Laser Doppler Vibrometry for Assessment of Pulse Wave Velocity

Application in an Experimental Setup and in Living Subjects

A. Campo, **J. Dirckx**, Laboratory of Biomedical Physics (Bimef), University of Antwerp

Abstract:

When a fluid flowing through an elastic vessel is subjected to a sudden change in pressure gradient, pressure pulses will propagate through the fluid. Velocity of these pulse waves (PWV) can be determined by simultaneous detection of wall distension on two separate points on the vessel wall, along its trajectory. PWV depends on wall stiffness, and under certain circumstances, wall stiffness can be calculated from the propagation velocity. In vivo detection of arterial PWV can have applications in cardiovascular risk management. Stiffness of large arteries has a very good predictive value for cardiovascular disease and overall mortality. This parameter can be estimated from arterial PWV. Current methods to measure arterial PWV suffer from several shortcomings. Laser Doppler vibrometry (LDV) can offer substantial advantages over existing techniques. In this work, we propose LDV as a non-contacting technique that allows measurement of wall distension on discrete locations. With two commercial vibrometers, we measured PWV in silicon tubes with different wall properties. Consequently, we determined PWV in living subjects. In a first step towards miniaturization, we used a custom built dual-beam LDV, with one laser source and one acousto-optic modulator (AOM) to evaluate PWV in elastic vessels. While measurements of PWV in living subjects with the dual-beam LDV are ongoing, we found that PWV as measured in elastic vessels agrees well with theoretically expected values, and measurement precision is better than 5%. Results of arterial PWV corresponded well with literature, but could not yet be validated.

Introduction:

a) Pulse wave velocity:

When a fluid flowing through an elastic vessel is subjected to a sudden change in pressure gradient, a pulse wave will propagate through the fluid. This pulse wave causes local changes in pressure, flow rate, and diameter of the tube wall. The pulse wave velocity (PWV), depends on wall stiffness, wall thickness and lumen diameter. PWV can be predicted with the Moens-Korteweg approximation, or analytical or numerical methods. PWV can be detected by measuring pressure, velocity, or wall distension. Under certain circumstances, detection of PWV can be readily used to study tube properties [1].

b) Arteriosclerosis:

The arterial PWV, as measured between the common carotid artery (CCA) and femoral artery is a clinically used measure of the speed of propagation of pulse waves along the arterial tree. These pulses originate from the heart, and propagate with a certain PWV in the arteries. Carotid–femoral PWV is proportional to overall stiffness of the arterial system, and it can be indicative for an early stage of arteriosclerosis. Therefore, it has a very good predictive value for cardiovascular disease and overall mortality when increased, and it is a potential diagnostic aid for detection of cardiovascular disease and assessment of cardiovascular risk [2,3,4]. However, the diversity of measuring methods and the lack of guidelines and standards limit clinical applications, while there is a growing demand for implementation in everyday practice [5,6]. Current methodologies to measure PWV in a clinical setting include techniques such as arterial applanation tonometry, Doppler ultrasound techniques and photoplethysmography. The latter methods suffer from several shortcomings. Optical techniques can offer substantial advantages over existing techniques [6].

c) Laser Doppler vibrometry:

Heterodyne laser Doppler vibrometry (LDV) allows to measure wall displacement of elastic vessels [7]. The pulse wave passing through an elastic vessel causes wall distension, and out-of-plane displacement of the vessel wall. By measuring this out-of-plane displacement at two points with mutual distance Δz along the trajectory of vessel, it is possible to measure

the delay between the passing of the pulse wave, or the pulse transit time (PTT). PWV is then:

$$PWV = \Delta z / PTT \qquad (1)$$

Heterodyne LDV is sensitive to velocity rather than displacement. This makes the technique suitable to pick up the out-of-plane velocity of the wall due to the pressure pulse, with minimum influence of slower background movements. In the present work, we explore detection of PWV based on the use of LDV both for in vivo and in vitro applications.

Materials and Methods:

a) Laser vibrometry:

Measurements were performed with two commercial vibrometer systems (vibrometer sensor head (OFV353) and controller (OFV5000), Polytec, Waldbronn, Germany). Additionally, a custom built dual-beam LDV was used. The dual-beam LDV operates with only one 1 mW HeNe laser source (Melles Griot, Carlsbad, CA, USA) and only one acousto-optic modulator (AOM) (Isomet, Springfield, VA, USA).

b) Signal processing:

The signals from the dual-beam LDV and the commercial LDV systems were recorded with a National Instrument (USA) 12-bit DAQ card, at 125 kHz sampling rate. After recording, the PTT was determined both from the recordings of the two commercial LDVs as from the dual-beam LDV. By performing a cross-correlation (the xcorr function in Matlab (Matlab, The Mathworks; Nattick, Massachusets, USA)) [8], we can estimate the PTT between two locations on the tube wall since the measured velocity profile does ample change shape over the considered distances. Through the cross-correlation analysis, velocity profiles of both locations are shifted, until an optimal correlation is observed. The time over which both profiles need to be shifted gives an estimate of the PTT. The distance between two measuring points Δz is then divided by the measured PTT, directly delivering the PWV for the vessel under consideration.

c) Experimental setup:

For a PWV measurement, the laser beams of the dual-beam system, or the beams of the two commercial systems were pointed on two separated measuring points on the elastic vessel. One measuring point was kept fixed at a certain distance from the pressure inlet, and the other was pointed at a distance Δz of from the former measuring point (see Fig. 1). At the site of measurement, the tube wall was provided with reflecting patches so as to obtain optimal measurements of radial velocity of the tube wall. For each tube, for each distance Δz, 5 measurements of 20 s were performed. To generate the pressure pulses, a water reservoir was placed at 1.5 m height above the tube. A valve was placed at the beginning of the tube and was activated with rectangular current pulses of 400 ms and a frequency of 0,5 Hz. The tube under investigation was taken sufficiently long (+10 m) and kept as straight as possible in order to avoid reflection sites, and it was connected to an additional reservoir to provide constant back pressure. The level of both upstream and downstream reservoirs was kept at a constant level. For our measurements, three different tubes (RX-Labo Silicone Medical, Eriks; Alkmaar, Netherlands) were used with different thickness h (h=1,00±0,20, 1,50±0,20 and 2,00±0,20 mm) and different inner tube diameter d (d=7,50±0,20, 8,50±0,20 and 7,00±0,20 mm respectively). Young's modulus of the material, was estimated with a simple uniaxial tensile test, and was found to lay between 2 and 3,5 MPa for the different vessels.
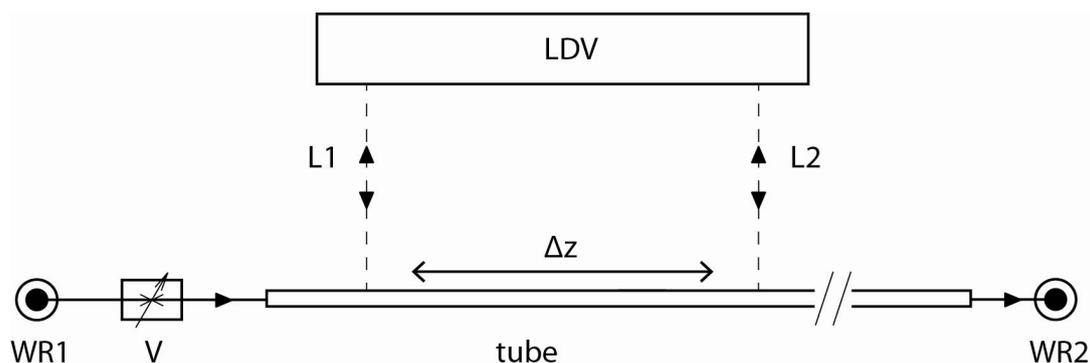

Fig. 1:   Experimental setup: dual-beam LDV system or commercial LDV systems (LDV), laser beams (L1 and L2), water reservoirs (WR1 and WR2), valve (V), distance between measuring points (Δz).

d) In vivo setup:

Two commercial LDV systems were aimed on the CCA in neck of the test subject, with measuring points being separated by a distance Δz along the trajectory of the CCA. The CCA was located by palpating the neck area, and verified with anatomical maps of the neck area. Δz was 1, 2, 3, 4 and 5 cm respectively (see Fig. 2). The laser heads were placed at about 30 cm perpendicular to the skin surface. At the site of measurement, the skin was coated with reflecting makeup so as to obtain optimal measurement of out-of-plane velocity of the skin surface. For our measurements, six young healthy male volunteers were summoned. For each distance, several measurements were performed. Measurements of PWV in living subjects with the dual-beam LDV are ongoing
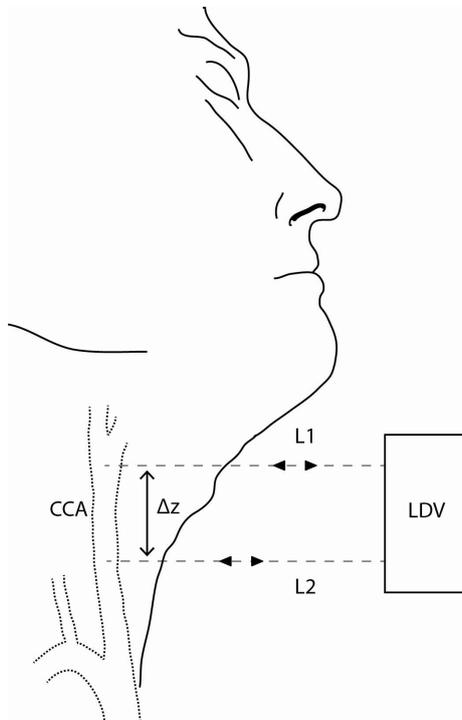

Fig 2:   In vivo setup: dual-beam LDV system or commercial LDV systems (LDV), laser beams (L1 and L2), common carotid artery (CCA), distance between measuring points (Δz).

Results:

PWV-values for the three different elastic vessels are summarized in Table 1. For each tube, values are averaged over all measurements and all distances Δz, and are represented with measurement error. PWV-values were determined with commercial LDV system ($PWV_{commercial}$) and custom dual-beam LDV system ($PWV_{dual-beam}$). Arterial PWV-values are summarized in Table 2. For each subject, values are averaged over all measurements and all distances Δz, and are represented with measurement error. Arterial PWV-values ($PWV_{arterial}$) were determined with commercial LDV system.

Table 1: PWV results for tubes with different wall properties. For each tube, PWV-values are represented as average over all measurements and all distances, with measurement error. PWV-values as measured with commercial LDV system ($PWV_{commercial}$) and custom dual-beam LDV system ($PWV_{dual-beam}$) are in good agreement with expectations from theory ($PWV_{theoretical}$).

tube	Hardness	Elasticity (E)	Diameter (d)	Wall thickness (h)	$PWV_{theoretical}$	$PWV_{commercial}$	$PWV_{dual-beam}$
(#)	(°shore A)	(MPa)	(mm)	(mm)	(m/s)	(m/s)	(m/s)
1	60	3,39±0,11	8,50±0,20	1,50±0,20	31,0±4,5	33,63±0,13	38,19±0,08
2	60	2,38±0,20	7,00±0,20	2,00±0,20	39,9±7,1	45,05±0,28	46,44±0,44
3	60	2,83±0,19	7,50±0,20	1,00±0,20	24,8±5,4	28,48±0,18	30,45±0,31

Table 2: Arterial PWV ($PWV_{arterial}$) results for six test subjects. For each subject, arterial PWV is represented as average with measurement error, over all measurements and all distances. PWV-values are in good agreement with expectations from literature.

subject	$PWV_{arterial}$
(#)	(m/s)
1	8,14±0,46
2	3,88±0,16
3	4,13±0,21
4	4,54±0,37
5	8,13±0,20
6	4,12±0,19

Discussion and conclusion:

Current methods to measure arterial PWV suffer from several shortcomings. In this work, we propose a non-contact method for measuring PWV based on LDV. Measurements with our system are straightforward and do not require intensive training. The required power of the laser sources is low, and measurements are safe and harmless. We demonstrate the feasibility of LDV for measurement of PWV in an experimental setup, using two commercial LDV systems, and a custom built dual-beam LDV. With possible clinical applications in mind, we also evaluated arterial PWV in living subjects with commercial LDV systems. Measurements with the dual-beam system are ongoing. In this preliminary study, results are very promising as measured PWVs are in good agreement with theoretically expected values, and measurement precision is better than 5%. Measurement of arterial PWV with LDV can have applications in cardiovascular risk management. Stiffness of large arteries has a very good predictive value for cardiovascular disease and overall mortality. This parameter can be estimated from arterial PWV [2,3,4]. However, current methods to measure arterial PWV suffer from several shortcomings. They need physical contact with the patient, they are expensive, and they need a skilled operator to handle the equipment and to perform the measurements. Moreover, current techniques do not allow local measurements of arterial PWV [5]. LDV can offer substantial advantages over existing techniques, as this technique is non-contacting, it is possibly very cheap and it is easy to perform. Additionally, the measuring points can be placed close together, allowing local measurements of PWV [6]. The arterial PWV as measured with LDV needs to be validated with additional measurement techniques.

[1] Milnor, W.R., [Hemodynamics], Williams and Wilkins, Baltimore (1989).

[2] Laurent, S., Boutouyrie, P., Asmar, R., Gautier, I., Laloux, B., Guize, L., Ducimetiere, P., and Benetos, A., "Aortic Stiffness Is an Independent Predictor of All-Cause and Cardiovascular Mortality in Hypertensive Patients," Hypertension 37(5), 1236-1241 (2001).

[3] Mattace-Raso, F. U., van der Cammen, T. J., Knetsch, A. M., van den Meiracker, A. H., Schalekamp, M. A., Hofman, A., and Witteman, J. C., "Arterial Stiffness As the Candidate Underlying Mechanism for Postural Blood Pressure Changes and Orthostatic Hypotension in Older Adults: the Rotterdam Study," Journal of Hypertension 24(2), 339-344 (2006).

[4] Blacher, J., Safar, M. E., Guerin, A. P., Pannier, B., Marchais, S. J., and London, G. M., "Aortic Pulse Wave Velocity Index and Mortality in End-Stage Renal Disease," Kidney International 63(5), 1852-1860 (2003).

[5] S. Laurent, J. Cockcroft, L. M. Van Bortel, P. Boutouyrie, C. Giannattasio, D. Hayoz et al., "Expert consensus document on arterial stiffness: methodological issues and clinical applications," Stroke 27(21), 2588-2605 (2006).

[6] De Melis, M., Morbiducci, U., Scalise, L., Tomasini, E. P., Delbeke, D., Baets, R., Van Bortel, L. M., and Segers, P., "A Noncontact Approach for the Evaluation of Large Artery Stiffness: a Preliminary Study," American Journal of Hypertension 21(12), 1280-1283 (2008).

[7] A. Campo, P. Segers, R. Baets, J. Dirckx, "Pulse Wave Velocity measurement in soft walled tubes using laser vibrometry: towards a new diagnostic technique for detection of atherosclerosis", Physics Express, in press.

[8] Orfanidis, S.J., [Optimum Signal Processing. An Introduction], Prentice-Hall, Englewood Cliffs (1996).