Experimental modelling of the venous muscle pump

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Abstract
One of the most interesting phenomena in the venous circulatory system is the vein pump mechanism in the legs. The veins in this area are surrounded by the calf muscle, which periodically deforms the vein walls and squeezes blood out of the section. Venous valves prevent the blood from backflow.
A measuring rig was designed to model and measure the periodic pulsation of the veins. The device contains a chamber containing a collapsible tube. In this paper the diameter of the tube was examined under periodically varying chamber pressure. Pictures were taken of the viscoelastic tube during the pulsation. The diameter as a function of time is calculated and compared with the pressure-time series. Also the operation of the check valves of the measuring rig is observed. The results are presented and discussed.

Keywords: veins, deformation, collapsible tube, pressure excitation

Introduction

Nowadays various diseases of the circulatory system are the main cause of mortality. According to the WHO Mortality Database of the year 2005 for Hungary, 52 percent of the deaths were caused by circulatory diseases. A major portion of them occurs in the venous system (e.g. varicose veins, thrombosis). To understand the main causes of various venous diseases it is essential to investigate the blood flow in veins. Venous blood flow is induced by several mechanisms. On the one hand the heart generates a pressure difference that induces the flow. However, this pressure gradient is remarkably smaller than the one in the arterial system. On the other hand, the pulsation of arteries and the contraction of muscles near the veins excite the vein wall. This excitation leads to a periodic wall deformation. Due to this deformation the blood volume in the vessel changes in time. In most of the vein segments so called venous valves are present to prevent blood from backflow. Thus the blood flow is induced in only one direction. In addition to these mechanisms, the effect of lung inflation and deflation also plays a significant role in the venous blood flow. The venous network contains several loops and branches. Also the mechanical behaviour of the venous wall is special: according to Monos[1] the vein walls are “bioviscoelastic”. Bioviscoelasticity can presumably be described using viscoelastic material models.

The present knowledge of venous hemodynamics is limited. Some observations have been made on the behaviour of the venous valves. Qui et al.[2] investigated the fluid dynamics of the venous valve closure. Their measurements confirmed that venous valves are pressure operated rather than flow operated devices. According to their experiments only a very little blood reflux is needed to close the valve completely. A three-dimensional fluid-structure interaction simulation of a vein valve has been carried out by Buxton and Clarke[3]. The fluid was modelled using a lattice Boltzmann model, while the solid mechanics of the valve leaflets and the vein wall was captured using a lattice spring model. The resulting numerical model was able to represent the dynamical behaviour of the vein valves. However the authors point out that the results give only a qualitative description of the vein valve. A. Boyd et al.[4] investigated venous pressures in ambulant patients. They developed a technique for measuring venous pressure that is more accurate than indirect methods.

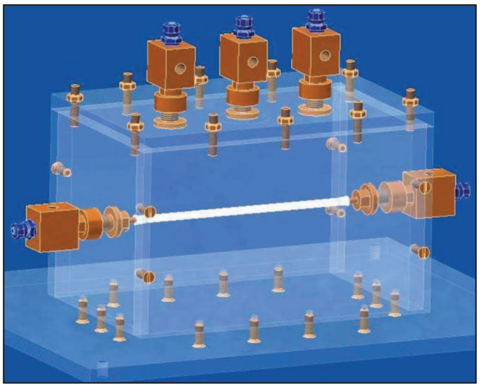
The collapse of a silicone tube was investigated by Fung[5]. He developed a so-called Starling reservoir. Conrad[6] constructed an improved reservoir. During the measurements the pressure in the reservoir was kept constant and the volumetric flow rate in the silicone tube was varied. The pressure difference between both ends of the tube was investigated as a function of the volumetric flow rate. The resulting curve was then analyzed by the author.

Development of the measuring rig

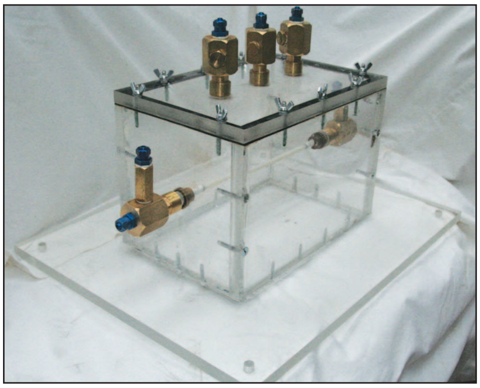
The aim of this project was to carry out measurements on a Starling reservoir similar to Fung's chamber. The main improvement contrary to the systems of Fung and Conrad would be the capability of creating unsteady pressure inside the reservoir. This would allow the investigation of periodically collapsing tubes and the check valves modelling the venous valves.

The measurement rig was designed to fulfil the requirements of the unsteady measurements. Multiple joints were attached to the system. Therefore pressure transducers can be connected to the reservoir in order to allow the continuous measurement of the inner pressure. A so called pressure signal generator can be connected to another joint – using this device one can generate periodically varying pressure inside the chamber. One additional joint is needed for de-gassing. The silicone tube is placed horizontally in the reservoir and connected to the joints from the inside. A simple thin-walled silicone tube was selected for the measurements. The tube itself is stretchable in a symmetrical way. The wall thickness changes as a function of pressure, but this effect was neglected. The pressure can be measured at the up- and downstream end of the tube. The measurement rig is shown in *Figure 1.*

The rig was manufactured in the laboratory of the Department of Hydrodynamic Systems.



a)

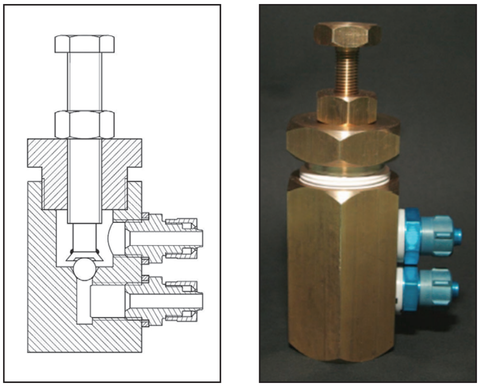


b)

Figure 1. 3D model *(a)* and photograph *(b)* of the measuring rig

The walls of the reservoir were made of plexiglass. Hence the phenomenon of the collapse will be visible and recordable using high frequency photo equipment.

Since the measuring rig will be used to model the venous muscle pump, check valves are needed for the role of venous valves. No check valves were found to accommodate the parameters of the measurement parameters (size, flow rate, etc.), therefore they also had to be manufactured. Two check valves were designed and produced. *Figure 2* shows the sketch and the picture of one check valve.



a) *b)*

Figure 2. Sketch *(a)* and photograph *(b)* of one check valve

The check valve consists of a small steel ball, two joints and a copper housing. The vertical movement of the ball can be adjusted.

Measurements

Two types of measurements were carried out. In the first part, the pressure in the reservoir was kept constant, while the volumetric flow rate through the collapsible tube was varied. The aim of these measurements was to reproduce the results found in Conrad[6]. Although the length, diameter and material of the silicone tube are different, the nature of the pressure-volume flow rate curves should be equivalent. This "static" measurement can be regarded as the validation of the measurement rig.

In the second part, the pressure signal generator was attached to the chamber, thus the pressure varied as a function of time.

The measurement setup for is shown in *Figure 3.* The water flows from the tank *(T)* through the silicone tube in the reservoir into the scaling tank *(K)*. Average volumetric flow rate was measured using this device. The pressure in the reservoir is varied using the pressure signal generator *(PSG)*. The check valves

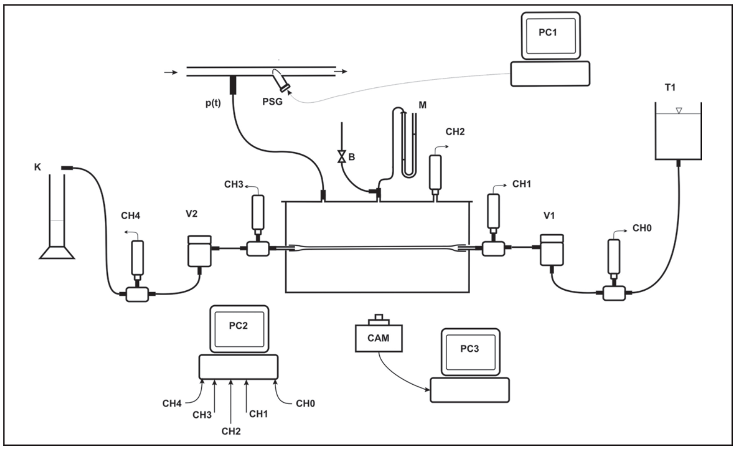


Figure 3. Sketch of the measuring equipment for unsteady reservoir pressure

(V1, V2) are installed at both ends of the silicone tube to avoid backflow in the tube. The pressure is measured using absolute pressure transducers (type HBM) in the reservoir *(CH2)* and at the upstream *(CH1)* and downstream *(CH3)* ends of the silicone tube. Two additional pressure transducers *(CH0* and *CH4)* were installed before *V1* and after *V2*. These transducers were only used in the measurement of the check valves. The periodic collapse of the tube is registered with a high frequency camera, type LaVision Imager Compact *(CAM)*.

The pressure signal generator is a development of the Department of Hydrodynamics Systems. The main part of it is an electronically controllable throttle valve. During the measurement three computers were used to process and to store the large amount of data. The first computer stored the signal from the pressure transducers and the trigger signal of the camera. With the second computer the pressure signal generator was controlled using a Labview code. The third computer was used for controlling the camera and storing the large amount of frames.

The aim was to create a varying pressure over time in the measuring equipment using the pressure signal generator. The altering pressure inside the reservoir causes a periodic collapse of the examined tube. During the collapse, the volume of tube changes with ΔV unit volume. Due to the check valves this extruded fluid can flow in only one direction. The goal of the measurement was to determine the average flow rate, the pressures as a function of time at the up- and downstream ends of the tube and the diameter of the tube as a function of time. The characteristics of the check valves also have to be investigated.

At the beginning of the measurement the water level of the *T* tank was adjusted to a fixed value which was nearly constant during the measurement. The average pressure in the chamber was determined with a U-tube manometer *(M)*. A sine wave was generated in the Labview program, the pressure control valve was controlled by this function. The electric motor actuated the valve, which was controlled by the signal. This action caused a periodic pressure change in the chamber, which generated a variable flow rate over time. The average flow rate was measured by scaling. The signals from the pressure transducers and the trigger signal from the camera were collected by an HMB Spider8 type data acquisition equipment with 1200 Hz sampling frequency. The high frequency was required by the trigger signal of the camera. The measured data were processed by a computer. During the measurement 40 snapshots were taken of the collapsible tube within each second.

High power LED lighting was used to illuminate the tube in order to get snapshots of reasonable contrast and quality.

Results

The results of the measurements with steady reservoir pressure were analyzed. The pressure inside the tube was plotted against the volume flow rate and compared with data gained from Conrad[6]. The characteristics of the measured curves showed a good agreement with the curves in the literature.

However this paper focuses on the second part of the measurements, where the pressure inside the reservoir was periodically varied. The signals of the pressure transducers were captured using a computer. Before the measurement, all transducers were calibrated. The average flow rate generated by the periodic pressure change inside the chamber was measured by scaling. The frequency of the pressure signal generator was set to 0,5 Hz. The average pressure of the chamber was kept at 100 mm Hg. The vertical distance between the water tank and the deformable tube was 200 millimetres. Therefore the average pressure at the upstream end of the tube was about 200 mm H_2O, i.e. 1962 Pa. The pipe connected to the downstream end of the tube was also lifted to this altitude, therefore the pressure gradient between the up- and downstream ends of the tube was zero at rest.

One of the main problems was to calculate the instantaneous diameter of the collapsible tube. Therefore the recorded images were loaded into the Matlab environment. Using the recorded trigger signal one was able to associate the images with the pressure data. The light intensity values were calculated for each pixel. The size of the matrices is equal to the resolution of the snapshots (640×480 pixels). The intensity values (colour index) are in a range of 0 (black) and 2500 (white). One image sample of the collapsible tube is shown in *Figure 4*.

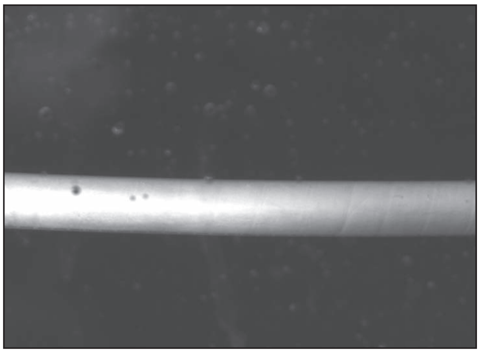


Figure 4. Image of the collapsible tube

To determine the instantaneous diameter, a simple edge detection algorithm was developed. The software calculated the intensity gradients perpendicular to the collapsing tube *(Figure 5)*. The highest gradients were selected as the edges of the tube. The diameter was calculated out of these values.

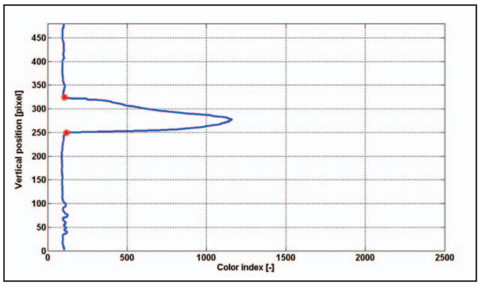


Figure 5. Colour index distribution along a vertical slice

Using this algorithm one gets the tube diameter in pixels. With the calibration of the camera the physical length (in millimetres) is determined. *Figure 6* shows the pressure in the measuring equipment *(pe)* and at the two ends of the examined tube *(p1, p2)* as a function of time. The diameter variation over time is presented in *Figure 7.*

The results of the measurement clearly show that the periodic pressure variation inside the chamber resulted in a periodic collapsing and

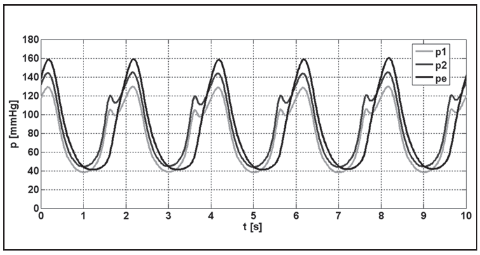


Figure 6. Time history of *p1, p2, pe* pressure signals

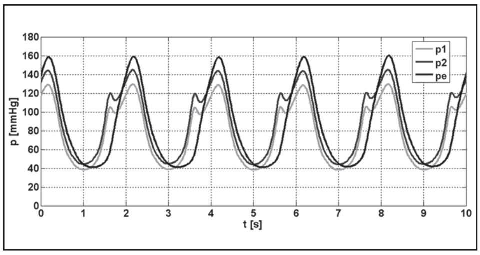


Figure 7. Time history of the deformed tube diameter

expanding of the investigated tube. Also, there is an offset between the peaks of the pressure curves and the minima of the diameters. The measured average flow rate for this measurement was 2 ml/sec. In case of an ideal collapse (where the inner cross section of the tube reaches zero) the calculated theoretical flow rate is 4,5 ml/sec. Thus the efficiency of the volumetric fluid transport is 44 percent.

Measurement of the check valves

One can see in *Figure 6* that before the peak of the upstream and downstream pressures some kind of oscillation occurs. It was assumed that it had to do with the characteristics of the check valves. On the other hand there was no proof that the valves worked properly during the measurement. Therefore the operation of the check valves had to be investigated in detail. The construction of the check valves is shown in *Figure 2*.

A further measurement was carried out. Five pressure transducers were placed in the measurement rig. The setup is presented in *Figure 3*. Relative pressure was measured before and after both check valves. The fifth transducer measured the relative pressure of the reservoir. The sampling frequency was lowered to 50 Hz since no optical measurement was carried out during this attempt. The frequency of the pressure signal generator was set to 0,5 Hz as in the previous measurements. The mean pressure in the chamber was about 75 Hgmm. This is lower than in the previous measurement. The cause for that is a modification in the measurement process: the *B* valve was opened in order to increase the degree of the collapse. The water level inside the *T1* tank was approximately on the same level as the outflow point *K,* the outflow. Thus there was no flow through the system without exciting the silicone tube.

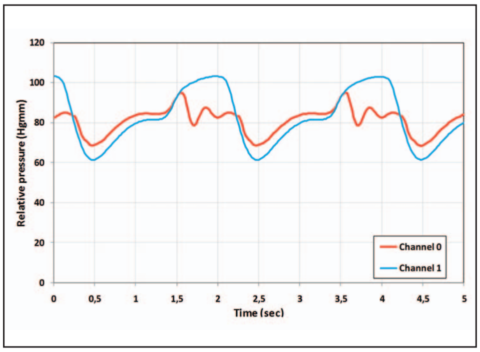


Figure 8. Pressure curves before *(Channel 0)* and after *(Channel 1)* the V1 check valve

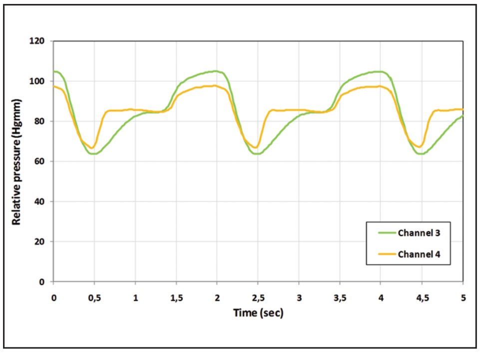


Figure 9. Pressure curves before *(Channel 3)* and after *(Channel 4)* the V2 check valve

The measured pressure curves for the V1 check valve are presented in *Figure 8,* the curves for the V2 valve are shown in *Figure 9.*

One can interpret the operation of both check valves from the two pressure curve-pairs. The first check valve *(Figure 8)* is located between the water tank and the silicone tube. The water tank creates a hydrostatic pressure before the valve. During the collapse of the silicone tube the pressure rises inside. If the pressure exceeds the hydrostatic pressure before the valve, then the check valve closes (approx. at 1.4 sec). This creates a pressure wave that travels between the *V1* check valve and the water tank. That is the explanation of the oscillation that can be seen between 1.5 and 2 sec. As the silicone tube expands, the pressure inside decreases. As the pressure falls below the hydrostatic pressure, the *V1* valve opens. Water flows into the tube, which creates a pressure difference on the valve (approx. from 2.2 to 3.4 sec). The second check valve *(Figure 9)* operates in the opposite period: during the collapse of the silicone tube the rising pressure inside opens the valve (at 1.4 sec). Water flows through the valve as long as the pressure inside the tube exceeds the hydrostatic pressure after the *V2* check valve. At approx. 2.2 seconds the pressure inside the tube decreases below this hydrostatic pressure, therefore the *V2* check valve closes. After a transient period, the pressure after the valve stays constant, while the pressure before the check valve stays below it. This state is maintained until the end of the period, when the check valve opens again (at 3.4 sec). In this case no oscillations occur.

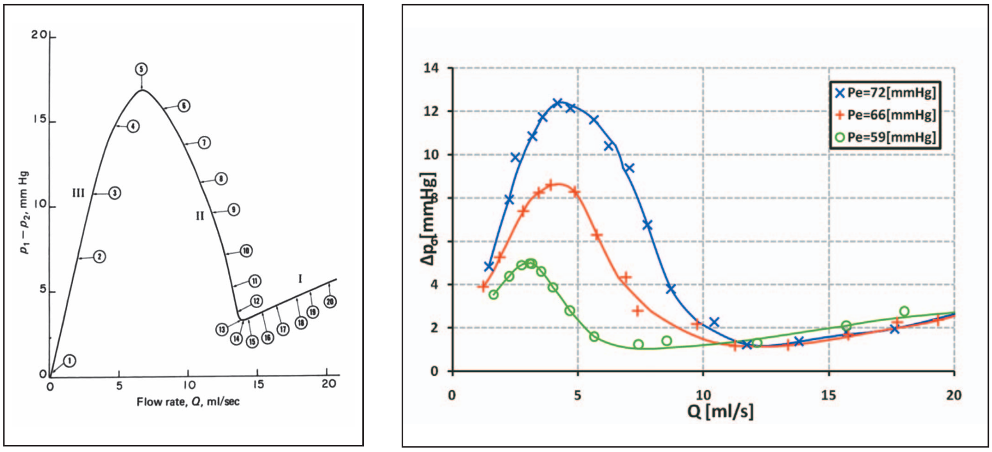
The measurement of the check valves proved that both valves are working correctly. The observer is able to follow the operation of them regarding the pressure-time curves. The closing oh the *V1* check valve generates pressure oscillations before the valve.

Conclusion

The aim of this paper was to model the venous muscle pump using a so-called Starling reservoir (chamber). The measuring equipment was designed and manufactured. The first measurements were carried out under constant reservoir pressure, in order to calibrate the equipment. The pressure difference along the collapsible tube was measured as a function of the volumetric flow rate. The results were compared with data gained from Conrad[6]. The agreement was reasonably good *(Figure 10)*.

Measurements with varying chamber pressure were carried out. The pressure inside the chamber and at both ends of the collapsible tube was measured using pressure transducers. Using a high frequency camera image sequences were taken of the pulsating tube. To determine the diameter change in the function of time, an edge detection algorithm was developed. The average volumetric flow rate was measured using the scaling technique.

The results of the measurement were presented and discussed. The most important out-



a) *b)*

Figure 10. Pressure differences along a collapsible tube as a function of the volumetric flow rate. *a)* the curve measured by Conrad[6]; *b)* the results of our measurement

come of the experiment was the fact that the collapsible tube can act as a volumetric pump, it is able to model the venous muscle pump.

A further measurement was carried out in order to investigate the operation of the check valves. Relative pressure was measured before and after both check valves and inside the reservoir. The resulting pressure curves were plotted against the time. Analyzing these curves one was able to explain the behaviour of the check valves.

In the future further measurements with five pressure transducers and the high speed camera will be carried out with various chamber pressure frequencies. Also other periodic functions aside the sine function will be set for the pressure signal generator. A novel method for measuring unsteady volume flow also needs to be developed. Later on the significance of the venous muscle pump mechanism has to be studied with the execution of in vivo measurements.

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