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Experimental evaluation of local wave speed in the presence of reflected waves

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ABSTRACT

Wave speed (also called pulse wave velocity) is the speed by which disturbance travels along the medium and it depends on the mechanical and geometrical properties of the vessel and on the density of the blood. Wave speed is a parameter of clinical relevance because it is an indicator of arterial stiffness and cardiovascular diseases.

The aim of this work is to compare different methods for the determination of local wave speed in bench experiments and investigate their relative accuracy when reflections are present.

Pressure (*P*), flow (*Q*) and diameter (*D*) were measured along a flexible tube far and close to three positive and three negative reflection sites. Wave speed was calculated using PU-loop, (ln*D*)*U*-loop, QA-loop, D^2P-loop, sum of squares and characteristic impedance methods. Results were compared to the foot-to-foot method.

We found that far from the reflections almost all methods give uniform results. Close to positive reflections the methods that rely on *P* and *Q* (or *U*) overestimate the wave speed value, while techniques based on *D* (or *A*) and *Q* (or *U*) underestimate it. On the contrary, close to negative reflections the methods that rely on *P* and *Q* (or *U*) underestimate the wave speed value, while techniques based on *D* (or *A*) and *Q* (or *U*) overestimate it. The D^2P-loop does not seem to be affected by positive or negative reflections.

Most of the methods currently used to determine local wave speed are affected by reflections, but the (ln*D*)*U*-loop remains the easiest technique to use in the clinic.

1. Introduction

Wave speed (*C*), widely known by physiologists and clinicians as pulse wave velocity, is the speed by which disturbance travels along the medium (Lighthill, 1978). *C* depends on the mechanical and geometrical properties of the vessel, and on the density of the blood (Bramwell and Hill, 1922). That is why *C* is used as an indicator of arterial stiffness and cardiovascular risk (Blacher et al., 1999).

In current clinical practice the most commonly used method to calculate *C* is the foot-to-foot, which involves pressure measurements in two different sites at a known distance apart. This technique gives an average speed along the path traveled by the wave, often called regional *C*. The two measurements are usually taken at the carotid and femoral arteries with the resultant wave speed commonly known as the carotid-femoral index. However, the carotid and femoral arteries have different mechanical properties, the former is an elastic and the latter is a muscular artery and they have different *C* (Borlotti et al., 2012). For this reason, regional *C* might not be an accurate parameter to determine the local arterial mechanical properties.

Local wave speed refers to the determination of *C* at a single measurement site; hence there can be clear prognostic value in determining local *C*. Several methods have been introduced to determine local *C* in arteries for diagnostic purpose. Westerhof et al. (1969) determined local *C* using Fourier-based frequency domain analysis, calculating the characteristic impedance (Z_C), which can be obtained from simultaneous measurements of pressure (*P*) and flow (*Q*) taken at the same site. More recently time-domain techniques were introduced for the determination of local *C* using two of the following simultaneous measurements: *P*, *Q*, velocity (*U*), diameter (*D*) and area (*A*). Khir et al. (2001) proposed the PU-loop method that relies on the linearity between *P* and *U* in the absence of reflections; the slope of the linear portion of the loop at early systole when most probably only forward waves are present indicates *C*. Rabben et al. (2004) introduced the QA-loop method that is based on the same principle

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of the PU-loop. To accommodate the co-existence of incident and reflected waves in the coronary arteries, Davies et al. (2006) proposed the sum of squares technique deriving a formula that minimizes the net wave energy over a complete cardiac cycle using simultaneously P and U measurements. Feng and Khir (2010) introduced a technique that uses D and U measurements. Local wave speed is determined from the slope of the linear portion of the (ln$D$)U-loop in early systole and is equal to 1/2 C. This method has the advantage that it does not rely on the invasive pressure measurement and uses D and U which can be easily acquired non-invasively in the superficial arteries. Alastruey (2011) proposed the D^2P-loop which relies on the determination of the slope of linear part of the loop in diastole assuming the arterial wall as Voigt-type visco-elastic material. The slope is equal to $D_0/\rho c^2$ (with D_0, mean arterial diameter). All of the loop methods rely on the linear relationship between two measurements in a period that is reflection free where the wave speed can be calculated from the slope of the linear part of the loop; early systole for PU-loop, (ln$D$) U-loop and QA-loop, and late diastole D^2P-loop. If the measurement site is close to a reflection site the reflection-free period might be too short to allow for determining C accurately, as we previously demonstrated that the PU-loop method is affected by reflections (Li et al., 2011).

In this work we propose an experimental comparison of currently used methods for calculating local C in flexible tubes. The aim of this study is to investigate the relative accuracy of these methods for the determination of local wave speed compared to the foot-to-foot method. The aim is also, to establish the effect of positive and negative reflections on the results of these methods.

2. Material and methods

2.1. Theoretical background

In this section a brief description and the equations of all methods are reported.

2.1.1. Characteristic impedance (C_z)

Wave speed can be calculated using the characteristic Impedance (Z_C) as

$$C_z = \frac{AZ_C}{\rho} \tag{1}$$

where Z_C is calculated as the averaged ratio of P to Q moduli over a chosen frequency range (Westerhof et al., 1969, 1971, 1973; Milnor and Bertram, 1978).

In this work, we used four frequency ranges: 3–10 Hz, C_{z3_10} (Westerhof et al., 1973), 2–12 Hz, C_{z2_12} (Pepine et al., 1979), 5–15 Hz, C_{z5_15} (Dujardin et al., 1980), 9–18 Hz, C_{z9_18} (Cox and Bagshaw, 1975).

2.1.2. PU-loop (C_{pu})

This method assumes that in early systole backward waves are negligible, the relationship between P and U is linear and the wave speed can be calculated from the water-hammer equation as the slope of initial linear part of the loop (Khir et al., 2001)

$$C_{pu} = \frac{1}{\rho}\frac{dP_{\pm}}{dU_{\pm}} \tag{2}$$

where dP and dU are the changes in pressure and velocity respectively, over the systolic initial linear range of the loop. ρ is fluid density and $\pm$ indicate the forward and backward directions respectively.

2.1.3. Sum of squares (C_{pu}^{22})

This method was particularly introduced to avoid the reflections existing predominantly throughout the cardiac cycle in the coronary arteries. It is based on the minimization of the net wave energies over a cardiac cycle (Davies et al., 2006)

$$C_{p^2u^2} = \frac{1}{\rho}\sqrt{\frac{\Sigma(dP)^2}{\Sigma(dU)^2}} \tag{3}$$

2.1.4. QA-loop (C_{qa})

In the absence of reflected waves during early systole, C can be determined as (Rabben et al., 2004)

$$C_{qa} = \frac{dQ}{dA} \tag{4}$$

where dQ and dA are the changes in the flow rate and cross sectional area respectively, over the systolic linear range of the loop.

2.1.5. (lnD)U-loop (C_{du})

In the absence of reflected waves in early systole, the wave speed can be calculated as (Feng and Khir, 2010)

$$C_{du} = \frac{1}{2}\frac{dU_{\pm}}{d\ln D_{\pm}} \tag{5}$$

where $d\ln D$ is the change in logarithm the diameter over the systolic initial linear range of the loop.

2.1.6. D^2P-loop (C_{dp})

Considering the arterial wall as a Voigt-type viscoelastic material, during diastole the relationship between D^2 and P is nearly linear (Alastruey, 2011), and wave speed can be written as

$$C_{dp} = D_0\sqrt{\frac{dP}{\rho d(D^2)}} \tag{6}$$

where D_0 is mean arterial diameter.

2.2. Experimental set-up

Pressure, flow and diameter were measured in a silicone tube, 10 mm diameter and 1 mm wall thickness, uniform along its 3 m length, which we called 'mother' tube (Fig. 1). Daughter tubes were connected to the mother tube to provide positive ($n=3$) and negative ($n=3$) reflection coefficients. The dimensions of the daughter tubes with the corresponding theoretical reflection coefficient (R_t) generated at the connection are reported in Table 1. R_t is calculated as

$$R_t = \frac{\frac{A_0}{c_0} - \frac{A_1}{c_1}}{\frac{A_0}{c_0} + \frac{A_1}{c_1}} \tag{7}$$

where 0 and 1 refer to up- and downstream the discontinuity, respectively. The mother tube was fully immersed into a water tank. The inlet and outlet of the tubes

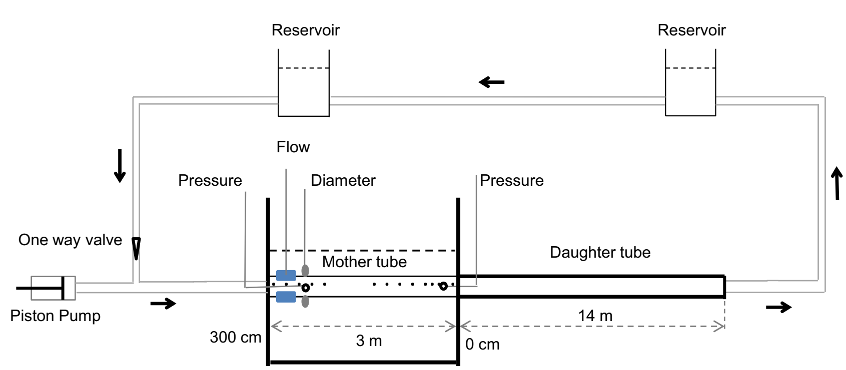

Fig. 1. Schematic representation of the experimental set-up. The arrows indicate the direction of flow. Dashed lines indicate level of fluid and the dots indicate the measurement sites.