# Modelling of the Human Blood Circulation and Detection of Pathophysiological Symptoms of Atherosclerosis in Dependence of the Arterial Blood Flow Volume and Blood Pressure

E Engelien[1], Y Bai[2], B Strathen[1], R Viga[1], T Hilbel[2], R Kokozinski[1]

[1]Institute of Electronic Components and Circuits, University Duisburg-Essen, Germany
[2]Department of Physical Technology, University of Applied Sciences Gelsenkirchen, Germany

## Abstract

*For the practical research on influences of vascular diseases on the cardiovascular system a torso model is developed that represents all major arteries and veins. The model allows analysing the reaction of vascular diseases on the time-dependant variance of pressure and volume flow distribution. Therefore the passages between arterial and venous vessels are equipped with flow sensors and pressure is detected at key points. In the following, investigations will be described based on simulation of 4 different stress situations of the torso (rest, exercise, brain work, after meal). In addition 4 different diseases (stages of occlusions and cavities) in the carotid artery are simulated and their impact on pressure and flow distribution in the torso will be described.*

## 1. Introduction

More than 10% of the population, in particular in industrial nations, suffer from hypertension and diseases of the cardiovascular system [4][5][10]. Of those, 5-10% depends on medical supervision and drug treatment. For improved monitoring and diagnostic possibilities for patients with pathological statement (e.g. cardiac arrhythmia, high or low blood pressure) various stationary devices have been developed for temporary invasive blood pressure and flow measurement [5][6][10][11]. As functional principle for blood pressure measurement capacitive sensors are applied by direct or indirect (NaCl as transmitter) applications and for the blood flow sensors with the functional principles of cold bolus, ultrasonic or anemometer.

As many patients depend on continuous measurement of their blood pressure and flow to improve their quality of life, the development of implants has been advanced in the past years[2][3][4][8]. Their realisation implies for the patients increased mobility linked with therapeutic measures. The main focus currently is the substitution of stationary equipment for blood pressure measurement and the processing of known measurement parameters out of the pressure-time-curve, e.g. systolic and diastolic pressure [10]. Widely unconsidered remain possibilities due to permanent capture and evaluation of measurement signals of pressure and flow detected at a specific location in the cardiovascular system.

For over 50 years, investigations on the mathematical description of the cardiovascular system are being done, e.g. in the format of electrical circuit models [1][9][14]. With the increase in possibilities of the numerical simulation pathological mutations of arteries are simulated [12]. These investigations allow a better understanding of the development and impact of pathological vascular mutations.

Following the preceding research works it is reasonable to analyse the pressure propagation and the situation-dependent flow distribution in the body with a look on the long-term course of diseases. In particular the added value in the synchronised detection of pressure and flow needs to be appraised.

## 2. Methods

To approach this question, a torso model is developed to investigate the impact of vascular diseases on blood pressure and volume flow. For this purpose 4 different stress situations (*rest, exercise, brain work, after meal*) combined with 4 different diseases in the carotid artery are simulated. In the following the results will be presented.

### 2.1. Experimental setup

The construction of the torso model consists of a vascular system in which the large arteries and veins are represented as mouth-blown glass-tubes in realistic size of a healthy man. The passage from the arterial to the venous system is realised by silicon tubes with diameters of Ø 8 mm up to Ø 12 mm and a wall thickness of 1.5 mm and 2.0 mm. In the middle of each passage a total of 17 sensors (FCH-m-POM-LC, B.I.O-TECH e.K.) are positioned to measure and control the volume flow. The volume flow through every tube is adjusted by chokings. The fluid medium (water) is driven by a pump (CCD-BC4-2-564, Henning Elektrowerke).

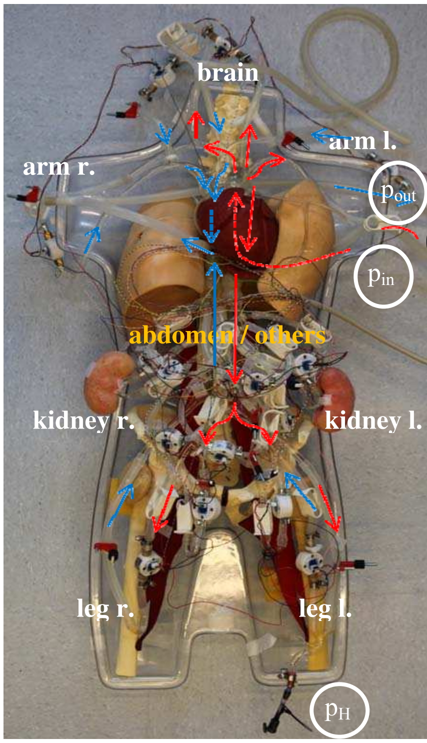


Figure 1. Torso model with all sensors and chokings are shown, the red arrowheads show arterial flow direction and the blue ones venous flow.

Thereby, the volume flow is controlled by the magnet-inductive flow sensor (OPTIFlux 5300, Krohne Messtechnik GmbH), the pressure before and behind the torso-model by pressure transmitter (type 8314, Bürkert) and the temperature by thermocouples type K. Additionally, the pressure at the external iliac artery is measured by HYPER-IMS pressure sensor from Osypka Medical GmbH. The experimental setup is controlled and the signals are measured by a CompactRio real-time system (NI 9024/9118, National Instruments).

## 2.2. Measurement theory

Starting point to the initial question is the adaptation of the body to short term (situation-based) or long term (disease-based) exposure. The physiological blood distribution is adapted accordingly. Through expansion and reduction respectively (up to 10%) of the vessel diameter and the increase of blood pressure and heart beat as well as through the correlated cardiac output per minute the organs are supplied with blood based on their needs. In case of vascular diseases the effect on the arteries varies significantly depending on the type of disease. For this reason the torso model was analysed at stationary circulation in four different stress situations (*rest, exercise, brain work, after meal* – Table 1). The flow distribution is taken from literature [7][10][11][13].

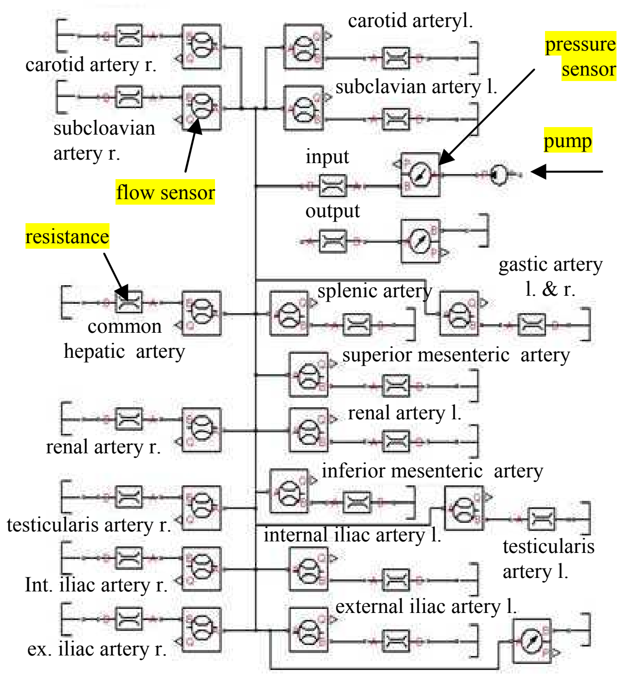


Figure 2. Theoretical flow model consisting of pump, adjustable resistances, flow and pressure sensors.

More than 80% of arterial diseases develop in the lower abdomen and the lower extremities [10]. Consequently, the pressure of the external iliac artery is additionally measured with the HYPER-IMS pressure sensor as a potential implant.

Table 1. Flow distribution in the body at stress situations.

| body region | stress situation [ml/min] | | | |
|---|---|---|---|---|
| | rest | exercise | work | meal |
| | 5300 | 15600 | 5300 | 5100 |
| brain | 750 | 750 | 1100 | 450 |
| arms | 500 | 4000 | 350 | 300 |
| legs | 700 | 8500 | 550 | 400 |
| kidney | 1100 | 600 | 1100 | 1200 |
| abdomen | 1400 | 600 | 1400 | 2000 |
| others | 850 | 1150 | 800 | 750 |

Vascular diseases can be divided into two types, arterioscleroses and aneurysm, the first one occurring more frequently. To control their impact on the four different stress situations in the case of stationary circulation an 80% and a 100% occlusion as well as a developed and an open aneurysm are applied (Table 2).

Table 2. Technical implementation of vascular diseases.

| vascular diseases | technical realisation |
|---|---|
| occlusion of 80% | reduced profile by chocking |
| occlusion | closed tube |
| formed aneurysm | inserted cavity |
| open aneurysm | open tube |

These cases were conducted in the torso model at the carotid artery as this is where the viability impact of vascular diseases is most serious.

## 3. Results

The presented results give a first outlook to the simulation of vascular diseases and their impact on flow and pressure in a stationary circulation. In the following the impact of diseases in the carotid artery on the whole of the torso will be described.

In the execution of the experiment a focus was put on the adjustment of the flow distribution. The pressure only is a reference parameter and is needed for further adaptation. At a typical flow volume of 5300 ml/min at rest situation the pressure difference of Δp = 149 mmHg is applied to the torso. As a comparison, in vivo measurements for human this is Δp ≈ 110 mmHg (ventricle left to atrium right).

The other pressures are shown in Table 3. They were all measured at the same level. The measured pressures in the stress situations *rest, brain work* and *after meal* show a good accordance with the HYPER-IMS pressure sensor. The measured pressures show that a change in flow distribution leads to a modified resistance of the entire system. In particular the stress situation *exercise* with high volume flow reveals that it is easy to decrease a tube diameter, but that it is impossible to increase a tube diameter as it would be necessary to adapt the pressure to realistic exigencies (Table 3). Same is shown by the law of Hagen-Poiseuille, which states that the volume flow stands to the forth power of the tube radius ($I \sim r^4$).

Table 3. Pressure measurement at stress situations.

| | normal body status [mmHg] | | | |
|---|---|---|---|---|
| | rest | exercise | work | meal |
| Δp | 149 | 1145 | 166 | 162 |
| p(in) | 157 | 1166 | 174 | 168 |
| p(out) | 8 | 21 | 8 | 6 |
| p(leg) | 133 | - | 151 | 144 |

In Figure 3 the simulations of four stress situations and the respective diseases are shown by measurands averaged over 5 seconds. Figure 3 represents that pressure values at the input (ventricle) adapt to the respective disease.

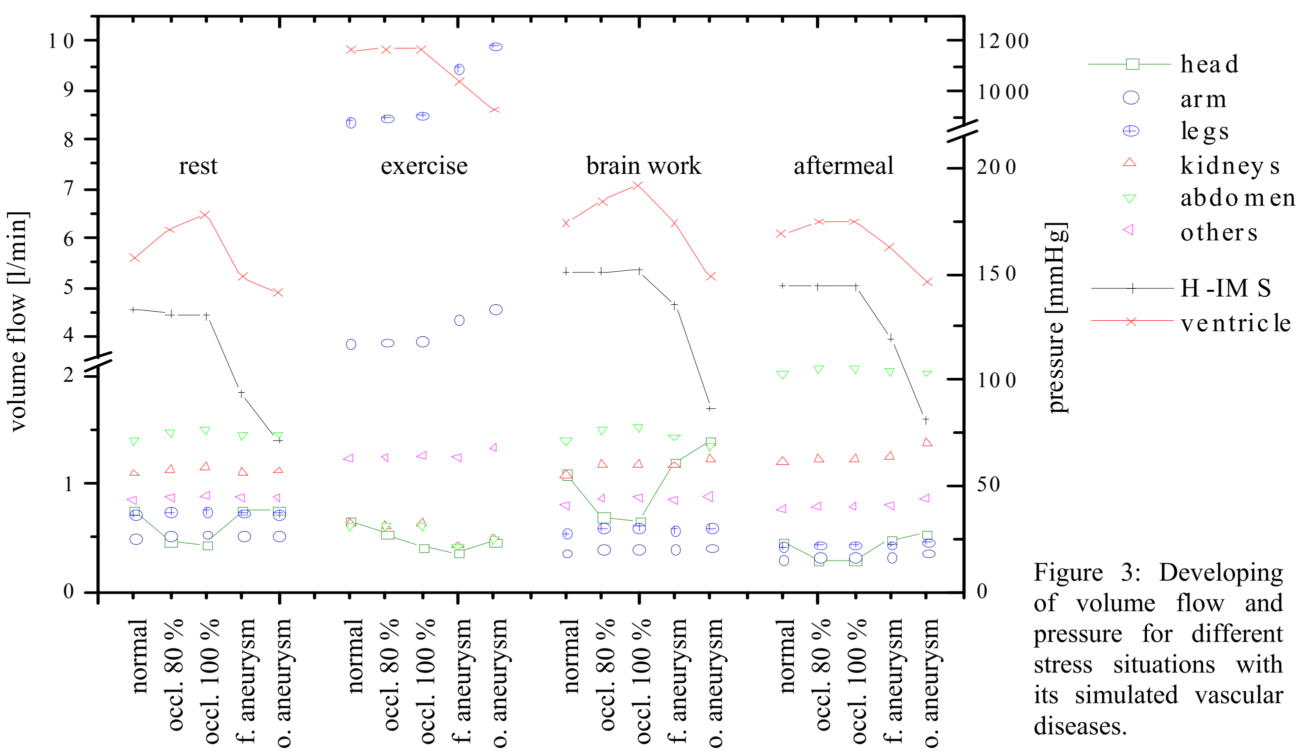


Figure 3: Developing of volume flow and pressure for different stress situations with its simulated vascular diseases.

At the start of the occlusion the pressure increases (flow resistance increases as vessel diameter decreases) and increases at inserted cavities (flow resistance decreases as in the short term more fluid can be absorbed). The pressure measurement with the intraluminal HYPER-IMS pressure sensor in the external iliac artery shows the behaviour of the pressure decrease even more clearly. An increase of pressure due to occlusion could not be measured. At *exercise* no measurands could be detected as they were outside the measurement range.

For the flow signals the head measurand consists 50% of the 2 signals of the carotid artery. In the signal sequence the simulated diseases in the left carotid artery can be well identified. Figure 3 represents in the same manner that the development of aneurysm can lead to an increase in volume flow.

In all stress situations the occlusion in the carotid artery leads to an increased volume flow in all other tubes. The development of cavities leads to an increased volume flow in arms, legs, kidneys and others. On the contrary, a decrease of volume flow can be observed in the abdomen.

## 4. Discussion

The first measurements on the analysis of the synchronised detection of pressure and flow shows that at stationary circulation small retroactive effects due to the simulated vascular diseases can be captured. For the volume flow measurement can be concluded that cavities have, similar to aneurysms, effects on the intensity of blood pressure – Figure 1 shows that this effect increases with increasing distance to the heart (blood pressure decreases with increasing distance). In the case of occlusions the pressure increase can only be detected at the point of input (ventricle).

In blood volume measurement all effects due to simulated vascular diseases are clearly detectable, but only with small modifications that are emphasised by the trend (Figure 3).

## 5. Future prospects

The whole of this work belongs to the area of physiological monitoring and its continuation in telemonitoring. It is a contribution to future enhanced diagnostic methods. Based on this background additional works on a dynamically circulated torso model (comparable to the heart beat model) is completed. Thereby specific fault analysis (similar to possible vascular diseases) for the largest arteries is included. A focus is put on specific network analysis in allusion to anatomic properties and geometries.

## References


[1] Azer K, Peskin CS. A One-dimensional Model of Blood Flow in Arteries with Friction and Convection Based on the Womersley Velocity Profile, Cardiovasc. Eng. 2007:7:51-73.

[2] Chow EY. Fully Wireless Implantable Cardiovascular Pressure Monitor Integrated with a Medical Stent. IEE Transactions on Biomedical Engineering 2010:57-6:1487-96.

[3] Cong P et al. Wireless Batteryless Implantable Blood Pressure Monitoring Microsystem for Small Laboratory Animals. IEEE Sensors Journal 2010:10-2:243-254.

[4] Fassbender H et al. Fully Implantable Blood Pressure Sensor for Hypertonic Patients. IEEE Sensors 2008:1226-30.

[5] Gupta B. Invasive Blood Pressure Monitoring. World Federation of Societies of Anaesthesiologists, 2009:36-42.

[6] Kersjes R et al. An Invasive Catheter Flow Sensor with On-Ship CMOS Read-Out Electronics for the Online Determination of Blood Flow. Eurosensors IX 1995:432-5.

[7] Laurent S et al. Flow-dependent vasodilation of brachial artery in essential hypertension. The American Physiological Society 1990:H1004-11.

[8] Locke SE et al. Implantable Blood Flow Measurement Techniques for Humans. IEEE Engineering in Medicine and Biology 2005:5515-8.

[9] Noordergraaf A et al. The Use of an Analog Computer in a Circulation Model, Progress in Cardiovascular Diseases, 1963:5-5:419-39.

[10] Renz-Polster H et al. Basislehrbuch Innere Medizin, 4. Auflage 2008, Elsevier Urban & Fischer, ISBN 978-3-437-41053-6.

[11] Schmidt RF et al. Physiologie des Menschen, 31. Auflage 2010, Springer, ISBN 978-3-642-01650-9.

[12] Snyder MF, Rideout VC. Computer Modeling of the Human Systemic Arterial Tree, J. Biomechanics, 1968:1:341-53.

[13] Takayama S et al. Changes of Blood Flow in the Superior Mesenteric Artery and Brachial Artery with Abdominal thermal Stimulation. Evidence-Based Complementary and Alternative Medicine, 2011:1-10.

[14] van de Vosse FN, Stergiopulos N. Puls Wave Propagation in the Arterial Tree, Annu. Rev. Fluid Mech. 2011:43:467-99.



Address for correspondence.

Eberhard Engelien
University Duisburg-Essen
Institute of Electronic Components and Circuits
Bismarckstraße 81
47057 Duisburg, Germany

Eberhard.Engelien@uni-due.de