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Wave intensity analysis in air-filled flexible vessels

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ABSTRACT

Wave intensity analysis (WIA) is an analytical technique generally used to investigate the propagation of waves in the cardiovascular system. Despite its increasing usage in the cardiovascular system, to our knowledge WIA has never been applied to the respiratory system. Given the analogies between arteries and airways (i.e. fluid flow in flexible vessels), the aim of this work is to test the applicability of WIA with gas flow instead of liquid flow. The models employed in this study are similar to earlier studies used for arterial investigations. Simultaneous pressure (P) and velocity (U) measurements were initially made in a single tube and then in several flexible tubes connected in series. Wave speed was calculated using the foot-to-foot method (c_f), which was used to separate analytically the measured P and U waveforms into their forward and backward components. Further, the data were used to calculate wave intensity, which was also separated into its forward and backward components. Although the measured wave speed was relatively high, the results showed that the onsets and the nature of reflections (compression/expansion) derived with WIA, corresponded well to those anticipated using the theory of waves in liquid-filled elastic tubes. On average the difference between the experimental and theoretical arrival time of reflection was 6.1% and 3.6% for the single vessel and multivessel experiment, respectively. The results suggest that WIA can provide relatively accurate information on reflections in air-filled flexible tubes, warranting further studies to explore the full potential of this technique in the respiratory system.

1. Introduction

The phenomenon of wave propagation in arteries has been extensively investigated experimentally (*in vivo* as well as *in vitro* studies) (Matthys et al., 2007; Feng and Khir, 2008; Parker and Jones, 1990) and computational models of pulse waves, propagating in the arterial network, have been developed with the arteries (or model arteries) considered as elastic tubes filled with blood (or water) (Sherwin et al., 2003; Alastruey et al., 2009; Alastruey et al., 2008; Formaggia et al., 2003). Wave intensity analysis (WIA) is a time domain analytical technique that was introduced by Parker and Jones (1990) for studying arterial waves. Although the mathematical derivation of WIA is quite complex involving the use of the method of characteristics to solve the 1-D conservation of mass and momentum equations, the results are very intuitive. Using WIA, it is possible to separate the forward and backward contribution of pressure (P) and velocity (U) waveforms for a straightforward interpretation of the existence and the distance of reflection sites (e.g. obstructions, bifurcations) by simply looking at the amplitude and arrival time of reflected waves, respectively.

The respiratory system, like the arterial system, is a branching network of elastic tubes where bifurcations, obstructions and the bronchioles represent the main source of reflections. Currently there are two main techniques for the diagnosis of airways obstruction and for a general assessment of respiratory mechanics; the forced oscillation technique (FOT) and the impulse oscillometry system (IOS), both measuring the response to artificial pulses induced at the mouth of the patient. The basic concept for these techniques relies on forcing an external signal that can be (i) sinusoidal (mono or multi frequency) for FOT (Oostveen et al., 2003) or (ii) an aperiodic single impulse of alternative direction for IOS (Smith et al., 2005). However, the results can be difficult to interpret since FOT and IOS provide information about the impedance of the overall respiratory system in the frequency domain; information about the location of single reflection sites is very difficult to determine unambiguously. It seems therefore reasonable to consider the use of WIA, which is a temporal rather than a frequency based analysis, as a possible tool to investigate the phenomenon of propagation and reflection of waves. We consider the waves involving the exchange of energy between the elastic airway walls and the kinetic energy of the air in lungs (i.e. air-wall waves), in which context the analysis of reflected air-wall waves could be applied, for example, as a non-invasive tool for the detection of bronchial obstruction. Therefore, the aim of this work is to test the applicability of WIA in simple configurations using air-filled flexible tubes. In this respect continuous measurements of P and U, which are the signals acquired routinely with IOS and FOT, are used to calculated wave intensity in simplified experimental models of airways. First a

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single distensible tube (single vessel experiment) is considered then the study is extended to three tubes connected in series (multivessel experiment).

2. Methodology

2.1. Wave intensity analysis: basic principles

WIA considers pressure and velocity waveforms as successive wavefronts, and wave intensity (dI) is defined as

$$dI = dPdU \quad (1)$$

Where dP and dU are respectively the change of pressure and velocity during a sample time, measured simultaneously at the same site. Assuming that forward and backward waves interact linearly, we can write

$$dP = dP_+ + dP_- \quad (2a)$$

$$dU = dU_+ + dU_- \quad (2b)$$

where the subscripts (+) and (−) denote the forward and backward directions respectively.

With a knowledge of wave speed (c), the fluid density (ρ), the Water hammer equation derived from the conservation of mass and momentum across the wavefornt in the (+) and (−) directions ($dP_\pm = \pm \rho c dU_\pm$) yields

$$dP_\pm = 1/2(dP \pm \rho c dU) \quad (3a)$$

$$dU_\pm = 1/2(dU \pm dP/\rho c). \quad (3b)$$

Integration of Eqs. (3a) and (3b) gives the pressure and velocity waveforms in the (+) and (−) direction.

$$P_+(t) = P_0 + \sum_{t=0}^{t} dP_+(t) \quad (4a)$$

$$P_-(t) = P_0 + \sum_{t=0}^{t} dP_-(t) \quad (4b)$$

$$U_+(t) = U_0 + \sum_{t=0}^{t} dU_+(t) \quad (4c)$$

$$U_-(t) = U_0 + \sum_{t=0}^{t} dU_-(t) \quad (4d)$$

where t is time, P_0, U_0 are the integration constants, chosen as pressure and velocity at t=0, when $P(0) = P_{+0}(0) + P_{-0}(0)$ and similarly $U(0) = U_{+0}(0) + U_{-0}(0)$

If we assume that the (+) and (−) waves interact linearly (additive), then the forward and backward wave intensities ($dI_\pm$) can be calculated (Parker and Jones, 1990)

$$dI_\pm = \pm \frac{1}{4\rho c}(dP \pm \rho c dU)^2. \quad (5)$$

Waves can be classified into four groups i.e. compression and expansion, according to their effect on pressure, and based on the direction of propagation. Compression waves induce an increase in pressure while expansion waves induce a decrease in pressure, in both the (+) and (−) directions (Feng and Khir, 2008). Forward compression waves (FCW) and backward expansion waves (BEW) induce an increase in velocity while forward expansion waves (FEW) and backward compression waves (BCW) induce a decrease in velocity (Table 1). The input pulse used in our experiments can be interpreted as a sequence of two forward waves (Feng and Khir, 2008): the first half of the waveform is a FCW since pressure increases, and the second half is FEW since pressure decrease.

Table 1
Wave classification: compression and expansion waves can propagate in forward or backward direction with different effects on pressure (dP) and velocity (dU) differences and consequently on dI (Feng and Khir, 2008). $dI > 0$ for forward travelling waves and $dI < 0$ for backward travelling waves.

Waves	dP	dU	dI	Flow direction
Compression	> 0	> 0	> 0	FORWARD
Expansion	< 0	< 0	> 0	
Compression	> 0	< 0	< 0	BACKWARD
Expansion	< 0	> 0	< 0	

3. Experimental set-up

A schematic of the experimental set-up is shown in Fig. 1. The simultaneous measurements of P and U in a single location (T connector in Fig. 1) as required by WIA were taken at 0.41 and 0.36 m away from the inlet for the single and multivessel experiment respectively (Fig. 2). We note the distance between the measurement point and the inlet is less than the theoretical entrance length (for both laminar and turbulent conditions) (Johnson, 1998) as would also be the case for measurements in the trachea. We decided not to use flow straighteners to avoid generating unwanted reflections.

The internal pressure of an air compressor (model 4-4, JUN-AIR, Denmark) was set at 4 atm. The compressor was attached to the inlet of a fast-switching solenoid valve (MHE3 FESTO, Germany), whose output was connected to the inlet of the tube system (Fig. 1B). Amplitude and duration of the initial pulse were controlled by regulating the pressure in the air compressor and the period of time that the solenoid valve was open, respectively. The opening duration of the solenoid valve and therefore the duration of the initial pulse was set at 15 ms for the single vessel experiment and 10 ms for the multivessel experiment. The peak of the initial pulse was 267 ± 7 Pa for the single vessel experiment and 705 ± 14 Pa for the multivessel experiment, similar in magnitude to those used in IOS (Smith et al., 2005; Ramos et al., 2010).

3.1. Flexible tubes

Four different flexible tubes were considered: a latex tube (LXT), a rubber tube (RT) and two silicon tubes denoted as ST1 and ST2. Table 2 shows the geometrical and mechanical properties of the tubes which, as far as we could determine, were uniform along their length. Young's modulus (E) was measured using tensile tests in the range 0–10% of strain. The rubber and the silicone tubes did not collapse at zero transmural pressure (under their own weight) whereas the latex tube did collapse. The wall thickness (h) of all tubes was measured using a digital caliper at zero transmural pressure (assuming h constant). The diameters (D) for rubber and silicon tubes were measured at zero transmural pressure while for the latex tube an internal pressure of 800 Pa was used, i.e. the pressure at which the latex tube first reached a circular cross-sectional area along its length.

3.2. Velocity and pressure measurements

The velocity probe used in the experiments was a split-fiber straight probe (55R55; Dantec Dynamics, Denmark). This probe was chosen as it allows for the measurement of the bidirectional flow, afforded by its two sensors. The probe was inserted in the tube using a rigid T connector on the axis of the lumen (Fig. 1D). The length of the connector (0.09 m) was assumed negligible compared to the length of the flexible tube. The measurement of the absolute value of velocity, in split fiber probes, is based on a modification of King's law (Helle, 1993)

$$E_1^2 + E_2^2 = A + B|U|^n \quad (6)$$

where E_1 and E_2 are the voltages of the two sensors. A, B and n are constant determined with the calibration process, which was conducted using a Streamline Pro Automatic Calibrator (Dantec Dynamics, Denmark). The plane of the probe splits was placed at the tube axis perpendicular to the direction of the mean flow (Bruun, 1995; Kiya and Sasaki, 1983), the flow direction was determined by comparing the voltages from the two sensors ($E_1 - E_2$), as suggested by Ra et al. (1990).

The pressure was measured using a 5 F transducer-tipped catheters (Gaeltec, Isle of Skye, UK) for the single vessel experiment and a 5 F transducer catheter (model SPC-760 Millar Instrument Inc, USA) for the multivessel experiment. The pressure catheter was inserted from the tube inlet (Fig. 1B) until its tip reached the T-connector to have P and U measured at the same location as required by WIA.

The signals were digitalized through a data acquisition board (DAQ) (National Instrument, USA), acquired using a custom written LabVIEW (National Instrument, USA) and smoothened with a third order Savitzky–Golay filter (frame size: 15 sample points) in Matlab (Mathworks Inc., USA). Data were sampled at either 2 kHz or 20 kHz.