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EXPERIMENTAL MEASUREMENT OF PULSE WAVE VELOCITY IN ELASTIC TUBE

H. Chlup*,, H. Macková*, R. Žitný*, S. Konvičková***

Summary: *The pulse wave velocity (PWV) in blood vessels is one of the important hemodynamical parameters for detection of artery health condition. In our laboratory, the PWV in elastic tubes and arteries is measured in vitro. The method is based on optical measurements of displacement of the pulsating tube wall. A high frame rate camera was used. The obtained data were evaluated by several methods and compared. The measured pulse wave velocities were in the same order of magnitude as values based on theoretical calculations and published physiological data.*

1. Introduction

The velocity of the pulse wave in elastic tubes under different hemodynamical conditions is an actual topic in recent cardiovascular research. The behavior of the pulse wave in deformable tubes was described by (Bertram, 2004). Their experiments were conducted on an experimental line with simplified topology of cardiovascular system. Similarly as a model of

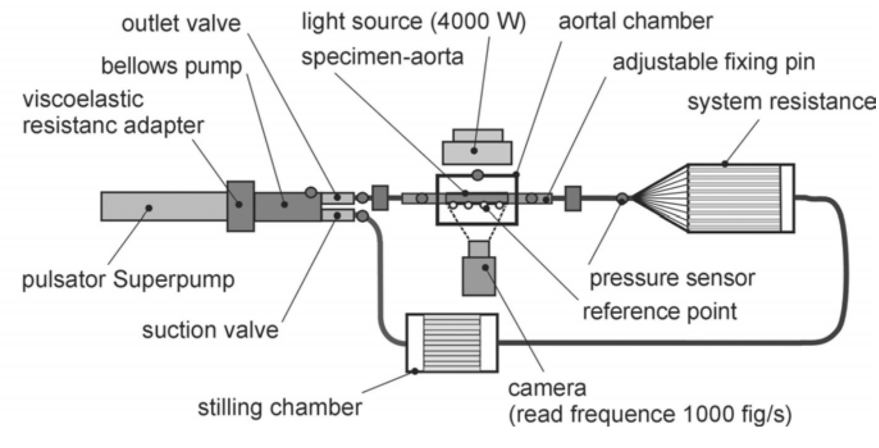

Fig. 1. The experimental line for detection of pulse wave velocity and identification of material properties of thin wall elastic tubes and blood vessels.

* Ing. Hynek Chlup, Ing. Hana Macková, Prof. Ing. Rudolf Žitný, CSs., Prof. Ing. Svatava Konvičková, CSc.: CTU in Prague, FME, Laboratory of Human Biomechanics, Technická 4, 166 07 Prague 6; tel.: +420.224 352 690; fax.: +420.233 322 482, e-mail: chynek@seznam.cz.
**Ing. Hynek Chlup: Academy of Sciences of the Czech Republic, Institute of Thermomechanics, Laboratory of Biomechanics, Dolejškova 5, 182 00 Prague 8; tel.: +420.266 053 294; e-mail: chynek@seznam.cz

(Khir, 2001), this model used free surface tank for simulation of systemic resistance. However this configuration can influence pulse wave properties by significant wave reflections and create nonrealistic characteristics. Much better closed experimental line was constructed by (Liou, 1999), (Liou, 2002) for measurement of aneurysm ruptures under pulse loading. Our experimental line was inspired by the Liou et al. and adjusted for measurements of pulse wave characteristics in elastic tubes. The free surface tank resistances were abandoned and replaced by numerous flow splits and capillary tubes simulating bloodstream. The hydraulic resistance is caused by friction losses (Fig. 1). The purpose of the research is detection of pulse wave velocity and identification of material properties of thin wall elastic tubes and blood vessels.

2. Methods

For examination of measurement and evaluation methods of pulse wave velocity detection, simplified experimental line was used. The systemic resistance element was replaced by a valve (Fig. 2.) and the required hydraulic resistance was simulated by throttling of flow.

Thin wall latex tubes with inner diameter 15 mm, initial length 150 mm and wall thickness 0.8±0.1 mm were used for the experiments. Mechanical properties of latex tubes are comparable with artery walls, therefore the latex tubes are used as analog for blood vessels in trial experiments. Tangential Young modulus of specimen $E = 1 \pm 0.1$ MPa was obtained from uniaxial tension experiments at MTS device. Seven reference points were adjusted to the tube. Time courses of the reference point radial displacements were recorded by a high speed camera simultaneously. The tube wall was deformed by pulsatile flow. The used fluid was distilled water.

Fig. 2. Configuration of experiment for examination of measurement and evaluation of pulse wave velocity.

While the experiment is being prepared, these questions appear:

1) What values of pulse wave velocity could be reached?
2) Which frame rate of the camera used for optical record is sufficient for the detection of time shift of the wall radial displacements on relatively short specimen?
3) Which method should be used for evaluation of obtained experimental data?
4) How could be the obtained velocity verified?

Approximate pulse wave velocity in a thin wall elastic tube was calculated from Moen-Korteweg's equation (1), (Bronzino, 2000), used for linear elastic thin wall tubes with circular cross section where density of surroundings is negligible to density of fluid and effects of viscosity could be neglected:

$$c_{teor1} = \sqrt{\frac{E \cdot h}{\rho \cdot d}} . \tag{1}$$

For the latex tube, the non-linear material properties could modify the equation (1) by coefficient $\alpha = 0.4$ in equation (2), (Klingerová, 2005):

$$c_{teor2} = \sqrt{\frac{8 \cdot \alpha \cdot E \cdot h}{3 \cdot d \cdot \rho}} . \tag{2}$$

For the properties and geometry of our specimen, the approximate value of pulse wave was calculated to $c_{teor1} = 7.3\ m/s$ according to the Moen-Korteweg equation (1) and $c_{teor2} = 7.5\ m/s$ according to the equation (2). Values of pulse wave velocity in blood vessels published in literature are for example 3.8 m/s (in arm), (Stephanis, 2003), or 4.8 m/s (canine carotid), (Khir, 2002).

2.1 Experiments

The elastic tube was attached to the experimental chamber to axially adjustable pins with pressure sensors. The specimen was axially preloaded by 15% of its initial length. Seven reference points were attached to the tube wall and their radial displacements under pulsatile loading were recorded by optical method (Fig. 3.).

The distance between reference points were 20 mm. With expected velocity and mentioned distances, the pulse wave could reach the next point in approximately 0.003 s. Therefore, the frame rate of camera must be in order of 1000 Hz.

Frame rate of 1000 Hz was used for recording the displacements in our experiment. The record was processed by APAS software. First, the record was divided to half frames, therefore the number of data was doubled (the frame rate increased to 2000 Hz with negligible error). Time course of x, y coordinates of all 7 reference points were obtained. From x coordinate, the accurate distances of points were calculated. Y coordinate was used for calculation of radial displacement (z coordinate was identically zero).

The pulse wave velocity was also evaluated invasively from pressure characteristics shift in the inlet and outlet of the elastic tube.

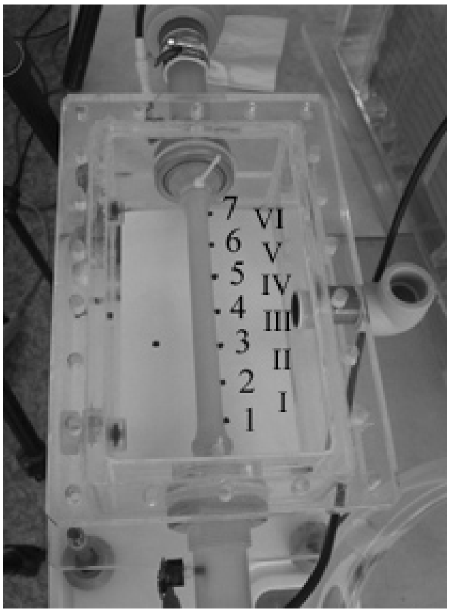

Fig. 3. The experimental chamber with thin wall elastic tube specimen.

The pulse rate of pulsatile flow was 1.33 Hz (80 pulse/min). Various pressure amplitudes were set. The elastic tube was loaded by atmospheric pressure from outside. Different external loading was not used in this experiment.

2.2 Evaluation of experimental data

MATLAB was used to create algorithms for evaluation of experimental data.

1st evaluation method: Experimental data obtained by optical method and processed by APAS software were treated by Fast Fourier Transformation. Three dominant frequencies of tube wall oscillation were found (Fig. 4). Obtained frequencies were used in approximation function (3) of the tube wall displacement in reference points $j = 1,2,...,7$:

$$y_j(t) = \sum_{i=1}^{3} a_i \sin(2\pi f_i t + \varphi_i). \qquad (3)$$

Parameters a_i and φ_i were identified by the least square method. For all points, maximal radial displacements in one period and corresponding time tj were found (Fig. 5 and 6). The time shift between the reference points could be calculated and together with known distances, the velocity was easily obtained.

2nd evaluation method: Identical procedure was used, however instead of maximal displacement, the minimal values of approximated function (3) were used (Fig. 6). The resulting pulse wave velocity should be close to the first method.

3rd evaluation method: Experimental data processed by APAS software were treated by cross correlation. A time value corresponding to maximum value of cross correlation function was identified.

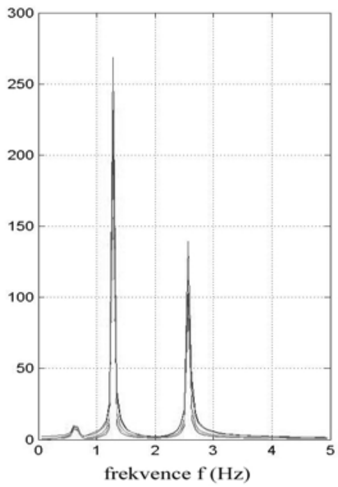

Fig. 4. Determination of dominant frequencies by FFT for experimental data from optical method (frame rate 1000 Hz).

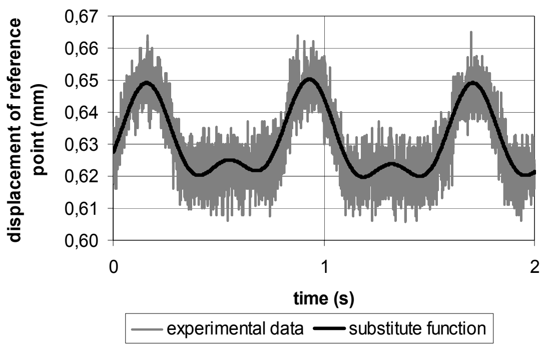

Fig. 5. Approximation function (3) for radial displacement of reference point no. 1

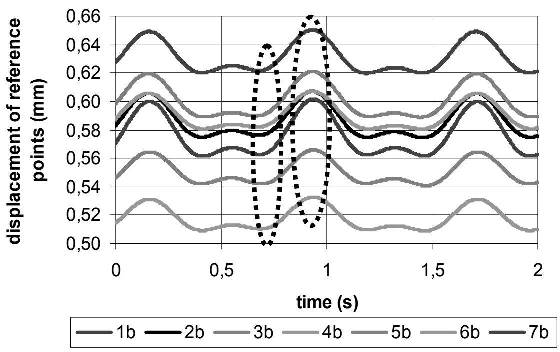

Fig. 6. Approximation functions (3) for all reference points (1b – 7b)

This time equals the time shift of two signals. As previously, from obtained times and known distances, the velocity was calculated.

4th evaluation method: Again, we used cross correlation, however not for evaluation of rough experimental data, but for approximated functions (3) of time courses of radial displacements. Although this method contains the error caused by approximation (compare to the 3rd method, where cross correlation is applied straight to data), it allows using more data from extrapolation and therefore better cross correlation analysis.

5th evaluation method: The previous four methods used the non-invasively obtained data. Comparison of pressure waves is invasive method; however it can provide us with an independent set of data. The time courses of pressure were measured in the inlet and outlet of the tube and compared. Times corresponding to maximal pressures were identified and time shift of pressure waves in the inlet and outlet calculated. Again, from time shift and distance of pressure sensors, the pulse wave velocity was calculated. Cross correlation was also used for pressure data.

3. Results and discussion

The pulse wave velocity was calculated for all intervals I – VI between the reference points 1 – 7 (Fig. 3) by optical method. This showed velocity differences on particular intervals, which cannot be measured only by pressure sensors in the ends of the tube. In the region attached to the pins, the local stiffness is thought to be elevated. Therefore, the wave velocity is presumed to be higher. This was confirmed by the experimental results. The velocities in the middle intervals were lower than in the boundary. For all intervals, mean wave velocity was calculated for comparison with all data evaluation methods and published physiological data (Fig. 7).

The differences between experimental and theoretical values could be explained easily by several factors. Assumption of the calculation using equations (1) and (2) is constant thickness and homogenous material of the specimen. The E and α parameters were estimated only roughly and the tube cross section is not ideally circular.

The experimental values of the wave velocity are higher, but in the same order of magnitude, as the values in vivo published by (Stephanis, 2003) or (Khir, 2002). The differences are not any contradiction. The tube material is different; there is different geometry of the tubes and different surroundings.

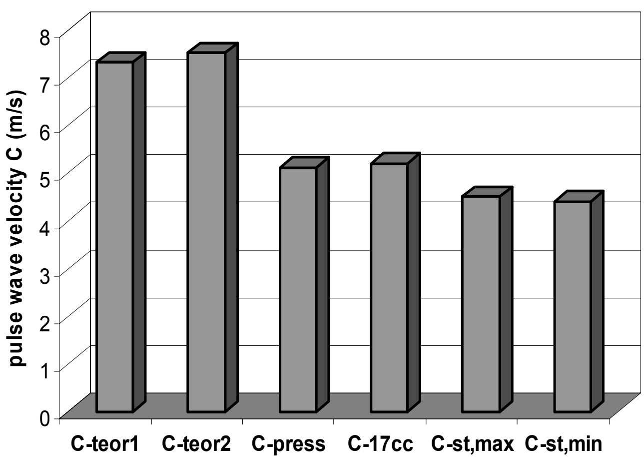

Fig. 7. The pulse wave velocity obtained by various methods.

The fluid is also different (however the densities of distilled water (998 kg/m3) and blood (1055 kg/m3) are similar, therefore it has not great influence on pulse wave velocity). However the same order of magnitude of the velocities shows that our method could be used also for blood vessel specimens.

4. Conclusion

The pulse wave velocity was obtained by the non-invasive optical method of wall radial displacement recording and verified by the invasive pressure method. The experimental data were evaluated by several methods and compared. The two experimental methods are in agreement. The theoretical values are around 7.5 m/s, higher than the experimental values, which are around 5 m/s (Fig. 7).

The difference is thought to be caused by idealized assumption of theoretical calculation, influence of boundaries and inaccurate values of parameters E and α. The non-invasive method of measuring time course of radial displacement and method of its evaluation proved to be suitable for detection of pulse wave velocity in blood vessels.

5. Notation

ai	(m)	amplitude of approximation function (3)
c-17cc	(m/s)	experimental pulse wave velocity calculated by method 4 between reference points 1 and 7
c-press	(m/s)	experimental pulse wave velocity based on pressure curves shift
c-st,max	(m/s)	mean experimental pulse wave velocity calculated by method 1 (maximum shift)
c-st,min	(m/s)	mean experimental pulse wave velocity calculated by method 1 (maximum shift)
cteor1	(m/s)	pulse wave velocity calculated from Moen-Korteweg equation (1)
cteor2	(m/s)	pulse wave velocity calculated from equation (2)
d	(m)	diameter of the tube
E	(Pa)	Young elastic modulus
Fi	(1/s)	dominant frequency of approximation function (3)
h	(m)	tube wall thickness
I	(1)	index of term in approximation function (3)
t	(s)	time
yj	(m)	radial displacement of tube wall for reference point j
α	(1)	coefficient modifying equation (1) for non-constant E
φi	(1)	phase shift
ρ	(kg/m3)	density of fluid

6. Acknowledgement

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