DOI:
10.1109/EMBC.2014.6944441

Citation for published version (APA):
Charlton, P., Smith, J., Camporota, L., Beale, R., & Alastruey, J. (2014). Optimising the Windkessel Model for Cardiac Output Monitoring During Changes in Vascular Tone. In *Engineering in Medicine and Biology Society (EMBC): 2014 36th Annual International Conference of the IEEE* (pp. 3759-3762). IEEE. https://doi.org/10.1109/EMBC.2014.6944441

OPTIMISING THE WINDKESSEL MODEL FOR CARDIAC OUTPUT MONITORING DURING CHANGES IN VASCULAR TONE

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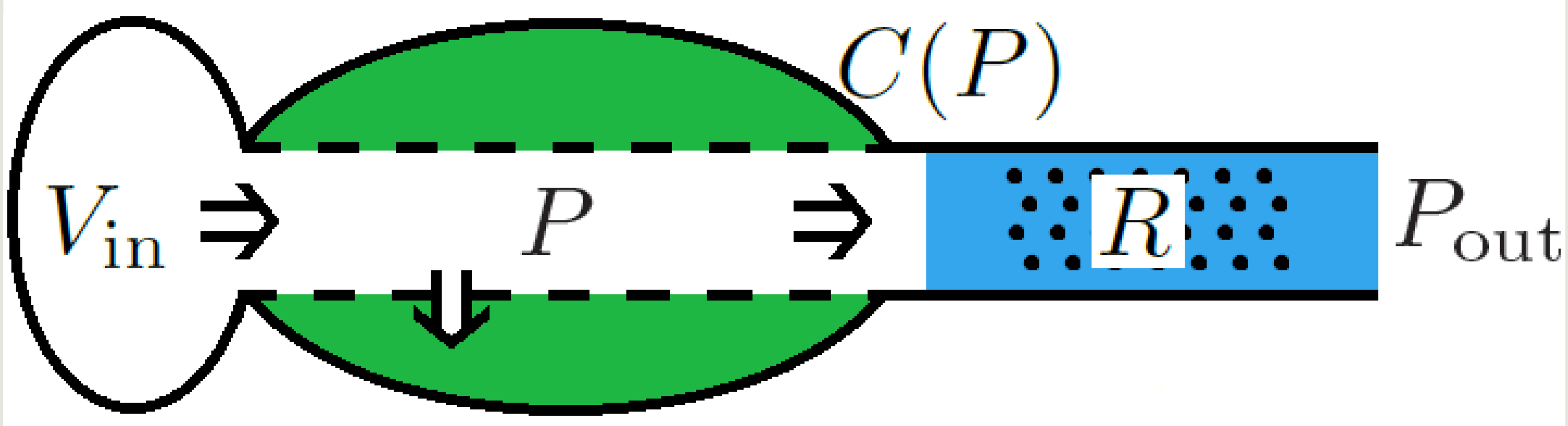
1. Why is this clinically important?

Cardiac output (CO) monitoring is used to assess the haemodynamics of critically ill patients. It is used to guide fluid administration and vasoactive drug use. However, it is often inaccurate during changes in vascular tone [1], which can be caused by fluid administration and vasoactive drug use. Monitors estimate CO from the arterial blood pressure (ABP) wave using the Windkessel model of the circulation.

Aim: To assess the accuracy of existing methods for CO monitoring using the Windkessel model during a change in vascular tone.

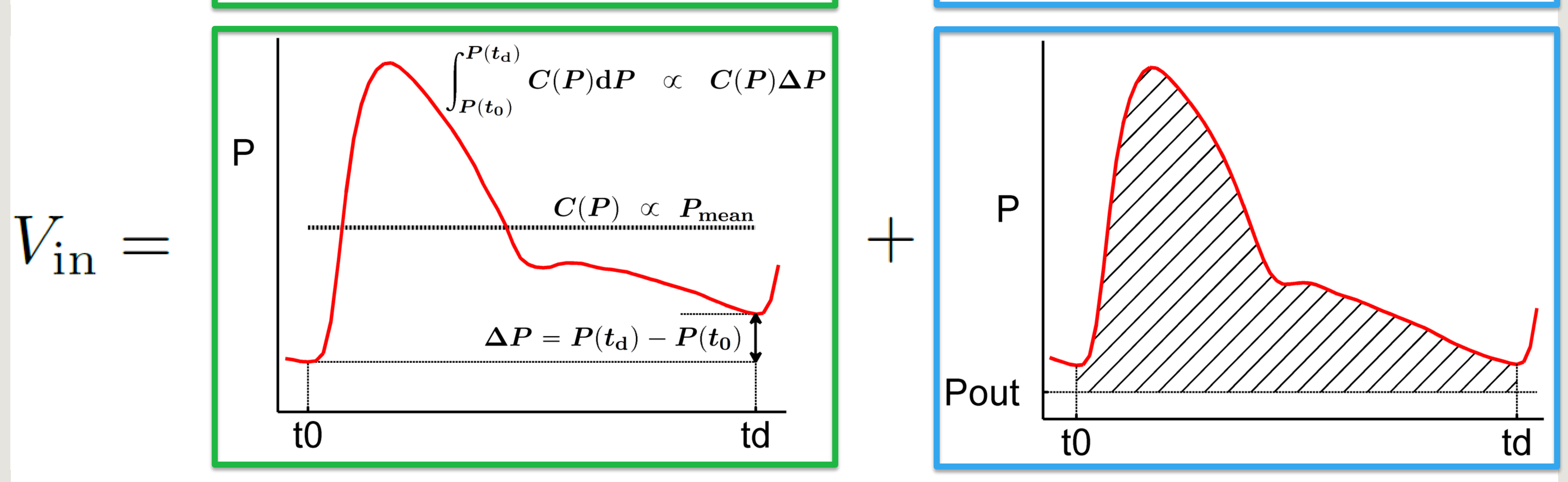
2. The Windkessel Model

This model expresses stroke volume, V_{in}, as the sum of **distending flow** and **outflow** terms. Each term contains an unknown physical variable: **compliance, C(P)**, or **resistance, R**.



Stroke Volume = **Distending Flow in the large arteries** + **Outflow through smaller arteries**

$$V_{in} = \int_{P(t_0)}^{P(t_d)} C(P)\,\mathrm{d}P + \frac{1}{R}\int_{t_0}^{t_d} [P - P_{out}]\,\mathrm{d}t$$



Several simplification methods have been used to eliminate one unknown variable. An independent calibration measurement is used to estimate the other variable, facilitating continuous CO monitoring.

3. Clinical Evaluation

Methods

ABP signals were acquired from 15 critically ill patients, alongside reference CO measurements, CO_{ref} [1]. The dosage of norepinephrine infusion, a vasoactive drug, was doubled during the recording giving a step-change in vascular tone. Continuous CO, CO_{est}, was estimated using each simplification method. CO_{est} values were calibrated with CO_{ref} prior to dosage increase. The precision of each method was assessed by comparing CO_{ref} during double dosage with the mean CO_{est} during that CO_{ref} measurement.

Results

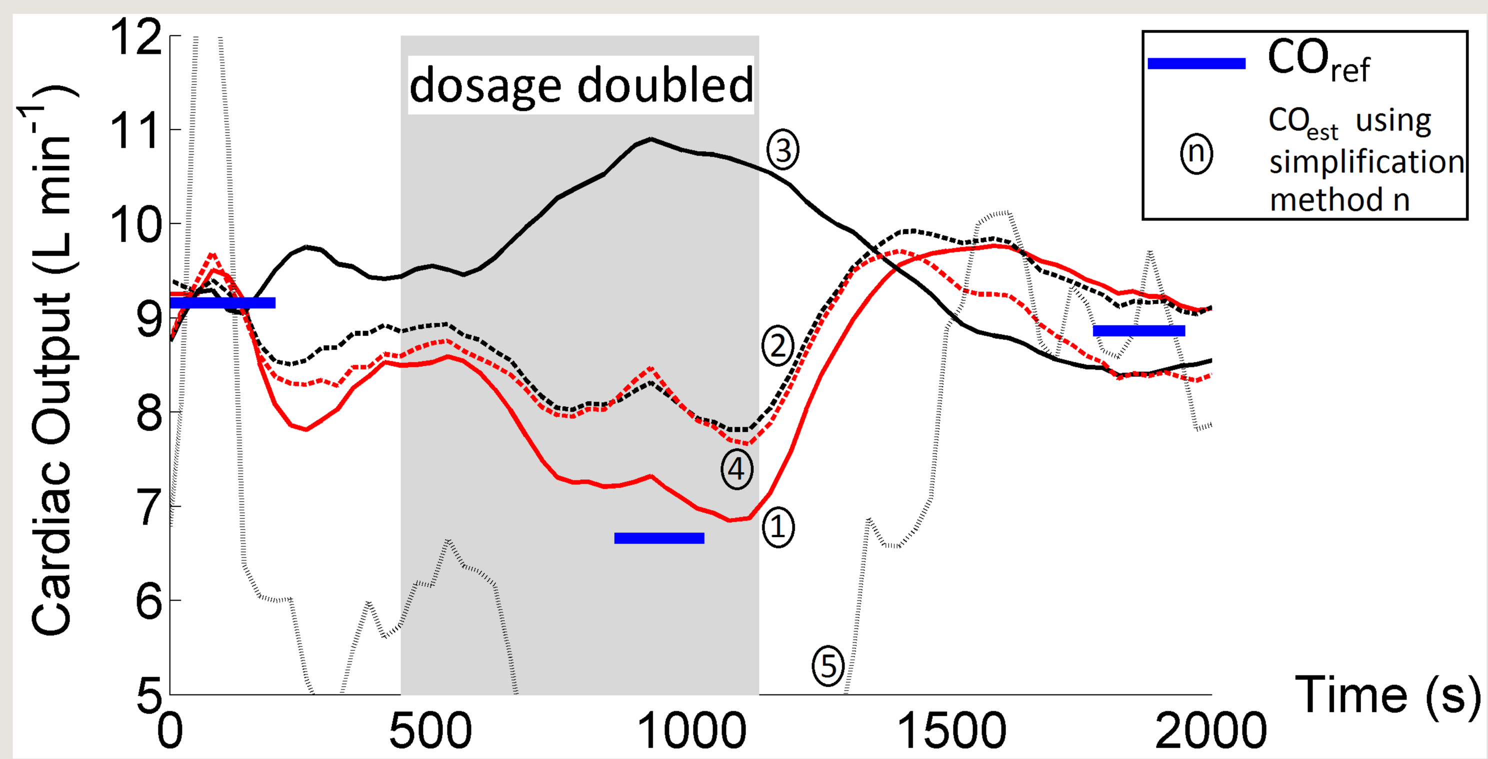
See table. The most accurate methods maintained both compliance and outflow terms. The remaining methods, which eliminated one of the terms, tracked CO less well during changes in vascular tone.

References

[1] J. Smith *et al.*, "Effects of norepinephrine-driven change in arterial blood pressure on four different continuous cardiac output systems in critically ill patients," *Intensive Care Med.*, vol. 37 Suppl 1, p. S280, 2011.

The paper accompanying this poster is:

Charlton P *et al.*, "Optimising the Windkessel Model for Cardiac Output Monitoring During Changes in Vascular Tone," *Engineering in Medicine and Biology Society (EMBC), 2014 36th Annual International Conference of the IEEE*, IEEE, 2014.



CO values for one patient: Methods (3) and (5) which used only one term were highly inaccurate.

4. Conclusion

CO monitoring using the Windkessel model is more accurate during changes in vascular tone when **distending flow** and **outflow** terms are maintained. No methods tracked CO within the clinically-acceptable ±30%.

Simplification Method	PE	RMSE	Bias [LOA]	R^2	Method Details	Terms	Accuracy
1) Constant C throughout beat	31	1.0	0.1 [-2.1 to 2.2]	0.62	The systemic time constant, $\tau = RC$, can be estimated from the diastolic decay, eliminating R.	■ ■	★★☆
2) Zero inflow during diastole	31	1.1	-0.2 [-2.3 to 2.0]	0.62	R can be written in terms of C by setting $V_{in} = 0$ during diastole. This is used to eliminate R.	■ ■	★★☆
3) Zero distending flow	37	1.9	1.4 [-1.2 to 3.9]	0.49	Eliminates C	□ ■	★☆☆
4) Stroke volume $\propto$ rms flow	43	2.3	1.8 [-1.2 to 4.7]	0.48	C is not required since power ($\propto$ root-mean-square flow) is only dissipated in the resistance.	□ ■	★☆☆
5) Zero outflow	97	3.6	-1.4 [-8.1 to 5.4]	0.56	Eliminates R	■ □	☆☆☆

PE: percentage error (%), RMSE: root mean square error (l min^{-1}), bias: mean difference (l min^{-1}), LOA: limits of agreement (l min^{-1}), R^2: coefficient of determination.

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KING'S HEALTH PARTNERS

This research was supported by the Department of Health via the National Institute for Health Research (NIHR) comprehensive Biomedical Research Centre award to Guy's & St Thomas' NHS Foundation Trust in partnership with King's College London and King's College Hospital NHS Foundation Trust. The views expressed are those of the authors and not necessarily those of the NHS, the NIHR or the Department of Health.

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