International Journal of Cardiology 176 (2014) 1009–1012

Contents lists available at ScienceDirect

International Journal of Cardiology

journal homepage: www.elsevier.com/locate/ijcard

Letter to the Editor

The case against the reservoir-wave approach

Jonathan P. Mynard *, Joseph J. Smolich

Heart Research, Clinical Sciences, Murdoch Childrens Research Institute, Department of Paediatrics, University of Melbourne, Parkville, Victoria, Australia

ARTICLE INFO

Article history:
Received 6 June 2014
Accepted 22 July 2014
Available online 30 July 2014

Keywords:
Haemodynamics
Arterial
Wave reflection
Wave separation
Wave intensity analysis
Reservoir-wave

We read with interest Tyberg et al.'s case for the reservoir-wave approach (RWA), appropriately described as a "controversial approach to [the analysis of] arterial hemodynamics" [1]. Lest readers of IJC be exposed to a one-sided debate, we feel it is important to also present the case against this approach, some aspects of which have been aired previously [2–6].

The RWA was initially proposed in 2003 [7] and has been championed primarily by two co-authors (Prof. Tyberg and Prof. Parker) who have made outstanding contributions to the field of haemodynamics, including the original description of wave intensity analysis [8]. Briefly, the RWA is an intuitive and empirical description of arterial haemodynamics, with measured pressure (P) considered to be the sum of two independent components: 1) a wave-independent reservoir pressure (P_{res}) that represents systolic filling and diastolic discharge of a compliant arterial reservoir, and 2) an excess pressure (P_{ex}) that governs all pressure-flow waves and is used in modified wave intensity and wave separation analyses (conventional analyses employ P rather than P_{ex}). The rationale presented for the RWA was initially quite appealing, as this approach 1) unified the analysis of systolic and diastolic haemodynamics within a single paradigm, and 2) avoided apparently artefactual 'self-cancelling' diastolic waves evident with conventional wave separation [9]. However, subsequent critical appraisal of the RWA, principally by our laboratory, has raised significant concerns not only about the proposed basis of P_{res}, but also more importantly, the validity of modified wave analyses using P_{ex}.

With respect to P_{res}, this variable was originally defined as a space-invariant (i.e. zero-dimensional, 0-D) and wave-independent component of pressure [7]. However, a key internal inconsistency in the current formulation of P_{res} is now recognised. Specifically, P_{res} calculated along a length of aorta using the same method described in [7] revealed significant spatial variation that was highly suggestive of wave phenomena, with the early-systolic foot of P_{res} clearly constituting a 'propagated disturbance', or by definition, a wave [2].

While Tyberg et al. have conceded that P_{res} is 'wave-like', it has now been asserted that P_{res} is "fundamentally different from the forward or backward … waves defined by wave intensity analysis" [1]. However, as we have argued previously, the 0-D equations governing P_{res} are a reduced form of the one-dimensional (1-D) wave equations, on which wave intensity is based, and hence P_{res} must be a subset of (*not independent of*) wave effects [2,6]. Indeed, modelling studies having shown that P_{res} is *generated by wave reflection* and that $P_{res} = 0$ in a reflectionless arterial network [10]. Recent clinical data confirmed the prediction in [10] that P_{res} is equal to twice the conventional backward (i.e. reflected) wave component of pressure [11], showing that P_{res} has no incremental clinical value over and above conventional wave separation. Given that reflected waves generate P_{res} [10,11], the continued contention that P_{res}, *rather than wave reflection*, is the main determinant of augmentation index [1] is therefore puzzling, especially given that Prof. Parker was a co-author of [11]. Moreover, Tyberg et al.'s statement that "further work is necessary to expand the current 0-D description of the reservoir to 1-D and beyond" not only acknowledges the limitations of the current description, but also gives the impression that the RWA is now being pursued more on the basis of conviction than firm evidence or strong theoretical foundations ('beyond 1-D' is meaningless when discussing a reservoir pressure).

Concerns about the validity of modified wave analyses using P_{ex} in the RWA arise from the observation that, when compared with conventional analysis, 1) reflected compression waves are smaller or absent, 2) decompression waves are larger, and/or 3) new waves appear [2,6,9,12]. Although it is suggested that these differences may simply be a product of how waves are defined [1], they lead to profoundly different conclusions about arterial properties and behaviour. Hence, understanding the underlying basis of these differences is of paramount importance. In this context, it is widely agreed that 1) wave reflection occurs whenever a propagating wave encounters vascular impedance mismatching, 2) a reflection coefficient (R_Z) can be calculated from vascular impedances, independent of haemodynamics (i.e. from changes in stiffness and diameter alone), and 3) R_Z should equal the haemodynamic reflection coefficient (R_P), i.e. the ratio of reflected and incident P (or P_{ex}) waves [13,14].

* Corresponding author at: Heart Research, Murdoch Childrens Research Institute, Flemington Rd. Parkville, VIC 3052, Australia.
E-mail address: jonathan.mynard@mcri.edu.au (J.P. Mynard).

http://dx.doi.org/10.1016/j.ijcard.2014.07.070

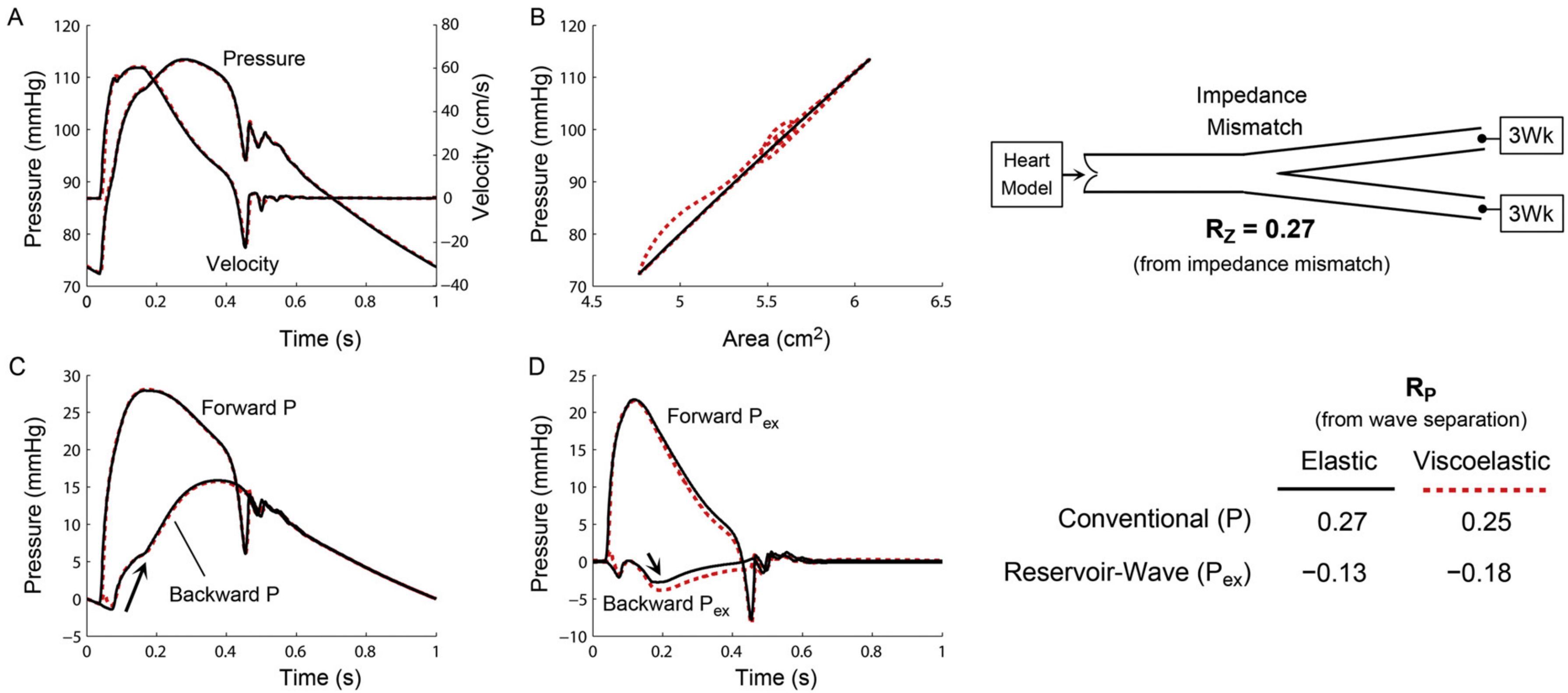

Fig. 1. (A) Pressure and velocity predicted from a one-bifurcation model. (B) Pressure–area relation of the proximal vessel showing hysteresis when viscoelasticity is included (dashed red line) but not for a purely elastic vessel (solid black line). (C) Forward and backward components of pressure obtained from conventional wave separation and (D) from the reservoir-wave approach, with arrows indicating the change in the backward component when a reflected wave from the junction would be expected to arrive back at the inlet. A realistic heart/valve model is used at the inlet [16], while the 3-element windkessel (3Wk) represents peripheral vessels. Parameters of the proximal/distal segments are: length, 10/25 cm; diameter, 2.64/1.64 cm; wave speed, 462/616 cm/s; characteristic impedance, 0.063/0.219 mmHg·s/cm^3. Reflection coefficient calculated from the impedance change ($R_Z = 0.27$) matched that calculated from wave separation (R_P) when employing the conventional but not the reservoir-wave approach.