B. Khanokh, M. Nitzan

THE PHOTOPLETHYSMOGRAPHY (PPG) APPARATUS FOR DIAGNOSIS OF THE PERIPHERAL BLOOD CIRCULATION

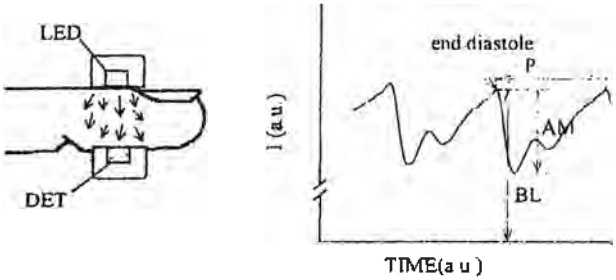
The modern photoplethysmography (PPG) uses the achievements of quantum electronics. Photoplethysmography (PPG) measures the cardiac induced changes in tissue blood volume by light transmission measurements. Like heart rate, the PPG signal shows spontaneous fluctuations. The heart rate variability (HRV), which is mediated by the autonomic nervous system, has been intensively investigated. The power spectrum of HRV contains fluctuations in very low and low frequencies, which are attributed to the activity of the sympathetic and the parasympathetic nervous systems, and fluctuations in high frequency, which are mediated via the parasympathetic nervous system [1]. While the use of spectral analysis of HRV for clinical use is well established for the low frequency (LF) and the high frequency (HF) fluctuations, the analysis of the very low frequency (VLF) fluctuations (below 0.04 Hz) and their physiological meaning is dubious.

Spontaneous fluctuations of similar frequencies were also found for the arterial blood pressure /1/ and for other parameters of the peripheral blood circulation. In recent studies /2,3/ the spontaneous fluctuations in the blood volume in the fingertip were obtained through photoplethysmography (PPG) - the measurement of light absorption by the tissue.

The PPG Device

The transmission PPG probe consisted of a light emitting diode (LED) of 865 nm (Fujitsu, Japan) and a PIN photo-detector (Hamamatsu, S1223-01), these perfect devices of quantum electronics, which were attached to the palmar and dorsal aspects of the index fingers bilaterally (fig. 1*a*). The light from the LED was modulated at a frequency of 3kHz and the detected transmitted light was filtered through a narrow band around 3kHz to avoid background light. The signal from the detector was then demodulated in order to obtain the PPG signal. A low-pass filter (0–40 Hz) was used in order to reduce high frequency noise. The PPG signals were sampled at a rate of 500 samples per sec and digitally stored for further processing.

The PPG photo-detector output oscillates in the heart cycle rate (fig. 1*b*) due to the higher light absorption in the fingertip during systole caused by the cardiac induced increase in the tissue blood volume during systole. In these studies two parameters were derived for each PPG pulse:



a *b*

Fig. 1. The PPG probe on the fingertip (*a*) and signal in the heart rate (*b*)
DET - photodetector; LED - light emitting diode, the light source. A small portion of the light is transmitted through the fingertip. At end-diastole the tissue blood volume is minimal and the light transmitted through the tissue is at maximal intensity. BL - baseline; AM - amplitude; P – period

its baseline (BL) and amplitude (AM) (fig. 1*b*). BL, the baseline of the PPG signal, is inversely related to the tissue blood volume, AM, the pulsatile component of the PPG signal, mainly depends on the tissue blood volume increase during systole and is related to the arterial wall compliance. Another parameter defined from them was examined: the statistical parameter STD/AVG of the ratio AM/BL, characterizing compliance.

Data analysis

After the examination, the stored data was digitally analyzed for the detection of the minimum and maximum of each PPG pulse. The PPG pulse minimum was identified at the point for which the value of the PPG signal was lower than that for the sixty neighboring points and the maximum was similarly defined. Erroneous detection of the PPG pulse notch was avoided by demanding minimal difference between the maximum and the subsequent minimum. Then the PPG pulses were carefully inspected in order to manually delete erroneous minima or maxima and add missing minima or maxima. For each PPG pulse, the baseline BL of the pulse and its amplitude AM were determined

The ten minute examination provided about 600 PPG pulses and consequently about 600 data points for BL and for AM. In some examinations part of the data points had to be discarded due to movement of the subject, but the final database included at least 350 data points for each subject. The correlation was performed for the whole set of points, except the first and last ten points. In this study, only the VLF spontaneous fluctuations i.e. those which lasted for about 30–80 PPG pulses were investigated. The LF and HF fluctuations were filtered out by the smoothing method of moving average, with linear decrease weights of the 27 adjacent points (13 on each side). The lower frequency fluctuations were removed (trend removal) by fitting a fifth order polynomial to the data and subtracting it from the original curve.

Statistical analysis

The coefficient of correlation between two parameters X and Y (series $x(n)$ and $y(n)$) and the lag between them was calculated by the formula :

$$CC(\tau) = \sum_{n=\tau+1}^{N}[x(n-\tau)-x_m]\,[y(n)-y_m]\Big/A^{1/2}\,,\ 0 \le \tau \le 20$$

where x_m, y_m are the mean value of $x(n)$ and $y(n)$ and

$$A = \sum_{n=\tau+1}^{N}[x(n-\tau)-x_m]^2\ \sum_{n=\tau+1}^{N}[y(n)-y_m]^2\,.$$

The lag of maximal correlation coefficient was taken as the lag between the two parameters.

The Student t-test was used for the evaluation of the significance of the difference from zero of the lag between the fluctuations of two parameters. The correlation between two parameters was assessed by linear regression analysis. $t > 2$ was considered statistically significant.

Subjects

Transmission PPG was measured on the index fingers of the hands and the foots of 54 male subjects aged 19–78 years. The subjects had no known cardiovascular or neurological disease and did not take any medication that can affect the vascular system. All subjects were non-smokers, and they were instructed not to drink coffee three hours before the examination. The subjects were lying down during the PPG examination, with their hands comfortably laid on the table at heart level. The examination lasted for ten minutes, after a rest period of ten minutes. Room temperature was 21–24°C.

The study was approved by the institutional ethical committee, and the subjects gave informed consent.

Results

For each examination AM and BL were derived for each PPG pulse, then displayed as a function of pulse number. Fig. 2 shows the AM and BL curves for the right and the left hands after low-pass filtering (smoothing) and detrending. The VLF fluctuations show high correlation between the right and the left AM or BL curves and a lower correlation between AM and BL.

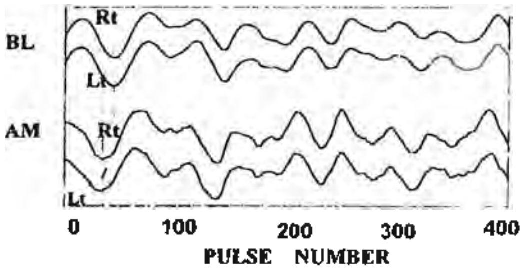


Fig.2. The curves of AM, BL and P as a function of the pulse number for the right hand of one of the subjects.
The low frequency fluctuations are more pronounced in the BL and AM curves than in the *P* curve

Fig 2 depicts the coefficient of correlation between AM(Rt) and BL(Rt) and between AM(Lt) and BL(Lt) as a function of time lag τ between them (measured in pulse numbers). The right and left AM curves match with no Lag between them.

The BL curve lags behind the AM curve by nine pulses: the highest correlation between the curves is found when AM(N) is compared with BV(N-9) (N is the pulse number). Similar results were found for the other subjects.

Rt-Lt correlation (CC1)

The big values of the right-left correlation coefficient (CC1) both for BL and for AM for hands and foots showed a dependence on the healthy male subject's age: CC1 decreases from 19 to 78 ages approximate on 7% (from 0,96 to 0,9 for fingers and 0.93 to 0.86 for foots both for BL and for AM).But Lag showed no dependence on the subject's age and was equal approximate on zero for both BL and AM for both hands and foots.

HAND-FOOT correlation (CC2)

The values of the hand-foot correlation coefficient (CC2) for BL and AM for the right and left sides as a function of the healthy male subject's age decreased too. But the values CC2 were below than CC1 both for BL and for AM and Lag is no zero. The CC2 showed the bigger than CC1 dependences (decrease) on the subject's age for BL (the reduction is on 16% as average to the left and to the right from 19 to 78 ages) and no dependences for AM for both left and right sides. The values of Lag were conversely: they showed no dependences for BL and the decrease for AM for both left and right sides (the reduction is on 3,5 number pulses as average to the right and to the left)from 19 to 78 ages). Lag of left side was higher than Lag of right side for both BL and for AM. This difference decreases with age

AM-BL correlation (CC3)

The coefficient of correlation between AM and BL (CC3) significantly decreased with age for both hands and for foots. The reductions was on 15.5% (as average to the right and to the left (R-L)) for both (R-L) hands and for (R-L) foots from 19 to 78 ages .

The Lag between AM and BL curves was significantly higher than zero. It showed no dependences on the healthy male subject's age for both hands and for foots. The Lag between the AM and the BL curves was for both left hand and for left foot below than for both right hand and for right foot accordingly: approximate differences for hands 0.8 and for foots 0.6 number pulses.

Ratio AM/BL

We found that the ratio STD/AVG (Am/BL) has the strong dependence on the subject's age for both hands and for foots. The decrease of the ratio STD/AVG(AM/BL) was on 40.5% for the hands and on 61.75% for the foots. Thus the decrease was stronger at the foots than at the hands, therefore changes may be discovered with help of foot's ratio earlier than with help of hand's ratio.

Conclusion

The measurement of the PPG signal VLF fluctuations and the correlation coefficients and the lag between its parameters provides a means for better understanding of the microcirculation regulation as well as a potential tool for the assessment of autonomic neuropathy. The VLF fluctuations are not periodic, hence their analysis in the time domain seems to be more appropriate than spectral analysis. While heart rate variability is commonly used for the assessment of cardiac autonomic innervation, fingertip PPG provides a useful tool for the assessment of the peripheral autonomic function. Being simple and noninvasive, the PPG measurement can easily be implemented for both clinical examinations and physiological studies.

References

1. Hemodynamic regulation: investigation by spectral analysis / S. Akselrod, D. Gordon, J.B. Madwed et al. // Am. J. Physiol. 1985. Vol. 249. P. H867–H875.
2. The variability of the photoplethysmographic signal - A potential method for the evaluation of the autonomic nervous system / M. Nitzan, A. Babchenko, B. Khanokh, D. Landau // Physiol. Meas. 1998. Vol. 19. P. 93–102.
3. *Nitzan M., Babchenko A., Khanokh B.* Very low frequency variability in arterial blood pressure and blood volume pulse // Med. Biol. Eng. Comput. 1999. Vol. 37. P. 54–58.