Continuous Blood Pressure Measurements in Stress Situations

Cord Volker Bauch[1], Dieter Barschdorff[2]

[1] Light Laboratory L-LAB, Salzkottener Str. 1, Paderborn, Germany

[2] Electrical Measurement, Faculty EIM-E, University of Paderborn, Paderborn, Germany

Abstract. When a person is exposed to physical and psychological challenge, the autonomic nervous system reacts in a way to cope the situation. Stress conditions are usually characterized by heart frequency or skin resistance changes. Though also the blood pressure is known to increase in stress situations, its measurement was not meaningful because of the insufficient time resolution of instruments using inflatable cuffs. We present the first model based continuous blood pressure determinations during stress tests. The measuring technique is based on the dependency of the systolic blood pressure on the pulse transit time and on individualized mathematical models. The Vienna Test System and car driving situations in the driving simulator "*Nightdriver*" are examined. With the new technique the blood pressure can be determined without interfering with the persons cognitive perceptions. It clearly correlates to different stress levels.

1 Introduction

Due to today's fast changing lifestyle and working conditions a majority of people feel that they are permanently in a state of physical and psychological stress. They speak of work-related tensions and burnout effects. An increased heart frequency, an accelerated blood circulation and, due to sweating, a decrease of the skin resistance are typical symptoms. Reactions of the autonomic nervous system are the release of the hormones adrenalin and noradrenalin which lead to a dilatation of blood vessels and an increased blood pressure. In order to characterize a person's physiological reaction in situations of special physical efforts and under emotional stress the heart rate, the heart rate variability and the skin resistance serve as measurable parameters. Blood pressure variations under such circumstances have not been investigated in detail because of the lack of an adequate measuring method with high time resolution which does not interfere with the person's cognitive perception.

Blood pressure measurements in stress situations so far are only possible utilizing the procedure of Riva-Rocci or with fully automated instruments, utilizing the oscillometric method. Due to the in- and deflating of the cuffs around the upper arm and the associated pump noise, the measurement highly influences on the persons attention, which also affects on the blood pressure. Even if an experienced person executes the measurement, it lasts about 30 seconds. Moreover, a time interval of about one minute should exist between two measurements. So the time resolution is rather poor

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and registrations of fast blood pressure variations, especially during exercise activities are not possible. If no movements of the subjects occur the accuracy is in the range of ±3 mmHg.

As "gold standard" the direct invasive measurement using an intra-arterial catheter is regarded. This technique measures the blood pressure continuously but it is connected with a high instrumental expenditure and significant risks for the patient. Thus it but cannot be used under laboratory conditions or in real life situations.

There exist non-invasive continuously operating blood pressure measuring systems using finger cuffs [1] like the Peñáz-method or piezoelectric pressure sensors placed above exposed arteries [2]. Disadvantage is that squeezing of the fingers by the cuffs can lead to pain and deafness. Beyond that, due to the movement sensitivity and because of their size these instruments could not be used in the present investigation.

Finally, the systolic beat-to-beat blood pressure can be computed utilizing a mathematical model with the heart frequency and the pulse transit time as physiological parameters. While former investigations in this context were based on assuming a linear dependency between blood pressure and pulse wave velocity [3] or used artificial neural networks trained with a great variety of patient data [4], we found, that a high accuracy and long term stability of the model based blood pressure determination can only be achieved using personalized mathematical models [5, 6]. This method is used for the present investigation on the influence of stress on the arterial blood pressure.

2 Method

On the basis of an idealized artery model a relationship between blood pressure and pulse transit time can be derived [7, 8, 9]. A quadratic equation is the basis for the blood pressure determination, utilizing normalized values of the pulse transit time T_{R_P} as input and the systolic blood pressure P_{sys} as output. In order to calculate the blood pressure continuously, the beat-to-beat pulse transit time, the individual model coefficients and the initial blood pressure values of the test person at rest are needed. The measurement requires appropriate sensors. As already shown in [5], a chest belt is suitable for detecting the QRS-complex in the ECG, which corresponds to the beginning of the pulse transit time interval. An optical ear sensor serves as pulse wave arrival indicator. After a few minutes the subjects were not aware of the sensors any more. So the method can be applied without interfering with the person's attention.

To define the model coefficients, the blood pressure and the pulse transit time have to be measured at different load conditions. Therefore we use the stair climbing test after Schellong [10] where the subject has to ascend and descend steps for a certain time. An immediate rise of the heart frequency, a decrease of the pulse transit time and a steep rise of the systolic blood pressure occurs after the test begins, Fig. 1. During recovery initial values from prior to the test are reached. Due to the different time constants of the pressure rise in the exercise phase and the pressure drop during recovery two sets of parameters characterizing exercise and recovery are being determined.

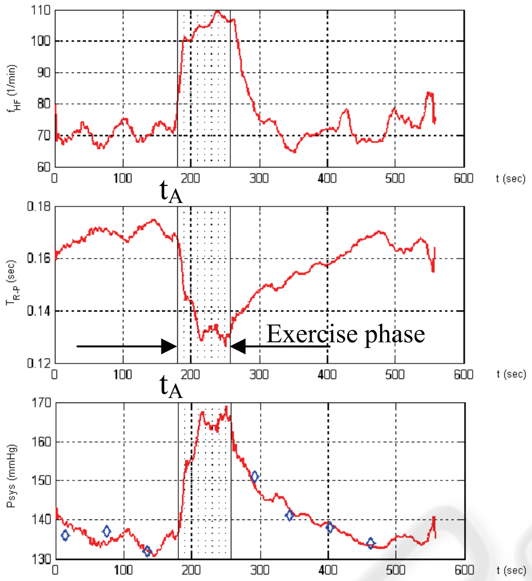

Fig. 1. Heart frequency, pulse transit time and computed systolic blood pressure together with measured systolic blood presure values, measured with Omron 705 IT.

Reliable reference values utilizing an oscillometric instrument can only be obtained if the test person is not moving. Therefore, measured values are available only during the resting and in the recovery phase. The maximum blood pressure at the end of the exercise phase also cannot be determined but is estimated using a polynomial approximation with the measured pressures during recovery. This maximum pressure is used together with the recovery values as additional point for the approximation function, yielding the recovery model (subscript: rec), see Eq. 1 and Fig. 2. As no measurements with the oscillometric device are possible during the exercise phase, we estimate the gradient of the pressure dp/dt for $t = t_A$ at the beginning of the step test, yielding the exercise model for strain activities (subscript: str):

$$\begin{aligned} \Delta P_{\mathrm{sys,str}} &= a_{1,\mathrm{str}} \cdot \Delta T_{\mathrm{R\_P}}^{\;2} + a_{2,\mathrm{str}} \cdot \Delta T_{\mathrm{R\_P}} + a_{3,\mathrm{str}} \\ \Delta P_{\mathrm{sys,rec}} &= a_{1,\mathrm{rec}} \cdot \Delta T_{\mathrm{R\_P}}^{\;2} + a_{2,\mathrm{rec}} \cdot \Delta T_{\mathrm{R\_P}} + a_{3,\mathrm{rec}} \end{aligned} \qquad (1)$$

The a_i are the separately to determine and subject specific model coefficients. $\Delta T_{\mathrm{R\_P}}$ and ΔP_{sys} refer to the normalized input and output values with respect to the subject at rest (subscript: rest), see Eq. 2:

$$\Delta P_{\mathrm{sys}} = P_{\mathrm{sys}} - P_{\mathrm{sys,rest}} \quad ; \quad \Delta T_{\mathrm{R\_P}} = T_{\mathrm{R\_P}} - T_{\mathrm{R\_P,rest}} \qquad (2)$$

This increases the robustness of the model coefficients concerning fluctuations of the physiological and psychological conditions and is in correspondence with the derivation of the linearized model equation [9]. The assumption is also supported by the observation, that quite different quiescent blood pressures can be determined, depending on previous activities and the general health condition of the person under test.

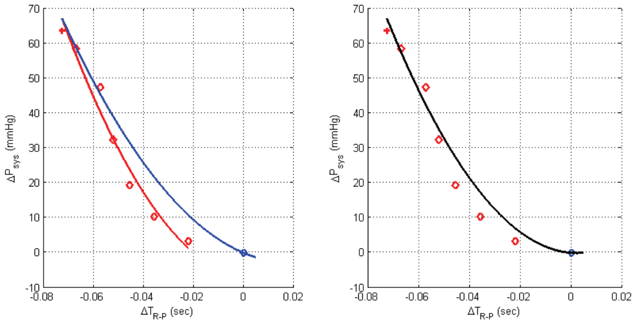

Fig. 2. Exercise and recovery model determined via step test (left) and mean model, used for systolic pressure determination (right).

The calibration test has to be carried out only once by each participant to determine the model coefficients which then can be applied at other applications. In most practical applications we cannot, however, a priori differentiate between exercise and recovery phases. We therefore have developed a mean model approach. A suitable pressure model is obtained by averaging the coefficients, yielding a mean blood pressure model equation for the person under test, Fig. 2. The inevitable error remains in most cases within the error of the oscillometric instruments, i.e. ±3 mmHg.

3 Applications

Stress usually is experienced as disturbing sensations. It leads to an activation of the organism and causes reactions [11]. It must be regarded, that factors, which lead to stress, can be very different from person to person. Stress reactions depend on the subjective judgement of the situation, earlier experiences and many further aspects [12]. Therefore, it is hardly possible to define a "standard stress factor". This leads to difficulties in the assessment, if several persons in a test are exposed to comparable stress situations. For the proof of stress reactions in the human organism most triggering indicators of activation are also suitable for the characterization of the reactions.

3.1 Investigations Using the Vienna Test System

The Vienna Test System (VTS) [13] is a computerized psychological testing system which provides a sophisticated method to evaluate and to train cognitive abilities, such as attention, memory or logical thinking. The system has also become a global standard in traffic psychology. Using the VTS we examined whether and how the blood pressure changes, if a test person is confronted with specific stress-inducing tasks. The test runs consist usually of a screen-supported instruction phase, a training phase and finally the actual exercise phase.

The "Tachistoscopic Traffic Test" is used to examine the optical perception on short time presentations of traffic scenes. The test persons are exposed to twenty pictures, Fig. 3, with a presentation time of one second each. Subsequently the person has to decide in a multiple choice among five possible answers what was to be seen in the picture: people, cars, bicycles, traffic signs and traffic lights. The task sounds simple, but due to the short presentation time the decision between the different objects given in the traffic situations seems quite difficult. Thus easily an uncertainty arises during the selection of the correct answers, which can lead to a stress sensation.

Fig. 3. Example from the Tachistoscopic Traffic Test.

The blood pressure graphs of two persons, Fig. 4 are found in a similar form for all test participants performing the Traffic Test. They show a more or less pronounced pressure maximum during the initial training phase, in which already situations occur like in the following test. For both persons the pressure remains after the first change practically constant for the test duration then falling to values before test begin. This indicates that after a first stage of insecurity about the forthcoming events a continuous strain is present. Compared with the initial pressure before test begin a mean pressure rise of approximately 14 mmHg for a person not familiar with the test and approximately 6 mmHg in the second case can be seen accompanied by some oscillations due to variable learning stress.

In summary systolic blood pressure changes up to 20 mmHg were observed with a tendency to higher changes between quiescent and test phase mean blood pressure for younger participants.

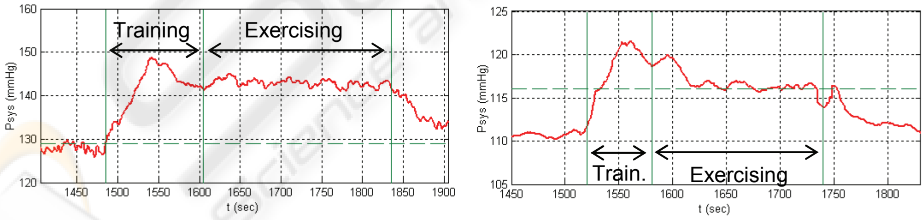

Fig. 4. Systolic blood pressure at Tachistoscopic Traffic Test (left: test unknown to test person, right: test is known from former experiments).

3.2 Investigation Using the Driving Simulator “Nightdriver"

In the following a potentially stressful everyday life situation is examined: driving a motor vehicle. Here the question arises to what extent one can judge from the recorded physiological signals, in particular from the blood pressure, on different mental load phases. And further it is to be examined, which factors lead to stress in the car driving situation at all.

In our investigation for the first time a continuous blood pressure determination could be performed during driving a car. To explore this topic the night driving simulator "*Nightdriver*" was used, which provides identically laboratory conditions for all participants. It consists of a "Smart"-vehicle and a three beamer projection of the traffic scenes. In the interactive virtual reality system, Fig. 5, the test participants can drive comparably to a normal passenger car. The landscape-street model with different scenarios like small villages, narrow streets as well as a short highway passage extends over a length of about 8 km. The participants were instructed to drive the distance as briskly as possible considering the traffic rules and not leaving the road.

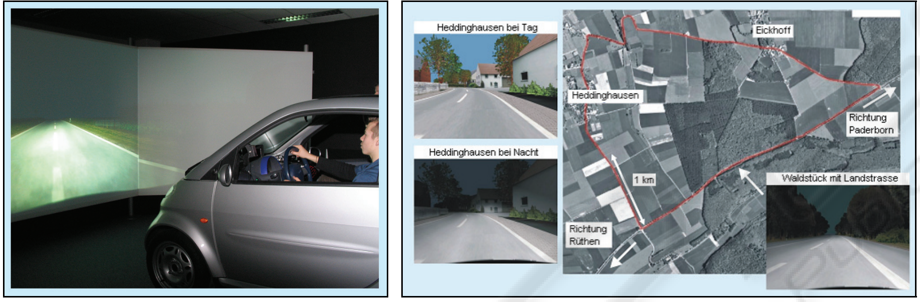

Fig. 5. Car Simulator "*Nightdriver*" and cockpit/ aerial view of test track (Source: L-LAB).

Fig. 6 shows the measured values from a test person to whom the simulator and the test track was unknown, while in Fig. 7 the simulation setup was known to the subject. At the beginning and after reaching the destination oscillometric blood pressure measurements (♦) were performed. The numbers above the P_{sys}-graph indicate specific track points to correlate the traffic situations with corresponding physiological reactions.

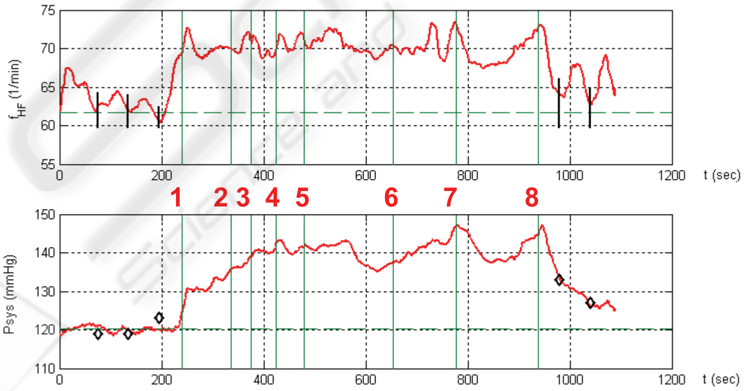

Fig. 6. Heart frequency and systolic blood pressure at driving (average speed: 45,3 km/h; simulator and track unknown to test person).

The signal waveforms of the two participants show interesting similarities. At the beginning of the ride at "1" the blood pressure of both drivers rises more or less rapidly. Interesting are the corresponding pressure maxima when entering and leaving a short highway passage ("7" and "8") and the pressure decrease, while steadily driving on a straight road and on the highway. The excellent correspondence of oscillometric and continuously measured blood pressure is remarkable.

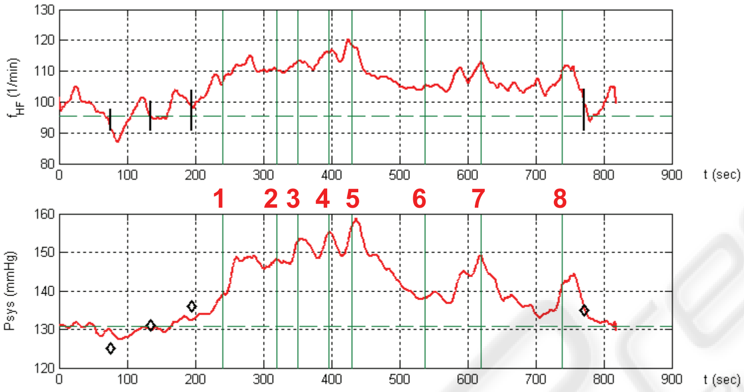

Fig. 7. Heart frequency and systolic blood pressure at driving (average speed: 63,5 km/h, simulator and track known from previous drives).

The driving results of further test participants exhibit very similar blood pressure graphs. In general it can be seen in Figs. 6 and 7, that the systolic blood pressure as well as the heart frequency respond to traffic situations. Pressure rises up to 30 mmHg are typical for normal traffic situations. With increasing experience in handling the simulator the influence on the individual pressure curves becomes smaller. The heart frequency also shows related variations but the changes in systolic blood pressure can more clearly be assigned to the specific traffic situations.

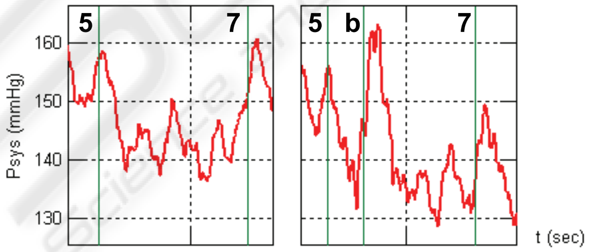

Fig. 8. Systolic blood pressure changes at same track part, first without and second with suddenly braking car in front (Numbers: "5" sharp curve, "7" turning point, "b" braking car).

In a second series of experiments the test persons had to follow another car on the same parcours. During the drive the car ahead suddenly changes the speed and the driver had to handle suddenly occurring obstacles. Fig. 8 shows the systolic blood pressure of a driver at the same part of the track first without any special occurrence and second with the car in front of him braking suddenly at point "b". The subject had no chance to avoid a simulated crash. A pressure rise of about 30 mmHg can be observed directly after the accident. Thinking of dangerous situations in real traffic much higher changes could be expected.

4 Discussion

Our investigations using the Vienna Test System and the driving simulator "*Nightdriver*" demonstrate the first continuous blood pressure measurements in realistic stress situations, pointing out the suitability of the systolic blood pressure as a reliable stress indicator. Arising stress leads to an increase of the blood pressure as discussed before. Other experiments calming down the subject with quiet and slow music show contrary results. The pressure keeps at the initial value or even drops below during the presentation.

Utilizing individual exercise-recovery and averaged model functions the systolic blood pressure could be determined continuously and non-invasively with high temporal resolution. Also brief fluctuations are indicated, which remain unidentified if classical cuff based instruments are applied. With the new method it is no problem any more to determine the blood pressure during exercise phases. The measuring system must be calibrated individually for the subjects under investigation using the Schellong stair climbing test. This calibration is to be accomplished only once for each person. The model parameters are stable at least for several days if no medication is taken. In all practical applications one cannot differentiate between strain and recovery, so that a single model with coefficients achieved by averaging is preferred. The preceding considerations are applied to the systolic blood pressure. Due to the relatively small pressure changes and the dispersion of the measured values, the error in defining an appropriate model for the diastolic pressure was found too high.

Since the pressure values during the calibration are measured using an advanced oscillometric device, a comparable accuracy of at least ±3 mmHg can be achieved. For a detailed failure analysis comparative invasive measurements would be meaningful. According to statements of medical experts, however, such measurements cannot be carried out due to the dangers for the subjects.

In order to investigate the psychological and physiological conditions of the subjects in greater detail, more than one parameter meaningfully would have to be evaluated. It has to be considered that not all parameters which correspond to physiological reactions could be measured in special test situations because of their unsufficient accuracy in field experiments or the high instrumental expenditure. Also, the fact that the subject is disturbed too much, has to be considered. Heart frequency changes correlate with the systolic blood pressure variations in general and could serve as stress indicators. However, the blood pressure variations give a more precise insight in the influencing reasons of the visible changes of the physiological signals and therefore in the situations which were analysed. Furthermore, the heart rate seems to be more affected by physical efforts than the blood pressure. Another parameter which is often used and relatively simple to register is the electrodermal activity or skin resistance. Disadvantage in this case is that quite often reactions can be observed which objectively are not correlated with any stressful situation.

Because the sensor technique of the continuous beat-to-beat measurement method is not at all influencing on the persons attention, the continuous model based blood pressure measurement proves as valuable additional indicator for the psychological conditions and the stress levels of the test participants. Although intraindividual differences in the reactions to special situations can be observed, in general it can be quoted that all participants show similar results. Due to personalized models our blood pressure determination method is sensitive even to small signal changes.

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