Journal of Biomechanics 48 (2015) 3969–3974

Contents lists available at ScienceDirect

Journal of Biomechanics

journal homepage: www.elsevier.com/locate/jbiomech
www.JBiomech.com

Effect of viscosity on the wave propagation: Experimental determination of compression and expansion pulse wave velocity in fluid-fill elastic tube

Bojana Stojadinović [a], Tamar Tenne [b], Dragoslav Zikich [c], Nemanja Rajković [a], Nebojša Milošević [a], Biljana Lazović [d], Dejan Žikić [a,*]

[a] Biophysics Institute, School of Medicine, Belgrade University, 11000 Belgrade, Serbia
[b] Raphael Recanati Genetic Institute, Beilinson Hospital, Petah Tikva, Israel
[c] Ella Institute for Melanoma Treatment and Research, Sheba Medical Center, Tel Hashomer, Israel
[d] Clinic of Internal Medicine, Pulmonology Department, University Clinical Hospital Center Zemun, Belgrade, Serbia

ARTICLE INFO

Article history:
Accepted 24 September 2015

Keywords:
Pulse wave velocity
Viscosity
Compression wave
Expansion wave
Hemodynamics

ABSTRACT

The velocity by which the disturbance travels through the medium is the wave velocity. Pulse wave velocity is one of the main parameters in hemodynamics. The study of wave propagation through the fluid-fill elastic tube is of great importance for the proper biophysical understanding of the nature of blood flow through of cardiovascular system. The effect of viscosity on the pulse wave velocity is generally ignored. In this paper we present the results of experimental measurements of pulse wave velocity (PWV) of compression and expansion waves in elastic tube. The solutions with different density and viscosity were used in the experiment. Biophysical model of the circulatory flow is designed to perform measurements. Experimental results show that the PWV of the expansion waves is higher than the compression waves during the same experimental conditions. It was found that the change in viscosity causes a change of PWV for both waves. We found a relationship between PWV, fluid density and viscosity.

1. Introduction

A proper biophysical understanding of arterial hemodynamics is of major importance for medical diagnosis as well as for the research of the cardiovascular disease causes. Pulsatile pressure and flow waveforms contain important information about the hart and the vascular system. One of the main parameters in hemodynamics is the pulse wave velocity (PWV) through the arteries. PWV is linked to the mechanical properties of the arterial wall. Studies have shown that PWV increases with aging (Safar et al., 2002) and that phenomenon has been related to the changes in collagen and elastin proteins. The reduction of elastic properties of the arteries is associated with cardiovascular diseases such as atherosclerosis and arteriosclerosis (Blacher et al., 1999).

Experimental determination of PWV is carried out more than a century ago. Moens and Kortweg have developed at the same time a derivation describing the rule for PWV in elastic thin-walled tubes (Tijsseling and Anderson, 2012)

$$c=\sqrt{\frac{Eh}{\rho d}} \tag{1}$$

where E – Young's modulus, h – wall thickness, ρ – fluid density and d – internal diameter. Eq. (1) is named after them. Joukowsky (1898) has used this formula for the fundamental equation of water-hammer theory that connects pressure change Δp with a change of fluid flow velocity Δv as:

$$\Delta p=\rho c v \tag{2}$$

These two equations are mostly used in the studies of wave propagation through fluid-filled elastic tube. Khir and Parker used the water-hammer equation for determination of PWV (Khir and Parker, 2002; Li et al., 2011). Westerhof has determined PWV from the pressure and flow waveforms (Westerhof et al., 1972). Feng and Khir have applied both equations for the detection of the reflected wave in the pressure and flow signals (Feng and Khir, 2010). Khir used the pressure–velocity loop to determinate arrival time of reflected waves (Khir et al., 2007). Papapgeorgio and Jones, part I (1987a) have investigated various elastic materials which are

---

* Corresponding author. Tel.: +381 11 360 7159; fax: +381 11 360 7061.
E-mail addresses: dzikic@gmail.com, dejan.zikic@mfub.bg.ac.rs (D. Žikić).

http://dx.doi.org/10.1016/j.jbiomech.2015.09.016
0021-9290/© 2015 Elsevier Ltd. All rights reserved.

used in the arterial models. They found that the differences between the real system and the physical model are minimized when the tubes with a non-linear elasticity are used (Papapgeorgio and Jones, part II, 1987b).

The compression and expansion waves are identified in the circulatory system. Compression waves propagate from the heart during systole to the periphery, while the waves from "pulling" effect (expansion) were observed in the pulmonary vein, coronary arteries and left ventricle (Smiseth et al., 1999; Davies et al., 2006; MacRae et al., 1997). Experimental measurements of the PWV of compression and expansion waves have found that these waves are not equal and that the expansion waves have a higher pulse velocity than compression waves (Feng and Khir, 2008).

So far, in most of the published studies dealing with determination of PWV (Khir and Parker, 2002; Li et al., 2011; Feng and Khir, 2010; Feng and Khir, 2008) the effect of fluid viscosity was either neglected or the experimental approaches have used a single fluid as a model. In addition, Eq. (1) is based on the assumption that the fluid is incompressible and inviscid.

The blood viscosity is normally 3–4 mPa s at 37 °C. Viscosity is higher in the cases of hemodialysis, intravenous infusion, polycythemia, cytostatic therapy, hypothermia, obesity, hypertension, etc., and can be a twofold increased over the normal value (Dhar et al., 2012, Mark et al., 2001; Rosenson et al., 2002). On the other hand, anemia can reduce blood viscosity, which can cause heart failure (Jeong et al., 2010). Durable exercises reduce blood viscosity and increased oxygen delivery, which lower the risk of coronary heart disease. Increase in body temperature leads to a reduction of viscosity. Recently, it was shown that elevated viscosity associates with the PWV increases in patients that suffer from diabetes (Li et al., 2015). To date, the other cases of blood viscosity changes and their influence on the PWV have not been clinically investigated.

The aim of this study is to experimentally determine whether and how the viscosity affects the PWV. Here we present the results of the experimental measurements of compression and expansion waves that propagate through the fluid-filled elastic tube. The solutions with different densities and viscosities were used in the experiment. Biophysical model of the circulatory flow was designed to measure PWV.

2. Methods

A schematic diagram of the experimental setup for PWV measurement of compression and expansion waves is shown in Fig. 1.

2.1. The pump

In the experimental setup we used a rubber bulb siphon pump. One-way valves at the inlet and outlet of the pump were installed by the manufacturer. The fluid volume within the pump was 84 ml.

2.2. Tube

In the experimental setup we used a silicone transparent elastic tube. The inner diameter was 5 mm with a wall thickness of 1.5 mm. Length of the tube (from the pump to the Reservoir 1) was 210 mm. Before the measurements, a diameter consistency of the tube was checked along the entire length. During the experiment, the tube was in a horizontal position. To avoid contact stress between the tube and the hard surface, the pressurized ring balloons were set around the tube at the distance of 10 cm.

2.3. Reservoirs

Two reservoirs were used for the experiment. The first reservoir had been set at the tube level while the height of the second one was adjustable. The first tank was closed with 1/3 volume of air (Windkessel trapped-air damping chamber). Other reservoir was set up at 1 m height above the elastic tube to produce the initial hydrostatic pressure of 10 kPa within the fluid.

2.4. Valves

Three one-way valves were placed inside the elastic tube. The valves were used to stop the reflected wave to return to the tube or to the pump. Although one-way valves were installed inside the pump, during the valve closure, a minor volume of the fluid was flowing backward (it happens due to mechanical constructions of the valves).

2.5. Sensors and data acquisition

A distance between the two pressure sensors was 1 m. The pressure sensor was composed of a ring of latex balloon, plastic non-elastic tube, manometer, air pump and electronic components. Ring balloon with the inner diameter 8 mm was connected to the end of the plastic tube and the other end of the plastic tube was

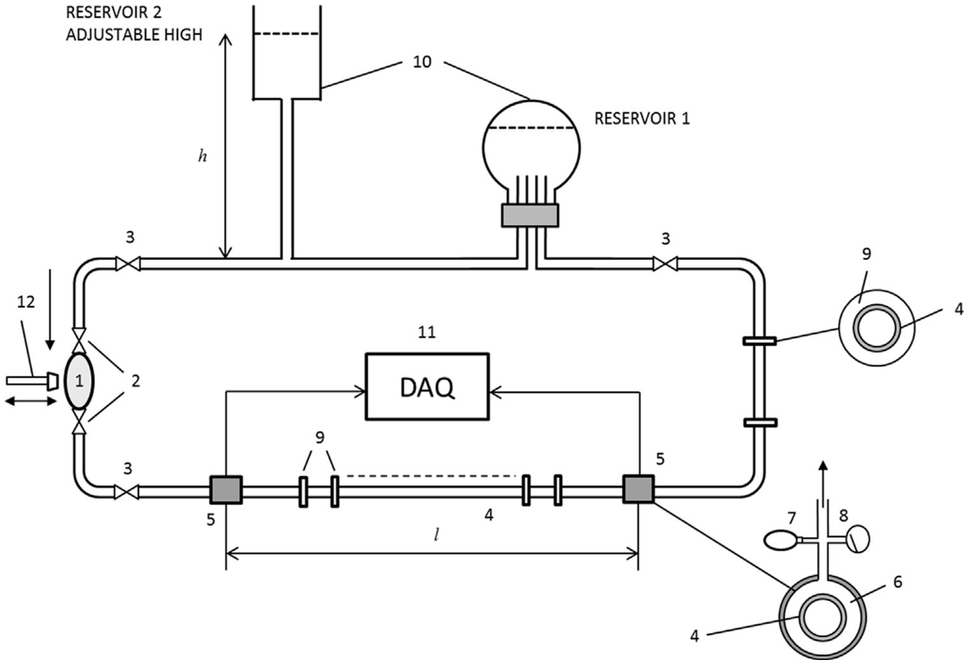

Fig. 1. A schematic diagram of the experimental setup: (1) rubber bulb siphon pump, (2) one-way valves inside the pump, (3) one-way valves, (4) silicone elastic tube, (5) pressure sensors, (6) ring latex balloon, (7) air pump, (8) manometer, (9) ring balloons, (10) reservoirs, (11) DAQ – data acquisition board, and (12) hammer.