Application of pulse wave analysis in a personal health monitoring device

Pulse wave (PW) is a physiological event, observable and measurable in the arterial system during blood circulation. One of characteristics that can be determined from a PW record is heart rate variability (HRV), an indication of beat-to-beat alterations in the heart rate. HRV is an accurate and reliable reflection of several physiological factors modulating the normal rhythm of the heart. HRV has escalated in use as an important diagnostic tool which indicates the balance between sympathetic and parasympathetic branches of the autonomous nervous system (ANS) and the synchronization between them. HRV patterns are also sensitive to changes in emotional state and can be used to distinguish positive and negative emotions.
However, HRV is just one of characteristics that can be extracted from a good quality pulse wave record. Other characteristics of the PW in the time and frequency domains can serve as an indication of the status of a cardio-vascular system.

While sensitivity and specificity of the characteristics derived from a pulse wave may not meet clinical requirements, they are adequate for daily or periodic monitoring by users who are affected by sedentary life style, high stress, and fatigue. A personal health monitoring tool, measuring pulse wave, can employ the data processing capability of a smartphone or a notebook. Sample embodiments in a consumer product include a computer mouse or a standalone device, connected with a notebook via USB port (fig. 1, a, b). The pulse wave signal can also be generated by a built-in camera in a smartphone or by a web camera (fig. 1), by analyzing the variations in the light flow caused by pulsation of blood in a finger held next to the camera. (These variations reach up to 1% of the total light flow).

In the developed device, operating in the reflectance mode, a light-emitting diode illuminates the finger of the user with infrared light (wavelength 890 nm). The light from the LED, entering the tissue, is partially scattered, partially absorbed by the hemoglobin in the erythrocytes, and partially reflected by deeper structures, "backlighting" superficial blood vessels [1]. Then, as the blood vessels in the finger fill with more blood, they absorb more light returning from the deeper tissues, and photodetector light intensity diminishes, following the Lambert–Beer law.
The reflected light, which is amplitude-modulated by the changing volume of the blood vessels caused by heart contractions, is converted into an electric signal by a photodetector. The output signal from the photodetector, which is proportional to the blood flow rate in the vessels, or, to the pressure drop, is further demodulated and filtered. The DC component is removed by the differential integrating filter, after which the signal is converted into a digital format. The resulting differential pulse wave signal **(dP/dt),** after sliding averaging, is interpreted by the data processing algorithms.

One of the major challenges in the developed device was to amplify weak modulation of the light signal without loss of stability. To that end, a relaxation oscillator (RO) generates bipolar rectangular pulses, with pulses of one polarity (signal pulses) corresponding to the measured signal, and pulses of the opposite polarity used as a reference. Duration of the signal pulses depends on the voltage supplied from the photodetector and is controlled by an optoelectronic couple. This design ensures DC uncoupling between the DC amplifier with high gain (used for the amplification of the measured signal and having a gain of up to10,000) and the relaxation oscillator. By doing so, it was possible to produce a high quality PW record in a compact device, with no intercoupling, which increases the stability, accuracy and repeatability of measurements.

The user is required to conduct both baseline and current measurements under the same (comfortable) conditions, at rest. The device first autocalibrates its gain factor to account for changes in ambient light and then gathers approx. 50 sec of data.

The practical application of the PW monitoring in a consumer product requires, besides software and electronic, selection of clinically meaningful characteristics of the pulse wave

and communicating them to a non-medical user. For this purpose, it is proposed to use, in addition to HRV, several characteristics which are calculated based on relationships between certain time intervals of the [1st derivative] PW. While amplitudes of the PW [and to less extent ratios of amplitudes] may be affected by environmental (ambient light, temperature), user-related (temperature of the fingers, contact with the sensor) and hardware-related factors (non-linear characteristic), the detected time intervals of the PW show remarkable reproducibility. The algorithms based on processing the time characteristics of the 1st derivative of the PW have been tested over 10+ years on multiple users and patients and have shown good correlation with the objective data. While multiple references describe using initial pulse wave and its second derivative, use of the 1st derivative has not been widely reported.

In the sample output shown in fig. 3, the PW analyzer calculates the following characteristics:

- pulse rate [1/sec] $P = 60/T_{av}$,
- variation range [sec] $R_t = (t_{max} - t_{min})$,
- variation coefficient $P_s = (100^*\sum \delta t_i) / (N^*T_{av})$,
- vascular resistance [sec] (determined (fig. 2) as a time interval during which is reduced by a factor of e (2.718)),
- vascular tonicity [%] (determined as a ratio of the duration of the anacrotic limb to the duration of the decaying limb, fig. 2) and
- the duration of the extreme load phase [sec] (fig. 2), during which the stress in the heart muscle reaches maximum, is related to the strength of the heart muscle,

where T_{av} is the average length of cardiointervals (sec), t_{max}, t_{min}, t_i are maximum and minimum lengths of the cardiac intervals t_i during the record (sec), $\delta t_i = |(T_{av} - t_i)|$, N is the number of (accepted) PW in the record.

For each of the measured characteristics shown are green, blue and red ranges, which indicate recommended, borderline and unhealthy levels of the measured parameters, established based on statistical data. While these statistics vary between an young health athlete and an older user, the green/blue/red ranges of the selected parameters have relatively low variation.

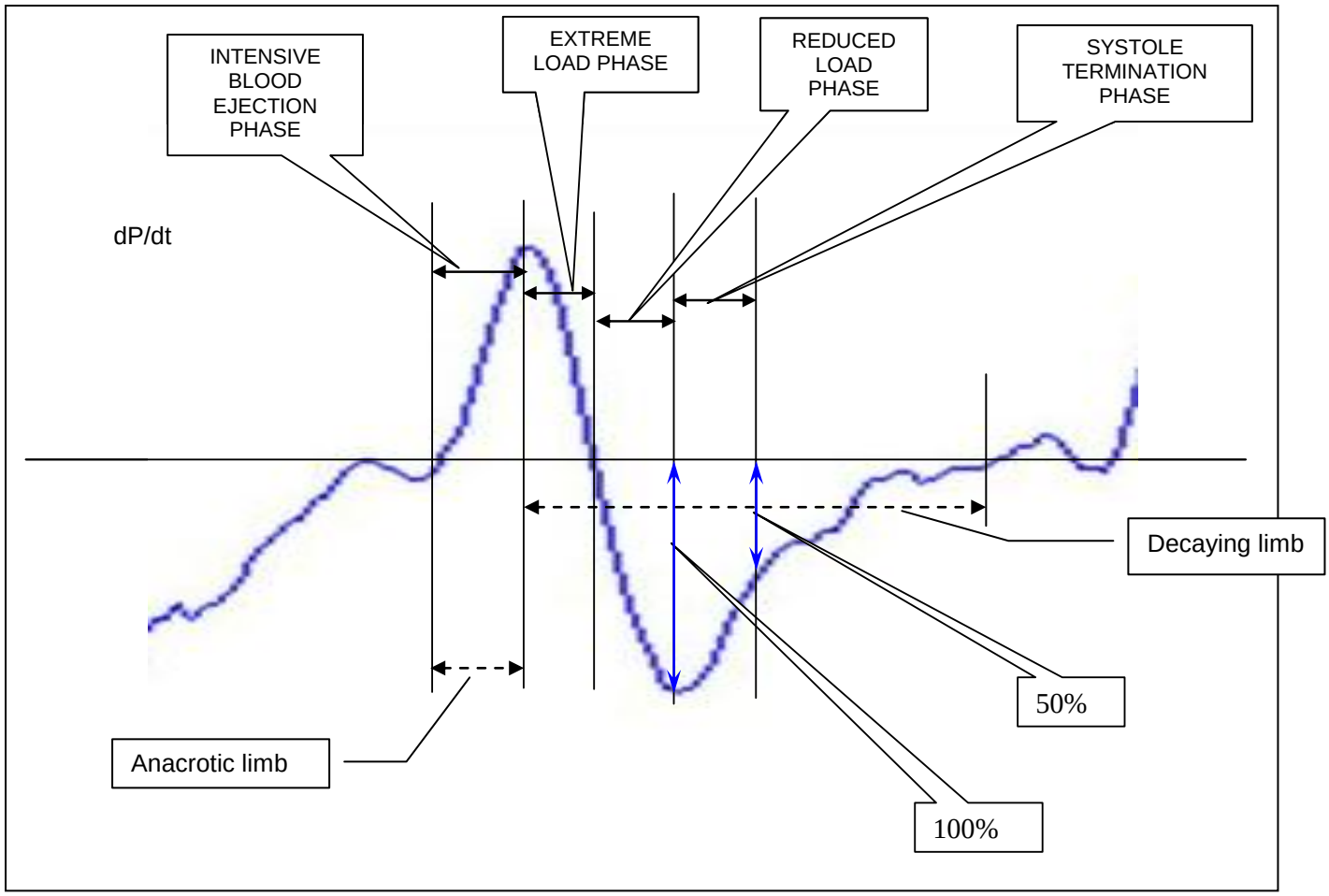
Measured parameters (characteristics of the heart rate and of the pulse wave) are presented to the user and compared with the baseline levels obtained for the same user under non-stressed conditions, or with the statistically established "normal" ranges (green zones, fig. 3).

This allows the user to preemptively contact a doctor if the characteristics show consistent deterioration, track the effects of changing activities or life style, as well as receive real time feedback to changing psycho-emotional status.

Key words: heart rate variability, pulse wave characteristics, personal health monitoring.

a b c

Fig. 1


INTENSIVE BLOOD EJECTION PHASE
EXTREME LOAD PHASE
REDUCED LOAD PHASE
SYSTOLE TERMINATION PHASE
dP/dt
Decaying limb
50%
Anacrotic limb
100%

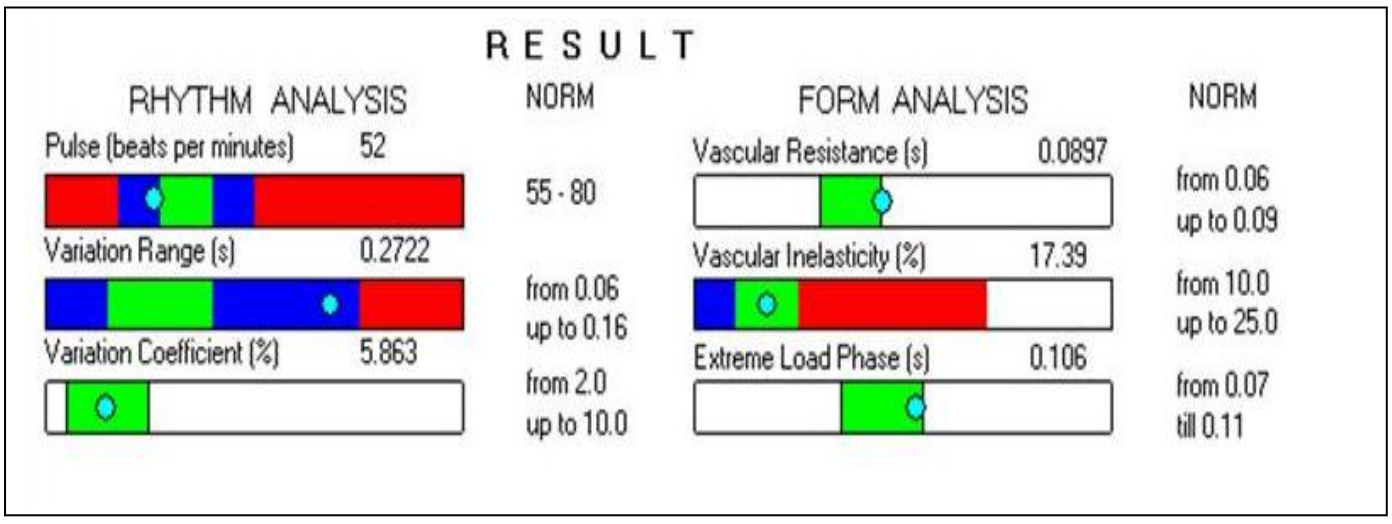

RESULT
RHYTHM ANALYSIS
NORM
Pulse (beats per minutes) 52
55 - 80
Variation Range (s) 0.2722
from 0.06 up to 0.16
Variation Coefficient (%) 5.863
from 2.0 up to 10.0
FORM ANALYSIS
NORM
Vascular Resistance (s) 0.0897
from 0.06 up to 0.09
Vascular Inelasticity (%) 17.39
from 10.0 up to 25.0
Extreme Load Phase (s) 0.106
from 0.07 till 0.11

Fig. 3

ТОНУС СОСУДОВ - соответствует упругости сосудов. Чем он выше, тем больше нагрузка на сердце во время его сокращения.

Vascular inelasticity [%]	ПСТ = (tmax-tx) ·100% (tc-tmax) где (tmax-tx) - длительность анакроты, (tc-tmax) - длительность катакроты (до пересечения изолинии РГ) The typical pulse wave morphology has two phases: the anacrotic phase being the rising edge of the pulse, and the catacrotic phase being the falling edge of the pulse http://www.clbme.bas.bg/bioautomation/2010/vol_14.3/files/14.3_05.pdf

The length of the extreme load phase,. A significant increase of this phase ~~(above 0.11 sec [for an average healthy person? Reference?])~~ may indicate deterioration of the ability of the heart muscle to contract.
Vascular resistance and vascular inelasticity [are they independent?] are related to the length of the systole termination phase. Too short duration can be caused by rigid artery walls, too long may indicate a weak heart muscle. Vascular resistance is determined (fig. 2) as a time interval during which dP/dt is reduced by a factor of e (2.718).
Vascular inelasticity [%] is determined as …
The boundaries for these parameters are selected based on …

http://www.tiferet.cl/pdf/contour_analysis_photoplethysmographic_pulse.pdf

[2] Contour analysis of the photoplethysmographic pulse measured at the finger
Sandrine C. Millasseau, , James M. Ritter, Kenji Takazawa, Philip J. Chowienczyk
Another approach to derive information about cardiovascular properties from the pulse wave is based on analysis of an optically derived finger or digital volume pulse (DVP). Although less widely used, this approach deserves further consideration, not least because of its simplicity and ease of use. The technique has the potential to provide an estimate of large artery stiffness.

The shape or contour of the pulse, however, remains approximately constant.
When individuals had cold fingers, this 'reduces the over-all amplitude but does not affect the configuration of the pulse wave'.

The contour of the DVP is primarily influenced by characteristics of the systemic circulation, as is the contour of the radial pressure pulse.

'an increase in the crest time, loss of the rebound wave and triangulation of the DVP' in individuals with hypertension [4,24] and arteriosclerosis [24]

The effect of organic nitrates and alcohol on the pulse wave, producing a 'depression of the dicrotic notch' [25].

A 'dicrotic index' has subsequently been used as a sensitive indicator of the vasomotor effects of drugs including nitrates [27–34], isoprenaline and nifedipine [33,35].

Takazawa et al. [37], Takada et al. [38] and Imanaga et al. [39] have proposed using the second derivative of the DVP (d2DVP/dt2, sometimes referred to as the 'acceleration photoplethysmograph'). This facilitates the distinction of five sequential waves called a, b, c, d and e waves (Fig. 3). The relative heights of these waves (b/a, c/a, d/a and e/a ratios), particularly the d/a ratio, have been related to age [37,38,40], arterial blood pressure [38,40], large artery stiffness [41] and effects of vasoactive drugs [42]. The b/a ratio has been related to

ageing and carotid distensibility [39]. Following analysis of the correlation of the b/a, c/a, d/a and e/a ratios with age, a more complex **'ageing index'** was defined as (b–c–d–e)/a [37].

We demonstrated that the relationship between the DVP and the radial pressure pulse (or the digital pressure pulse, which is almost identical to the radial pulse) can be represented by a single mathematical transfer function [50].

The PWV is closely related to the distensibility of the aorta and large arteries (and hence to the magnitude of the Windkessel effect) [Vascular resistance]

[1] Anesthesiology 2008; 108:950–8
Utility of the Photoplethysmogram in CirculatoryMonitoring
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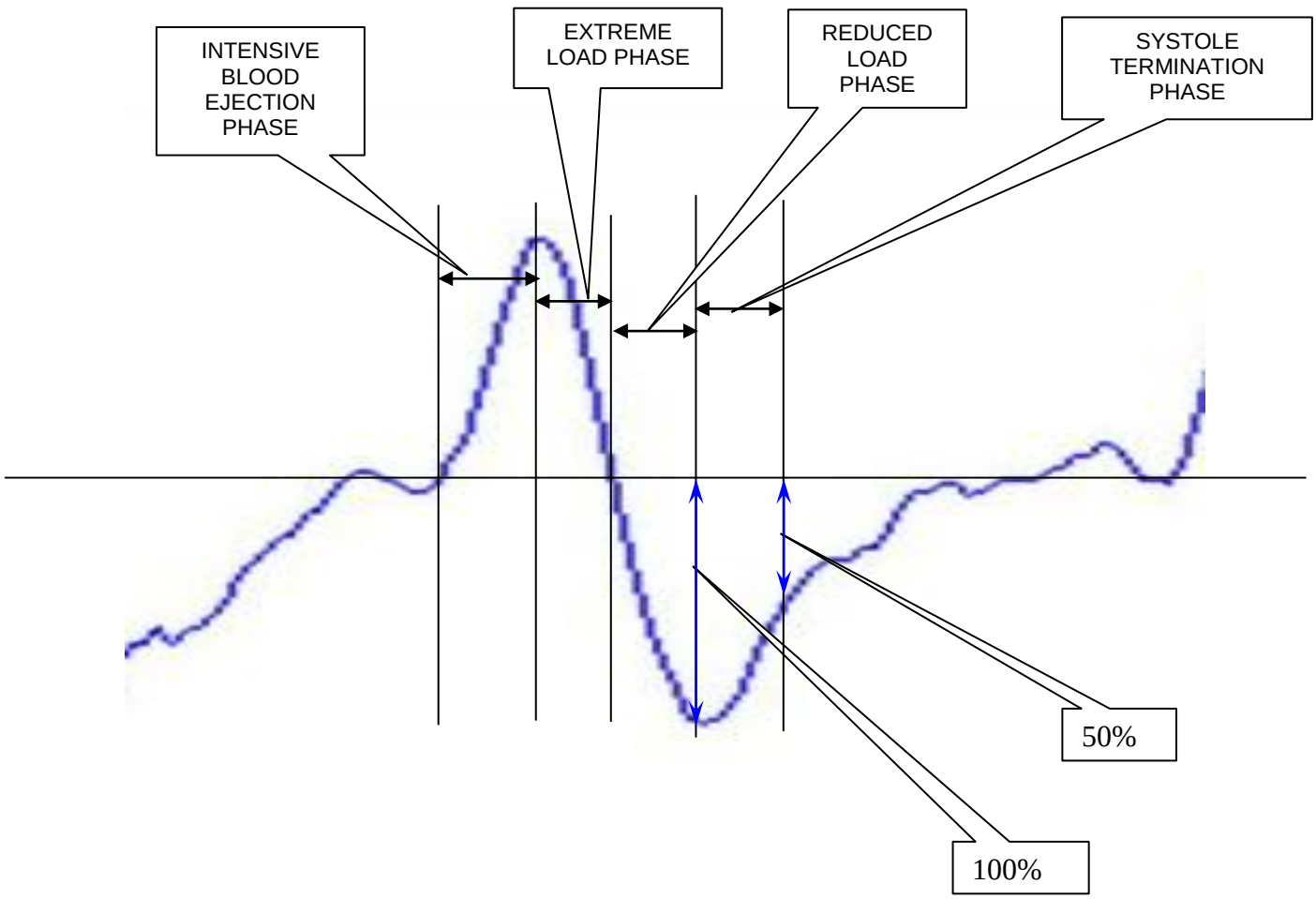
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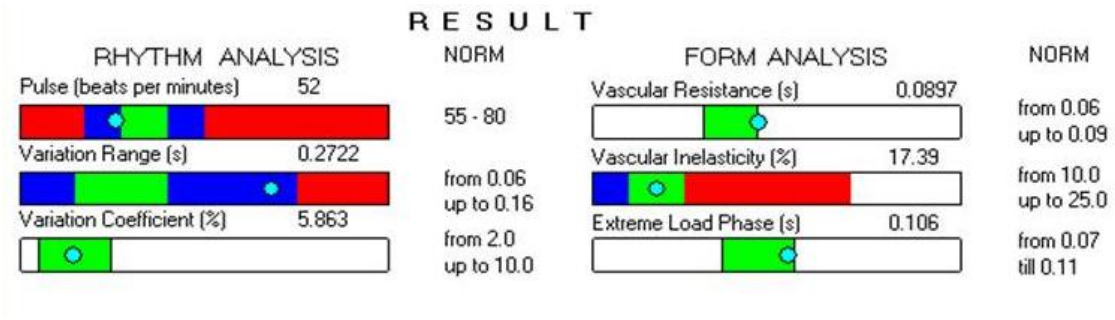
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It should also be noted that the velocity of blood flow affects the photoplethysmogram, probably because of reorientation and/or packing of erythrocytes that is flow dependent.[17,18] Even in a rigid (*i.e.*, constant volume) glass pipe, oscillating blood flow gives rise to an oscillating photoplethysmogram.[1] There are classic references to photoplethysmography as a flow (rather than volume) measurement (*e.g.*, references 1 and 19), although flow effects may be minor *in vivo*.[1,20–23] It is difficult to sort out the effects of blood flow *versus* volume pulsations *in vivo*.[24]

The processing algorithms vary between manufacturers, and their precise methods are often proprietary.

Vascular resistance
[In Wikipedia, Vascular resistance has dimensions $MPa \cdot s/m^3$, not sec]