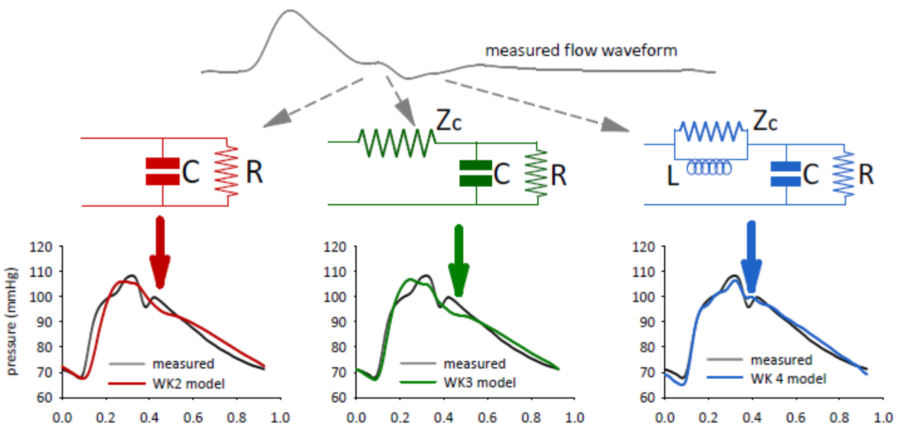
WINDKESSEL MODEL

What is it?	'Windkessel models' encompass a class of conceptual models of the arterial system, which can *physically* exist as bench models, but also as a *mathematical* or digital computer model, when they are often represented as an electrical analogue (see figure). The 'Windkessel', referring to the German word for air chamber, refers to the presence of a buffering element (compliance, C) in the model, needed to mimic the expansion of the aorta as the heart contracts in systole and builds up pressure, and its recoil in diastole. The other element, minimally needed to mimic arterial behaviour, is a resistance (R), representing the total hydraulic resistance of the arterial circulation. When these 2 elements are put in parallel and connected to a pumping heart, a system is obtained where pressure first rises in systole, to decay exponentially in diastole with a time constant given by the product of R and C (the 2-element windkessel model acts as a low pass filter). The behaviour of the model improves greatly with the proximal addition of a smaller resistive element, representing the characteristic impedance (Zc) of the aorta (yielding the 3-element windkessel model that most would consider as reference), and minor further improvement is found when adding a fourth component (L, effects of blood inertia). Important is that Windkessel Models are so-called zero dimensional models, with variables (pressure and flow) that change in time, but not in space (it is assumed that pressure changes take place simultaneously accross the model). These models therefore cannot describe the propagation of waves over the arterial tree. Mathematically, the windkessel model is described by a linear ordinary differential equation, usually written with pressure as the unknown variable and flow as input variable (the model predicts pressure for a given input flow).
Why do we measure it?	When used *physically*, Windkessel models provide a straightforward and very flexible way to mimic the behaviour of the arterial tree (or parts of it). As a *mathematical/computer* model, they can exist on their own as a model of the arterial tree, or as part of more complex models e.g., connected to 1D or 3D arteries to represent the arterial network further downstream from the connection site. They can also be used to estimate the total compliance of the arterial tree
How can it be measured?	Seminal work on heart-arterial interactions has been done using isolated heart preparations, with the heart pumping in a *physical* windkessel model. The *mathematical* model forms the basis of many different methods to estimate total arterial compliance. When pressure and flow waveforms are available, a typical workflow is to impose the flow to the model with initially unknown parameters, and use a model fitting technique to optimize model parameters in such a way that the pressure predicted by the model matches the measured pressure. A known variant to this approach is provided by the Pulse Pressure Method. An important consideration is that a model can only be properly fitted to data if the system where the data is measured is appropriately represented by the model. Windkessel models can generally do this very well for the normal systemic circulation, but less so in vasodilated

<table>
<tr><td></td><td>or low resistance systems (the normal pulmonary circulation) when also pressure waveforms much less exhibit the clean exponential decay in diastole. In these conditions, compliance estimation can become highly inaccurate.</td></tr>
<tr><td>Where is it measured?</td><td>Windkessel models are mostly used to represent the arterial system (systemic or pulmonary) as a whole, but they can also represent parts of it with tuned model parameters.</td></tr>
<tr><td>Figure</td><td>

The figure shows how well the 2-, 3- and 4-element windkessel models predict pressure for a given flow waveform, after model fitting. The 2-element WK model acts as a low pass filter, delaying pressure and filtering the pressure waveform; note the improvement obtained with the 3-element WK model and the excellent fit obtained using the 4-element WK model.
Figure adapted from Segers et al. 2022 </td></tr>
<tr><td>References</td><td>Segers et al. 2022. ISBN 9780323913911</td></tr>
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FEEDBACK AND SUGGESTIONS FOR THESE DEFINITIONS* CAN BE SUBMITTED AT

https://vascagenet.eu/feedback-for-official-glossary-of-key-terms

* These definitions have been downloaded from https://vascagenet.eu/official-glossary and were released on 12th July, 2022.