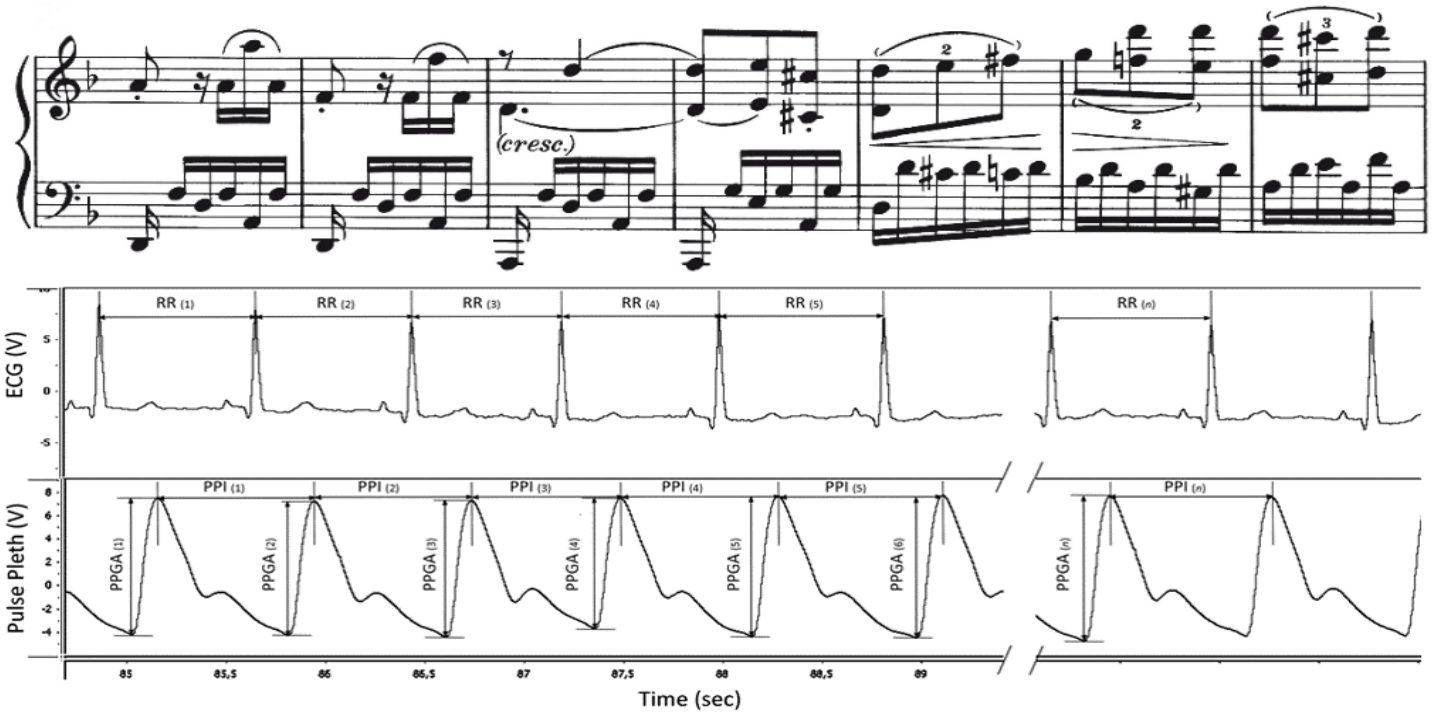
PPG Blood Dynamics Measurement: Modelling and Classification

Karel Kupka, Jaroslav Jansa, Martin Sikora, Vladimír Grygar



MAPO innovations

TriloByte® Ltd STATISTICAL SOFTWARE

NovioSys

CardioAnalyst Project

Computer aided photoplethysmography

Photoplethysmographic curve

First mentioned in 1930

During last years uncovered diagnostic potential in cardiology and cardiovascular and related diseases –

A. Simple – Non-Invasive – Low cost: Suitable for both clinical and Wide preventive use.

B. Waveform shapes of the PPG wave contains complex information about cardiovascular system.

C. Many authors point to high potential of numerical/mathematical analysis of PPG curve (see citations)

Computer aided photoplethysmography

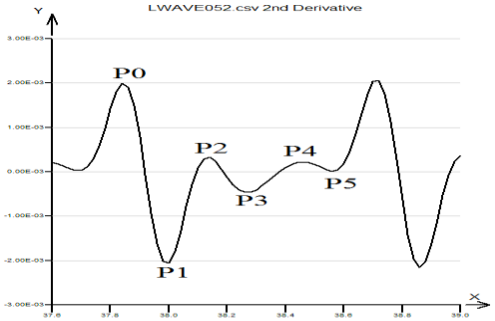
Measuring devices and signal processing

PPG curves have been measured with commercial finger oximeters:

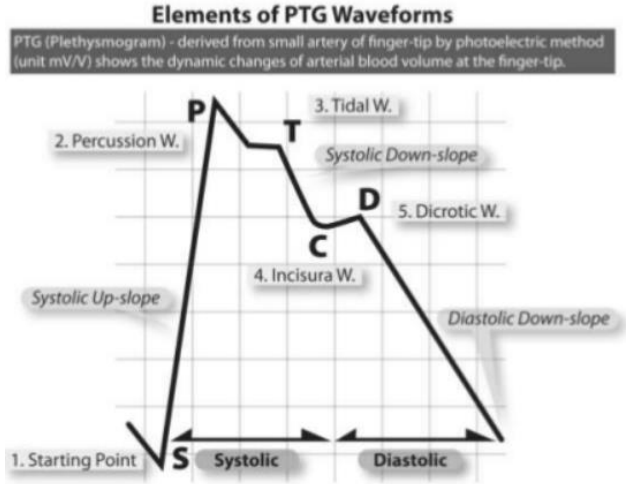
Nonin WristOx2™, Model 3150 @ 60Hz sampling rate
CONTEC Pulse Oximeter CMS50FW @ 50Hz

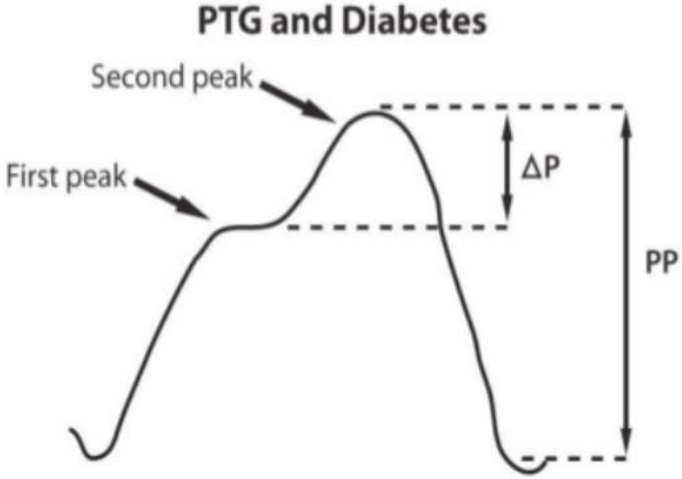
Computer aided photoplethysmography

Disadvantages of graphical morphology approach



P0 : Basal value for comparing easily in wave evaluation
P1 : Initial systolic negative wave (intensity of cardiac output)
P2 : Late systolic re-increased wave (vascular compliance)
P3 : Late systolic re-decreased wave (residual blood volume)





Disadvantages of graphical morphology approach

1. The crucial algorithms for computing the second derivative are unclear and poorely defined. The final APPG pulse curve is extremely sensitive on the smoothing algorithms and their free-parameters settings.

2. The true shapes are usually different from the idealized curves and the specific points are often not present or the actual curve is not assignable unambiguously to any of the listed „normalized“ shapes. Assessment of the PPG is then strongly subjective and interpretations of the same curve may thus differ substantially.

3. Graphical features are discontinuous and there is no clue when a feature (eg. minimum or maximum) disappears or is not detectable, or inversely, there is a multiplet of points instead of one, etc.

Possible alternatives

Parametrization of the identified pulse in a continuous parametric space and assigning diagnosis (or, more quantitatively, probabilities of diseases) to subsapaces of certain combinations of parameters.

We used two approaches. One is based on orthogonal polynomial approximation, second is based on harmonic (again orthogonal) approximation. The latter approach proved to be more adequate and useful.

Time stability of the signal, eg. on daily basis can be monitored with Hotelling control chart routinely used in technology and manufacturing processes. This chart is based on Mahalanobis distances in the parametric space.

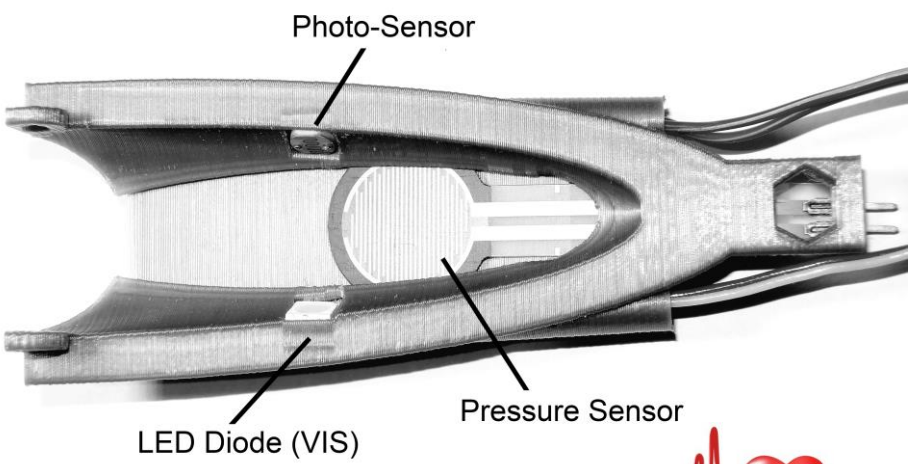
PPG signal was complemented by baroplethysmographic (BPG) signal to extend informative content by simultaneous blood pressure curve and combine both signals.

Computer aided photoplethysmography

Measuring devices and signal processing

Simultaneous measurement of relative pressure BPG (Baroplethysmography) and PPG (Photoplethysmography) curves

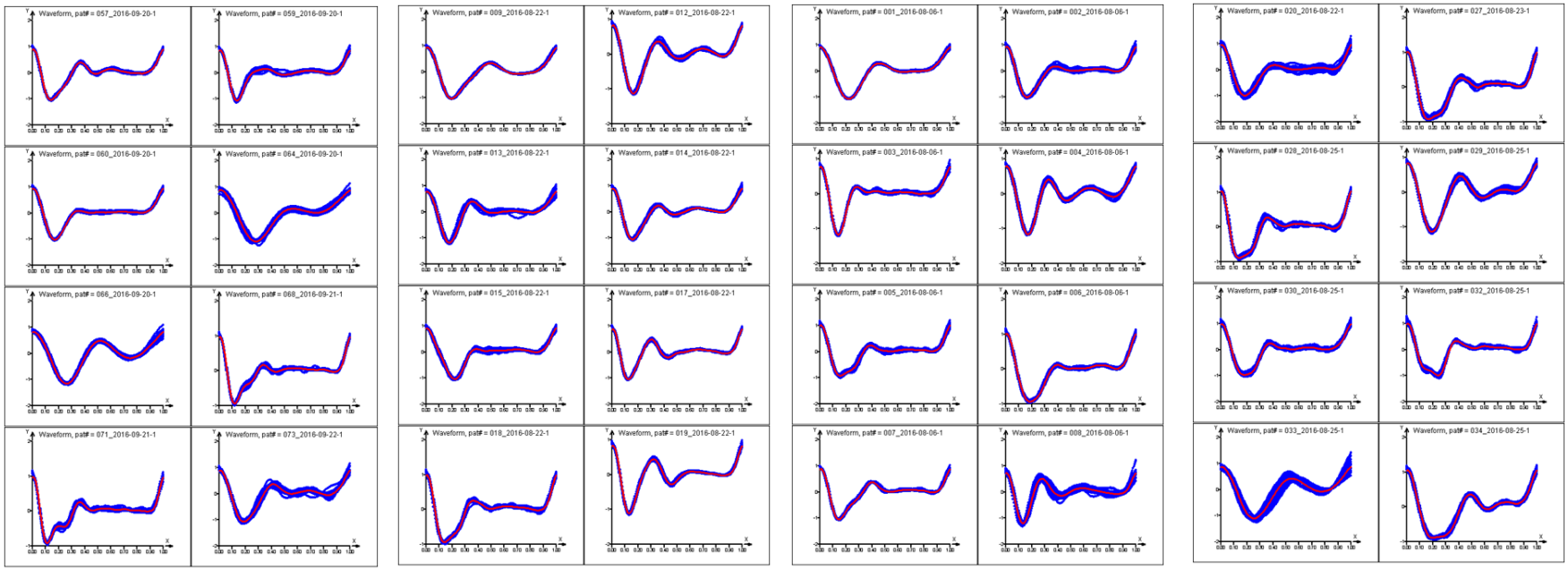
Simultaneous PPG and BPG curves were recorded using specially developed and manufactured measuring finger probe shown on the following figures. This probe must be made of rigid, non-elastic material to record pressure correctly.



CardioAnalyst

Computer aided photoplethysmography

The displayed curves (in blue) represent 32 different patients and their cardiovascular system. The pulse shape depends of its state, on the micro-circulation and haemodynmics of the blood flow. Parametrization (in red) using orthogonal harmonic function system (linear harmonic regression) will transform the patient´s waves into points in multivariate space. Here, they can be classified (with classical Fisher discrimination, Mahalanobis metric, Neural networks or Vapnik´s Support Vector Machines) and assigned into corresponding group of probable diagnoses. The plots below suggest that the waveform (in fact, several tens of repeated waveformsin each plot) of a single patient is rather stable (except cases of arythmia), which implies relative stability of the respective classification.



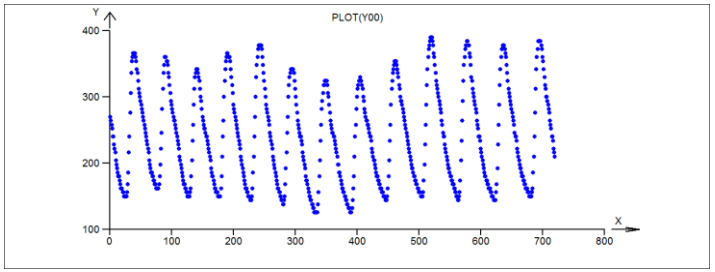
CardioAnalyst Project

CardioAnalyst

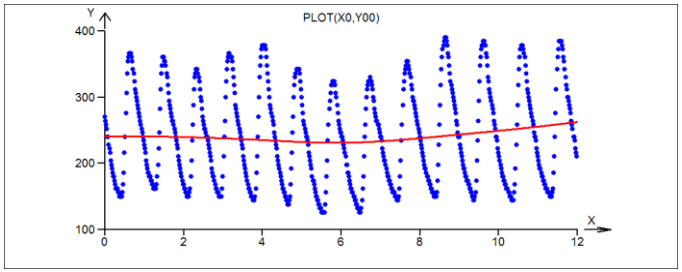
Computer aided photoplethysmography

The procedure

Raw signal

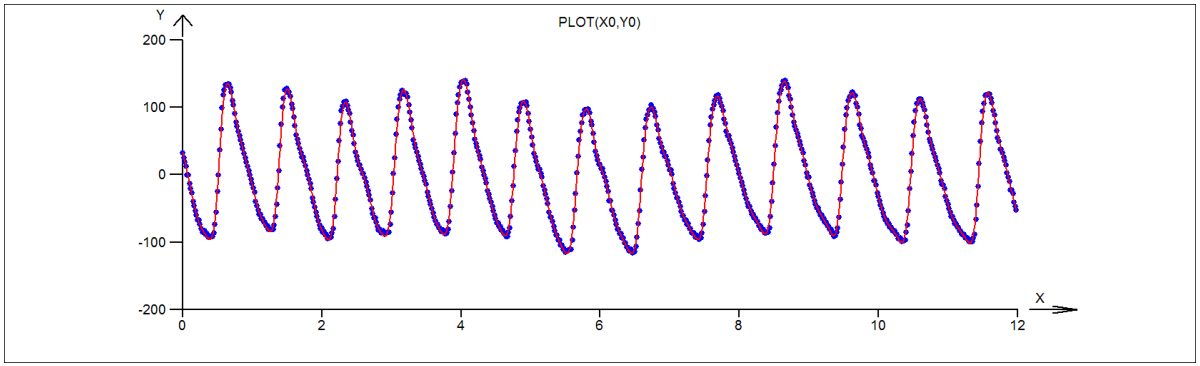


Baseline correction – controlled by # of inflections



Smoothing: Reinsch cubic spline: Minimize $\int_{start}^{end} \left[\frac{d^2}{dx^2} f(x) \right]^2 dx$ with constraint $s_R = \frac{1}{d_2} \frac{1}{n-1} \sum_{i=2}^{n} |x_i - x_{i-1}|$

$$d_2 = \frac{2}{\sqrt{\pi}}$$



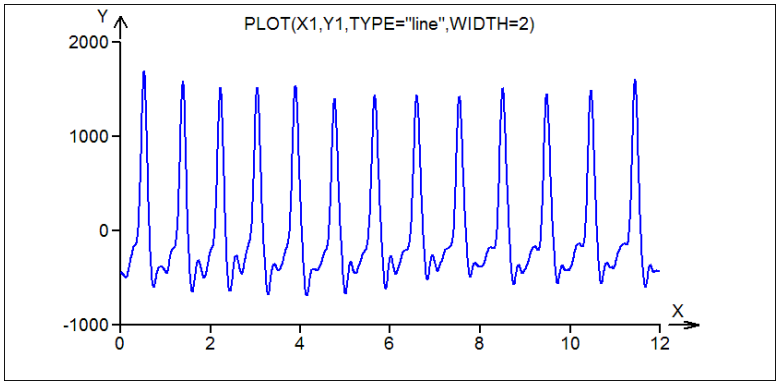
CardioAnalyst Project

CardioAnalyst

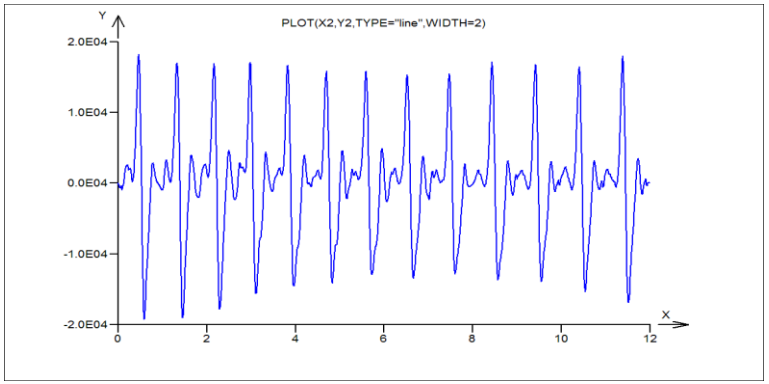
Computer aided photoplethysmography

The procedure

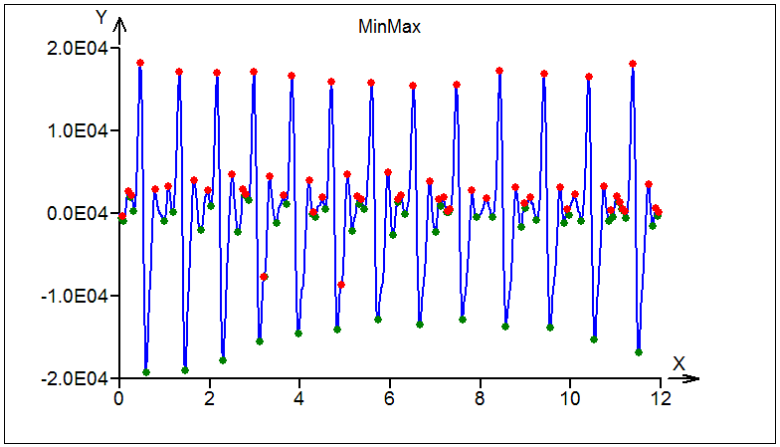
First Derivative



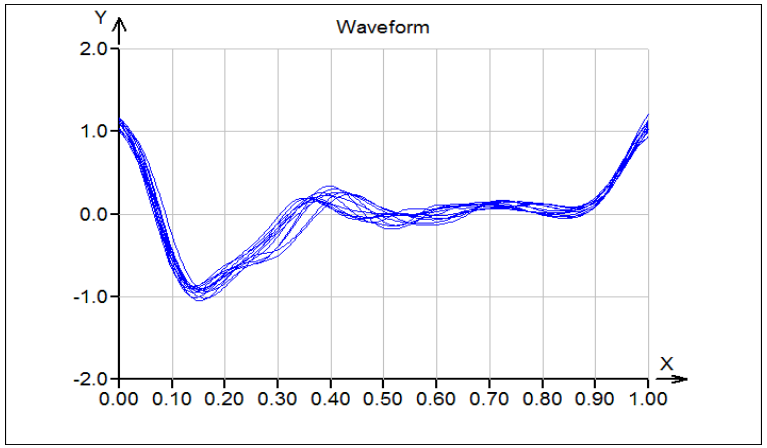
Second Derivative



Pulse Detection



Normalized Waveform



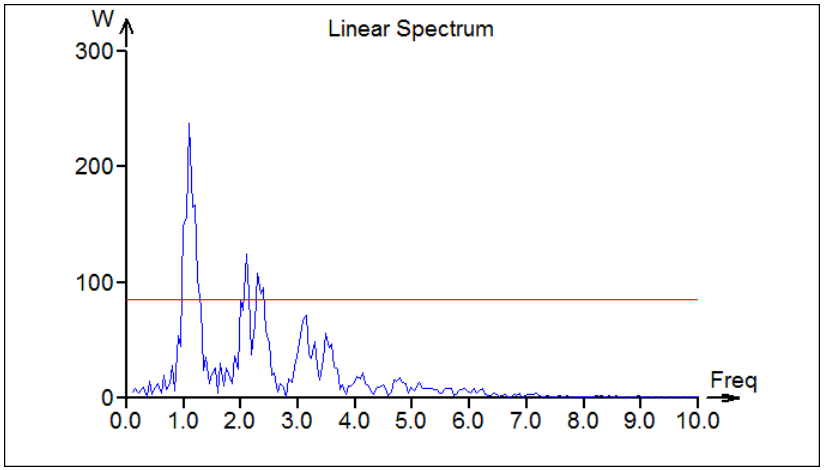
CardioAnalyst Project

CardioAnalyst

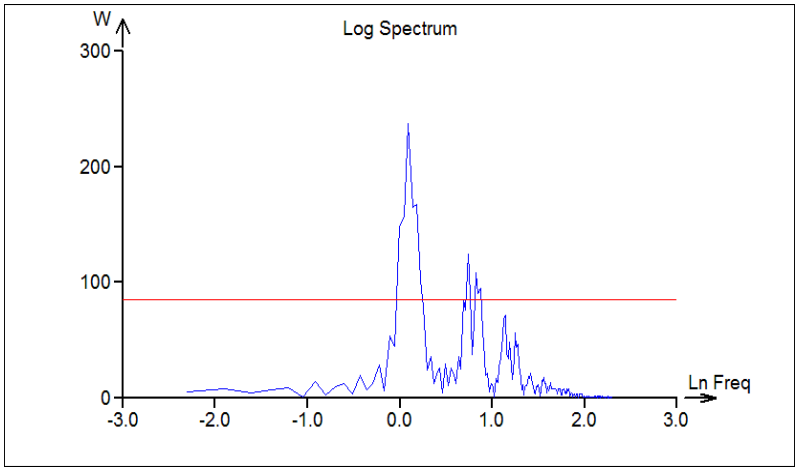
Computer aided photoplethysmography

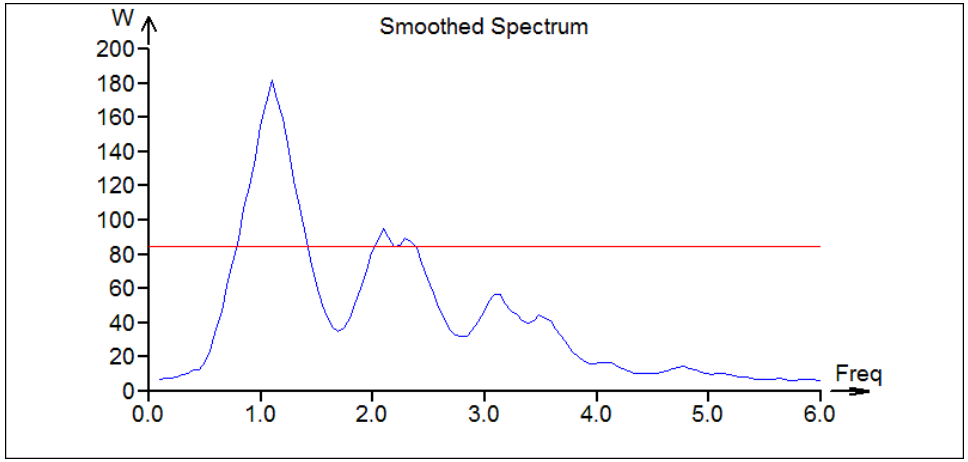
The procedure

Linear Spectrum



Log Spectrum





CardioAnalyst Project

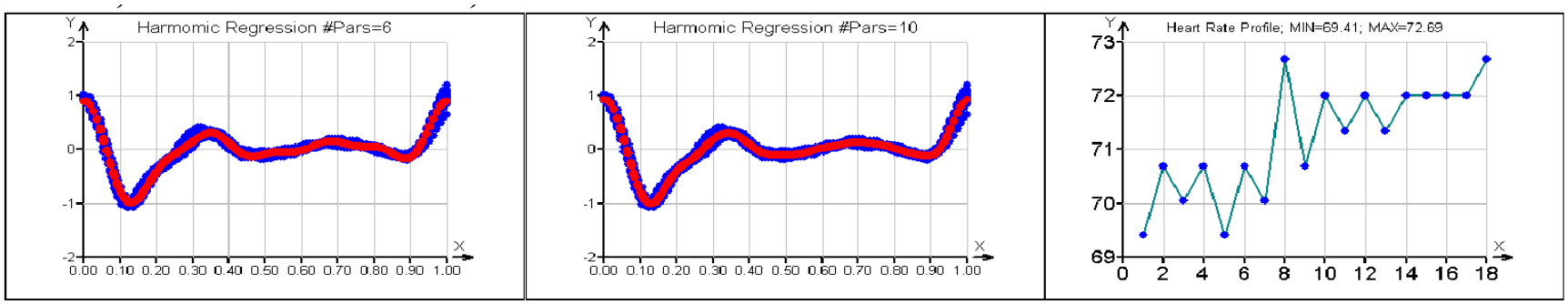
CardioAnalyst

Computer aided photoplethysmography

Harmonic regression

$$y = a_0 + a_1 \sin x + b_1 \cos x + a_2 \sin 2x + b_2 \cos 2x + \ldots + a_m \sin mx + b_m \cos mx =$$

$$= a_0 + \sum_{i=1}^{m} a_m \sin mx + b_m \cos mx$$



Thirteen parameter model parameters:

X1	X2	X3	X4	X5	X6	X7	X8	X9	X10	X11	X12	X13
-8	-145	-7	-198	128	-32	367	63	204	35	133	61	84

Twenty-one parameter model parameters:

X1	X2	X3	X4	X5	X6	X7	X8	X9	X10	X11	X12	X13	X14	X15	X16	X17	X18	X19	X20	X21
-8	-145	-7	-198	127	-32	367	63	203	35	132	61	83	37	13	0	3	-3	1	-7	7

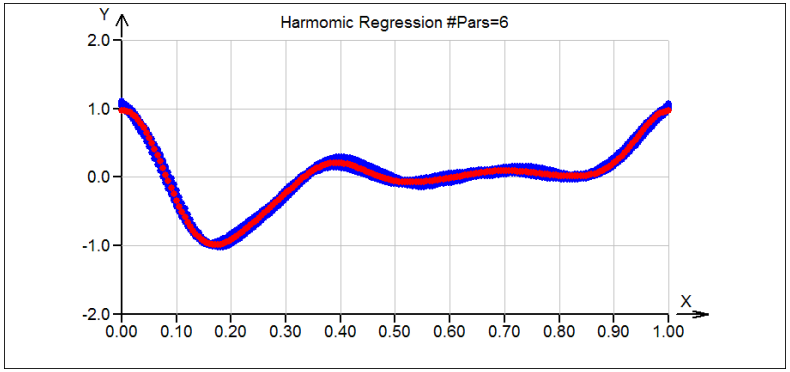
CardioAnalyst Project

CardioAnalyst

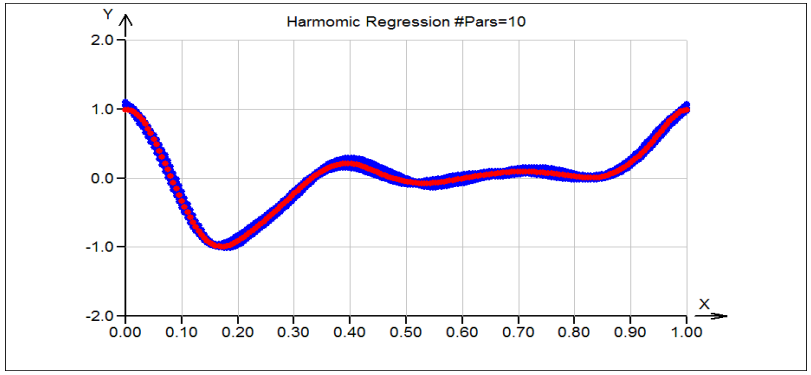
Computer aided photoplethysmography

The procedure

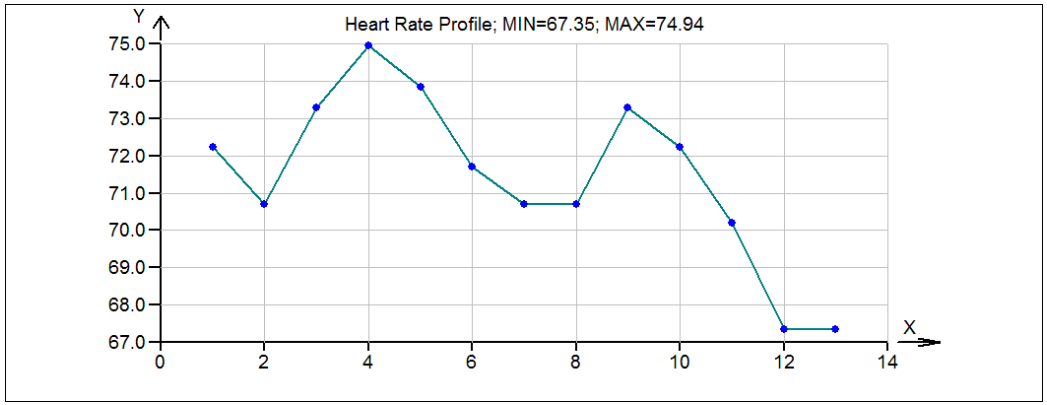
13-par model



21-par model



HRV- profile



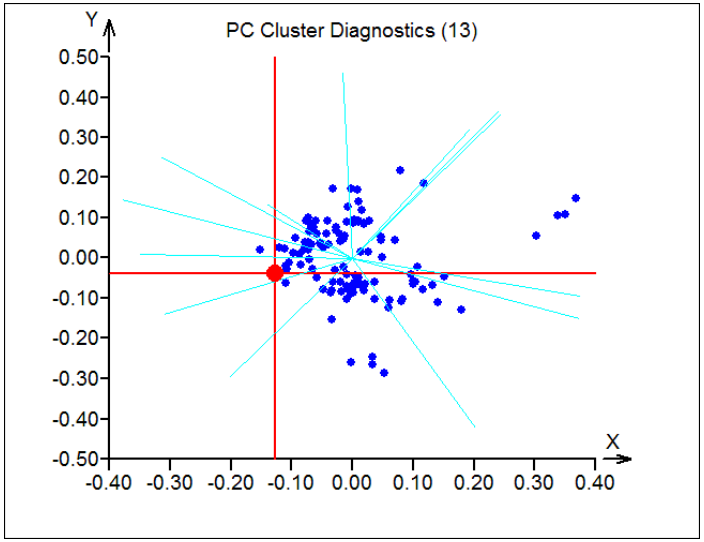
CardioAnalyst Project

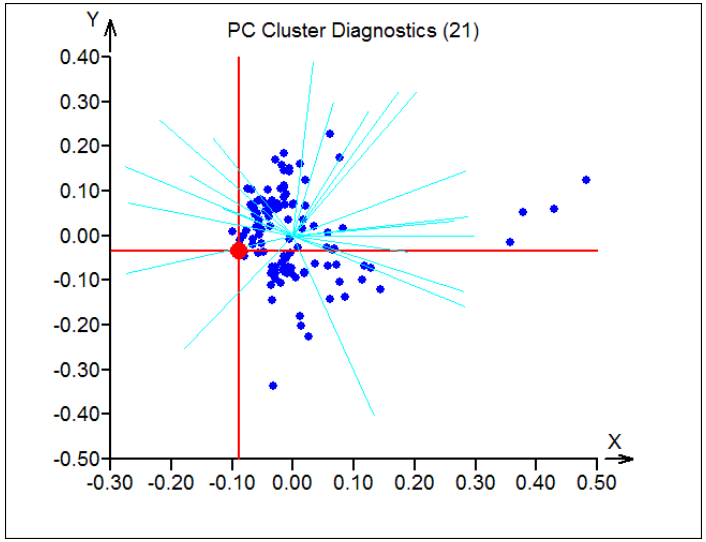
CardioAnalyst

Computer aided photoplethysmography

The procedure

Classification in 13d / 21d





CardioAnalyst Project

CardioAnalyst

Computer aided photoplethysmography

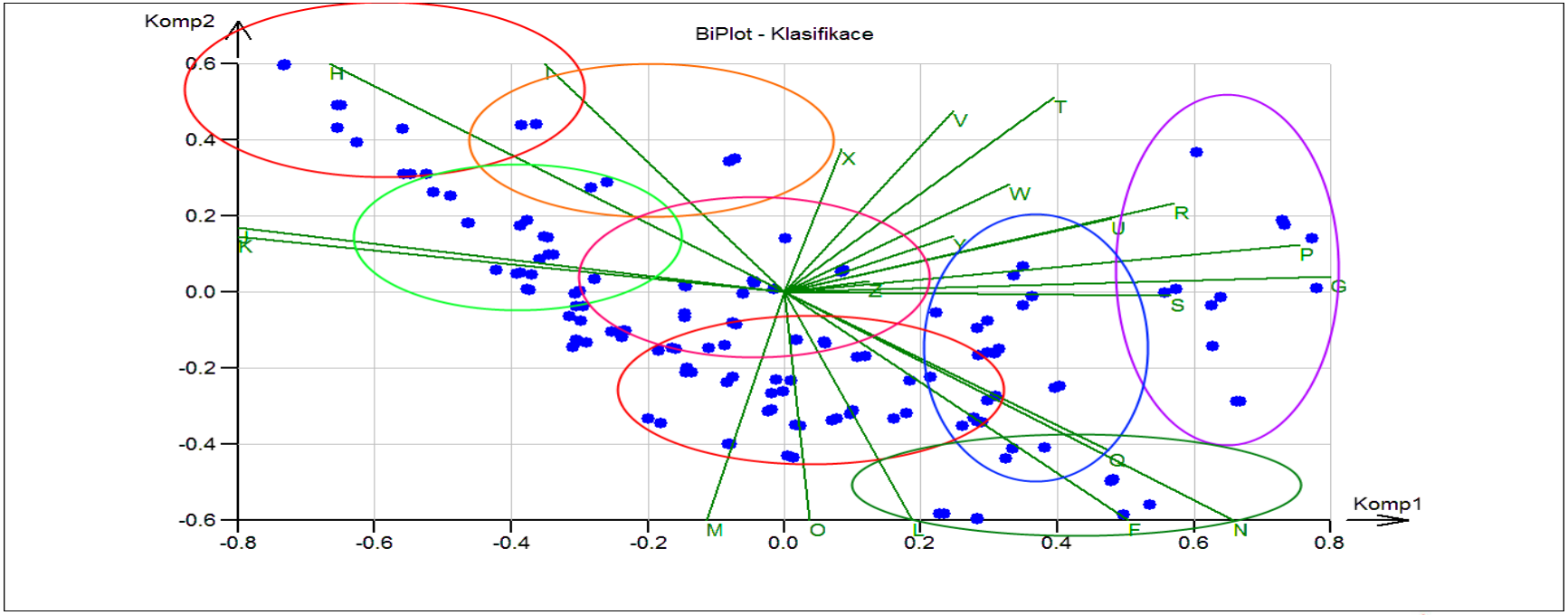
Every point in the 2D-projection on the following plot represent a waveform of a single patient. Every patient´s waveform can be typically described by 15 numerical values. The circles represent an example of clustering/classifying 100 patients into diagnostic groups based on the waveform shape.

The simple Harmonic Regression model:

$$y = a_0 + a_1 \sin x + b_1 \cos x + a_2 \sin 2x + b_2 \cos 2x + \ldots + a_m \sin mx + b_m \cos mx =$$

$$= a_0 + \sum_{i=1}^{m} a_m \sin mx + b_m \cos mx$$

This plot is based from the real data from 100 patients and subsequent projection of rhe wave parameters in the first two principal components.



CardioAnalyst Project

CardioAnalyst

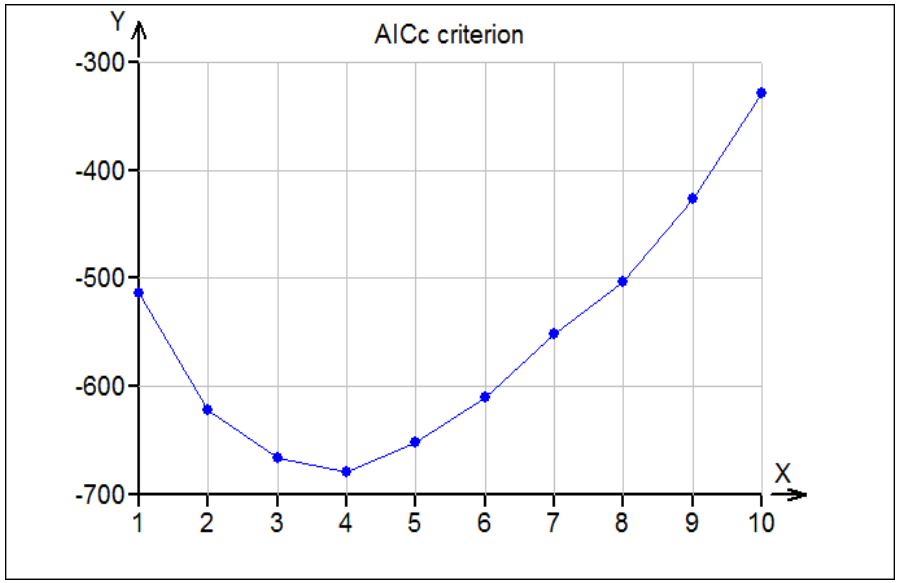
Computer aided photoplethysmography

The analysis – 120 patients, cardiology, physicians

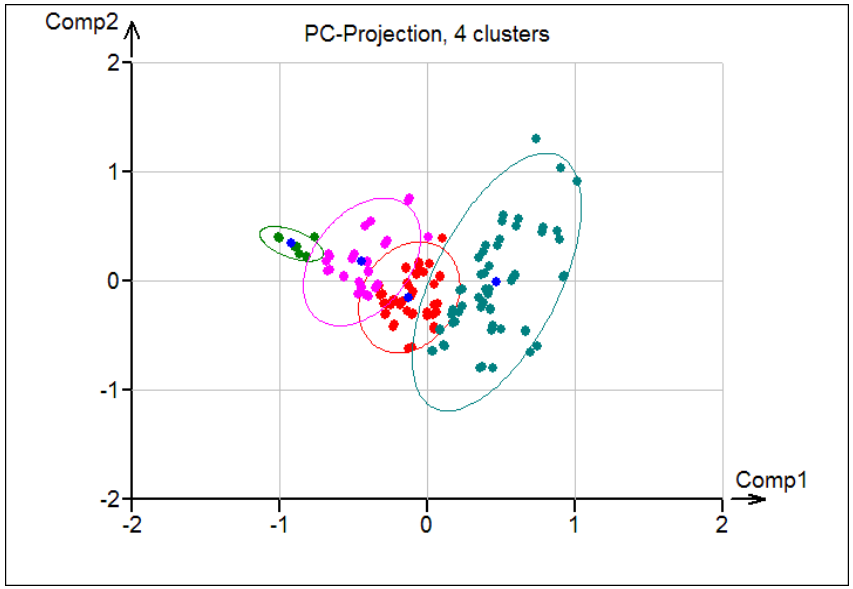
Unsupervised learning – Cluster analysis

AIC identifies four groups of patients with different PPG curve shapes without knowledge of their diagnosis

Number of Clusters detection



Identified 4 health status clusters



CardioAnalyst Project

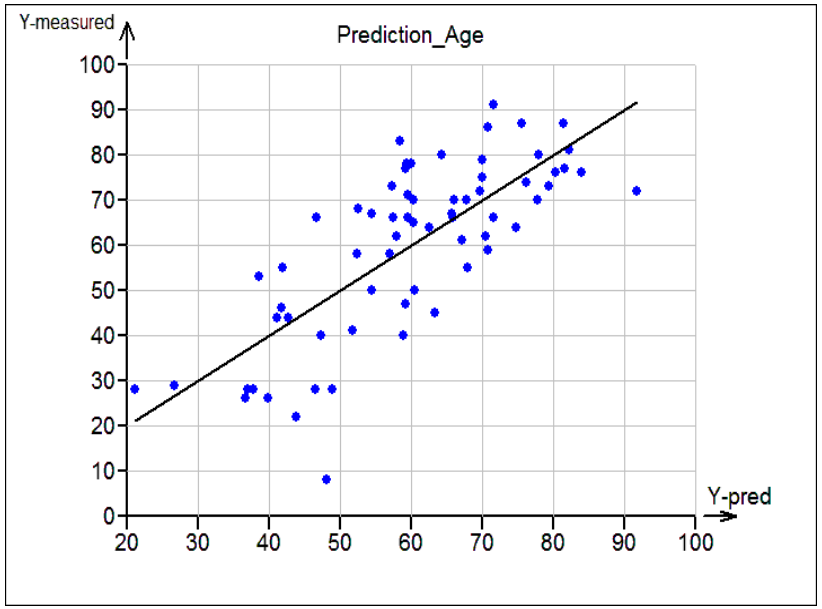
CardioAnalyst

Computer aided photoplethysmography

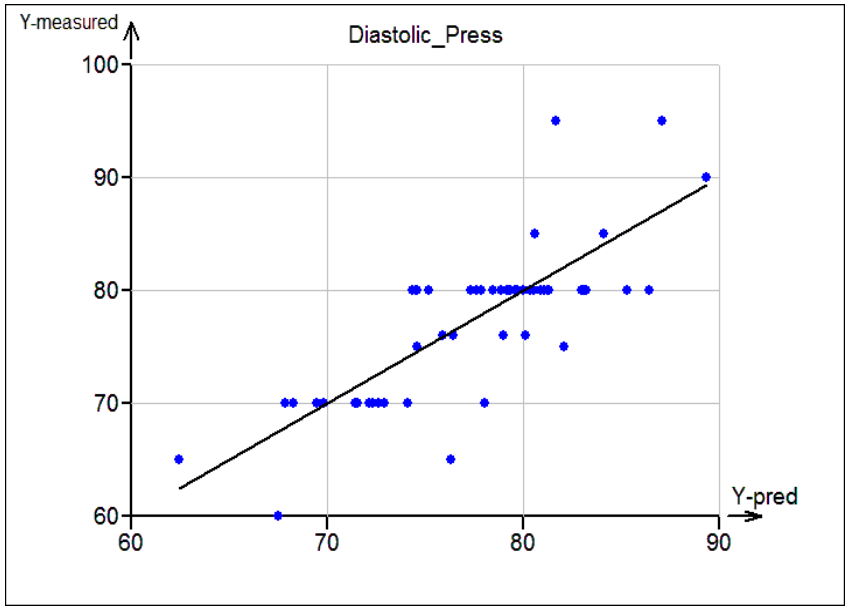
Multiple Regression

Patient age or diastolic pressure is roughly predictable based on PPG curves.

Predicting age



Modelling Diastolic pressure

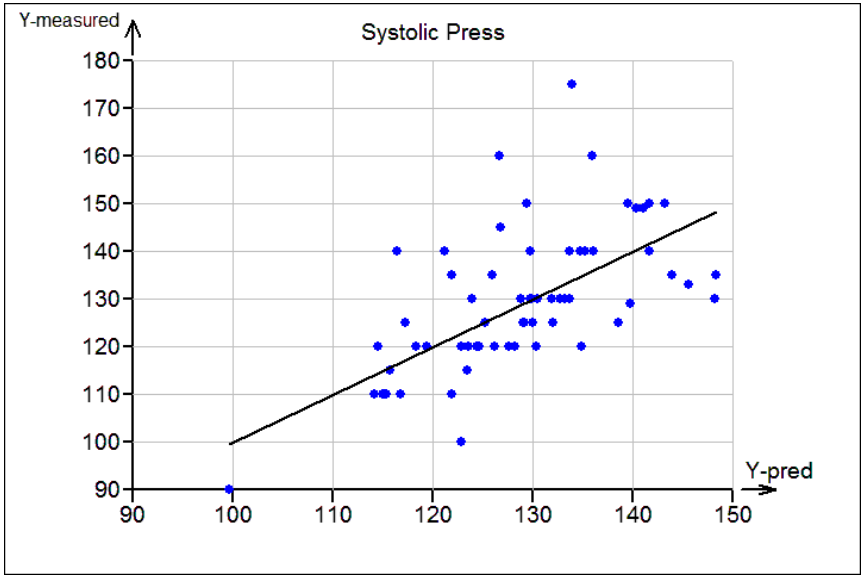


Computer aided photoplethysmography

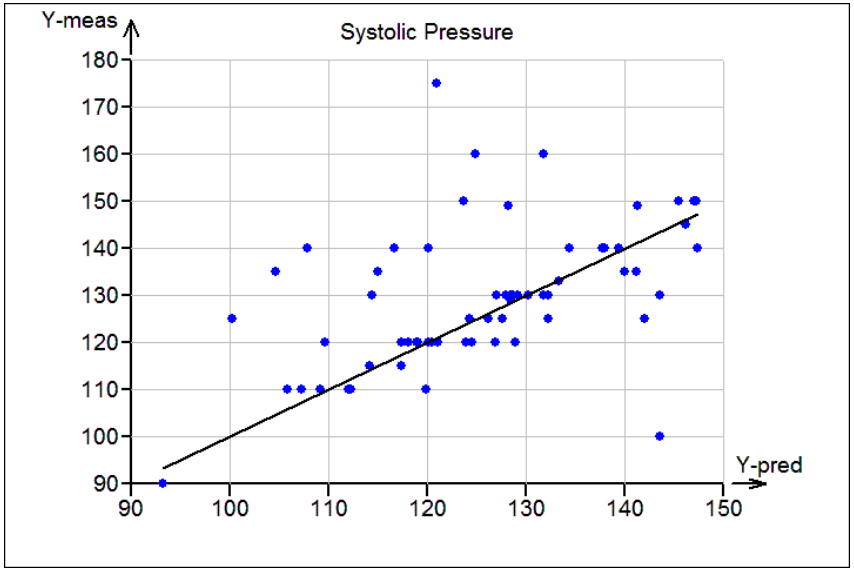
Multiple Regression – Systolic pressure

Patient systolic pressure predicted by PPG curves. Robust regression finds better fit for 80% of patients.

Least Squares



Robust M-estimate Welsch

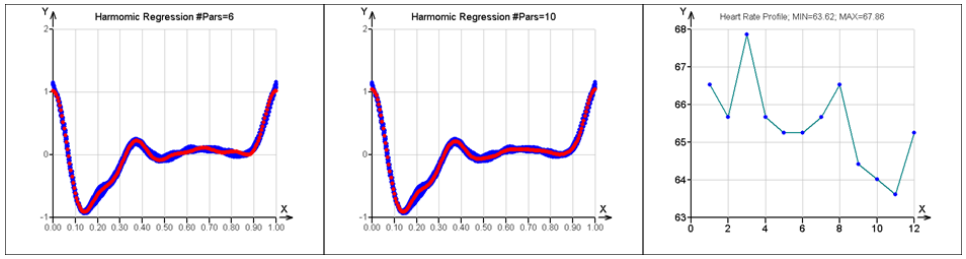


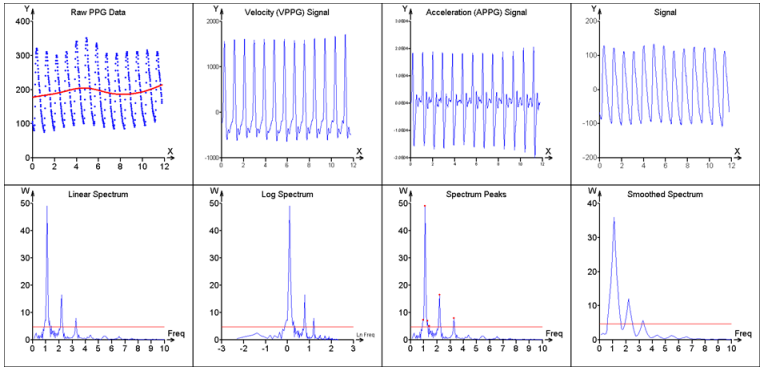
CardioAnalyst

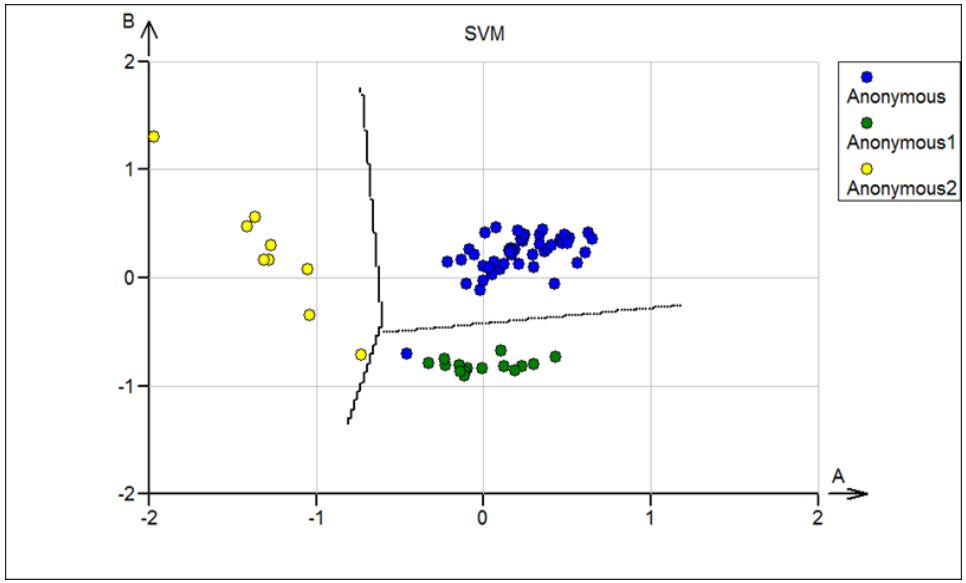
Computer aided photoplethysmography

Classification

Classification of three different healthy patients using Vapnik´s Support Vector Machines







Vladimir Vapnik in NEC Lab Princeton, NJ

CardioAnalyst Project

CardioAnalyst

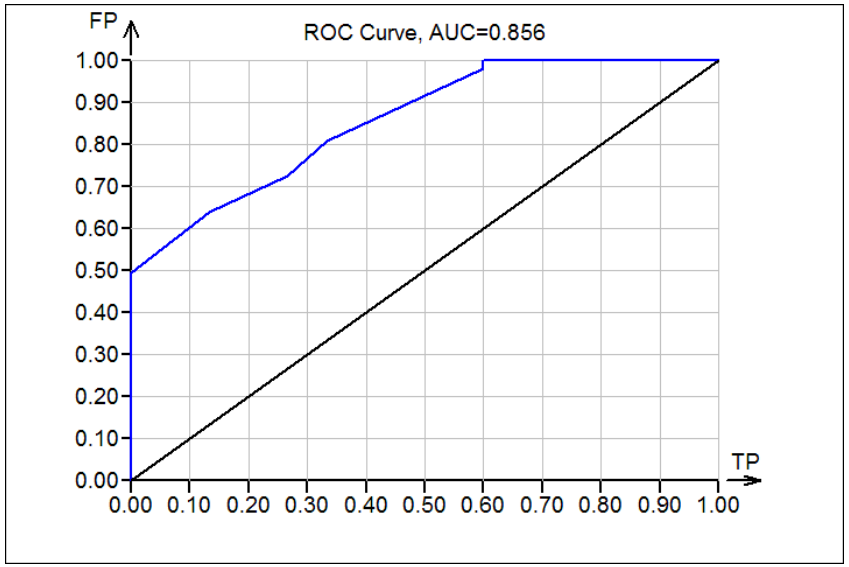
Computer aided photoplethysmography

Classification - SVM

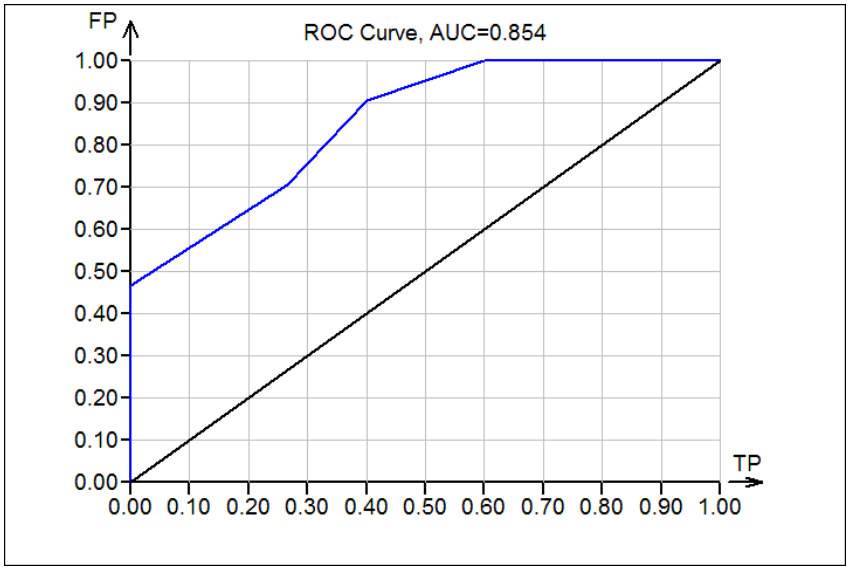
Arteriosclerosis of the upper or lower limbs using 13 vars

Three classification models to predict probability of arteriosclerosis based on PPG curves.

Linear kernel



RBF Kernel



CardioAnalyst Project

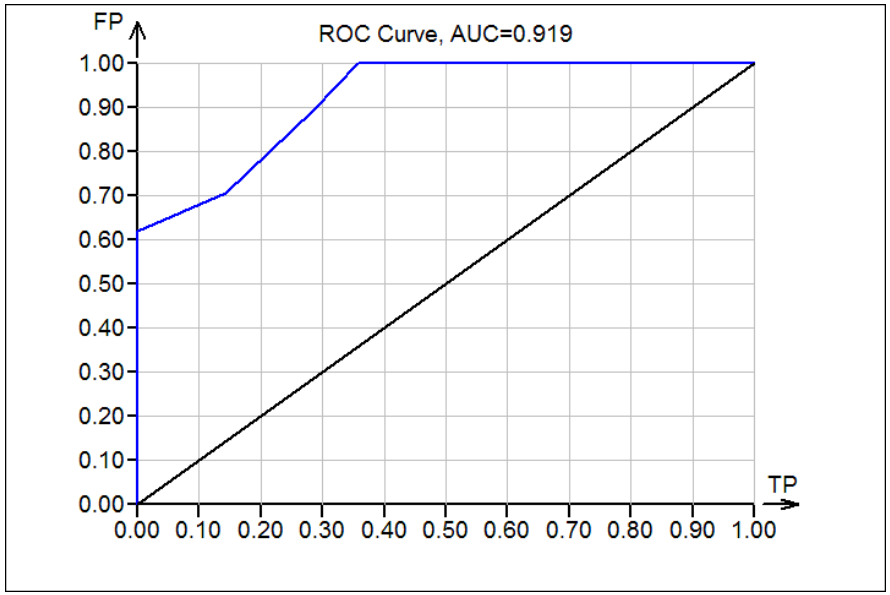
CardioAnalyst

Computer aided photoplethysmography

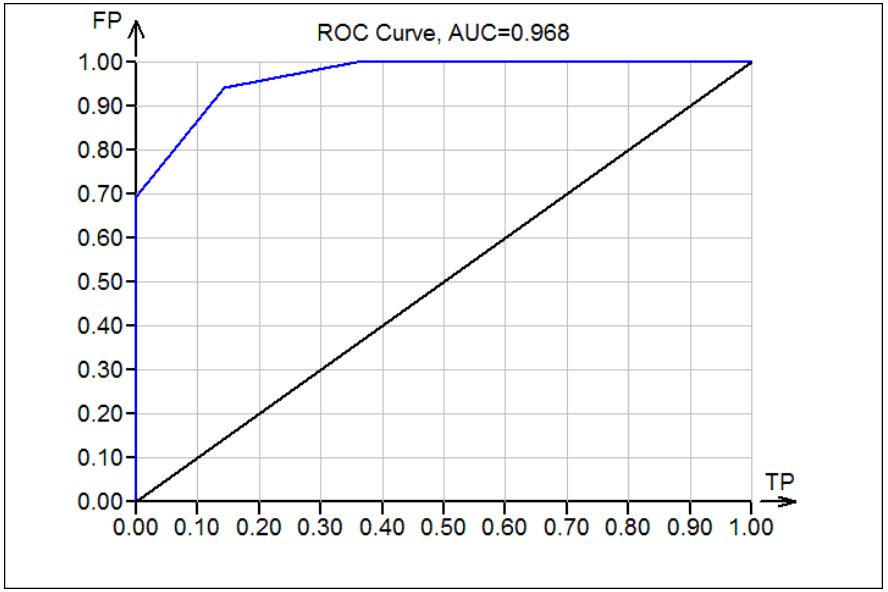
Classification - SVM

Arteriosclerosis of the upper or lower limbs using 21 vars

Linear kernel



RBF Kernel



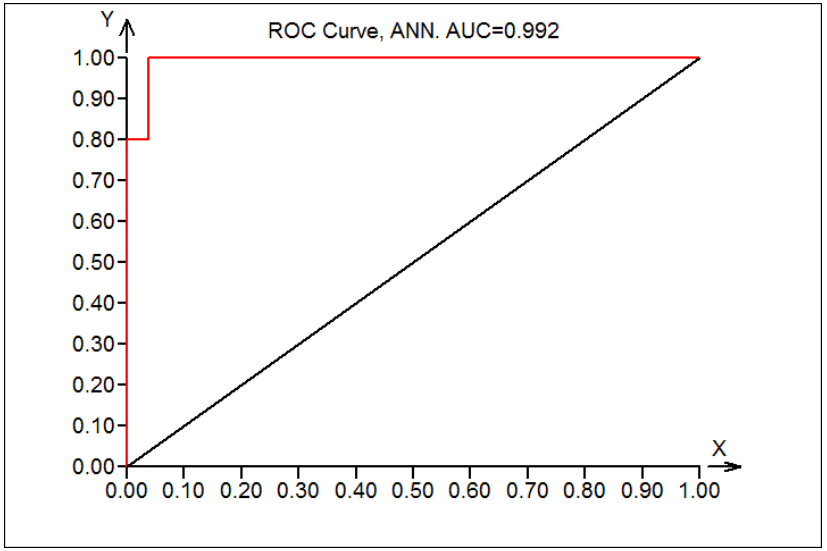
CardioAnalyst Project

Computer aided photoplethysmography

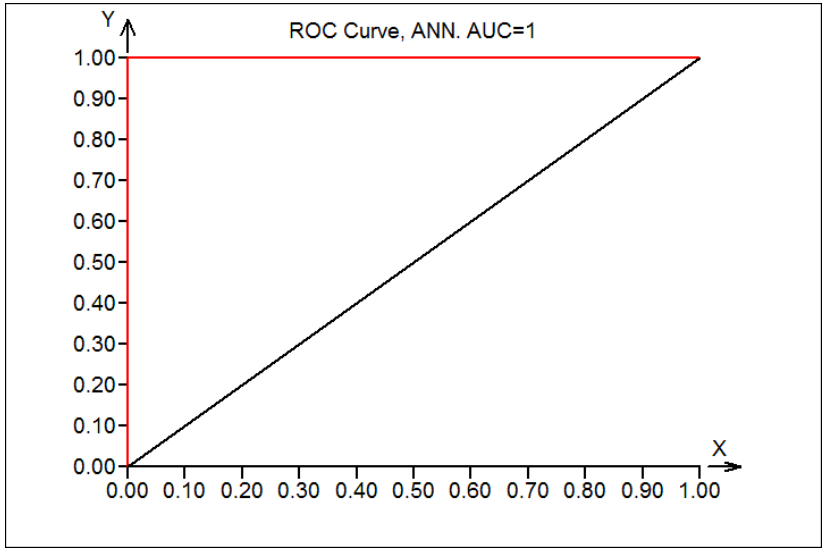
Classification – Neural Network

Arteriosclerosis of the upper or lower limbs using 13 vars

2-neuron 1 layer



3-neuron 1 layer



CardioAnalyst

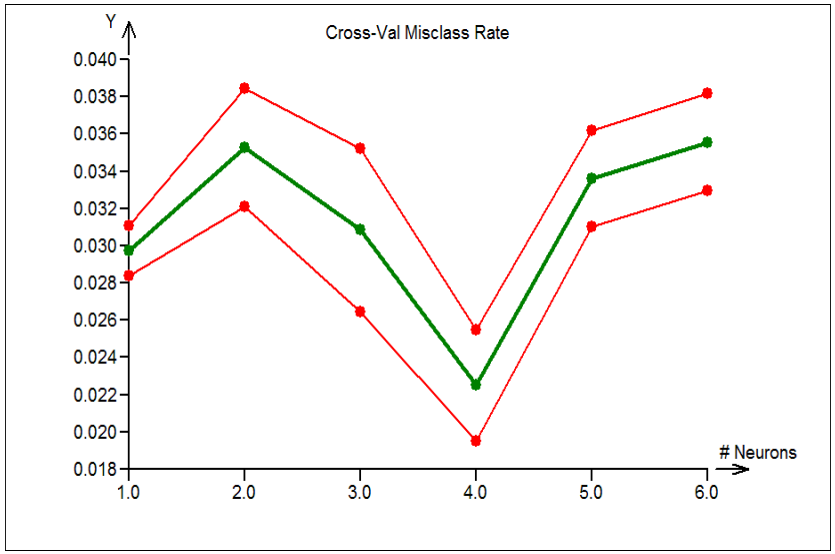
Computer aided photoplethysmography

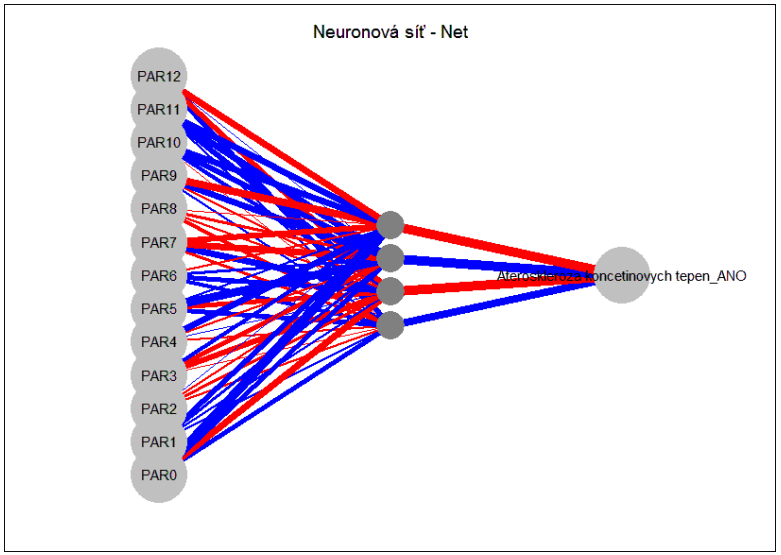
Classification – Neural Network

Arteriosclerosis of the upper or lower limbs using 13 vars

Best prediction reached with relatively simple single layer 4-neuron neural network with less than 3% miclassification.

Actual Cross-val misclass rate for 13 pars





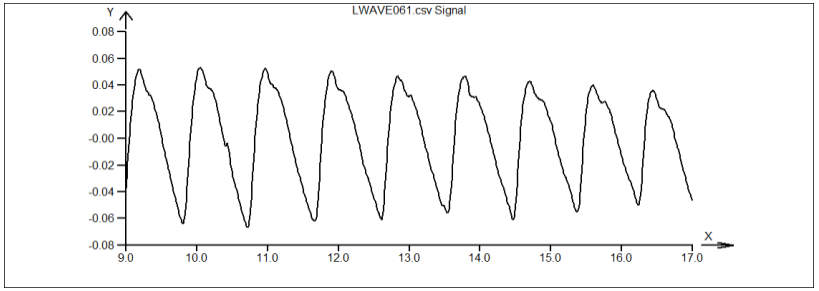
CardioAnalyst Project

CardioAnalyst

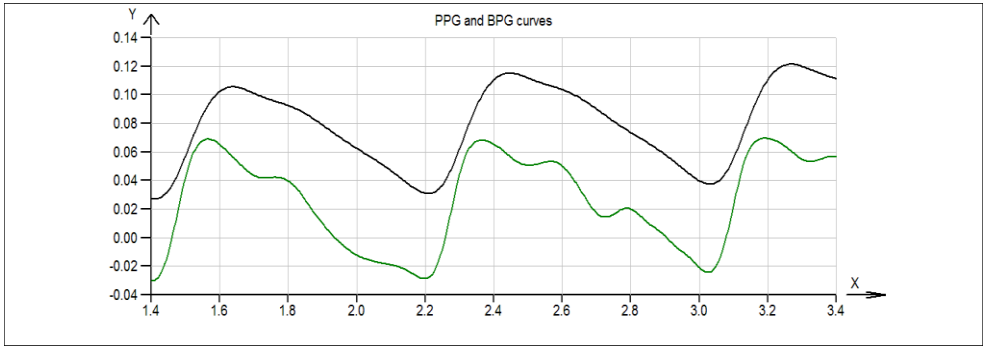
Computer aided photoplethysmography

Further work

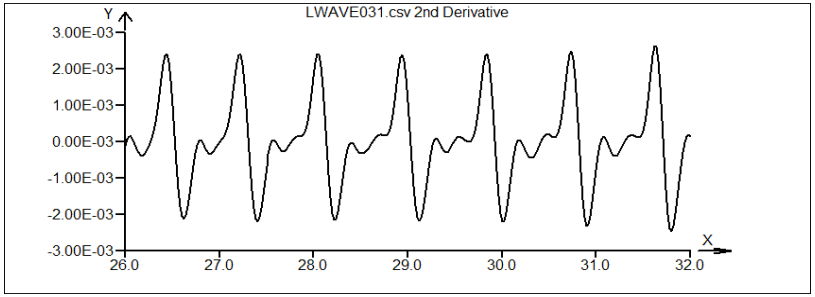
Volume capacity PPG (original PPG signal)



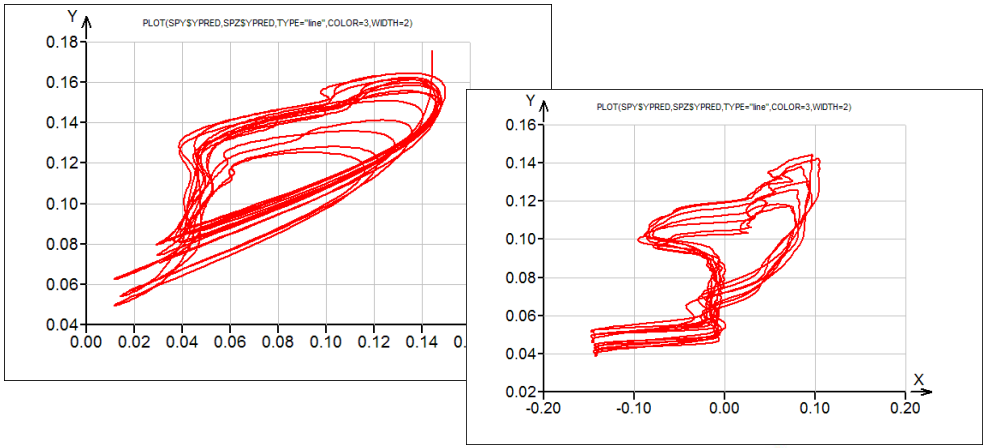
Combined PPG and BPG Signal Analysis



APPG waveforms



The relationship between PPG and BPG curves can be visualized by phase diagrams which plot the pressure against PPG



CardioAnalyst Project

Recent references

CardioAnalyst

Computer aided photoplethysmography

Recent references

Photoplethysmography.
Anaesthesiology - Hemodynamic Monitoring Devices. Volume 28, Issue 4, December 2014, Pages 395–406.

Aymen A. Alian, M.D. (Professor of Anesthesiology, Yale University School of Medicine)
Kirk H. Shelley, M.D., PhD. (Professor of Anesthesiology, Yale University School of Medicine)

The photoplethysmographic (PPG) waveform, also known as the pulse oximeter waveform, is one of the most commonly displayed clinical waveforms. First described in the 1930s, the technology behind the waveform is simple. The waveform, as displayed on the modern pulse oximeter, is an amplified and highly filtered measurement of light absorption by the local tissue over time. It is optimized by medical device manufacturers to accentuate its pulsatile components. Physiologically, it is the result of a complex, and not well understood, interaction between the cardiovascular, respiratory, and autonomic systems. All modern pulse oximeters extract and display the heart rate and oxygen saturation derived from the PPG measurements at multiple wavelengths. “As is,” the PPG is an excellent monitor for cardiac arrhythmia, particularly when used in conjunction with the electrocardiogram (ECG). With slight modifications in the display of the PPG (either to a strip chart recorder or slowed down on the monitor screen), the PPG can be used to measure the ventilator-induced modulations which have been associated with hypovolemia. Research efforts are under way to analyze the PPG using improved digital signal processing methods to develop new physiologic parameters.

It is hoped that when these new physiologic parameters are combined with a more modern understanding of cardiovascular physiology (functional hemodynamics) the potential utility of the PPG will be expanded. The clinical researcher's objective is the use of the PPG to guide early goal-directed therapeutic interventions (fluid, vasopressors, and inotropes), in effect to extract from the simple PPG the information and therapeutic guidance that was previously only obtainable from an arterial pressure line and the pulmonary artery catheter.

CardioAnalyst Project

Computer aided photoplethysmography

Recent references

Characteristics of beat-to-beat photoplethysmography waveform indexes in subjects with metabolic syndrome. *Microvascular Research*, Volume 106, July 2016, Pages 80–87

Yaw-Wen Changa, Hsin Hsiub, Shu-Han Yangb, Wen-Hwei Fanga, Hung-Chi Tsaib,
National Defense Medical Center, Taipei, Taiwan
Taiwan University of Science and Technology, Taipei, Taiwan

Metabolic syndrome (MetS) increases the risk of the subsequent development of cardiovascular disease. This study aimed to determine if the harmonic indexes of finger photoplethysmography (PPG) waveforms can be used to discriminate different arterial pulse transmission conditions between MetS and healthy subjects. Three-minute PPG signals were obtained in 65 subjects, who were assigned to 3 age-matched groups (MS, with no less than three MetS factors; pre-MS, with one or two MetS factors; Control: with no MetS factor). FDT (foot delay time) and amplitude proportions (Cn) and their standard deviations (SDn) and coefficients of variations (CVn) were calculated for harmonics 1 to 10 of the PPG waveform. FDT was smaller in MS than in Control. C1 and C2 values were significantly smaller, whereas C4–C9 values were significantly or appeared to be larger in MS than in pre-MS. Most of the SDn and CVn values were largest in MS. This study is the first to demonstrate that harmonic-analysis indexes of the beat-to-beat PPG waveform can provide information about MetS-induced changes in the arterial pulse transmission and cardiovascular regulatory activities. The present findings may therefore be useful in developing a noninvasive and easy-to-perform technique that could improve the early detection of cardiovascular diseases.

Computer aided photoplethysmography

Recent references

A pilot study of venous photoplethysmography screening of patients with chronic venous disorders. *Applied Nursing Research* 23 (2010) 178–183

Teresa J. Kelechi, PhD, RN (Medical University of South Carolina, USA)
Rebecca B. McNeil, PhD (Biostatistics Unit, Mayo Clinic, Jacksonville, FL, USA)

In office and clinical practice settings, standard methods do not exist to objectively quantify lower extremity venous dysfunction. This pilot feasibility study examined venous refill time, an objective measure of skin microcirculation reflux, using photoplethysmography in 13 patients with known chronic venous disorders. The test was found to be feasible and easy to administer and provided objective data to corroborate clinical signs. Further research is needed to evaluate and validate the relationships among clinical signs, comorbid conditions, and objective findings with the severity of venous dysfunction in patients with suspected or known chronic venous disorders.

Computer aided photoplethysmography

Recent references

Noninvasive Monitoring by Photoplethysmography. *Clin Perinatol* 39 (2012) 573–583, 2012 Elsevier.

Rakesh Sahni, MD, College of Physicians and Surgeons, Columbia University, New York, NY, USA

The development of pulse oximetry is unarguably the most important advance in clinical monitoring in the past 3 decades. Pulse oximeters, which compute blood oxygen saturations (SpO2) using photoplethysmography with at least 2 different light wavelengths, often display a photoplethysmogram (PPG) to help clinicians distinguish between reliable SpO2 measurements (associated with clean, physiologic waveforms) and unreliable measurements (associated with noisy waveforms). Because of the success of pulse oximetry and recent advances in digital signal processing, there is growing research interest in seeking circulatory information from the PPG and developing techniques for a wide variety of novel applications. This article reviews the basic physics of photoplethysmography, physiologic principles behind pulse oximetry operation, and recent technological advances in the usefulness of the PPG waveform to assess and monitor the microcirculation and intravascular fluid volume during intensive care.

Computer aided photoplethysmography

Thank you