

Diagnosics of the human circulatory system: Application of high resolution beat-to-beat blood pressure measurement to stress and traffic situations

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Abstract – When a person is exposed to physical and psychological challenge, the heart beat is increased, blood vessels are dilated, the blood pressure increases and the skin resistance decreases. While heart rate and skin resistance can easily be measured, continuous blood pressure measurement was not possible in stress situations because of the poor time resolution of oscillometric or Riva-Rocci/Korotkow based instruments. We apply a novel high resolution blood pressure measurement technique based upon the pulse transit time dependency on the systolic pressure and making use of individualized mathematical models. The method can be used without interfering with the persons cognitive perceptions. Thus we can present the first continuous blood pressure measurements during stress tests utilizing the Vienna Test System and the driving simulator "Nightdriver".

Keywords: Continuous blood pressure measurement, pulse transit time, stress, Vienna Test System, car driving.

1. INTRODUCTION

Due to today's fast changing lifestyle a majority of people feel that they are permanently in a state of stress, i.e. in a situation of physical and psychological threat or challenge. Typical reactions are an increased heart frequency, an accelerated blood circulation and, due to increased sweating, a decrease of the skin resistance. At the same time released hormones like adrenalin and noradrenalin lead to dilated blood vessels, which causes the blood pressure to increase.

In order to characterize how a person withstands physical efforts and emotional stress, heart rate and skin resistance serve as measurable parameters. High resolution blood pressure determination so far was not possible in stress situations. Due to the in- and deflating of the cuffs around arms or wrists and the associated pump noise, the oscillometric or Riva-Rocci/Korotkow based instruments highly influence on the persons attention. Another reason is the poor time resolution of these units, used as standard measuring devices. They cannot be used for the registration of dynamic cardiovascular changes.

The oscillometric method is used today in fully automated systems, suited for blood pressure self measurement. Advanced algorithms with fuzzy logic support guarantee accuracies in the range of ± 3 mmHg. But the measurement also has disadvantages. The results are influenced by movements and cramping of the person, so that the blood pressure cannot be determined in particular during exercise phases. In addition no continuous registration of the blood pressure is possible, since the individual measurements including in- and deflating the cuff last about 30 to 40 seconds. Moreover,

a time interval of at least one minute should exist between two measurements, again preventing the registration of fast blood pressure changes.

A non-invasive continuous blood pressure determination could meaningfully be applied in a variety of new applications. First the wide range of exercise-ECGs is to be mentioned, which serve for the diagnostics of cardiovascular efficiencies, but also heart diseases. Further the regulation characteristics and the dynamics of the cardiovascular system could be examined in detail due to high temporal resolution of the method. And finally the procedure could be used in the sport medicine for the diagnostics of a person's cardiovascular performance. Stress situations are among applications, in which a continuous blood pressure measurement with a high time resolution would be very useful. The invasive measuring method with intravenous catheters cannot be used due to the high risks for the patients. Here our new method [1] is suitable, which is based on the evaluation of the pulse transit time dependency on the arterial blood pressure.

There are however other completely different areas of application. Compared with the conventional cuff devices the blood pressure can be determined completely unnoticed by the subjects. During the entire test time the influence of the sensors remains constant, while the test subject is made attentive to the forthcoming measurement when a cuff is inflated.

In the following new results are presented concerned with the influence of stress on the arterial blood pressure. The subjects under test are listening to music and must accomplish stress-inducing tasks at the Vienna Test System (VTS) [2]. As a major advantage, the persons are not affected by the sensor technology.

Further the continuous blood pressure monitoring is used while driving a car under reproducible conditions in a simulator setup. The influence of different traffic situations on the driver is examined. In addition the acceptance and learning behaviour of a person when using driver assistant systems can be analysed. This gives insight in strategies for the evaluation of these systems, in order to make an optimal adjustment to the needs of humans possible. The knowledge of blood pressure variations will contribute valuable references.

2. METHOD

We have developed a high resolution continuous blood pressure measurement technique utilizing heart frequency and pulse transit time [1]. It is based on former investigations of our institute [3, 4]. Using an optical ear sensor and a

standard chest belt known from sport activities, we determine the blood pressure via an individual mathematical model from the pulse transit time. The method can be applied without interfering with the subjects cognitive perceptions.

The following considerations are applied to the systolic blood pressure. Due to the relatively small pressure changes and the dispersion of the measured values, no generally suitable procedure for the determination of the diastolic pressure could be found in this investigation.

The mathematical model, which is the basis for the pressure evaluation utilizes the pulse transit time as input and the systolic blood pressure as output. The model is separately defined for exercise and for recovery situations. The model coefficients are determined separately for each activity and are subject specific.

To define the model coefficients, we have to measure the blood pressure and the pulse transit time at different load conditions. Therefore we searched for an easy to perform exercise test which does not need supporting devices. The stair climbing test after Schellong [5] proved as suitable. The subject has to ascend and descend steps for a certain time. An immediate rise of systolic blood pressure and heart frequency with constant or slightly dropping diastolic pressure is expected. Each participant can find an own rhythm and climbing speed. We determine two sets of parameters, one for exercise and another one for the recovery phase. The test has to be carried out only once by each participant to determine the model coefficients which then can be applied at other applications.

However, in most practical cases we cannot distinguish between exercise and recovery phases. For instance, when evaluating the blood pressure during driving a car, we cannot a priori differentiate between time intervals of excitement or calming down of the driver. We therefore have developed a mean model approach. We obtain a suitable pressure model by averaging the coefficients of the both models, yielding a mean blood pressure model for the person under test. The inevitable error remains in most cases within the error of the oscillometric instruments.

In order to compute the systolic blood pressure continuously, one needs the beat-to-beat pulse transit time, the individual model coefficients and the initial quiescent blood pressure values of the person. This requires appropriate sensors. A full ECG derivation is not necessary. As already shown in [3], a chest belt, used for pulse measurement during sport activities, is suitable for measuring the beginning of the pulse transit time interval. An optical ear sensor, also from the fitness area, serves as pulse wave arrival indicator.

3. APPLICATIONS

3.1. Preparation and execution of the experiments

The investigation took place in a laboratory of the Institute for Electrical Measurement at the University of Paderborn. Only the measurements using the night driving simulator "Nightdriver" were accomplished in the L-LAB, Paderborn. All necessary preparations were completed before the arrivals of the test persons in order not to disturb them before test begin. So a possible influence on the phy-

siological perception could be avoided. The subjects first put on the chest belt and the ear sensor for the continuous determination of the pulse transit time and then the cuff at the upper arm for the calibration measurements using the oscillometric blood pressure instrument. The values obtained at rest serve as quiescent normalizing values and are further used for verifying the computed pressure patterns. After a sufficient resting phase the measurement was started. The participants were asked not to speak during the investigation and to keep the appropriate arm calm in a suitable position during the cuff measurements.

3.2. Music and blood pressure

In this part of the investigation the influence of music on the blood pressure was to be determined. In our experiments two music pieces were chosen for each person. The first piece was the same for all participants, the second one was the favourite of the concerned persons. We used a headphone in order to reduce the influence from ambient noise.

For the model based pressure determination only the initial mean quiescent blood pressure values and the individual model parameters are needed. Intermediate pressure measurements served for a later control and a possible model adjustment. Figs. 1 and 2 show the blood pressure curves for two participants. In addition, the rms values of the music pieces were computed.

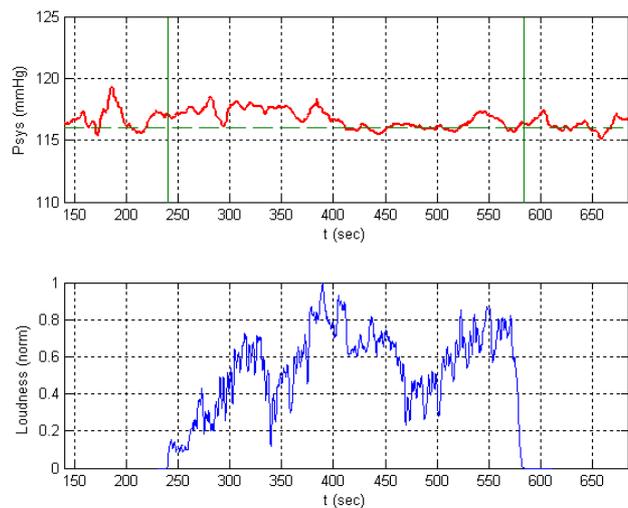


Fig. 1. Systolic blood pressure (upper part) while listening to the given music piece (ID22), loudness of the music (lower part)

Fig. 1 shows a measurement, where no changes in the blood pressure due to the music content can be observed. There are small pressure fluctuations, but they do not correlate with the music sound intensity profile. Another example is shown in Fig. 2. Some individuals show a stronger systolic pressure variation while listening to the music pieces, than shown in Figs. 1 and 2. But only rarely the changes exceed 5 mmHg.

No systematic dependency on the loudness profile of the music could be recognized. For some participants the blood pressure drops at the beginning of the music piece, for others it rises, then remaining relatively constant during the presentation.

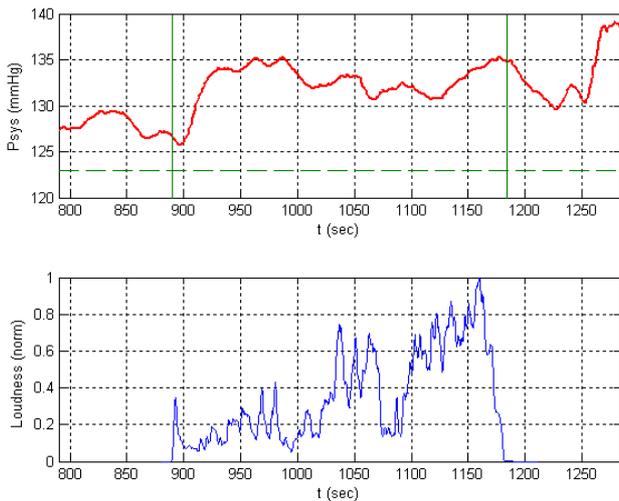


Fig. 2. Systolic blood pressure (upper part) while listening to favourite music piece (ID10), loudness (lower part)

In a study by Chafin, Roy, Gerin and Christenfeld [6] patients were exposed to different styles of music after a mental mathematics test. A decrease of the blood pressure was observed. Classical music proved for faster reaching the initial quiescent pressure values than music of other styles. Without music the pressure dropped even slower.

In summary, analysing 14 individuals we did not find any correlation between music intensity or the character of the pieces and the course of the measured systolic blood pressure curves. This applies to both the given piece and the favourite music. If small blood pressure changes arise, then usually the pressure is affected by both music pieces in the same way. That means that either with both pieces an increase or with both a reduction of the pressure was observed. It is therefore assumed that the test participants in general are affected differently by music.

We must consider, however, that the laboratory situation, in which the investigation took place, did not contribute to the person's relaxation. And there might be other parameters characterizing the musical contents and the reactions of the test participants, but this could not be investigated in detail here.

3.3. Investigations using the Vienna Test System

The Vienna Test System (VTS) [2] as a computerized psychological testing system is a sophisticated method to evaluate and to train cognitive abilities, such as attention, memory or logical thinking. It has also become a global standard in traffic psychology. Using the VTS we will now examine whether and how the blood pressure changes, if a test person is confronted with specific stress-inducing tasks.

For this investigation we could borrow a VTS from the L-LAB, Paderborn, Fig. 3. The operation is quite simple and therefore no problem even if the person has no computer experience. The test runs consist usually of a screen-supported instruction phase, a training phase and finally the actual exercise phase.

Stress usually is experienced as disturbing sensations. It leads to an activation of the organism and causes reactions [7]. 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 [8]. Therefore, it is hardly possible to define something like "standard stress factors". This leads to difficulties, if several persons in a test should be exposed to comparable stress situations.

For the proof of stress reactions in the human organism there are different suggestions. Since stress can be regarded as a special case of activation, most triggering indicators are also suitable for the characterization of stress reactions.



Fig. 3. Vienna Test System [2]

In the following both the "Tachiscopic Traffic Test Mannheim" and the "Vienna Determination Test" are used. The "Determination Test" is a complex multiple stimulus test, with both colour and acoustic signals acting simultaneously on the test person. The participant has to react as fast as possible by means of pressing buttons at the universal panel and also by stepping on foot pedals.

With such devices the reaction behaviour under heavy psycho-physical load can be analyzed. By choosing accordingly high signal frequencies each person can be brought into an overextension, in which reaction movements are not reliable any longer. A load situation of extreme kind exists if a highly motivated person is not capable to carry out appropriate reactions in due time.

Within a single allocation of stimulus and reaction these achievements do not represent any considerable difficulty. The challenge during the Determination Test is caused by the quick sequentially and continuously required reactions to fast changing situations. Therefore the difficulty depends particularly on two variables:

- the speed, with which the presentation changes, and
- the number of the stimuli and reactions, between which can be chosen.

The presentation of the colour stimuli occurs on the screen of the system, Fig. 4. Ten optical signs in the colours white, yellow, red, green and blue are shown, forming an upper and a lower row. In addition, from time to time two white rectangular fields are displayed on the left and on the right lower side of the screen, requiring the appropriate foot pedal to be pressed. Finally, two acoustic signals (high or deep beep) are assigned to two "sound-keys" in the centre of the panel. They have to be pressed if a tone is emitted.

In the adaptive form of the test the speed of the stimuli display depends on the persons operating velocity. Due to this kind of performance the subject always operates at the

boundary of its capability. In comparison with other available test forms the Determination Test is probably the most unpleasant stressor.



Fig. 4. Subject at the Vienna Test System, Determination Test

With the "Tachistoscopic Traffic Test Mannheim" the optical perception and the viewing speed on short time presentations of traffic scenes are examined. The test persons are exposed to twenty pictures with a presentation time of one second each. Subsequently, the person has to decide in a multiple choice among five possibilities, what was to be seen in the displayed picture, Fig. 5. There is enough time available for this decision. The task sounds simple, but due to the short presentation time the decision between the traffic situations seems quite difficult. Thus easily an uncertainty arises during the selection of the correct answers, which again can lead to a subjective stress sensation.



Fig. 5. Example from the Tachistoscopic Traffic Test (left), possible answers to the presented traffic situations (right)

The blood pressure graph shown in Fig. 6 is found in a similar form for all test participants performing the Traffic Test. It shows a more or less pronounced pressure maximum during the initial training phase, in which already situations occur like in the following test. For some participants this maximum exists near the transition to the exercise phase.

After the first change the pressure remains 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.

In summary participants of higher age produced at approximately the same number of correct answers than younger ones clearly more wrong inputs, so that objects were recognized, which were not present in the pictures at all. Thus a smaller number of totally correct identified traffic scenes were counted. 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.

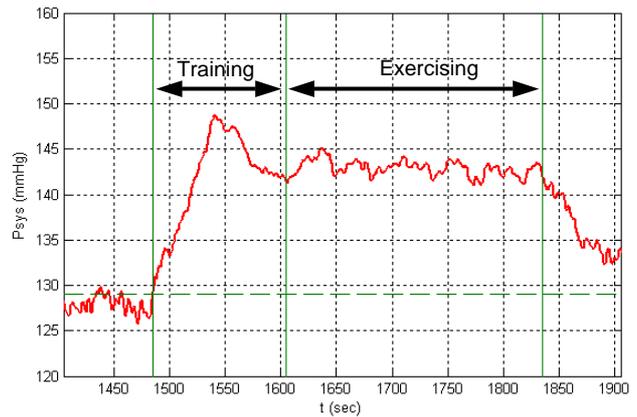


Fig. 6. Systolic blood pressure at Tachistoscopic Traffic Test (ID13)

The following Figs. 7 and 8 display typical blood pressure graphs for the Determination Test.

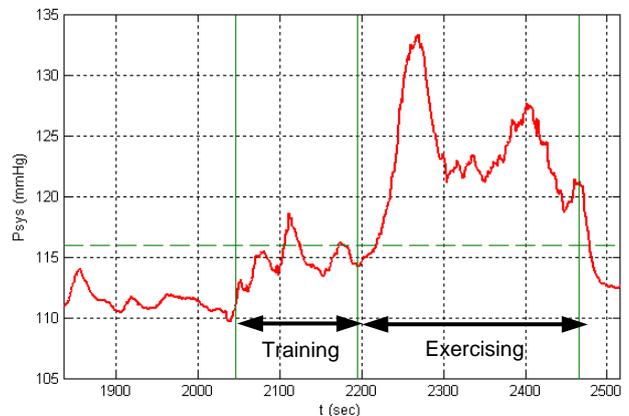


Fig. 7. Systolic blood pressure at Determination Test (ID22, Test is known from former experiments)

In both presentations the time interval can be recognized, in which successively the handling of the input devices is learned. Compared with the initial pressure before test begin a mean pressure rise of approximately 5 mmHg accompanied by oscillations due to variable learning stress can be seen. At the beginning of the exercise part for ID22 the blood pressure once again rises significantly in the order of 18 mmHg. The transition from training to exercise is less pronounced for ID23.

The strong pressure variation in Fig. 7 indicates that ID22 has lost the rhythm and was overtaxed with the required short time reaction to all the symbols. After the speed of presentation was reduced, the blood pressure regulates to smaller changes. The Determination Test was previously known to ID22. However, this fact cannot be deduced from the pressure curve.

On the other hand ID23, Fig. 8, seems to be able to retain a better rhythm. The maximum blood pressure change between resting and exercise phase is clearly smaller at ID23 with approx. 12 mmHg than for ID22 with approx. 20 mmHg. As expected, the blood pressure of all subjects rises during the two test phases. The increase while performing the Determination Test is usually more significant than with the Traffic Test. One reason might be the high short-lasting stress due to the continued presentation of symbols, to

which an immediate reaction is necessary. Performing the Traffic Test this is not required.

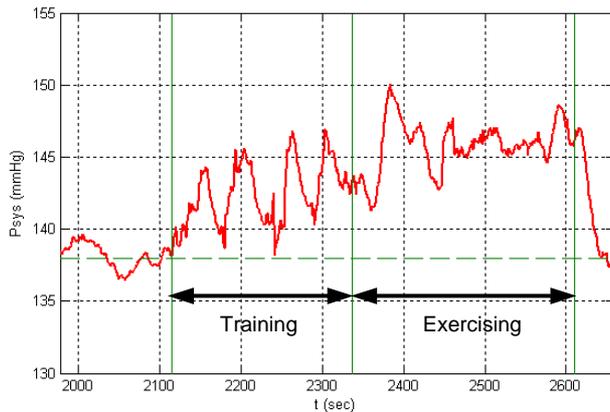


Fig. 8. Systolic blood pressure at Determination Test (ID23, Test is not known)

Also, the physical work which is to be performed by pressing the buttons and pedals fast enough is considerably higher during the Determination Test. This certainly contributes to a blood pressure rise.

In conclusion it can be stated, that a continuous blood pressure monitoring while using the Vienna Test System VTS could be accomplished for the first time, pointing out the suitability of the systolic blood pressure as a reliable stress indicator. The high temporal resolution of the method allows the continuous registration of fast blood pressure fluctuations, which would not have been recognized with a cuff-based measuring device.

3.4. Investigation using a driving simulator

In the following we examine a potentially stressful everyday life situation: 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 is to be examined, which factors at all lead to stress in the car driving situation. In [9] it was found, that backing-up, building construction sites and parking lead to stress, which correlates with measurable changes of the blood pressure. An Omron wrist measuring instrument was used, but necessary measuring requirements - no movements during measurement - were not always regarded.

In our investigation for the first time a continuous blood pressure determination could be performed during driving a car. In these first experiments the motoring itself, without external influences, is considered. To investigate this topic the night driving simulator "Nightdriver" was used, which is located in the L-LAB, Paderborn. A "Smart" motor vehicle is placed within the interactive system, in which the test participants can drive comparably to a normal passenger car. A landscape-street model is projected with three beamers on canvases in front of the car, Fig. 9.

Reasons for using a driving simulator are both identically laboratory conditions for all participants and certain safety aspects, since it cannot be excluded that the test persons are impaired in their freedom of movement and associated reactivity by attached devices and cables.



Fig. 9. Car Simulator "Nightdriver" (Source: L-LAB)

The "Nightdriver" displays beside day representations also a detailed and physically correct illumination of traffic situations at night. We selected the digitalized route of a really existing test track extending over a length of about 8 km, Fig. 10.

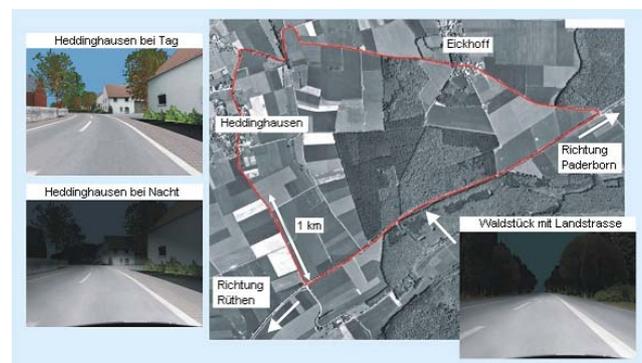


Fig. 10. Cockpit and aerial view of test track (Source: L-LAB)

Different scenarios like small villages, narrow streets as well as a short highway passage are included. To produce impressions as realistic as possible, objects like trees, houses and traffic signs are integrated into the model.

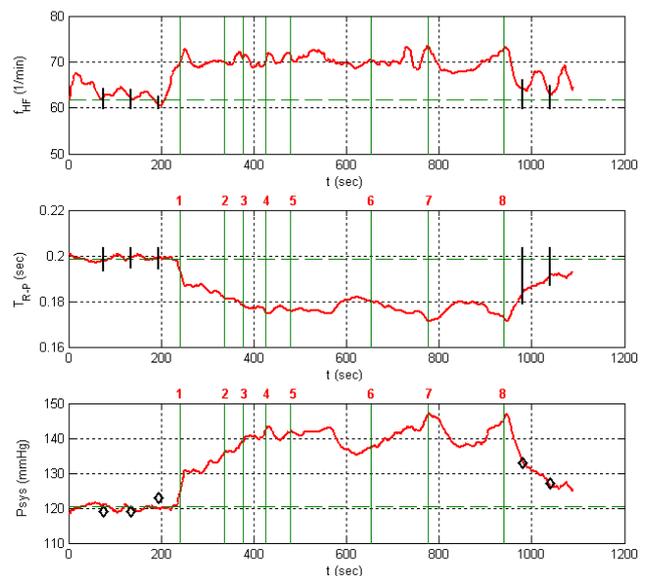


Fig. 11. Heart frequency (upper part), pulse transit time (middle) and systolic blood pressure (lower part) at driving (ID01, average speed: 45,3 km/h, simulator and track unknown)

The participants were instructed to drive the distance as briskly as possible considering the traffic rules and not lea-

ving the road. At the beginning and after reaching the start/goal position oscillometric blood pressure measurements were performed. Also, at interesting points the passing times were noted in order to correlate the signs with corresponding physiological reactions, especially the blood pressure, see numbers above the P_{sys} -graph in Figs. 11 and 12. The excellent correspondence of oscillometric (\blacklozenge) and continuously measured blood pressure is remarkable.

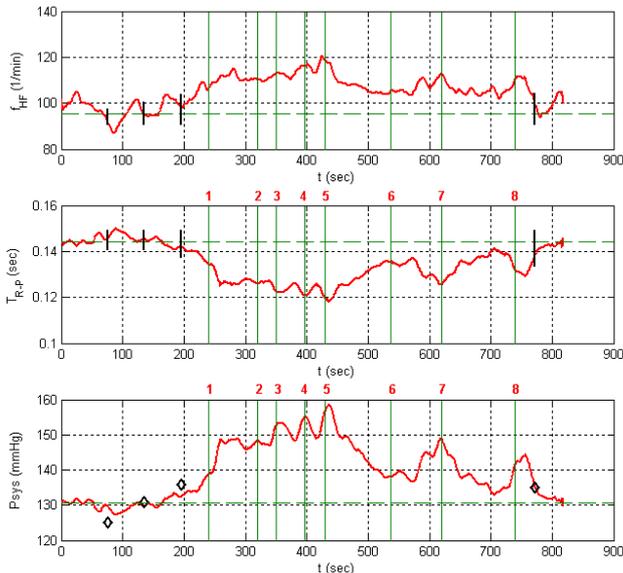


Fig. 12. Heart frequency (upper part), pulse transit time (middle) and systolic blood pressure (lower part) at driving (ID22, average speed: 63,5 km/h, simulator and track known from previous drives)

The signal waveforms of the two participants, Figs. 11 and 12 show an amazing similarity. At the beginning of the ride in both drivers the blood pressure rises more or less rapidly. Interesting are the corresponding pressure maxima when entering and leaving the short highway passage (7 and 8) and the pressure decrease, while steadily driving on the small road and on the highway.

The driving results of further test participants exhibit very similar blood pressure graphs. Also, the increasing experience in handling the simulator appears to influence on the individual pressure curves.

4. DISCUSSION

With our approach of utilizing individual exercise-recovery or averaged model functions we could determine the systolic blood pressure continuously and non-invasively with high temporal resolution. Also brief fluctuations are indicated, which remain unidentified if classical cuff based instruments are applied. The measuring system must be calibrated individually for the subjects under investigation using the Schellong stair climbing test. 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.

The model calibration is to be accomplished only once for each person. Then the blood pressure can be computed using the model function with the individually derived pa-

rameters. In order to apply an exercise-recovery model to new tests, additional standardisation steps are necessary. In all practical applications one cannot differentiate between strain and recovery, so that a use of double models is excluded. The best possibility is the use of a single model with coefficients achieved by averaging.

For a detailed failure analysis of the model based blood pressure determination comparative invasive measurements would be meaningful. According to statements of medical experts, however, such measurements can not be carried out due to the dangers for the subjects.

Our investigations using the Vienna Test System and the driving simulator "Nightdriver" demonstrate the first continuous blood pressure measurements in stress situations. 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.

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