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Review

Waves and Windkessels reviewed

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Abstract Pressure and flow are travelling waves and are reflected at many locations. The forward and reflected waves, obtained by wave separation, are compound waves. This compounded character of the reflected wave explains why its magnitude decreases with increased peripheral resistance, why it appears to run forward rather than backward, and why its return time relates poorly with aortic wave speed. A single tube (aorta) with distal reflection is therefore an incorrect arterial model. Wave Intensity Analysis (WIA) uses time derivatives of pressure and flow, augmenting rapid changes and incorrectly suggesting a 'wave free period' in diastole. Assuming a 'wave free period', the Reservoir-Wave Approach (RWA) separates pressure into a 'waveless' reservoir pressure, predicted by Frank's Windkessel, and excess pressure, accounting for wave phenomena. However, the reservoir pressure, being twice the backward pressure, and location dependent, is a wave. The Instantaneous wave Free pressure Ratio distal and proximal of a stenosis, iFR, also assumes a 'wave free period', and is based on an instantaneous pressure-flow ratio, an incorrect resistance measure since Ohm's law pertains to averaged pressure and flow only. Moreover, this ratio, while assumed minimal, was shown to decrease with vasodilation.

Windkessel models are descriptions of an arterial system at a single location using a limited number of parameters. Windkessels can be used as model but the actual arterial system is not a Windkessel. Total Peripheral Resistance and Total Arterial Compliance, (the 2-element, Frank Windkessel), supplemented with aortic characteristic impedance (3-element Windkessel) mimics the arterial system well.

Introduction

The pulsatile cardiac pump sets up time and location dependent waves of pressure and flow in the arterial system. These waves travel over the system, and are

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(partially) reflected at many locations. Both pressure and flow waves consist of forward and reflected (backward) components. The forward and backward waves are the sum of many individually reflected waves and thus compounded waves.

We here review the different methods of (pressure) wave analysis. We will start with Wave Separation Analysis (WSA), i.e. the separation of pressure and flow into their forward and backward components[1] and explain how analysis of the measured pressure wave alone, so-called pressure Wave Form Analysis (WFA) relates to arterial properties.[2] Subsequently we will discuss Wave Intensity Analysis (WIA) and show the similarities and differences with Wave Separation Analysis.[3] Then two methods based on Wave Intensity Analysis will be discussed, the Reservoir-Wave Approach (RWA)[4] and the instantaneous wave Free Ratio (iFR) of pressures distal and proximal of a stenosis.[5] Finally, we will discuss Windkessel models as description of pressure-flow relations, and show that with three parameters the arterial system can be described. Most calculations and examples will be discussed using proximal aortic pressure and flow waves.

Wave Separation Analysis

If no reflections of waves would be present in the arterial system the pressure and flow waves would have similar shape and their ratio is given by the characteristic impedance, Z_c, of the vessel at the measurement location (Fig. 1A). The Z_c depends on vessel size, wall stiffness (compliance) and blood properties, and can be seen as the combined effect of the accelerating blood mass taking place during the ejection phase into the compliant artery. The Z_c relates to Pulse Wave Velocity, PWV, as $Z_c \cdot A = \rho \cdot PWV$ with A cross-sectional area of the artery. For large arteries (aorta and conduit arteries) the characteristic impedance is a (mathematically) real quantity, and without reflections pressure and flow have similar shape (Fig. 1A). At bifurcations and other discontinuities both pressure and flow waves are (partly) reflected. The reflection coefficient of pressure and flow are quantitatively the same but their signs are opposite. This can be understood as follows. When a vessel is closed at the end, the flow wave reflects completely but inversely and the net (measured) flow is zero. Pressure however also reflects completely and measured pressure is twice as large as the incoming pressure.

Therefore, the forward pressure and forward flow wave are related by characteristic impedance, $P_{forward}/Q_{forward} = Z_c$. The backward waves being inverse with respect to each other relate as $P_{backward}/Q_{backward} = -Z_c$. Reflections are therefore the reason that measured pressure and flow waves, i.e., the sum of forward and backward waves, are different in shape (see Fig. 1B). Since reflections take place at all discontinuities, many reflection sites exist and the forward and backward waves are actually a summation of many individual waves, compound forward and compound backward wave.

Up to the early 1970's pressure waves were almost exclusively studied and considered, while flow waves were not. An example is given in Fig. 1C.[6] The 'incident' (i.e.

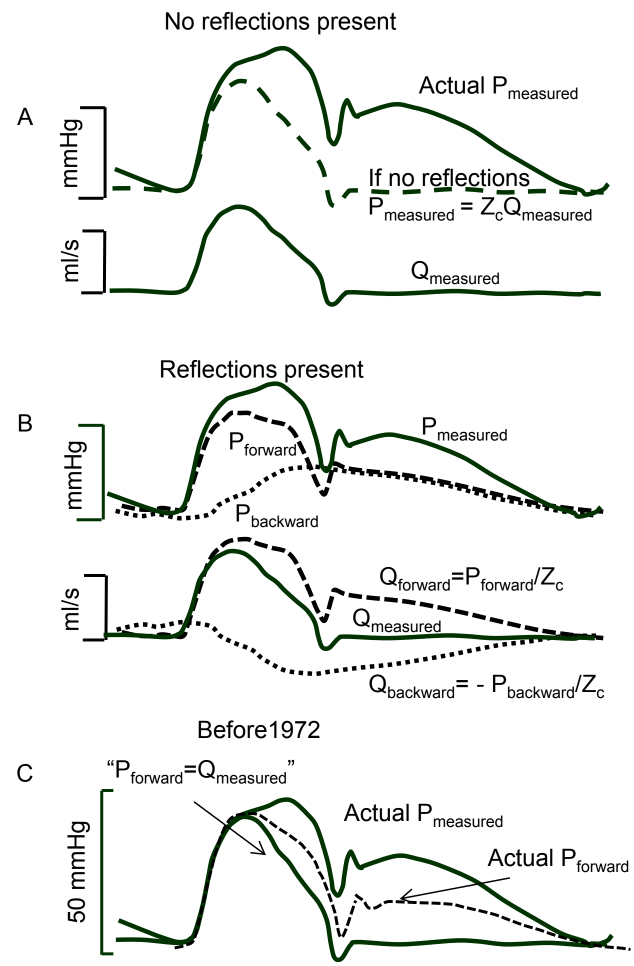

Figure 1 Separation of pressure and flow waves. Panel A: Without reflections the pressure and flow wave have the same shape, their ratio is the characteristic impedance, Z_c; The measured (actual) pressure is also given. Panel B: Pressure and flow waves consist of forward and backward (reflected) waves. The forward pressure and flow waves are related by Z_c (dashed lines); the backward pressure and flow waves relate by $-Z_c$ (dotted lines), meaning that backward pressure and flow waves have the same shape but are inversed with respect to each other. Panel C: Before 1970 pressure waves were assumed to reflect while flow waves were assumed not to consist of forward and backward components; it was generally assumed that the forward pressure wave was equal to the measured flow wave and that the reflected pressure wave was therefore the difference between measured pressure and flow wave scaled with Z_c (Redrawn from Kouchoukos and McDonald).[6]

forward) pressure wave was set equal to the measured flow wave, and the backward wave was thus supposed to be the difference between measured pressure wave and measured (scaled with Z_c) flow wave. This implies that the heart was assumed to be a flow source (complete negative reflection of the backward flow wave at the heart). However, as also shown in Fig. 1C, and derived below, the forward waves of pressure and flow have the same shape (dashed line) and the reflected wave adds to the forward pressure wave to result in the measured pressure wave while the reflected

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