TAMPERE UNIVERSITY OF TECHNOLOGY

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Citation
Peltokangas, M., Huotari, M., Verho, J., Mattila, V. M., Röning, J., Romsi, P., ... Oksala, N. (2017). Short-term stability of combined finger and toe photoplethysmogram analysis. In *EMBEC and NBC 2017 - Joint Conference of the European Medical and Biological Engineering Conference EMBEC 2017 and the Nordic-Baltic Conference on Biomedical Engineering and Medical Physics, NBC 2017* (pp. 342-345). (IFMBE Proceedings; Vol. 65). Springer Verlag. https://doi.org/10.1007/978-981-10-5122-7_86

Year
2017

Version
Peer reviewed version (post-print)

Link to publication
TUTCRIS Portal (http://www.tut.fi/tutcris)

Published in
EMBEC and NBC 2017 - Joint Conference of the European Medical and Biological Engineering Conference EMBEC 2017 and the Nordic-Baltic Conference on Biomedical Engineering and Medical Physics, NBC 2017

DOI
10.1007/978-981-10-5122-7_86

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The final publication is available at Springer via http://dx.doi.org/10.1007/978-981-10-5122-7_86

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Download date:19.02.2021

Short-term stability of combined finger and toe photoplethysmogram analysis

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Abstract— **Arterial pulse waves (PWs) provide information on the vascular health and could be utilized in the early detection of atherosclerosis. The aim of the study is to characterize the short-term repeatability of combined finger and toe photoplethysmographic (PPG) signal analysis method which we call finger-toe plot (FT-plot) and compare it with other methods proposed for vascular characterization. PPG signals were recorded from 24 atherosclerotic and 47 control subjects from finger and toe. The repeatability of the method was analyzed by means of intra-class correlation coefficients (ICC) and free-marginal multirater κ agreement. The metrics were computed for individual PWs as well as for averages based on 10–100 PWs. The ICCs increased with number of PWs utilized — ICCs and κ agreements higher than ≥ 0.90 were widely achieved based on the averages of ≥ 20 PWs, depending on the parameter or study group. Based on the present results, the FT-plot based detection of atherosclerotic changes has at least equal repeatability compared with a current clinical standard, ankle-to-brachial pressure index. However, further studies should validate the findings before the method is ready for the screening of atherosclerotic changes.**

Keywords— **Atherosclerosis, Photoplethysmography**

I. INTRODUCTION

The degenerative changes of the arterial tree include stiffening and thickening of the arterial walls. From a clinical point of view, both conditions are a continuum of degenerative changes and can be asymptomatic for relatively long time. Methods for estimating these changes include the angiograms and the measurement of carotid-femoral pulse wave (PW) velocity or the intima media thickness of the carotid artery by using ultrasound transducers [1, 2, 3], but they require a skilled operator and expensive equipment. Advanced occlusive atherosclerosis can be diagnosed by measuring ankle-to-brachial pressure index (ABI), but its performance decreases when there are also mediasclerotic changes present [4]. To be able to detect especially subclinical atherosclerosis and to reduce morbidity by risk factor modification, there is a growing need for alternative cost-effective and rapid methods for monitoring the vasculature.

Many methods utilizing non-invasively recorded arterial PWs have been reported for characterizing the vascular status as e.g. in [5, 6]. Earlier, we have presented a method called finger-toe (FT) plot analysis for finding the atherosclerotic changes and analyzed its discrimination capability, finding an average area under curve (AUC) value of 91.6% [7]. The method combines the photoplethysmographic (PPG) signals recorded from the index finger and the second toe. The aim of the present study is to characterize the short-term variation of the results of the FT-plot analysis and how averaging of PWs affects to the variation.

II. MATERIALS AND METHODS

A. *Measurement conditions and study subjects*

All the volunteer test subjects participating in the study were examined in supine position in two Finnish University Hospitals (Tampere and Oulu) and in Tampere University of Technology (TUT) with transmissive PPG probes connected to a wireless body sensor network (WBSN) [8]. The WBSN filters out the DC-component of the PPG (cut-off frequency 0.15 Hz) and its sampling frequency is 500 Hz [8]. 15 of the subjects were also examined with a PPG-devise using phase-sensitive technique (PSP, phase-sensitive PPG) having a sampling frequency of 1 kHz and pass-band from DC to 47 Hz. Approximately 15-min PPG signals were recorded from the left index finger and the second toe. The excitation wavelengths of the PPG were 905 nm (WBSN) and 920 nm (PSP).

The study subjects were divided into different groups as shown in Table 1. Group A was consisted of older than 65 years atherosclerotic patients having abnormal ABI (ABI $<$ 0.9 or ABI $>$ 1.3). Group B consisted of old control subjects

Table 1: Different study groups and the numbers and proportions of test subjects having different cardiovascular risk factors.

Group	A	B	C	D	B,C,D	A,B,C,D	E&F
Subjects	24	18	17	12	47	71	15
Age criteria	>65	> 70	40–69	<40	-	-	-
Age ($m \pm s$)	73.0±7.1	76.4±5.5	60.9±7.1	29.6±4.6	58.9±19	63.6±17	70.1±3.7
Males	18 (75%)	6 (33%)	11 (65%)	12 (100%)	29 (62%)	47 (66%)	7 (47%)
Diabetes	13 (54%)	1 (6%)	1 (6%)	1 (8%)	3 (6%)	16 (23%)	5 (33%)
Dyslipid.	16 (67%)	3 (17%)	2 (12%)	0 (0%)	5 (11%)	21 (30%)	9 (60%)
Smoking	19 (79%)	3 (17%)	3 (18%)	0 (0%)	6 (13%)	25 (35%)	10 (67%)
Rheum. a.	1 (4%)	3 (17%)	1 (6%)	1 (3%)	5 (11%)	5 (7%)	3 (20%)
Hypertens.	19 (79%)	3 (17%)	3 (18%)	0 (0.0%)	6 (13%)	25 (35%)	10 (67%)

having normal ABI. Groups C and D consisted of younger test subjects with no cardiovascular problems. 15 subjects in groups A–C were examined with both systems (WBSN and PSP), forming datasets E (WBSN) and F (PSP). The groups A–D contain data from 75 subjects, but the signal-to-noise ratio (SNR) was too low for the repeatability analysis in 4 subjects.

The study was approved by the ethical review boards of the hospitals and the Finnish National Supervisory Authority of Health and Welfare. Informed consents were obtained from the test subjects.

B. Finger-toe plot analysis

Details for computation of the FT plot are presented in [7]. In FT plot analysis, the PPG signal from the second toe (Figs. 1a–b and 2a–b) is drawn as a function of the PPG signal recorded from the index finger and the features are extracted from region that represents the falling parts of the PWs, i.e. the region from the peak value of the PW to the baseline of the PW. This corresponds in Figs. 1b and 2b to the curve from the right upper corner to the left lower corner and this region is extracted to Figs. 1c and 2c. Before the features are extracted from the region shown in Figs. 1c and 2c, it is rotated by $-60°$ in order to enable curve fitting in cartesian coordinates. After the rotation, a 9^{th}-order polynomial p is fitted to the rotated curve by using least mean square (LMS) algorithm. The 9^{th}-order polynomial follows sufficiently the original curve but does not suffer from overfitting. In addition to the polynomial, a line l is fitted to middle-region (i.e. to the region where $x_1 < x < x_2$, $x_1 = 0.15\Delta x$ and $x_2 = 0.85\Delta x$ where Δx is the width of rotated the FT-plot curve) of the rotated part of the FT-plot by using LMS algorithm. 11 different features are extracted from the FT-plot and labeled as 1–11 [7]:

1. Maximum difference of the slopes in the middle-region, i.e. $\max(p') - \min(p')$.
2. Mean absolute slope of the middle-region, i.e. $\text{mean}(|p'|)$
3. Standard deviation of the slope of the middle-region, i.e. $\text{std}(p')$
4. Standard deviation of the absolute slope of the middle-region, i.e. $\text{std}(|p'|)$
5. Integral absolute error between the fitted line and polynomial fit in the middle-region, i.e. $\int_{x_1}^{x_2} |l(x) - p(x)| \mathrm{d}x$
6. Integral square error between the fitted line and polynomial fit in the middle-region, i.e. $\int_{x_1}^{x_2} (l(x) - p(x))^2 \mathrm{d}x$
7. The arc length of the middle-region normalized by the distance between its endpoints, i.e. $\frac{1}{\sqrt{(x_2-x_1)^2+(p(x_2)-p(x_1))^2}} \int_{x_1}^{x_2} \sqrt{1+[p'(x)]^2} \mathrm{d}x$

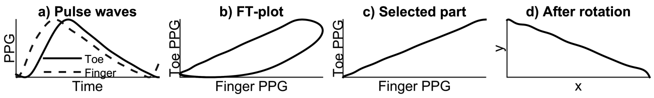

Figure 1: Finger and toe PPG PWs for an atherosclerotic patient (a). FT-plot, i.e. toe-PPG drawn as a function of finger-PPG (b). Region selected for the analysis (c). The selected region after the rotation (d).

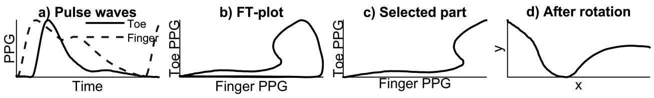

Figure 2: Finger and toe PPG PWs for a healthy subject (a). FT-plot, i.e. toe-PPG drawn as a function of finger-PPG (b). Region selected for the analysis (c). The selected region after the rotation (d).

8. The arc length of the middle-region normalized by the distance between the endpoints of the rotated curve, i.e. $\frac{1}{\sqrt{(\Delta x)^2+(\Delta y)^2}} \int_{x_1}^{x_2} \sqrt{1+[p'(x)]^2} \mathrm{d}x$
9. The maximum absolute difference between the slope of the polynomial fit and the slope of the fitted line, i.e. $\max(|p' - l'|)$
10. The slope of the fitted line, l'.
11. Ratio of the areas under the finger and toe PPG, i.e. $\frac{A_{finger}}{A_{toe}}$.

Seven linear discriminant analysis (LDA) based classifiers (Table 2 and [7]) labeled as I–VII were composed. The short-term repeatability of the resulting LDA-outputs, both numerical values of the classifying variables and the binary classification results, are analyzed in the present study.

C. Evaluation of the repeatability

Intra-class correlation coefficient (ICC) is commonly used parameter for estimating the repeatability. It is defined as a ratio of between-subject variance and the sum of between- and within-subject variances and can be estimated as

$$\text{ICC} = (\text{MS}_{\text{bs}} - \text{MS}_{\text{ws}})/(\text{MS}_{\text{bs}} + (k-1)\text{MS}_{\text{ws}}) \quad (1)$$

in which MS_{bs} is between-subject mean-squares, MS_{ws} is within-subject mean squares as a result of 1-way analysis of variance (ANOVA) and k is the number of observations per subject [9]. In addition to ICC, the repeatability of the results is estimated also with free-marginal multirater κ coefficient as

$$\kappa = (P_o - P_e)/(1 - P_e) \quad (2)$$

in which P_o is the proportion of overall observed agreement and $P_e = 1/2$ is the proportion of agreement expected by chance [10]. The free-marginal κ was selected instead of Fleiss' fixed-marginal κ because the value of the latter one

Table 2: Features that different classifiers I-VII utilize.

Classifier	I	II	III	IV	V	VI	VII
Features	5,6,10,11	1,5,6,10, 11	2,3,5,6, 11	5,6,7,10, 11	5,6,9,10, 11	1,3,5,6, 10,11	4,5,6,7, 10,11

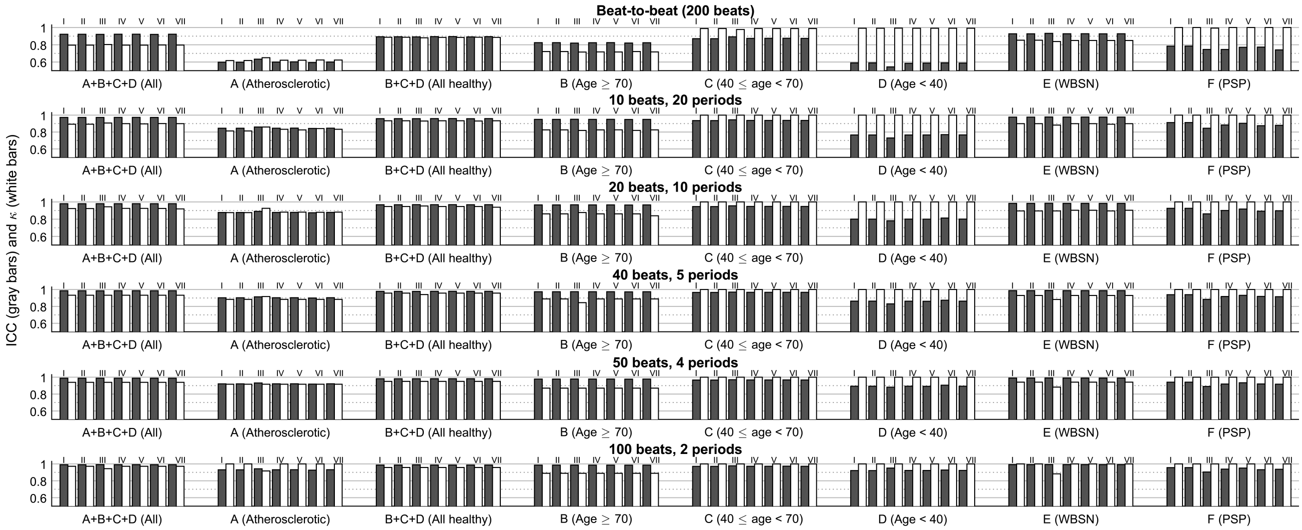

Figure 3: ICC (gray) and κ values (white) for different classifiers I-VII, datasets and numbers of averaged PWs.

depends strongly on the symmetry of the data [10]. The classification into healthy or atherosclerotic for the κ analysis is based on the same data utilized in the ICC analysis: the test subjects are categorized based on the values of parameters derived from the FT-plots and the thresholds presented in [7]. Both ICCs and κ are computed for different datasets and study groups as follows: beat-to-beat data for a single period of 200 beats, and averaged features (arithmetic mean) based on 20 periods of 10 beats, 10 periods of 20 beats, 5 periods of 40 beats, 4 periods of 50 beats and 2 periods of 100 beats.

III. Results

All the ICCs having the p-values less than 10^{-5}. κ-values for the different features, study groups and different numbers of PWs are shown as barplots in Fig. 3. ICCs are shown in gray bars and κ-values in white bars. The ICC and κ-values are in almost all the cases higher than 0.80 except beat-to-beat data which contain widely lower values especially in atherosclerotic group. Generally, this is supported by our earlier studies: there can be differences of 20 percentage points between the PW parameters derived from two successive PWs [8]. Thus, there is no sense to make any diagnosis based on individual PWs as a source of information since higher number of PWs is easily recorded when the PPG-probes are once attached. According to our results, increasing the number of the PWs from e.g. from 40 to 100 does not increase as significantly the ICCs or κ-coefficients and ICC (Fig. 3) as e.g. the change from individual PWs to averages based on 10 PWs does. If there is uncertainty in the interpretation of a single measurement, the experiment having a duration less than one minute (e.g. 10 to 40 PWs) is quick to repeat a couple of times. This is a benefit compared to the ABI since obtaining a single ABI reading may take several minutes.

As seen in Fig. 3, there are many cases in which the youngest test subjects' and atherosclerotic patients' ICC values are lower than those in other study groups. With the atherosclerotic patients, the explanation might be lower SNR due to decreased blood perfusion and with younger subjects, high heart rate variability and vasoregulatory oscillations which may affect the propagation of the PWs and thus alter their waveforms.

IV. Discussion

The repeatabilities found in this study and the classification performances in [7] for different classifiers are close to each other. The set of all possible classifiers contains also the classifiers with poor performance [7], and the best-performing classifiers are practically alternatives to each other.

A. *Comparison with ABI*

There are many studies reporting that the typical differences of the ABI values between different measurements are ±0.1 ABI points. [11, 12, 13]. For the within-visit repeatability of the ABI, ICCs of 0.90–0.93 have been reported in [14] and 0.72–0.85 in [15]. Lower ICC value of 0.75 has been reported in [16]. For comparison, 58% out of all the computed ICCs (Fig. 3) are higher ICC than 0.93 and 95% are higher than 0.72. For the averages based on 20 PWs, all ICCs shown in Fig. 3 are higher than 0.72 and 62% of them are higher than 0.93, and for the averages based on 100 PWs, all ICCs are higher than 0.72 and 85% of them are higher than 0.93.

B. Comparison with other PW derived indices

Depending on the study group and the number of analyzed PWs, the ICCs found in this study are mostly at the same level or better than ICCs reported for direct PW derived features. ICCs of 0.93–0.96 have been reported for the augmentation index (AIx) based on the radial artery PWs [5]. The ICC of 0.84 has been reported for the index finger PPG based aging index (AGI) [17]. These are at the same level as we found in our comparative study in which the repeatabilities of AIx, reflection indices, and AGI were studied for the features extracted from the data recorded as PPG signals from index finger and second toe as well as dynamic pressure PWs from cubital fossa, wrist and ankles [6].

Even the repeatabilies of the FT-plot analysis and direct PW-derived parameters are approximately at the same level, there are differences in the discrimination capabilities: AUCs of 0.8–0.97 were found for the FT-plot [7] whereas AUCs in maximum of 0.88 were found for the direct PW-derived parameters when study subjects were divided into healthy and atherosclerotic patients based on the PW signals [6].

V. CONCLUSIONS

The short-term stability of combined finger and toe PPG analysis (FT-plot) was studied. Compared with the results found for individual PWs, the repeatability of the method improved when multiple PWs were utilized in the analysis. According to the results, 40, 50 and 100 PWs were required for obtaining the repeatability level having the ICCs of 0.80, 0.85 and 0.90, respectively. The repeatability found in this study and discrimination capability reported in [7] emphasize the potential of the simple and non-invasive PPG measurement. The method could be useful in the vascular screening in health centers besides the ABI measurement facilitating the preventive strategies against vascular diseases. Still, further investigations are required for the generalization of the results and because the repeatability was lower in the groups consisting of atherosclerotic patients and the youngest subjects.

VI. ACKNOWLEDGMENT

The test subjects and the personnel in the Tampere and Oulu University Hospitals (vascular diseases) are acknowledged. The work was funded by the Doctoral Programme of the President of the TUT, Finnish Funding Agency for Technology and Innovation (TEKES, VitalSens project 40103/14), and grants from Finnish Cultural Foundation, Tekniikan edistämissäätiö and Emil Aaltonen Foundation.

CONFLICT OF INTEREST

The authors declare that they have no conflict of interest.

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