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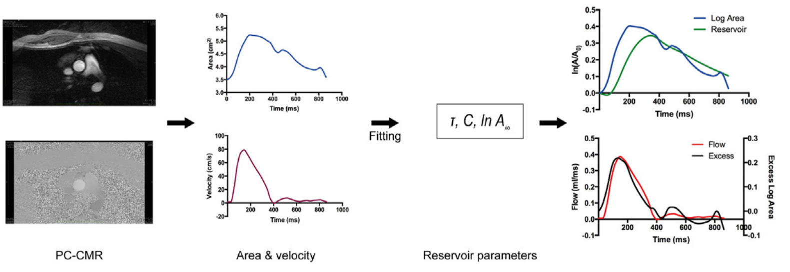
A method to implement the reservoir-wave hypothesis using phase-contrast magnetic resonance imaging

Robert D.M. Gray[a], Kim H. Parker[b], Michael A. Quail[c], Andrew M. Taylor[c], Giovanni Biglino[c,d,*]

[a] CoMPLEX, University College London, London, United Kingdom
[b] Bioengineering Department, Imperial College London, London, United Kingdom
[c] Centre for Cardiovascular Imaging, Institute of Cardiovascular Science, University College London & Great Ormond Street Hospital for Children, NHS Foundation Trust, London, United Kingdom
[d] Bristol Heart Institute, University of Bristol, Bristol, United Kingdom

GRAPHICAL ABSTRACT



ABSTRACT

The reservoir-wave hypothesis states that the blood pressure waveform can be usefully divided into a “reservoir pressure” related to the global compliance and resistance of the arterial system, and an “excess pressure” that depends on local conditions. The formulation of the reservoir-wave hypothesis applied to the area waveform is shown, and the analysis is applied to area and velocity data from high-resolution phase-contrast cardiovascular magnetic resonance (CMR) imaging. A validation study shows the success of the principle, with the method producing largely robust and physically reasonable parameters, and the linear relationship between flow and wave pressure seen in the traditional pressure formulation is retained. The method was successfully tested on a cohort of 20 subjects (age range: 20–74 years; 17 males).

* Corresponding author at: Bristol Heart Institute, School of Clinical Sciences, University of Bristol, Upper Maudlin St, Bristol BS2 8HW, United Kingdom.
E-mail address: g.biglino@bristol.ac.uk (G. Biglino).

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This paper:

- Demonstrates the feasibility of deriving reservoir data non-invasively from CMR.
- Includes a validation cohort (CMR data).
- Suggests clinical applications of the method.

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Methods

Rationale

The reservoir (Windkessel) model of arterial mechanics [1] represents the arteries as a single compliant compartment and with a single outflow resistance. This model predicts exponentially falling pressure in diastole, but not the sharp rise in pressure seen in systole. The more modern wave theory separates the pressure waveform into a combination of forward and backward travelling waves [2]. This analysis provides a good description during systole, where the separation produces an initial forward compression wave followed by backward reflected waves. However, in diastole this approach predicts large cancelling forward and backward waves to explain a falling pressure and a zero velocity [3]. The reservoir-wave hypothesis is an attempt to combine these two methods and benefits from the good predictions of the wave theory in systole and the reservoir theory in diastole.

In the reservoir-wave hypothesis [4], the pressure waveform in diastole is fitted with a single exponential model from which the reservoir parameters are extracted. We can then calculate the reservoir pressure and the excess pressure, which refers to the remaining part of the pressure waveform when the reservoir is subtracted. The latter is found to have the interesting property of being proportional to the flow into the arterial system. This indicates that the nearly identical excess pressure (P_{ex}) and inflow (Q_{in}) waveforms result only from forward-traveling compression and decompression waves generated by the left ventricle [5].

The reservoir-wave parameters describing the reservoir and excess pressure have been shown to have physiological and pharmacological significance. Their importance has been discussed in various areas including as a measure of left ventricular relaxation [6], as being related to hypertension [7], as a possible therapeutic target [8] and as a significant predictor of cardiovascular events carrying information for selection of pharmacological therapies [9].

Considering the clinical value of the reservoir-wave model, an implementation of the method for medical imaging, and cardiovascular magnetic resonance (CMR) imaging in particular, is desirable.

Implementation

The analysis is incorporated in a Python script. CMR data provides area (A) and velocity (U) as functions of time, sampled with a set temporal resolution (approximately 10 ms), and hence the flow $Q_{in} = UA$.

In complete analogy to the derivation of the reservoir pressure, we derive the reservoir area as follows. We have an equation for the reservoir pressure [3]:

$$\frac{dP_{res}}{dt} = \frac{(P_{res} - P_{\infty})}{RC} = \frac{Q_{in}(t)}{C} \quad (1)$$

where R and C are the resistance and compliance of the arterial system respectively, Q_{in} is the flow of blood into the arterial system and P_{∞} is the pressure at which flow through the circulation ceases. We