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Research Article

From Contour Analysis of Pulse Volume Curves to Wave Component Analysis

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Abstract

Introduction: Today there is good evidence that the pulse volume curve (PVC) contains information about the systemic circulation and that the information content is not influenced by peripheral or local conditions at the recording site. In advancing the interpretation of PVC it appears necessary to identify individual wave components that contribute to the pulse wave. **Methods and patients:** In this study we applied the theory of constructive and destructive addition of forward and reflected arterial pulse waves to PVC recorded from finger pulse oximetry sensors in a group of cardiovascular healthy subjects (n=53) and compared them to those recorded in a group of patients with confirmed cardiovascular diseases (n=46). For this purpose PVC were processed by Fast Fourier transformation (FFT) and isolated sine wave components were used in a sine wave simulation to identify the two major wave components (forward and largest reflected wave) in their phase angle and amplitude. Amplitude amplification was calculated by comparing the identified forward travelling wave to the measured PVC. **Results:** The cardiological patients had much smaller phase angles between forward and reflected waves ($p < 0.01$), and much higher wave amplification effects ($p < 0.01$). This was also true for the subgroups of the cardiological patients (Hypertension, n = 19, Cardiomyopathy, n = 8, Aortic stenosis, n = 6, Coronary artery disease, n = 13). The healthy subjects had phase angles >104° that are associated with decreased systolic pressure, decreased stroke work, and decreased peripheral resistance. The cardiological patients had phase angles < 104° that are associated with a constructive addition of both waves and with negative effects like increased systolic pressure, increased stroke work, and increased peripheral resistance. **Discussion:** By pulse wave component analysis it was possible to distinguish between cardiovascular healthy participants and patients with different cardiovascular diseases. The new method enables to do a cardiovascular risk assessment by analysing a simple and highly available signal, the PVC. This could contribute to a reduction of cardiovascular mortality when an arterial overload condition is identified in an early stage before organ or tissue damage occurs.

Background

Finger pulse oximetry is essential in all polysomnographic and polygraphic recordings in the detection of sleep disordered breathing. In addition pulse oximetry is used for monitoring of patients in intensive care units and all other applications where oxygen saturation (SpO2) and heartrate (HR) give important information about the physiological status. Beside these two main physiological parameters SpO2 and HR many pulse oximeters are able to record the pulse volume curves with high accuracy. The amplitude of the pulse volume curve is influenced by respiration, sympathetic nervous system activity and other factors that influence local perfusion [1-4]. But the shape or contour of the waves seems to remain approximately constant.

Cold fingers are reported to reduce the over-all amplitude of the pulse wave but not to affect the configuration of the pulse wave [5]. This was already found by Hertzman and Spealman [6,7]. In addition they noted that heat has the opposite effect. Furthermore the infusion of vasodilator drugs in the brachial artery was reported to increase forearm blood flow and the amplitude of the pulse wave with little effect on its contour that remained similar to that recorded from a finger of the non-infused contralateral arm [8]. So not the peripheral or local conditions are reflected in the pulse wave contour, but the systemic circulation instead seems to have the major influence on the contour of the pulse volume curve.

In 1941 John Dillon and Alrick Hertzman were the first researchers who have done a contour analysis of photoplethysmographic pulse volume curves [9]. They were the first to describe a normal pulse volume contour in healthy persons with the typical secondary peak in the descending right flank and how this is systematically modified in hypertension and arteriosclerosis. They observed a tendency of the incisura before the secondary peak to rise with generalized systemic vasoconstriction and to decrease after inhalation of amyl nitrite [9]. They already interpreted the pulse volume curves as a summation of forwards and backwards travelling waves and reported 'loss of the rebound wave and triangulation of the' pulse wave in individuals with hypertension and arteriosclerosis [9].

The transformation of the pulse wave from its central origin at the aortic valve to peripheral sites has been investigated in several studies. Especially in the development of transfer functions to calculate the central aortic pressure from peripheral blood pressure measurements at the brachial or radial artery [10-18]. Millasseau et al. [19] and Allen et al. [20] have shown that peripheral pulse volume curves are comparable to peripheral pressure pulse waves. Millasseau et al. demonstrated that the relationship between the pulse volume curve at the finger and the radial pressure pulse (or the digital pressure pulse, which is almost identical to the radial pressure pulse) can be represented by a single mathematical transfer function [19]. This relation shows that the physiological determinants that take influence on the contour of radial pressure curves are identical to those that determine the contour of the pulse volume curve.

The influence of ageing on the contour of the pulse volume curve is well described [21-24]. The pulse contour changes observed in dependence on age are mainly related to an increase in large artery stiffness. Increased stiffness increases the pulse wave velocity (PWV) and shortens the arrival time of the reflected wave at the finger. Measurement of PWV allows to compare age related normal values against accelerated arterial ageing due to disease, lifestyle or genetic predisposition. This leaded to the establishment of PWV as biophysical marker of arterial ageing and the assessment of cardiovascular risk [25–28].

From the studies on the analysis of the contour of pulse volume curves done so far, it is difficult to estimate the precision with which cardiovascular risk predictions can be derived from them.

In advancing the interpretation of pulse volume curves it appears necessary to identify individual wave components that contribute to the pulse wave. According to the proposal by Quick et al. (2001) it seems promising to understand a pulse wave as a summation of forward and backward travelling sine waves. The theory of constructive and destructive addition of forward and reflected arterial pulse waves also explains the dependence of arterial resistance and stroke work from phase angle and amplitude of the initial forward travelling wave and the main reflected wave of a pulse wave [29]. In (Figure 1a and 1b) the theory is explained in a sine wave model.

In this study, we decomposed pulse volume curves into sinusoidal wave components and determined phase angle and amplitude of the major wave components in order to assign them to diseases resulting from chronic cardiac or vascular overload conditions.

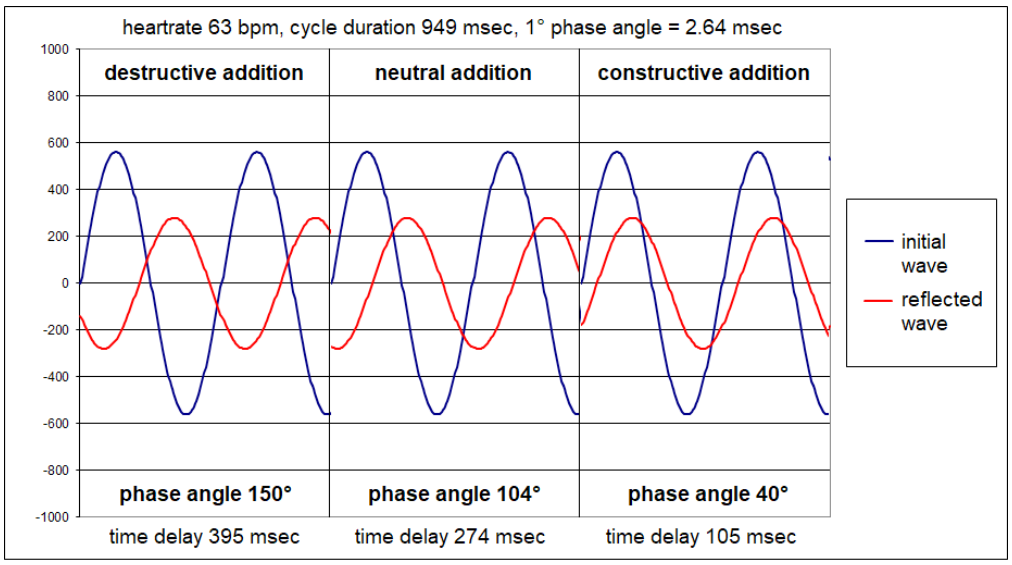

Figure 1a: Sine wave model: Initial wave and largest reflected wave originating from the bifurcation site in the pelvic region with a reflection coefficient of 0.5, resulting in half of the amplitude height of the initial wave.

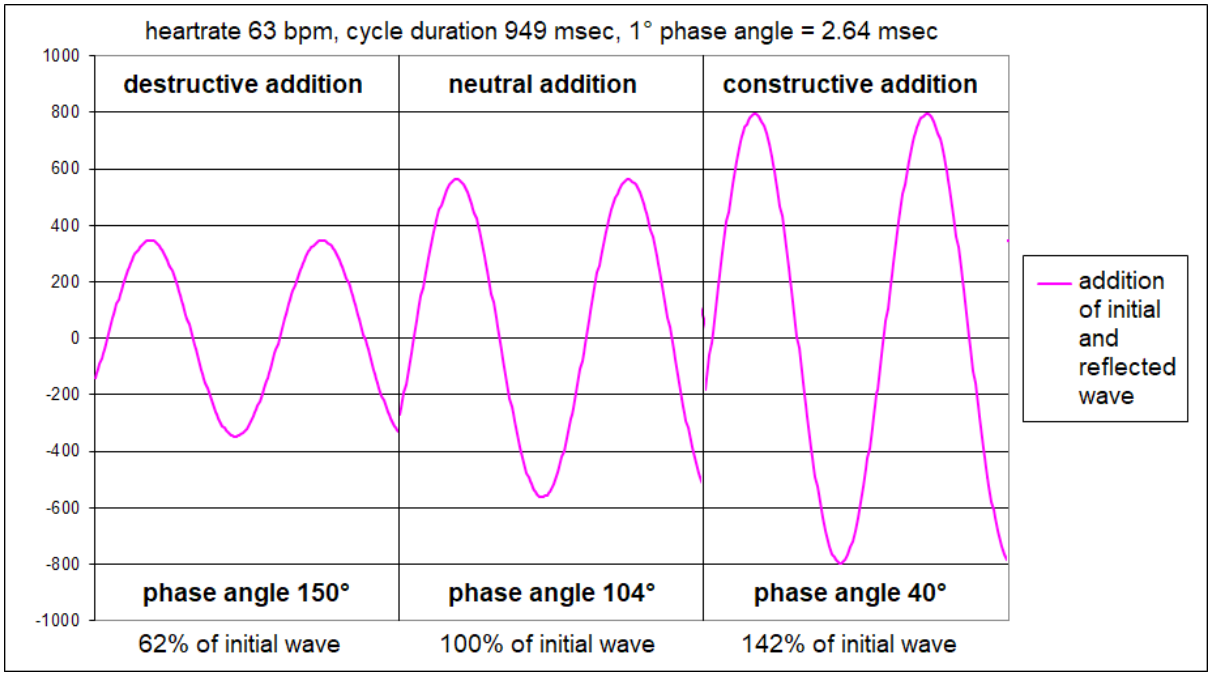

Figure 2a: Phase angles > 104° are associated with a destructive result of addition of both waves with a lower amplitude than the initial wave and have the effect of decreased systolic pressure, decreased stroke work, and decreased peripheral resistance. Phase angles < 104° are associated with a constructive addition result of both waves. According to Quick et al. (2001) the negative effects of constructive wave addition start at phase angles of 90° on downwards and result in increased systolic pressure, increased stroke work, and increased peripheral resistance.

Methods

The easiest way to obtain the sine wave components of a certain signal is the application of the fast Fourier transformation (FFT) [30]. By using FFT any signal can be represented by composite sine wave functions and the result is usually the frequency spectrum of the obtained sine wave frequencies as a graph. When applied to pulse waves, the largest first peak represents the heart rate, while the following peaks represent integer multiples of the heart rate with steadily decreasing amplitude (power). As additional result the phase angle between the peaks is reported in the FFT. However, the largest peak just represents the center frequency (heartrate) of the largest identified sine wave component of the pulse wave and contains no separated information about forward and backward travelling waves.

By EXCEL worksheets a sine wave simulation was created. The FFT results (frequency, amplitude, phase angle) of the first three sine wave components (centre frequency peak and the first two harmonics) were used to calculate corresponding sine waves. For the center frequency (heartrate) two sine waves were calculated: One for the major wave component - the forward travelling wave - and a second one for the reflected wave component. The reflected wave component had a starting amplitude of half of the forward travelling wave (the reflection coefficient at a reflection site - a bifurcation - is usually not larger than 0.5) and a variable phase angle to the forward travelling wave. The FFT phase angle results were kept stable between the forward travelling wave and the first two harmonics. 5.45 seconds of recorded individual pulse volume curves (4-8 pulse waves, sampling rate 128 Hz) were used as a template. The measured pulse volume curve and the curve composed of four sine wave components were overlaid on the same graph to achieve optimal agreement. Curve fitting was done by varying the phase angle between the forward and backward travelling wave and the amplitude of the reflected wave until optimal agreement between the measured and the simulated wave was indicated by minimum deviation of all data points of the graphs (Figure 2). In a second graph the measured pulse wave was displayed together with all four separate sine wave components (Figure 3). From these graphs the amplification can be calculated that describes the amplitude difference between the initial forward travelling sine wave component and the amplitude of the measured pulse wave.

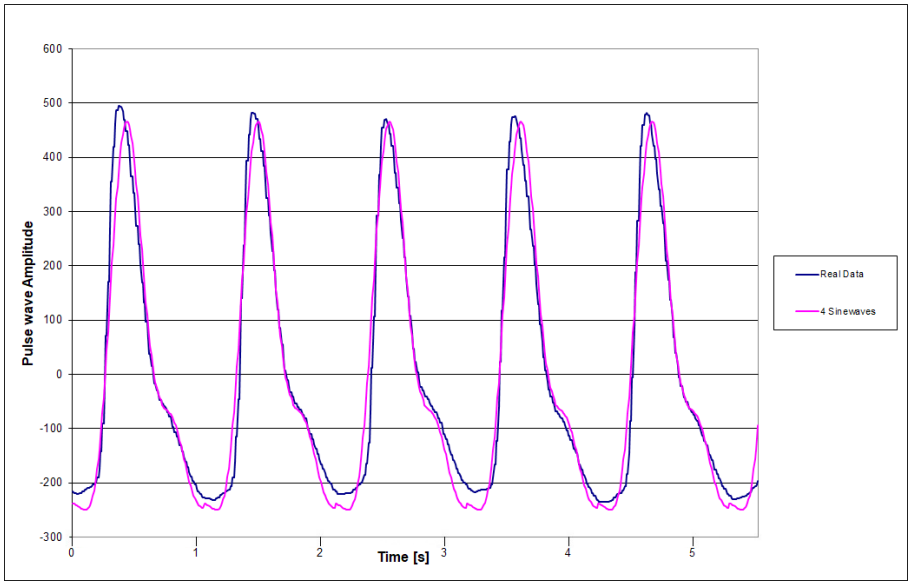

Figure 2: Measured pulse volume curve and the curve composed of four sine wave components overlaid on the same graph for visual control of optimal agreement. Healthy female, 33 years, BMI 25.

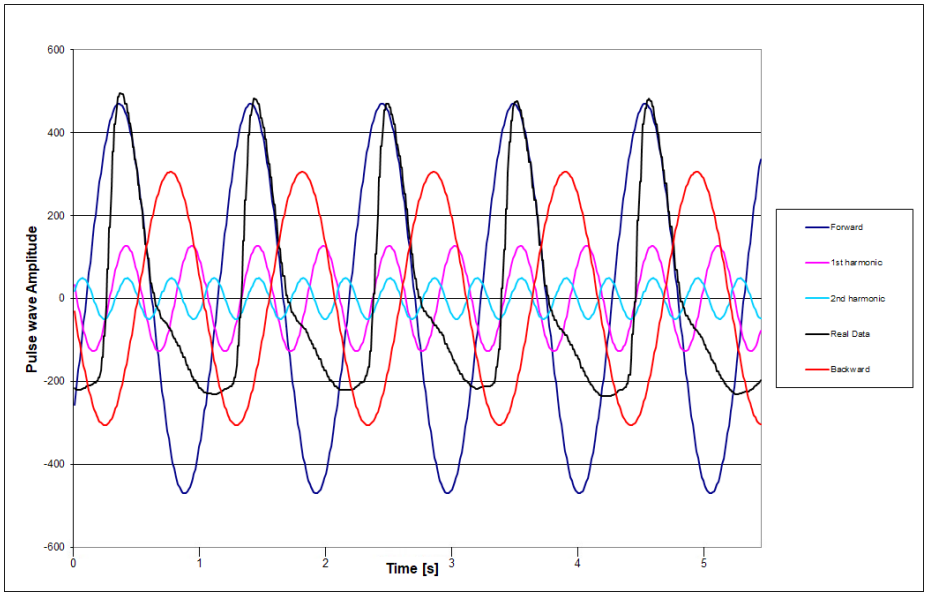

Figure 3: Measured pulse wave from the same patient as in figure 2 displayed together with all four separate sine wave components. Amplitude of the initial forward travelling sine wave component and the measured pulse wave are similar (100,9 %) so that no amplification effect occurs. Phase angle between forward and backward travelling wave is 141 degrees. Healthy female, 33 years, BMI 25.

The study protocols were approved by the responsible ethics committees. Before data acquisition both studies were registered at the German Registry of clinical trials (DRKS). The study was performed in accordance with the ethical standards laid down in the Declaration of Helsinki. Written informed consent was obtained from all subjects. Two study groups were investigated. From the first group (ethics committee of the Philips University at Marburg, Germany, registration No. 93/18, clinical trials No. DRKS00016123) the data of healthy 53 patients without cardiovascular diseases were used as reference for normal values of wave component analysis (Table 1). Central blood pressure and pulse wave velocity (PWV) was measured by the Mobil-O-Graph® System (I.E.M., Germany). NT-pro BNP was determined from blood samples as a marker for acute ischemic heart stress. All patients underwent diagnostic polysomnography according to AASM rules. Data acquisition was done by SOMNOscreen® recorders and DOMINO® sleep recording software (SOMNOmedics, Randersacker, Germany). Nonin® pulse oximetry circuits were inbuilt in the SOMNOscreen® devices. In phases of polysomnographically confirmed sleep and electromyographically confirmed muscular relaxation sequences of 8-10 pulse waves with almost equal interbeat intervals and homogenous amplitude were selected for pulse wave component analysis.

	Women	Men	Total	p-value
Number	27	26	53	
Age	35.6 ± 10.6	41.5 ± 11.9	38.5 ± 11.5	0.19
BMI	25.1 ± 4.0	26.7 ± 3.7	25.9 ± 3.9	0.14
BP systolic	112.5 ± 9.4	123.6 ± 15.9	117.5 ± 13.8	< 0.02
BP diastolic	75.6 ± 9.9	85.3 ± 11.7	80.0 ± 11.7	< 0.02
Pulse Press.	36.8 ± 6.9	39.6 ± 13.0	38.1 ± 10.1	0.29
NT-proBNP	55.9 ± 27.9	38.6 ± 14.3	47.6 ± 23.9	< 0.01
PWV [m/s]	5.7 ± 0,9	6.6 ± 1.4	6.1 ± 1.3	< 0.05
FFT 1W [%]	60.3 ± 4.4	60.4 ± 5.3	60.3 ± 4.8	0.40
Phase Angle	148.0 ± 19.9	144.7 ± 18.1	146.4 ± 18.9	0.17
Amplification	95.3 ± 22.2	100.6 ± 22.0	97.9 ± 22.1	0.13

BMI Body Mass Index, **BP systolic** systolic blood pressure, **BP diastolic** diastolic blood pressure, **Pulse Press**. Pulse Pressure (Central blood pressure values measured by Mobil-O-Graph®), **NT-proBNP** NT-proBNP [pg/ml], PWV [m/s] pulse wave velocity [m/s], **FFT 1W [%]** Power percentage of the first peak in the frequency spectrum of the fast fourier transformation Phase Angle Phase angle between forward and backward travelling wave [Degrees], **Amplification** Size of measured wave amplitude in relation to the amplitude of the initial forward travelling wave [%], p-value p-values from t-tests women vs. men

Table 1: Healthy subjects.

From the second group (ethics committee Medical Association, Wilhelms University Muenster, Germany, registration No. 2016-538-f-S, clinical trials No. DRKS00012573) pulse volume curves from patients with cardiovascular diseases (n=46) were obtained (Table 2). The same recorders and sleep recording software (SOMNOscreen® recorders, DOMINO® Software, SOMNOmedics®, Randersacker, Germany) were used in this patient group. These patients underwent cardiac catheterization and the aortic pressure in the catheter (when filled with an aqueous solution) was recorded simultaneously with the pulse waves from the pulse oximetry sensor at a finger of the contralateral arm. All patients of this group had an indication for cardiac catheterization and were referred by a cardiologist. In this group, the results of the wave component analysis could be assigned to confirmed cardiac or vascular diagnoses.

	Women	Men	Total	p-value
Number	11	35	46	
Age	70.8 ± 13.3	65.4 ± 10.6	66.7 ± 11.4	0.12
BMI	29.0 ± 5.0	29.0 ± 6.2	29.0 ± 5.9	0.49
BP systolic	138.5 ± 23.9	140.3 ± 23.3	139.9 ± 23.2	0.42
BP diastolic	72.5 ± 15.8	74.8 ± 13.5	74.3 ± 14.0	0.34
Pulse Press.	66.0 ± 23.8	65.5 ± 23.9	65.6 ± 23.6	0.48
NT-proBNP	67.9 ± 40.6	197.1 ± 309.4	164.8 ± 273.6	< 0.02
EF [%]	49.3 ± 9.2	49.3 ± 14.0	49.3 ± 12.7	0.50
FFT 1W [%]	66.8 ± 4.8	63.9 ± 6.0	64.6 ± 5.8	0.06
Phase Angle	70.4 ± 29.5	90.1 ± 42.9	85.4 ± 40.7	< 0.05
Amplification	190.3 ± 24.9	177.0 ± 47.4	180.2 ± 43.2	0.12

BMI Body Mass Index, **BP systolic** systolic blood pressure, **BP diastolic** diastolic blood pressure, **Pulse Press.** Pulse Pressure (central blood pressure values measured through the catheter lying in the aorta), **NT-proBNP** NT-proBNP [pg/ml], **EF [%]** Ejection Fraction, **FFT 1W [%]** Power percentage of the first peak in the frequency spectrum of the fast fourier transformation Phase Angle Phase angle between forward and backward travelling wave [Degrees], **Amplification** Size of measured wave amplitude in relation to the amplitude of the initial forward travelling wave [%], p-value p-values from t-tests women vs. men

Table 2: Cardiological patients

Results

The characteristics of the healthy subjects and the cardiological patients are summarized in Table 1 and Table 2. In both groups central blood pressure was measured. In the healthy subjects noninvasively by the Mobil-O-Graph® System and in the cardiological patients through the catheter lying in the aorta accedes.

Women and men in the healthy subjects group did not differ in age and body mass index (BMI). Significant differences between women and men are observed in the systolic and diastolic central blood pressure, but not in the pressure pulse. All blood pressure values were in the range of normal values. NT-pro BNP was significantly higher in women than in men, but in each case in the range of normal values < 125 pg./ml so that heart insufficiency could be ruled out. PWV was significantly higher in men than in women, but all measured PWV values were in the range of normal values published by Boutouyrie and Vermeersch (2010) [31] so that arterial stiffness as marker of cardiovascular risk could be ruled out. The proportion of the first peak in the frequency spectrum of the fast Fourier transformation (FFT) that represents the amount of sine wave components in the heartrate range is 60.3 ± 4.8% without difference between women and men and contributes most to the overall pulse wave. The phase angle between the initial forward propagating wave and the reflected wave determined after optimal curve fitting is very large (146.4 ± 18.9°), so that no amplification effects due to constructive addition occurred (97.9 ± 22.1%). Phase angle and amplification do not differ between women and men.

In the cardiological patients (Table 2) the only differences between women and men were observed in the NT-pro BNP values and the phase angle between the forward and backward travelling wave. NT-pro BNP values and phase angle were larger in men than in women ($p < 0.02$, $p < 0.05$). Age, BMI, blood pressure, FFT first peak proportion, and amplification did not differ between women and men. Compared to the healthy subjects numerous significant differences were observed. The cardiological patients were much older ($p < 0.01$) than the healthy subjects, have a higher BMI ($p < 0.01$), higher systolic ($p < 0.01$) and lower diastolic ($p< 0.02$) central blood pressure, higher pressure pulse ($p < 0.01$), higher FFT first peak proportion ($p < 0.01$), much smaller phase angles between forward and backward travelling waves ($p < 0.01$), and much higher wave amplification effects ($p < 0.01$).

The group of cardiological patients was divided into subgroups corresponding to the main diagnosis of the patients (Table 3). These were hypertension (Hypertens, n = 19), Cardiomyopathy (CM, n = 8), Aortic stenosis (Aortic ste, n = 6), and Coronary artery disease (Coronary, n = 13). All these subgroups were significantly different from the healthy subjects in age, systolic blood pressure, pulse pressure, phase angle, and amplification. BMI is only in the hypertension group significantly higher than in healthy subjects. The CM group is in diastolic blood pressure comparable to healthy subjects, while it is significantly lower in all other groups. NT-pro BNP values are only in the Coronary group significantly higher than in healthy subjects, while no difference is observed in the other groups. The Power percentage of the first peak in the frequency spectrum of the fast Fourier transformation (FFT 1W [%]) is in the CM group comparable to healthy subjects, while it is significantly higher in all other groups.

	healthy	Hypertens.	CM	Aortic ste.	Coronary
Number	53	19	8	6	13
Age	38.5±11.5	*62.3±9.3	*64.5±17.3	*73.9±10.3	*71.1±7.6
BMI	25.9±3.9	*29.7±5.3	27.9±4.6	26.9±3.7	29.7±8.1
BP systolic	117.5±13.8	*139.1±19.8	*140.0±20.5	*138.5±24.6	*141.6±30.4
BP diastolic	80.0±11.7	*74.8±13.4	82.0±13.9	*64.7±13.8	73.1±13.4
Pulse Press.	38.1±10.1	*64.2±19.2	*58.0±24.1	*73.8±22.4	*68.5±30.2
NT-proBNP	47.6±23.9	57.2±95.8	365.0±513.3	81.2±43.7	*187.6±162.8
Vasodilators	none	13/19, 68.4%	8/8, 100%	4/6, 66.7%	11/13, 84.6%
FFT 1W [%]	60.3±4.8	*64.4±5.5	65.3±9.2	*65.6±5.2	*63.9±4.4
Phase Angle	146.4±18.9	*94.3±42.9	*82.1±38.9	*87.8±45.7	*73.3±37.6
Amplification	97.9±22.1	*170.7±42.6	*189.3±45.8	*167.3±49.5	*194.4±39.3

BMI Body Mass Index, **BP systolic** systolic blood pressure, **BP diastolic** diastolic blood pressure, **Pulse Press.** Pulse Pressure (central blood pressure values), **NT-proBNP** NT-proBNP [pg/ml], **Vasodilators** ACE blockers, calcium channel blockers, AT1 receptor antagonists, **FFT 1W [%]** Power percentage of the first peak in the frequency spectrum of the fast Fourier transformation **Phase Angle** Phase angle between forward and backward travelling wave [Degrees], **Amplification** Size of measured wave amplitude in relation to the amplitude of the initial forward travelling wave [%], hyper tens. Hypertension as main diagnosis, CM Cardiomyopathy as main diagnosis, Aortic ste Aortic stenosis as main diagnosis, Coronary Coronary artery disease as main diagnosis, * significant difference ($p < 0.05$) to normal value

Table 3: Cardiological diagnoses groups compared to healthy subjects values

With the look on the parameters of wave component analysis in the cardiological patients the constructive addition of forward and backward travelling waves due to small phase angles (72.9° to 94.3°) is observed, so that an amplification of the amplitude of the forward travelling sine wave component occurs and the amplitude of the measured pulse wave is much higher (180,2 ± 43.2%) than the initial wave (Figure 4 and Figure 5). Even though a vasodilator therapy is established in the majority of all patients (Table 3) that reduces afterload this effect is seen in all cardiological patient subgroups. It results in a pulse wave contour without a distinct notch on the downward slope of the pulse wave and with no change in the angle of the descent contour occurs (Figure 2 and Figure 4).

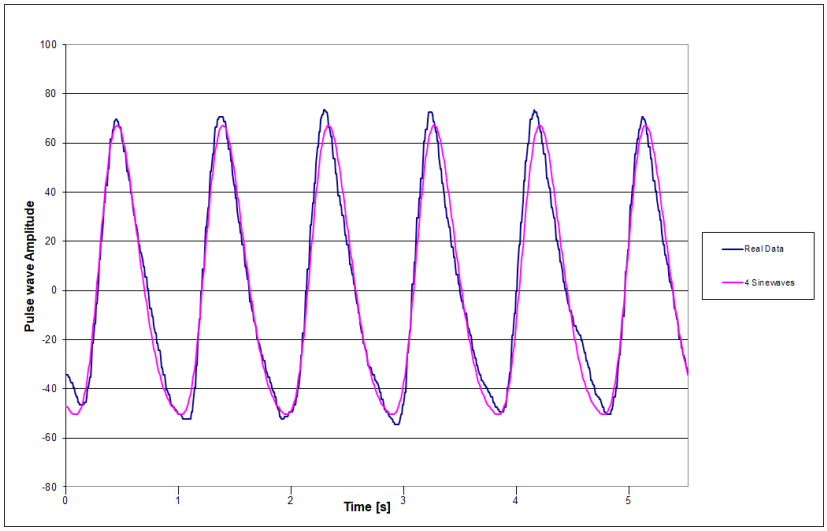

Figure 4: Measured pulse volume curve and the curve composed of four sine wave components overlaid on the same graph for visual control of optimal agreement. 3 vessel coronary artery disease, condition after bypass surgery 4 month ago, male, 66 years, BMI 28.

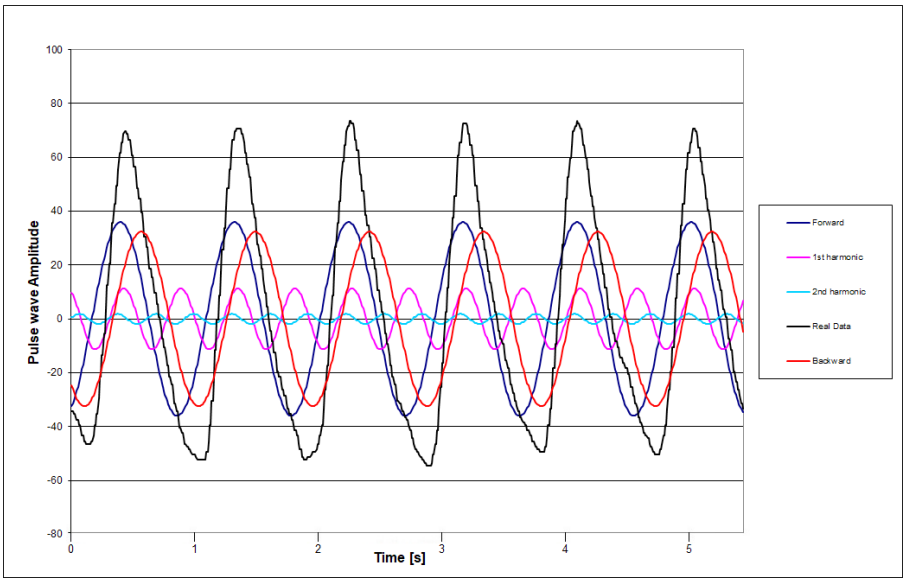

Figure 5: Measured pulse wave from the same patient as in figure 4 displayed together with all four separate sine wave components. Amplitude of the initial forward travelling sine wave component is much smaller than the measured pulse wave. Constructive addition of forward and backward travelling wave due to the small phase angle of 66 degrees, so that an amplification of the original signal to 198,9 % results.

Discussion

In this study we applied the theory of constructive and destructive addition of forward and reflected arterial pulse waves from Quick et al. (2001) [29] on measured photoplethysmographic pulse volume curves from healthy subjects and cardiological patients. A prerequisite to apply this theory on pulse waves is to decompose the original signal into sine wave components. This was done by FFT and resulted in an amount of 60.3 ± 4.8% (healthy subjects) to 64.6 ± 5.8% (cardiological patients) sine wave components in the heartrate range that could be used for analysis. The following peaks in the frequency power spectrum represent 35-40% of the total signal (integer multiples of the heart rate with steadily decreasing amplitude) and they are a necessary result of the transformation into sine wave components. But they represent no real existing wave components. The wave propagation in the arterial vascular system does not produce any integer frequency changes in the output signal, only reflections that arrive at the measurement point with different time delays. Due to the fact that the sine wave integer multiples of the heart rate are necessary for calculation of a correct addition result the 1st and 2nd harmonics were incorporated into the sine wave simulation. The mathematical addition of four sine wave components (forward and backward travelling wave plus 1st and 2nd harmonic) leaded to a good fit quality of the resulting pulse wave model and the measured pulse volume curves (Figure 2 and Figure 4).

Quick et al. (2001) reported that 'reflection has the least effect on pulse pressure and stroke work at normal blood pressure but a greater effect with vasodilation and vasoconstriction. The input impedance, pulse pressure, and stroke work are increased or decreased depending on the relative amount of constructive and destructive addition of forward and reflected arterial pulse waves.' [29] Phase angles between forward and backward travelling waves in the range of 0° - 90° are associated with an increased arterial load [29]. Within this range the arterial load increases with decreasing phase angle. In the cardiological patients of this study a mean phase angle of 85.4° ± 40.7° was observed what corresponds well to the above described increased arterial load conditions. The major diagnoses (Table 3) hypertension and coronary artery disease can be interpreted as long-term effects of a chronic arterial overload condition, while in dilated cardiomyopathy chronic vasoconstriction and high blood pressure are a consequence of the adaptation of the arterial tree to ensure perfusion in the presence of a weak ventricular performance. In aortic stenosis there is concern regarding the development of significant LV myocardial hypertrophy and irreversible myocardial fibrosis due to ventricular pressure overload [32,33]. In coronary artery disease the chronic pressure overload already leaded to tissue damage that is not reversible any more. In the hypertension group in 18 from 19 cases a coronary artery disease was excluded by cardiac catheterization so that in a subgroup the negative effect of chronic arterial overload might be reversible.

In the healthy subjects a mean phase angle of 146.4° ± 18.9° between the initial forward travelling wave and the reflected wave was observed. This is within the range between 90° and 180° that is associated with neutral or destructive addition of forward and reflected arterial pulse waves. In our sample this state can be observed in a broad age range that reached from 20 to 55 years in women and from 25 to 71 years in men without systematic age related elevation or variation.

From the presented data it can be concluded that the pulse wave component analysis is very sensitive to distinguish between conditions of normal arterial and ventricular load and conditions of chronic arterial and ventricular overload. In daily routine applications where pulse volume curves are recorded (e.g. sleep laboratory, intensive care monitoring) the pulse wave component analysis could be used to identify patients with an elevated cardiovascular risk that might be unknown before. This strategy could contribute to a reduction of cardiovascular mortality when an arterial overload condition is identified in an early stage before organ or tissue damage occurs. This opens the way to preventive therapy options that could contribute to preserve cardiovascular health.

Study Limitations

Signal quality

When analysing photoplethysmographic pulse volume curves the results will depend on the accuracy of the recording device. There is some evidence that the Nonin® pulsoximetry circuit inbuilt in the SOMNOscreen® recorders used in this study modifies the recorded signal. Especially in patients with early extra systoles, when just an electrical systole appears before the left ventricle was refilled with blood, a large interval results between two consecutive pulse waves. During this time, the signal is continuously pulled up from the negative amplitude range toward mid-amplitude. The pulse amplitude following this large interbeat interval is extra high because the signal amplification is obviously continuously increased during the interval time. The second pulse wave after the interval time immediately has the former amplitude level again. This kind of dynamic signal adjustment seems to have the purpose of compensating for the natural amplitude changes of the pulse volume curves in order to always display a signal with a constant amplitude level on the monitor. As a result, part of the signal is cut off at the lower end and is not available for analysis. However, the majority of the signal remains in the original contour, so that the pulse wave analysis still provides good results. Even better results can be expected using a pulse oximeter that does not alter the original signal in any way.

Sine wave as an impulse model

The FFT analysis applied on pulse waves showed that they can hardly be represented by addition of real existing sine wave components in the time domain. The shape of a sine wave does not seem to represent the shape of the impulse contour that is produced by the left ventricle during systole. For a more precise analysis it would be necessary to develop a similar theory to that of Quick et al. (2001) on the basis of an impulse wave model that comes

close to that of the systolic impulse from the left ventricle. This might be precise enough to distinguish between different cardiac and vascular diagnoses when arterial overload is present.

Established vasodilation therapy

The group of cardiovascular patients were recruited from consecutive patients that received a cardiac catheterization. In 36 from 46 (78.3%) of these patients a vasodilation drug therapy was already established. This leaded to the consequence that in several cases the effect of the underlying cardiovascular disease was completely compensated and phase angles in the healthy range (> 104°) resulted. For this reason the sensitivity/specify of this method to distinguish between cardiovascular risk patients and healthy patients cannot be calculated on the basis of this study group. To determine the sensitivity/specify of the method another study population is needed that recruits only vasodilator drug naive patients with cardiovascular diseases.

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