Wave potential and the one-dimensional windkessel as a wave-based paradigm of diastolic arterial hemodynamics. *Am J Physiol Heart Circ Physiol* 307: H307-H318, 2014.

Wave separation V2

- Blood pressure converges to an 'undisturbed pressure' (P_{ud})
- New expressions for wave separation (non-arbitrary offset)

$$P_{\pm} = \frac{1}{2}\left(P - P_{ud} \pm Z_c Q\right) \qquad Q_{\pm} = \frac{1}{2}\left(Q \pm \frac{1}{Z_c}\left(P - P_{ud}\right)\right)$$



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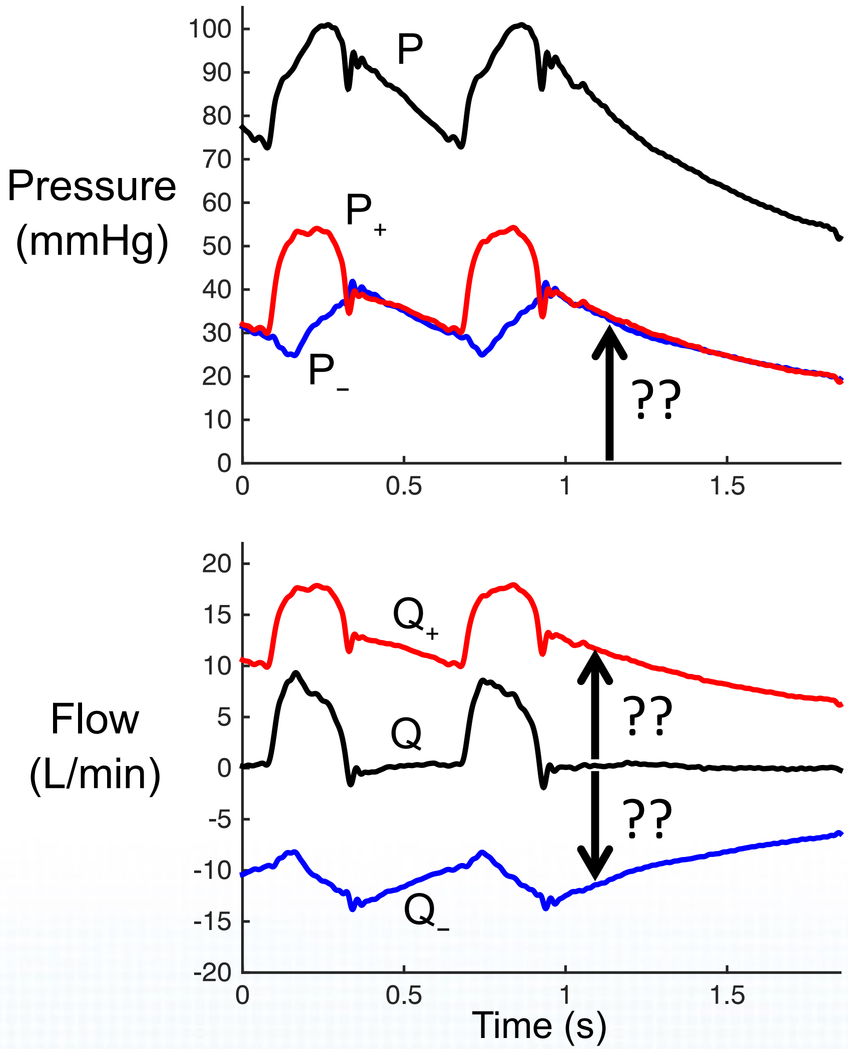
Wave potential



What is the physical meaning of absolute $P_\pm$ and $Q_\pm$?

…

Wave potential!

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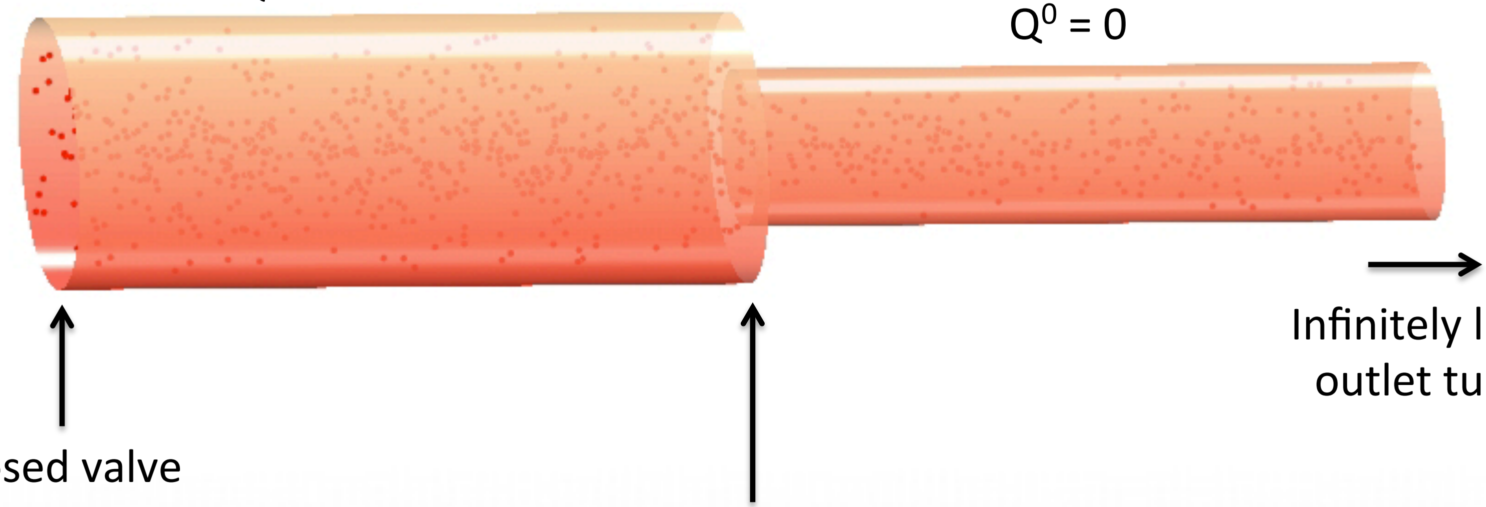
Wave potential and waves

$P_{\pm} = 5$ mmHg
$Q_{\pm} = \pm 78.6$ mL/s

$P^{0} = 10$ mmHg
$Q^{0} = 0$

$P_{\pm} = 0$ mmHg
$Q_{\pm} = 0$ mL/s

$P^{0} = P_{ud} = 0$ mmHg
$Q^{0} = 0$



Wave potential and waves

$P_{\pm}$ = 5 mmHg
$Q_{\pm}$ = ±78.6 mL/s

P^0 = 10 mmHg
Q^0 = 0

$P_{\pm}$ = 0 mmHg
$Q_{\pm}$ = 0 mL/s

$P^0 = P_{ud}$ = 0 mmHg
Q^0 = 0

Infinitely long outlet tube

Closed valve

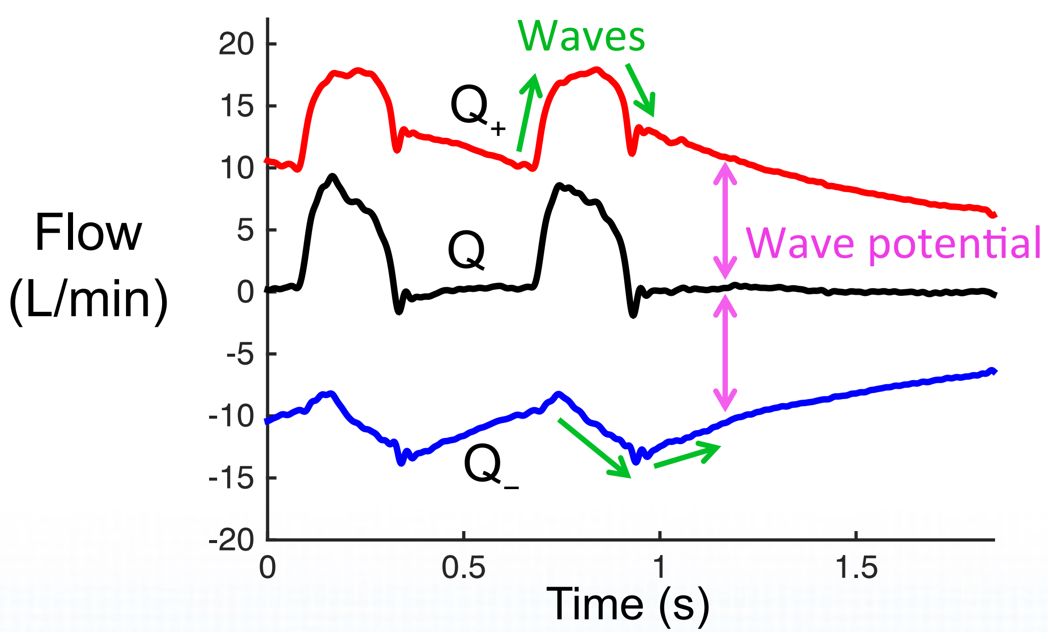
dP_{-} = −5 mmHg
dQ_{-} = 78.6 mL/s

dP_{+} = 5 mmHg
dQ_{-} = 78.6 mL/s

Valve opens

Wave potential and waves

- **<u>Wave potential</u>** (absolute $P_{\pm}$ & $Q_{\pm}$) represents the potential for wave generation
- Spatial gradients of $P_{\pm}$ and $Q_{\pm}$ produce propagating waves
- **<u>Waves</u>** cause spatio-temporal perturbations of $P_{\pm}$ and $Q_{\pm}$ (i.e. propagating $dP_{\pm}$ and $dQ_{\pm}$)



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Wave potential and reservoir function

$P_{\pm}$ = 5 mmHg
$Q_{\pm}$ = ±78.6 mL/s

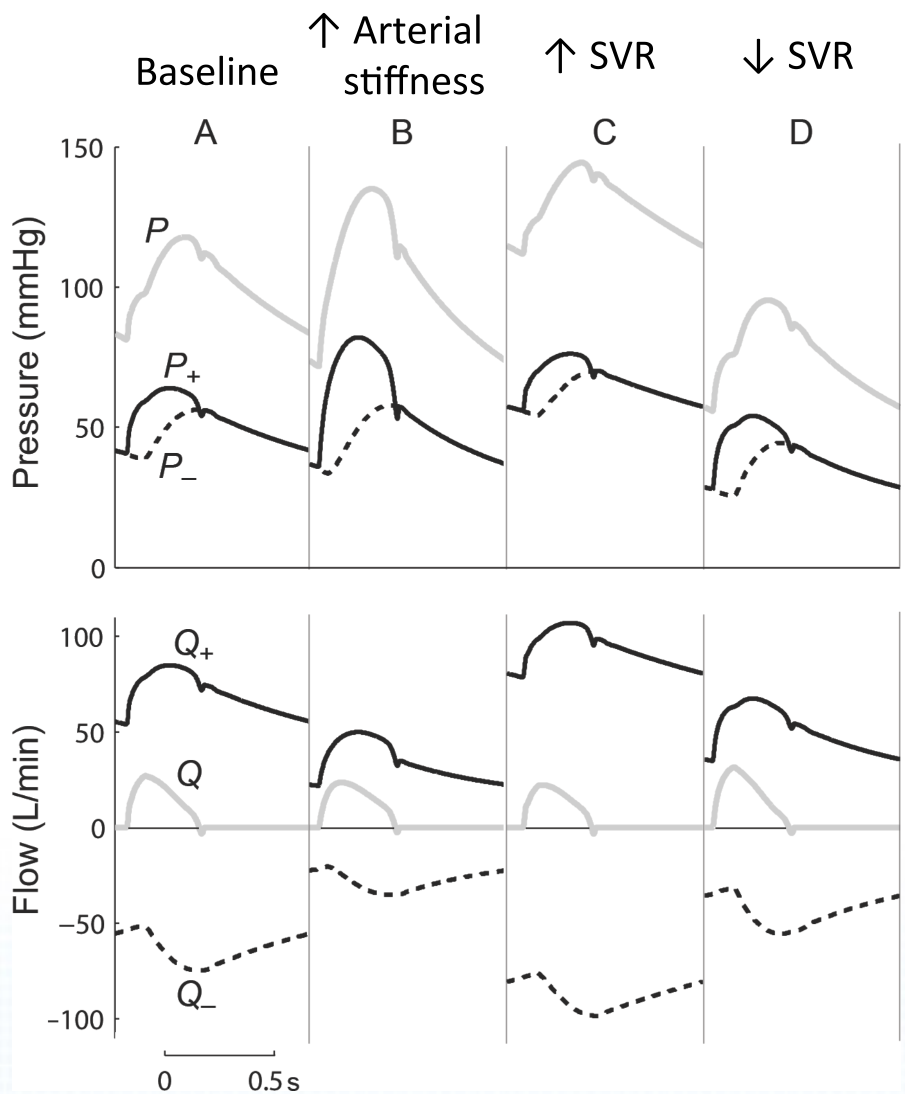
P^0 = 10 mmHg
Q^0 = 0

$P_{\pm}$ = 0 mmHg
$Q_{\pm}$ = 0 mL/s

$P^0 = P_{ud}$ = 0 mmHg
Q^0 = 0

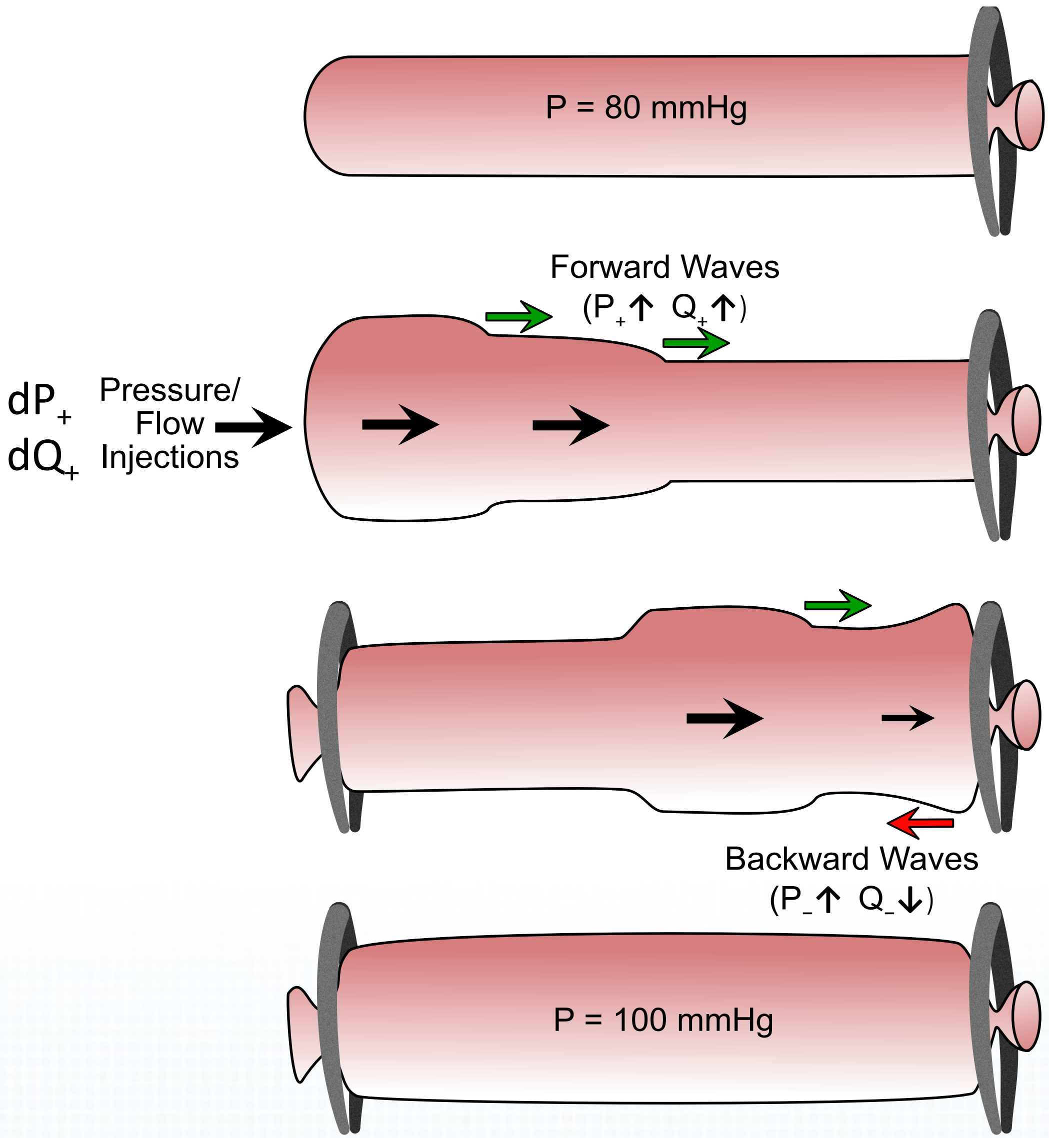
Volume stored/discharged in the first vessel: $V = \int \frac{1}{c}\left(Q_{+}^{0} - Q_{-}^{0}\right)dx = 5.9\ \text{mL}$

Wave potential and reservoir function



Flow wave potential ($Q_\pm$ offset) is an indicator of reservoir function that is directly integrated into wave separation analysis.

Waves and mean pressure



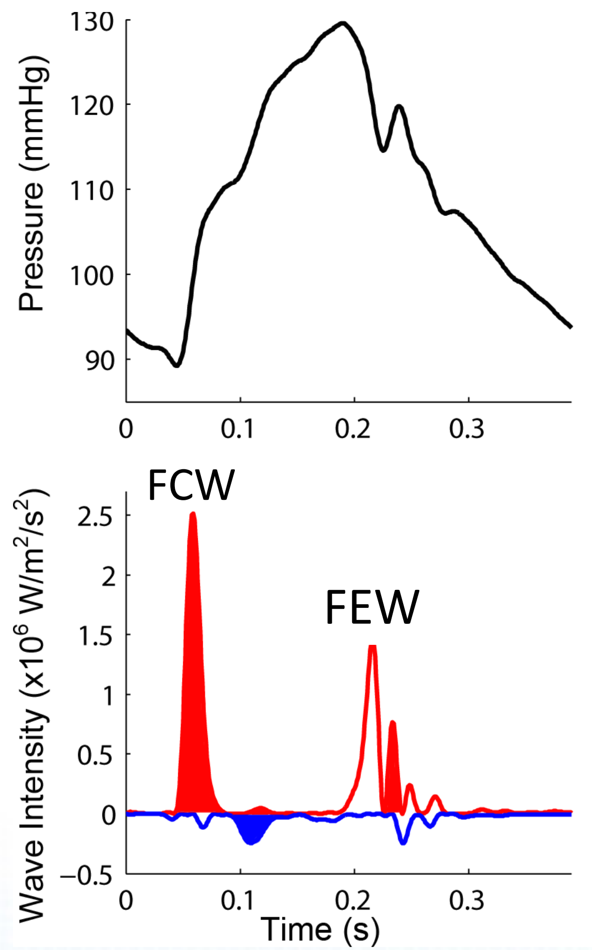
Waves generate and maintain mean pressure

Waves and mean pressure are linked via wave potential

Wave-based explanation of the diastolic pressure decay

Exponential decay is explained by

- distributed/diffuse (re-)reflection of FEW



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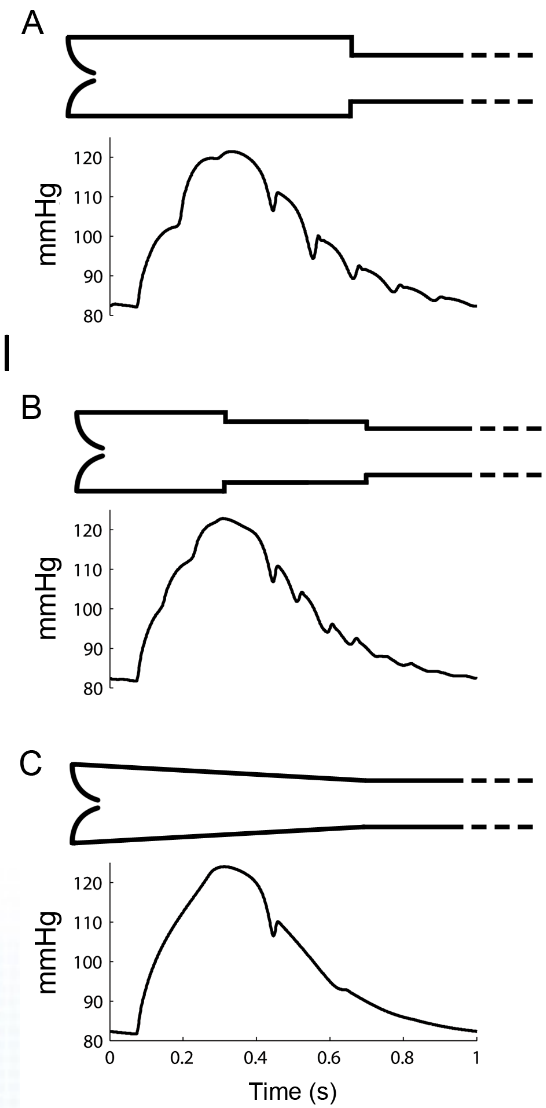
Wave-based explanation of the diastolic pressure decay

Exponential decay is explained by

- distributed/dispersed (re-)reflection of FEW
- total reflection of P_ at the aortic valve
- distal leakage of blood volume and wave potential



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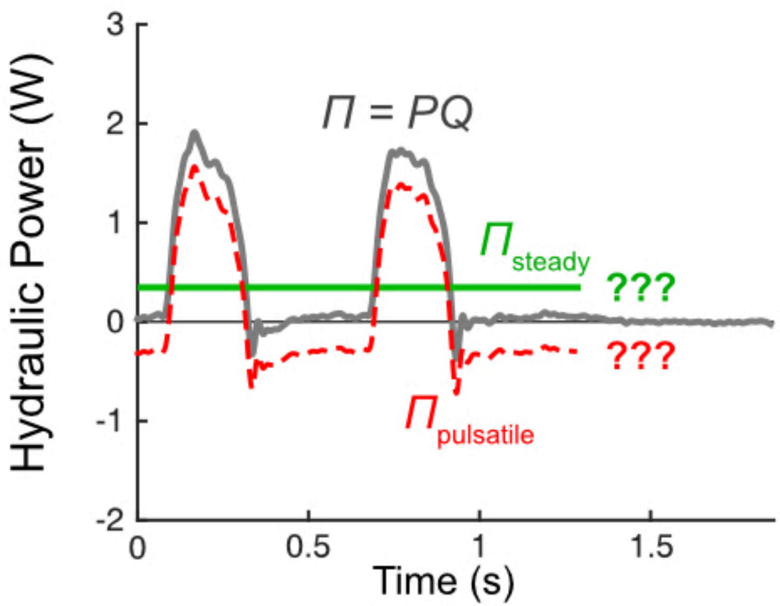
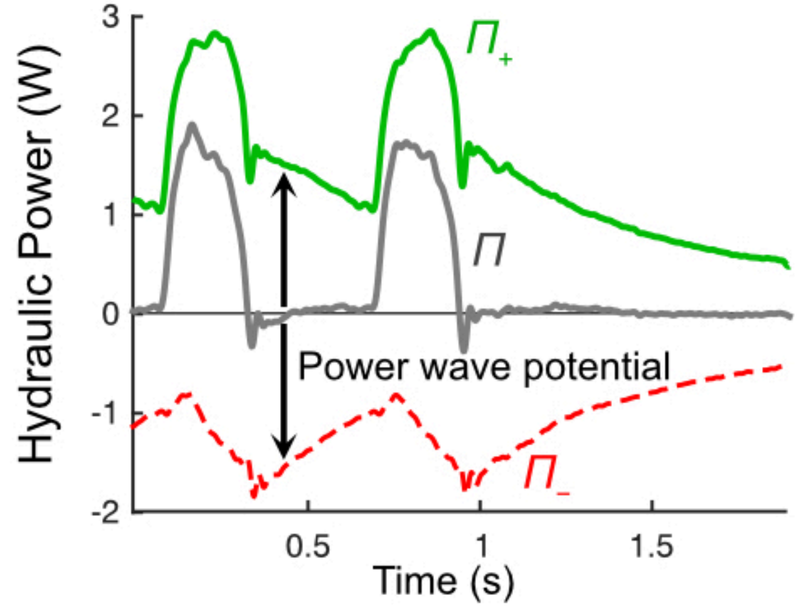
Wave separation for hydraulic power





Hydraulic energy potential:

$$E = \int \frac{1}{c}\left(\Pi_{+}^{0} - \Pi_{-}^{0}\right) dx$$

In the single vessel example:

E = 3.75 mJ

Mynard JP, Smolich JJ. Novel wave power analysis linking pressure-flow waves, wave potential and the forward and backward components of hydraulic power. Am J Physiol Heart Circ Physiol. 2016;310:H1026-H38.

Wave potential - a unified model of haemodynamics

	Wave (Potential) Model
Mean Pressure	✓
Volume storage	✓
Exponential P decay	✓
Pulse propagation	✓
P Augmentation	✓
P Amplification	✓

'Reservoir' effects

↕

'Wave' effects

Wave separation for hydraulic power → ventriculo-vascular coupling efficiency?

Thank you!

Funding

- National Health and Medical Research Council of Australia

Acknowledgments

- Joe Smolich
- Patrick Segers
- Berend Westerhof