Feasibility of Pulse Presence and Pulse Strength Assessment during Head-up Tilt Table Testing Using an Accelerometer located at the Carotid Artery

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***Abstract*— Neurally mediated syncope (NMS) is a disorder of the autonomic regulation of postural tone, which is characterized by hypotension and/or bradycardia, resulting in cerebral hypo-perfusion and finally in a sudden loss of consciousness. Prediction of an impending NMS requires detection of pulse presence to derive heart rate (HR) as well as to assess the pulse strength (PS) related to systolic blood pressure (SBP) preferably from a single body location only.**

This paper analyses the basic feasibility of using a single accelerometer positioned above the common carotid artery to assess pulse strength and pulse rate towards NMS prediction. A physical model has been investigated to gain insights into expected signal morphologies and potential feature candidates vs. hemodynamic parameters such as SBP, pulse pressure (PP) and PR relevant for NMS detection. Model results are compared with first measurements obtained in a head-up tilt table test (HUTT) from a patient during impending syncope. We show that an accelerometer positioned at the carotid artery is a potential approach offering a valuable tool in syncope management.

I. Introduction

Falls are a major issue in particular for the elderly and are associated with a high risk of injury, compromised life quality as well as with significant costs for the healthcare system, e.g., due to hospital admissions [1-2]. One of the main underlying causes of falls is neurally mediated syncope (NMS), which is characterized by hypotension, bradycardia, and consecutive cerebral hypo-perfusion resulting in temporary loss of consciousness. Continuous monitoring could provide valuable information into the causality of these events, which might enable the timely prediction of syncope onset by appropriate algorithms, thus providing the means to develop effective early warning systems for the protection of high risk populations.

NMS is defined by the European Society of Cardiology (ESC) if a patient experiences syncope in the presence of bradycardia (i.e., HR < 40 bpm), hypotension (SBP < 80 mmHg), or both during a head-up tilt table test (HUTT) [3], as visualized in Fig. 1. Therefore, a monitoring system for syncope management must provide at least the following two parameters: 1) a measure of pulse rate including reliable detection of pulse presence and 2) a measure of SBP trend or - preferably – even classify normal blood pressure (BP) vs. hypotension in terms of absolute SBP.

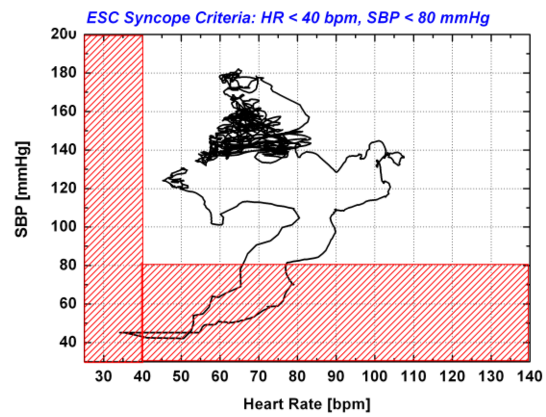

Fig. 1: Visualization of the ESC Criteria for NMS based on the presence of bradycardia (HR < 40 bpm), and/or SBP less than 80 mmHg.

In previous work the feasibility of using the pulse arrival time (PAT), estimated as a time delay between an electrocardiogram (ECG) and a peripheral photoplethysmogram (PPG), has been demonstrated for early detection of hypotensive events in patients with NMS [4-5]. However, a PPG signal obtained, e.g., at the finger tip is known to be sensitive to hydrostatic effects. In addition, the sensor can hinder the patient in daily activities. Therefore, an alternative or complementary system embodiment for detection of impending NMS would be beneficial.

A potential technical and user-friendly solution could be based on a single accelerometer (ACC) placed on the skin surface above the carotid artery to detect acceleration due to arterial dilatation. This approach is intrinsically different from ballistocardiography since the primary signal of interest is detected from momentum changes at the skin surface caused by the dilatation of the underlying artery at a specific location whereas ballistocardiography refers to the detection of global body momentum changes due to the pumping action of the heart [6-11]. Assessment of arterial dilatation is closely related to pulse palpation – the elementary method for clinical hemodynamic assessment. Pulse palpation from the common carotid artery serves as a reference when comparing pulse strengths at other sites around the body (e.g., the elbow, groin, temple, wrist, etc.), so this body location is a natural choice for a monitoring system in NMS management [11].

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This paper discusses a physical model to simulate the acquisition of arterial dilatation signals by an ACC sensor placed on the skin surface above the carotid artery. The model is used investigate expected signal morphologies dependent on SBP, HR and pulse pressure (PP). The basic feasibility is evaluated using experimental data gathered from a syncope patient during a HUTT procedure.

II. Model to Simulate Accelerometer signals during palpation at the common carotid artery

A. Overview of the physical model

Fig. 2 shows a block diagram of the implemented physical model which has been developed to gain insight into basic signal properties and their dependencies from hemodynamic parameters of interest pertinent to NMS management.

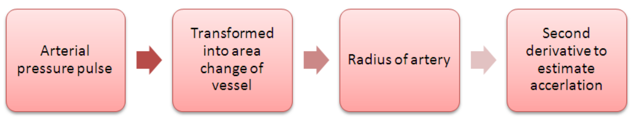

Fig. 2: Overview of the basic building blocks of the implemented physical model

It assumes the detection of the radial acceleration component due to arterial dilatation detected above an underlying artery from a passing pressure wave. Transmission properties of the tissue from the artery to skin surface are not covered so far. Model parameters include: age, externally applied contact pressure (cP), gender, HR, PP and SBP. Arterial pressure waves, which serve as model input, can be either obtained from a measured arterial BP signal or can be modeled BP wave, e.g., based on the Fourier-series approach described in [12].

A visualization of the implemented model is shown in Fig. 3 with the input pressure waves shown in subplot C.

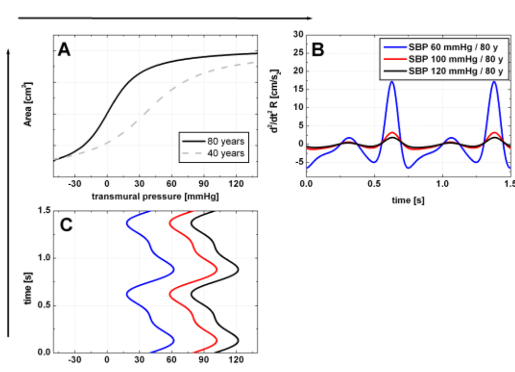

Fig. 3: Transformation of BP waves at different SBPs with constant PP into acceleration signals by the implemented physical model

The non-linear function in subplot A of Fig. 3 is the pressure-volume curve, which relates the blood pressure wave (here cP = 0 is assumed) to artery dimensions, where the response depends on age and gender e.g. discussed for the brachial artery [12] or aorta [13]. The time course of the artery radius is translated into an ACC signal by taking the second derivative. Fig. 3 shows simulated BP waves of three different SBP of 120 mmHg, 100 mmHg and 60 mmHg at a constant PP of 40 mmHg and a HR of 60 bpm (Fig. 3-C). These pressure waves cause different arterial diameter changes given by the non-linear transfer-function schematically shown in Fig. 3-A at ages of 80 years and 40 years. As expected decreasing BP results in higher amplitude of the aortic diameter change as shown in (Fig. 3-B), here presented for a transfer-function related to an age of 80 years.

B. Experimental setup for the head-up tilt table tests

Measurement data were acquired during scheduled HUTT involving patients with an unexplained history of syncope. The study was approved by the local clinical ethical committee as well as by a Philips internal ethical review board. All participants gave written consent to participate in the study. The HUTT was conducted according to the guidelines of the ESC and consisted of 3 phases: 1) an initial supine period at rest, 2) a passive standing exercise at a 70° angle, and 3) a supine period at rest. If no syncope manifested after 20 min during the second phase of the HUTT then nitro-glycerin was administered sublingually in order to trigger a hemodynamic response.

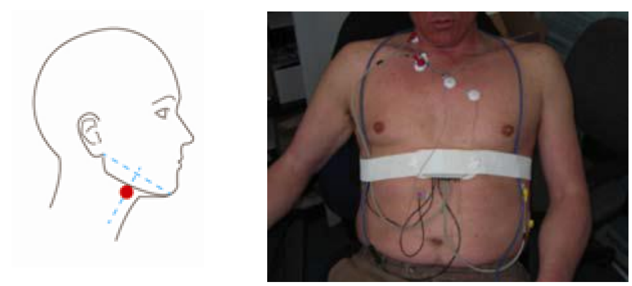

Fig. 4: (left) Location of the acceleration sensor at the left or right common carotid; (right) The SENSATRON system attached to a subject (a detailed description of the system can be found in [14]).

ACC signals from the common carotid (Fig. 4, left) were measured with a multi-parameter, battery operated device called the “SENSATRON” (Fig. 4 right). Signals from a 3-axis ACC sensor were sampled at 125 Hz. Additionally an one-lead ECG sampled at 250Hz was acquired synchronously. A detailed description of the device can be found in [14]. BP was continuously monitored using a Taskforce – Monitor (Graz, Austria) [15].

III. Results

A. Influence of SBP, HR and PP on morphology of simulated accelerometer signals

The influence of SBP, HR and PP on pulse morphology compared to a reference acceleration signal for the SBP at 120 mmHg, with a PP of 40 mmHg and a HR at 80 bpm is presented in Fig. 5. All simulations with artificial BP waves are performed for a 60 year old female. For constant HR and PP the maximum positive amplitude (MPA) increases due to increased vessel compliance at lower pressures (Fig. 5 left) as expected from typical pressure-volume curves. In the middle plot of Fig. 5 MPA at a HR of 70 bpm is reduced compared to its value for the reference HR of 80 bpm. This decrease is a consequence of the fact that an acceleration signal is proportional to the square of the HR due to the second derivative of the arterial dilatation - an effect, which can be easily compensated. The signal morphology is also changed, if the PP is reduced from 40 mmHg to 20 mmHg as shown in Fig. 5 right. HR, PP and SBP exert obviously a significant influence on the acceleration signal morphology.

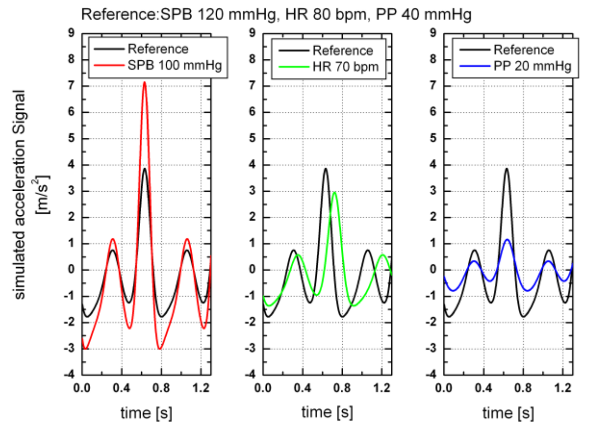

Fig. 5: Simulated acceleration signals using the proposed physical model; The impact of SBP, HR and PP are shown for a reference pulse at SBPs of 120 mmHg, HR 80 bpm, with a constant PP of 40 mmHg: (left) SBP of 100 mmHg, (middle) HR equal to 60 bpm and (right) PP of 20 mmHg.

B. Two features extracted from the simulated acceleration signals in the SBP range from 60 mmHg to 140 mmHg

In our terminology, "pulse strength" refers to the relation of a surrogate measure to SBP to be derived from the ACC-signal morphology within one pulse period. A quantified analysis of two features in the SBP range from 60 mmHg to 140 mmHg is presented in Fig. 6.

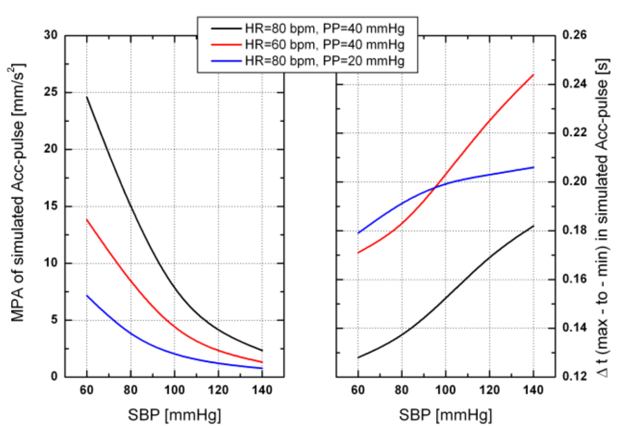

Fig. 6: Dependency of two features extracted from the simulated acceleration signals in the SBP range from 60 mmHg to 140 mmHg: (left) MPA, (right) time difference from maximum to the next minimum in the simulated acceleration pulse (graphs are shown for various HR and PP settings).

The left diagram shows the MPA of the ACC signal, which increases monotonically but non-linearly with decreasing SBP due to the impact of HR and PP. The change of MPA within the relevant SBP range can be easily measured. The SBP dependency of another feature based on time differences within a pulse sequence is shown in Fig. 6, right. This feature is defined as the difference in time from the MPA to the next local minimum within a pulse sequence. A monotonic increase in this feature can be observed; however, this increase depends on the HR and the PP as well. Again, the simulated changes of about 40 ms should be easily resolved from experimental data.

C. ACC signals measured at the common carotid artery during HUTT

An acceleration signal – with one axis perpendicular to the skin surface - obtained from a patient during HUTT under stable conditions (SBP at 120 mmHg, HR 80 mmHg, PP 40 mmHg) is shown in Fig. 7 for a 53 year old female syncope patient during standing. The measured signal morphology qualitatively matches the simulated signals shown in Fig. 5, which indicates that this signal likely corresponds to arterial dilatation. Acceleration signals measured in the other two axes were more influenced by ballistocardiography signals overlapping the arterial dilatation signals. Clearly the HR can easily be obtained by applying appropriate algorithms as shown, e.g., in [7]. During the following measurements, the orientation of the ACC sensor did not change.

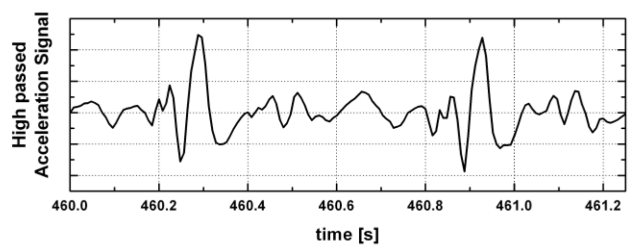

Fig. 7: Accelerometer signal component perpendicular to the skin surface obtained at the common carotid artery of a 53 year old syncope patient during a HUTT (SBP 120 mmHg, HR 80 bpm, PP 40 mmHg)

D. Comparison of the MPA from the ACC signal obtained from the model using the measured BP wave vs. the ACC data acquired in the HUTT

The implemented model has been used to compare simulated ACC signals with measured ones. For that purpose, the continuously acquired BP wave was applied as an input signal to the model along with parameters matched in age and gender to the actual patient. For comparison the MPA in each pulse sequence have been extracted for the simulated (blue curve) as well from the measured ACC-signal (black curve) presented in Fig. 8 for a period of about 10 min during a HUTT spanning a SBP range of 70 - 140 mmHg. Data were averaged over a 10s window to reduce noise. The Pearson-correlation coefficient of both signals and for this time interval is 0.83. It was also observed that the measured MPA divided by HR^2 shows the expected negative correlation within a SBP decrease as discussed in section III/A with a Pearson–correlation coefficient of -0.8.

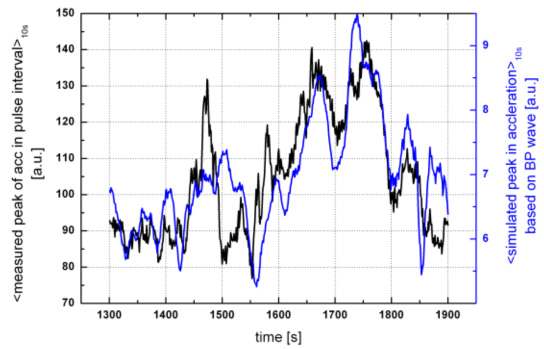

Fig. 8: Comparison of the measured and simulated accelerometer signals obtained at the carotid artery of a syncope patient during a HUTT. The left and right axes correspond to the measured and simulated signals, respectively.

To show, that it is in principle possible to track an impending NMS from a stable state using a single ACC sensor only, Fig. 9 presents an xy-plot of the extracted HR and our BP surrogate measure MPA normalized by HR^2 covering a measurement period of more than 30 min reaching syncope. Both parameters were averaged using a time window of 10s. Some artifacts were observed due to motion of the patients as well, which can be filtered out easily. The observed behavior is similar to the plot shown in Fig. 1 as well as to a pattern obtained previously for the PAT measurements.

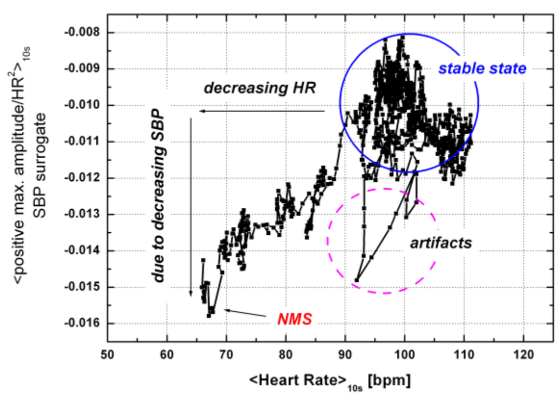

Fig. 9: MPA normalized by HR^2 PAT-HR plot during HUTT experiments with critical boundaries of PAT and HR; the sign of the BP surrogate measure was inverted for easy comparison with Fig. 1.

IV. Discussion

The simple physical model developed to simulate ACC signals due to arterial dilatation was found to reproduce measured acceleration perpendicular to the skin signals at the common carotid artery during HUTT reasonably well. This was verified by comparison with data obtained from a patient undergoing a HUTT procedure during passive standing in a period of about 30 min. Signal morphologies acquired from the common carotid artery of the subject resample the morphology as expected by artery dilatation. However, the two other ACC signal axes were affected by ballistocardiographic signals, which could make signal interpretation challenging. This will be explored further in future research. The proposed physical model provides reasonable insights into the dependencies of the ACC signal morphology features on relevant NMS parameters, i.e., SBP, HR and PP. As expected there is no simple relation for the most important parameter, SBP, within the range of interest from normal to hypotensive phases, owing to the significant and nonlinear impact of HR and PP. However, SBP is obviously encoded in the acceleration signal and can be tracked using a single sensor located at the common carotid during stable measurement conditions, i.e., fixed accelerometer sensor orientation.

Basic feasibility has been shown that an accelerometer provides pulse rate as well as pulse strength information from a single body location to assess an impending NMS. However, more data and improved signal interpretation methods for the performance of this novel approach are needed. In conclusion, acceleration sensors probing large arteries might be a valuable tool in ambulatory hemodynamic assessment, e.g., to allow tracking of HR and BP surrogate parameters and could enable improved NMS management.

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