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RESEARCH ARTICLE

HRV-based Stress Level Assessment Using Very Short Recordings

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Abstract
The increased stress level of an individual often influences the medical test results. Heart rate variability (HRV) can be used to characterize stress level. Parameters in the time domain are preferred, as they make the assessment possible from relatively short (3 - 5 minute-long) recordings. Electrocardiographic signal (ECG) in Einthoven I lead and photoplethysmographic signal (PPG) at the fingertip were recorded in parallel. This paper analyzes the differences between the lengths of successive heart cycles (NN); the ratio of these differences exceeding 50 ms (pNN50) is considered to be a good measure of stress. The parameter triplet pNNtri has been defined dividing the differences of successive NN intervals into three categories: pNN0_20 (0 – 20 ms), pNN20_50 (20 – 50 ms) and pNN50 (greater than 50 ms). pNNtri characterizes the actual stress level significantly better (especially for senior persons) than pNN50 alone. NN intervals determined from PPG differ from those determined from ECG recorded in parallel.

Keywords
stress, HRV, relaxation, balance test

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1 Introduction

The sympathetic and parasympathetic divisions of the autonomic nervous system regulate the body's unconscious actions. The former is responsible for the fight or flight response, the latter for the rest-and-digest operation. Sympathetic dominance increases, whereas the parasympathetic division decreases, stress that is a rather intricate phenomenon. Several physiological parameters (e.g., heart rate and blood pressure, BP) typically depend upon stress level. Selye considered stress and the related general adaptation syndrome so complex that complete human comprehension of it might never be attainable [1]. In the biological sense, he took stress as the interaction between damage and defense. Measuring stress is not easy. A good summary was provided by the Centre for Studies on Human Stress [2]. Even more difficult is the simple assessment of the momentary stress level of people without involving medical experts. It would be advantageous to know the stress level, as it may influence the results of medical assessments. The relationship between stress and BP is well-known [3-6]. Mental, as well as emotional, stress can cause a temporary increase in BP [7]. The determination of heart rate variability (HRV) is recommended to assess momentary stress level. An extensive summary and theoretical grounding of HRV is given in [8] and [9]. Chen et al. [10] suggested a novel index to continuously and quantitatively characterize cardiac stress status during physical exercise. The relationship between subjective self-reported stress and objective HRV-based stress was studied in [11]. Methods used for mental stress assessment via short-term HRV analysis were described in [12]. Advanced and easy-to-use software for HRV analysis was developed at the University of Eastern Finland. Kubios software [13] supports the experimental analysis of electrocardiographic signal (ECG) recordings; it can also handle the lengths of heart cycles (NN) calculated from photoplethysmographic signal (PPG) recordings.

The aim of our research was to propose a parameter able to characterize the momentary stress level of people based on very short (1 – 2 minute long) recordings. This can help prevent health personnel from using measured physiological data distorted by stress (e.g., white coat effect). It can also increase the reliability of home health measurements. The research work also aimed at comparing ECG and PPG based measurement of beat-to-beat time intervals to assess how efficiently devices able to measure PPG (e.g. smartphones) can be used for HRV measurement.

HRV characterizes the variation in the NN interval. These intervals should be measured by detecting R peaks in ECG. The beat-to-beat intervals in ECG are called RR intervals. In the frequency domain, the dominant bands of HRV are as follows: high-frequency (HF) 0.15 – 0.4 Hz, low-frequency (LF) 0.04 – 0.15 Hz and very-low frequency (VLF) 0.0033 – 0.04 Hz. Some sources [14] also define the ultra-low frequency band (ULF) below 0.0033 Hz. Analysis of the VLF range needs a resolution of at least 2 mHz, requiring a minimum 500-s long recording. A nearly 10-minute recording is quite long. A BP monitor requiring a 10-minute testing period before starting the measurement is not ideal. Time domain analysis is better for relatively short recordings; pNN50 is a widely used parameter. The differences in successive NN intervals are calculated; pNN50 is the ratio of differences exceeding 50 ms to the total number of differences. A decrease in pNN50 indicates an increase in stress level [15]. Nonlinear methods [16] are powerful, but come at a higher computational cost. Melillo et al. [17] reported the stress assessment of students awaiting examination at a university; the recordings taken were 5 minutes long. Patil et al. [18] suggested using HRV to evaluate mental stress.

NN intervals (NNppg) can also be derived from the PPG. Different research groups have studied comparisons of HRV parameters derived from ECG and PPG. Bolanos et al. [19] found good correlation for time domain parameters that did not depend on the order of beat-to-beat interval lengths, including minimum, maximum, mean, and standard deviation. Measurements were made from a healthy female and a healthy male. Lin et al. [20] analyzed recordings taken from 8 young healthy individuals at rest and following mild exercise. At least 3 minute-long recordings were necessary for the frequency domain analysis. The correlation between ECG- and PPG-based parameters was found to be good for people at rest and worse following mild exercise. Jeyhani et al. [21] reported measurements taken from 19 young healthy males. NNppg values were determined in two ways: by detecting the (a) peak values and (b) maximum values of the second derivative of PPG. The maximum deviation from ECG-based values in pNN50 was 30 % using the (a) method and 43 % using the (b) method.

2 Materials and methods

2.1 The device and signal processing applied

A home health monitoring device (HHMD [22], [23], see Fig. 1) was developed at the Department of Measurement and Information Systems, Budapest University of Technology and Economics.

Einthoven I lead ECG was taken by electrodes touched by the palms. An additional electrode under the right palm was used for body surface potential driving to increase signal-to-noise ratio. ECG quality was not worse than that taken with conventional limb electrodes.

Fig. 1 A tested person with the HHMD watching a relaxing video.

The HHMD was applied to measure BP and to record the ECG in Einthoven I lead as well as the PPG from the index finger. The sampling frequency was 1000 samples/s, and the amplitude resolution of the AC coupled signals was 12-bit. The cuff pressure (CP) profile of the HHMD is the following. The pressure change rate during both inflation and deflation is approximately 6 mmHg/s. During the first 24 s the cuff is completely deflated. Then inflation starts and lasts until the maximum is reached at CP = 180 mmHg. Should the HHMD detect the systolic pressure at a lower CP, inflation is terminated. Slow deflation lasts until the CP reaches 40 mmHg when it abruptly drops to 0 mmHg. ECG and PPG values are recorded for a further 24 s. Two versions of HHMD were used. The first version has reflection mode PPG sensors for both index fingers. The second version uses a transmission mode PPG sensor that can be fixed with a clip to the index finger of the tested person. This also allows for the PPG measurement of standing people.

The R peak in the ECG indicates the beginning of ventricular contraction. Following a short – but modestly varying – isovolumetric contraction (duration 15 – 25 ms), the aortic valve opens and the pulse wave starts traveling to the index finger, reaching the tip in about 150 – 200 ms. Upon arrival, the blood volume in the fingertip begins to increase decreasing the output light intensity. The light sensor is coupled to an inverting amplifier thus the decrease in light intensity causes the PPG to increase. The time interval from the QRS in ECG until the next local minimum in PPG is called pulse wave transit time (PWTT). The PPG minimum points were detected following bandpass filtering (4^{th} order IIR Butterworth filter, cutoff frequencies 1 and 6 Hz) and detrending. No interpolation was used. NN intervals were determined at a resolution of 1 ms. The software of the HHMD was developed in C++. MATLAB R2007b (The Mathworks) was used for analyzing the ECG and the PPG.

2.2 Test procedures

All attempts were made to record measurements at the same time of day. There were two types of test procedures.

(A) Test subjects were sitting in a chair comfortably. Parallel ECG and PPG recordings were taken while tested persons placed their hands on the ECG electrodes of the HHMD as shown in Fig. 1. PPG was recorded with either a reflection or a transmission type sensor. One test step lasted for two minutes when the cuff was not inflated (tests (a), (c), (d) and (e)). It lasted for about 100 s when cuff-based oscillometric BP measurement was taken with the HHMD (test (b)). Tests (c) and (d) were supposed to increase the stress level.

- (a) Test subjects were sitting in a chair at rest. The cuff around their upper arm was completely deflated.
- (b) Oscillometric BP measurement was taken using the CP profile given in 2.1.
- (c) The tested person's stress level was influenced by two different movies: one relaxing (meadows, rivers and relaxing music) and one with offensive actions and hard rock music.
- (d) Test subjects counted down from 1058 by 17 while saying the numbers aloud. In cases of a mistake, counting was repeated from 1058 once more.
- (e) Test subjects tried to reach deep relaxation with their eyes closed, deep breathing and meditating.

(B) Test subjects were performing balance tests. An inertial measurement unit (x-IMU, [24]) was fixed to the back of the persons and a PPG sensor clip was fixed to their index finger (see Fig. 2). The minimum length of the test sequence was 140 s when only test (a) was performed. The maximum length of the test sequence was 300 s when tests (a), (b) and (c) were performed one after the other. PPG was recorded continually from the beginning until the end of the test sequence. The output signals of x-IMU were recorded from the beginning until the end of each test step. Based on these signals the stability in standing could be characterized.

- (a) Standing on the floor. There were five steps of the test: standing on both feet with eyes open, standing on both feet with eyes open while holding their breath, standing on both feet with eyes closed, standing on the left foot only, and standing on the right foot only. Each test step lasted for 20 seconds with 10-second breaks in-between.
- (b) Standing on a sponge rubber. Recording lasted for 60 seconds.
- (c) Difficult balance tests, either standing on a rocker board or on a board-on-stone. Recording lasted for 60 seconds.

2.3 Population

Altogether 68 2-minute recordings were taken from four healthy subjects sitting comfortably at rest (measurement situation A, test (a), number of recordings in brackets): 66-year-old male (21), 28-year-old male (19), 24-year-old male (20) and 23-year-old female (8).

Parallel ECG and PPG recordings were taken from 56 people at rest while measuring their BP with the HHMD (measurement situation A, test (b), results given in Table 3). Forty-five young (age 22 – 26 years) healthy people, three senior (age 55 – 65 years) healthy people and eight senior patients with cardiovascular diseases (age 55 – 65 years, seven of them went through open chest cardiovascular surgery) were tested. The aim of the evaluation of these recordings was to assess the difference between RR and NNppg intervals. In all more than 3500 heartbeats were analyzed.

Fig. 2 Tested person standing on the floor. The PPG sensor was placed on the right index finger, and x-IMU was fixed to her back.

Twenty-one people (9 females and 12 males) performed the (c) and (d) tests of measurement situation A. Of them, 16 were young (20 - 28 years old, 6 females, 10 males), 2 were between 35 and 40 years (both females), and 3 were senior (60 - 65 years old, 1 female, 2 males).

Measurement situation A, test (e) was performed by one 65-year-old healthy male six times, one 28-year-old healthy male six times and a 23-year-old healthy female once.

Twenty-five people (8 females and 17 males) performed the tests of measurement situation B. Of them, 21 were young (20 - 24 years old, 5 females, 16 males) and 4 were senior (50 - 80 years old, 3 females and 1 male). All tested persons performed the measurement situation B test (a). Tests (b) and (c) of measurement situation B were performed by 10 young (3 females and 7 males) persons and one senior (male) person.

3 Results

The differences in successive NN intervals were classified into three categories: 0 – 20 ms (pNN0_20), 20 – 50 ms (pNN20_50) and 50 < ms (pNN50). The three categories were expected to provide better resolution than the widely used pNN50 parameter alone. The three parameters together are referred to as pNNtri.

3.1 Comparison of beat-to-beat intervals derived from ECG and PPG

The lengths of the heartbeats derived from ECG differed from those derived from PPG recorded in parallel.

3.1.1 During oscillometric blood-pressure measurement

For each of the tested 56 persons (see Table 3), pNN0_20, pNN20_50 and pNN50 parameters were determined both from ECG and PPG while CP was lower than the systolic BP. The relative difference in pNN0_20,

$$\text{diff0\_20} = \frac{\text{pNN0\_20}_{ECG} - \text{pNN0\_20}_{PPG}}{\text{pNN0\_20}_{ECG}} \times 100 \tag{1}$$

was found to exceed 20 % in 13 recordings (23 %). The difference in pNN0_20 can be extremely high, especially for patients: the same recording showed 83.8 % calculated from ECG and 45.9 % from PPG (P02). diff20_50 and diff50 were calculated similarly to equation (1). diff20_50 was found to exceed 20 % in 31 recordings (55 %). The difference in pNN20_50 can be extremely high: evaluation of the same recording showed 2.5 % from ECG and 30 % from PPG (P04). diff50 was found to exceed 20 % in 21 recordings (38 %). The difference in pNN50 can be extremely high: evaluation of the same recording showed 0 % from ECG and 24 % from PPG (P02).

In 44 recordings (79 %), the calculated pNN0_20 value was smaller from PPG than from ECG. In 40 recordings (71 %) pNN20_50 was greater when calculated from PPG than from ECG. For pNN50, the percentage change could not be calculated in all cases. The reason for this is that pNN50_{ECG} can be zero while pNN50_{PPG} for the same recording is not zero.

The standard deviation of RR is similar to that of NNppg. The mean difference between standard deviations was 7 % for all 56 recordings and 4 % for young people.

3.1.2 During two-minute recording at rest while CP = 0

Sixty-eight recordings were taken from four healthy persons. For one test the following parameters help characterize the difference in results calculated from ECG and PPG: RR(i), NNppg(i), ΔRR(j), ΔNNppg(j), differenceNN(i), differenceΔNN(j).

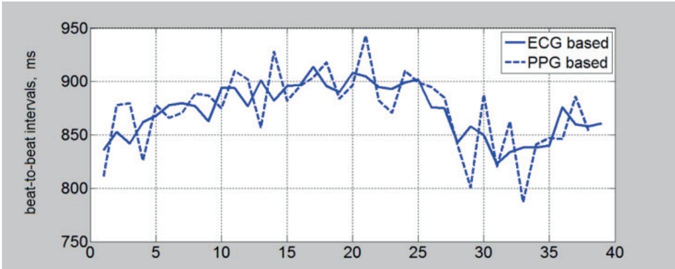
$$\Delta RR(j) = RR(j+1) - RR(j), j = 1, 2, ..., i-1 \tag{2}$$

$$\Delta NNppg(j) = NNppg(j+1) - NNppg(j), j = 1, 2, ..., i-1 \tag{3}$$

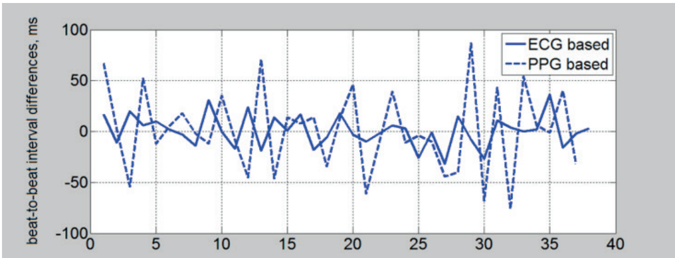
$$\text{differenceNN}(i) = \frac{\text{abs}(RR(i) - NNppg(i))}{\dfrac{RR(i) + NNppg(i)}{2}} \times 100 \tag{4}$$

$$\text{difference}\Delta\text{NN}(j) = \frac{\text{abs}(\Delta RR(j) - \Delta NNppg(j))}{\dfrac{\Delta RR(j) + \Delta NNppg(j)}{2}} \times 100 \tag{5}$$

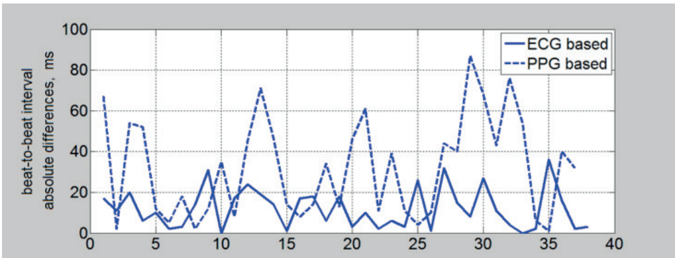
Fig. 3 shows the beat-to-beat intervals (a.), the interval differences (b.) and the absolute values of the differences (c.) of a senior person calculated from ECG and PPG.



a.



b.



c.

Fig. 3 Beat-to-beat intervals (a.), beat-to-beat interval differences (b.) and beat-to-beat absolute differences (c.) calculated from ECG and PPG recorded in parallel. 65-year-old senior healthy male at rest.

The mean value and the standard deviation of the differences for the 68 recordings are given in Table 1.

Table 1 Relative differences in NN and ΔNN values calculated from ECG and PPG (sixty-eight recordings taken from four healthy persons at rest).

	mean value	standard deviation
differenceNN	0.71 %	0.27 %
differenceΔNN	36.6 %	17.7 %

3.2 Age differences in pNNtri

The regularity of pulse frequency changes with aging. The recordings in Table 3 were analyzed. For the senior group (8 patients, 3 healthy persons), smaller differences between adjacent heart cycles dominate than for the young group (see Table 2).

Table 2 The average values and standard deviations of pNNtri values calculated from RR intervals for persons during oscillometric BP measurement.

	pNN0_20	pNN20_50	pNN50
senior persons	81.8±15.8	17.4±15.6	0.8±1.6
young persons	50.8±19.4	29.5±8.4	19.7±16.2

3.3 Stress test results

The aim of these tests was to assess the characteristics of pNNtri not to measure the actual stress level of persons. The parameter values were calculated from RR intervals. The two movies (measurement situation A, test (c)) did not result in significant differences in pNNtri values for any tested person.

Fig. 4 shows the results of a 65-year-old male at rest, sitting in a chair (measurement situation A, test (a)). Recordings were taken for four consecutive weeks in the same time of day.

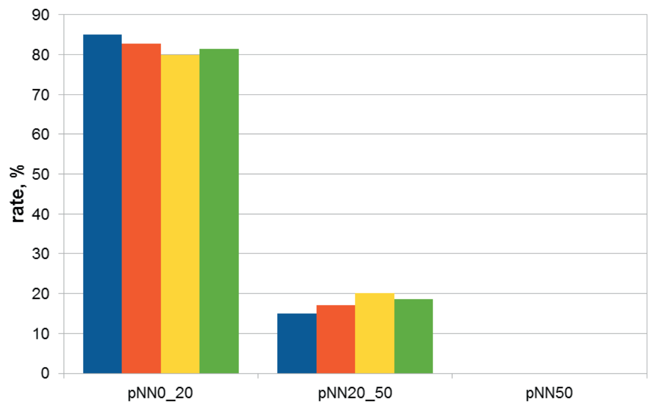


Fig. 4 pNNtri components of four recordings taken from a 65-year-old male under normal stress. One week passed between the recordings.

Fig. 5 shows the results of a 65-year-old male at rest and in forced relaxed state (measurement situation A, test (e)).

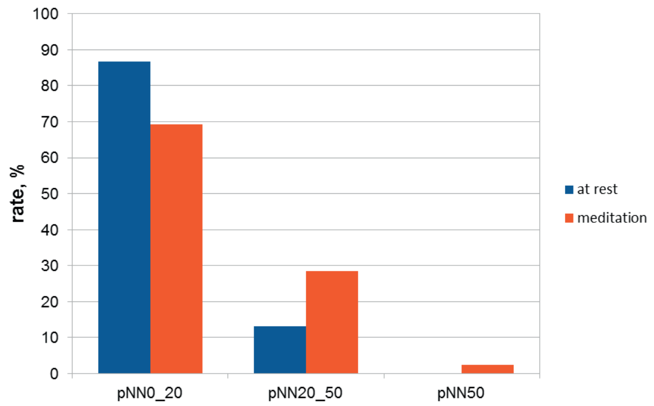


Fig. 5 pNNtri components of recordings taken from a 65-year-old male under normal and forced relaxed state.

Fig. 6 shows the results of psychological stress applied to a 39-year-old female (measurement situation A, test (d)).

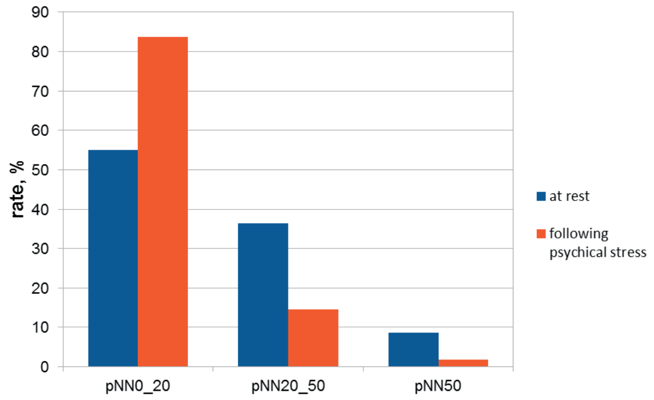


Fig. 6 pNNtri components of recordings taken from a 39-year-old female under normal and increased stress. There was no break between the two recordings.

3.4 Balance test results

The stress level during the balance tests was estimated from PPG by calculating pNN0_20, pNN20_50 and pNN50. Fig. 7 shows the results of a 22-year-old male during different balance tests.

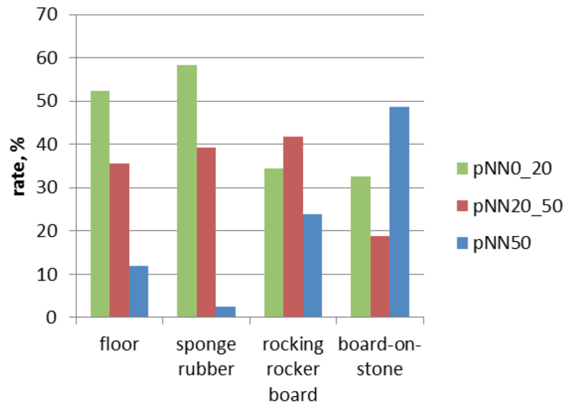


Fig. 7 Results of a 22-year-old male during different balance tests.

4 Discussion

PWTT fluctuates in time thus the difference between RR and NNppg intervals belonging to the same heartbeat also fluctuates. PWTT may change in every heartbeat; it was not constant during the recordings. Its variation causes a difference in beat-to-beat intervals derived from PPG (NNppg) and ECG (RR). The absolute differences of adjacent beat-to-beat intervals are typically greater when calculated from PPG than from ECG. The sign of (PWTT(i+2) – PWTT(i+1) is typically different from the sign of (PWTT(i+1) – PWTT(i)). This results in the following typical relations:

$$\mathrm{abs}(\Delta RR(j) - \Delta \mathrm{NNppg}(j)) > \mathrm{abs}(\mathrm{RR}(i) - \mathrm{NNppg}(i)) \quad (6)$$

$$\mathrm{RR}(i) + \mathrm{NNppg}(i) >> \Delta \mathrm{RR}(j) + \Delta \mathrm{NNppg}(j) \quad (7)$$

Table 3 Recordings in relaxed state. PO: patients who underwent open chest cardiac surgery. P: patient with cardiac disease. S: senior healthy, Y: young healthy persons.

	pNN0_20			pNN20_50			pNN50			beat-to-beat interval (NN), ms					
										from ECG		from PPG			
	ECG	PPG	diff0_20, %	ECG	PPG	diff20_50, %	ECG	PPG	diff50, %	mean	std	mean	std	NN diff, %	tested persons
PO1	100.00	87.20	12.8	0.00	10.3	n.a.	0.00	2.6	n.a.	749.5	6.9	747.7	13.5	0.2	senior patients with cardiovascular disease
PO2	83.80	45.90	45.2	16.20	29.7	-83.3	0.00	24.3	n.a.	872.6	24.5	873.6	34.4	0.1	
PO3	54.1	51.4	5.0	43.2	35.1	18.8	2.7	13.5	-400.0	1048.3	33.0	1048.4	34.9	0.0	
PO4	97.5	62.5	35.9	2.5	30.0	-1100.0	0	7.5	n.a.	806.4	12.6	806	17.8	0.0	
PO5	89.2	70.3	21.2	10.8	29.7	-175.0	0	0.0	n.a.	835.4	9.6	835.5	13.5	0.0	
PO6	80.6	66.7	17.2	19.4	30.6	-57.7	0	2.8	n.a.	1042.7	13.8	1044.8	18.2	0.2	
PO7	90.5	81	10.5	4.8	14.3	-197.9	4.8	4.8	0.0	685.6	14.7	686.1	20.6	0.1	
P8	96.5	98.8	-2.4	3.5	1.2	65.7	0	0.0	n.a.	555.3	14.8	555.1	13.9	0.0	
S1	83	60	27.7	16.1	37.0	-129.8	0.9	3.0	-233.3	817.4	18.8	817.3	22.2	0.0	healthy senior persons
S2	57.9	60.5	-4.5	42.1	39.5	6.2	0	0.0	n.a.	934.7	27.2	931.9	26.2	0.3	
S3	67.1	66.4	1.0	32.2	31.5	2.2	0.7	2.1	-200.0	849	25.2	849	25.9	0.0	
Y1	34.4	28.3	17.7	29.5	33.3	-12.9	36.1	38.3	-6.1	941.2	105.9	940.3	110.2	0.1	young healthy persons
Y2	13.6	20.5	-50.7	31.8	40.9	-28.6	54.5	38.6	29.2	989.4	92.9	990.8	91.2	0.1	
Y3	85.7	57.1	33.4	10.7	32.1	-200.0	3.6	10.7	-197.2	695.4	23.6	695.6	27.7	0.0	
Y4	81.8	77.4	5.4	18.2	22.6	-24.2	0	0.0	n.a.	654.9	26.7	655.2	27.7	0.0	
Y5	50	47.5	5.0	36.9	39.3	-6.5	13.1	13.1	0.0	772.2	56.3	772.6	57.3	0.1	
Y6	57.3	48.3	15.7	29.2	38.2	-30.8	13.5	13.5	0.0	584.3	59.4	583.7	61.8	0.1	
Y7	42.9	46.2	-7.7	27.7	25.2	9.0	29.4	28.6	2.7	832.9	87.3	833.7	87.7	0.1	
Y8	67.3	71.4	-6.1	28.6	22.4	21.7	4.1	6.1	-48.8	608.2	60.6	609.9	60.7	0.3	
Y9	69.1	65.5	5.2	29.1	33.6	-15.5	1.8	0.9	50.0	771	41	771.2	41.8	0.0	
Y10	35.9	32.6	9.2	38	35.9	5.5	26.1	31.5	-20.7	807.1	45.9	806.7	47.7	0.0	
Y11	17.8	14.9	16.3	25.7	25.7	0.0	56.4	59.4	-5.3	873.9	68.7	874.5	70.7	0.1	
Y12	55.2	50	9.4	36.2	37.9	-4.7	8.6	12.1	-40.7	619.8	62.9	619.5	65.3	0.0	
Y13	25	20.6	17.6	29.4	29.4	0.0	45.6	50.0	-9.6	826.1	95.8	825.2	99.7	0.1	
Y14	20.2	17.2	14.9	46.5	48.5	-4.3	33.3	34.3	-3.0	897	48.9	896.5	50.7	0.1	
Y15	63.9	56.3	11.9	31.9	39.5	-23.8	4.2	4.2	0.0	785.6	32.8	785.4	33.1	0.0	
Y16	70.1	57.1	18.5	11.7	28.6	-144.4	18.2	14.3	21.4	672.8	65.8	672.7	67	0.0	
Y17	45.6	36.8	19.3	35.3	43.4	-22.9	19.1	19.9	-4.2	651.4	54.8	652	55.9	0.1	
Y18	55.3	47.7	13.7	32.6	37.9	-16.3	12.1	14.4	-19.0	901.3	49.9	899.5	47.9	0.2	
Y19	74	51	31.1	22	39.0	-77.3	4	10.0	-150.0	661.7	58.6	661.5	62.6	0.0	
Y20	28.2	28.2	0.0	41	38.5	6.1	30.8	33.3	-8.1	726.6	69	731	67	0.6	
Y21	51.1	45.7	10.6	30.4	35.9	-18.1	18.5	18.5	0.0	794.2	56.9	793	57.6	0.2	
Y22	54.8	52.1	4.9	37	39.7	-7.3	8.2	8.2	0.0	649.3	44.1	649.6	45	0.0	
Y23	50	42.1	15.8	34.2	44.7	-30.7	15.8	13.2	16.5	853.6	40.5	854.1	42.7	0.1	
Y24	55	47.5	13.6	22.5	30.0	-33.3	22.5	22.5	0.0	830.7	50.8	832.8	51.3	0.3	
Y25	67.7	68.5	-1.2	24.6	25.4	-3.3	7.7	6.2	19.5	721.2	51.8	721.8	52.5	0.1	
Y26	77.7	64.3	17.2	21	32.5	-54.8	1.3	3.2	-146.2	668.9	24.2	669	26.4	0.0	
Y27	30.8	23.1	25.0	35.9	43.6	-21.4	33.3	33.3	0.0	732.1	76.6	732.9	78.4	0.1	
Y28	70.7	62.7	11.3	28	36.0	-28.6	1.3	1.3	0.0	751.9	37.1	753.3	37.7	0.2	
Y29	59.1	55.7	5.8	36.4	38.6	-6.0	4.5	5.7	-26.7	714.6	29	714.4	30.1	0.0	
Y30	40.4	44.7	-10.6	38.3	31.9	16.7	21.3	23.4	-9.9	648.9	35.1	649.3	28.2	0.1	
Y31	45.6	35.1	23.0	31.6	43.9	-38.9	22.8	21.1	7.5	692.2	74.6	694.7	76.7	0.4	
Y32	27	10.8	60.0	10.8	29.7	-175.0	62.2	59.5	4.3	1100.2	74	1099	75.2	0.1	
Y33	46.7	37	20.8	31.1	34.8	-11.9	22.2	28.1	-26.6	722.4	50.8	722	54.3	0.1	
Y34	64.1	77.2	-20.4	28.3	21.7	23.3	7.6	1.1	85.5	844.1	34.3	842.6	28.2	0.2	
Y35	86	74.8	13.0	14	24.3	-73.6	0	0.9	n.a.	554.9	20.4	555	20.9	0.0	
Y36	67.4	54.3	19.4	23.9	39.1	-63.6	8.7	6.5	25.3	732.3	40.9	732.3	43.7	0.0	
Y37	66.7	56.1	15.9	31.6	38.6	-22.2	1.8	5.3	-194.4	618.9	36.7	617.4	38.4	0.2	
Y38	41.1	42.9	-4.4	39.3	36.6	6.9	19.6	20.5	-4.6	803.6	91	804.7	91.5	0.1	
Y39	43.2	41.7	3.5	31.1	30.3	2.6	25.8	28.0	-8.5	734.8	55.7	734.9	57.2	0.0	
Y40	31.6	36.8	-16.5	36.8	42.1	-14.4	31.6	21.1	33.2	714.4	85	717.2	85.5	0.4	
Y41	56.8	52.3	7.9	18.2	27.3	-50.0	25	20.5	18.0	1082.3	49.9	1083.5	49.9	0.1	
Y42	32.7	31	5.2	41.6	43.4	-4.3	25.7	25.7	0.0	829.5	61.8	829.8	62.8	0.0	
Y43	76.9	69.2	10.0	20.5	28.2	-37.6	2.6	2.6	0.0	709.9	46.4	707.6	44.6	0.3	
Y44	29.5	26.2	11.2	34.4	32.8	4.7	36.1	41.0	-13.6	847.2	109.9	847.1	111.7	0.0	
Y45	21.9	29.7	-35.6	34.4	28.1	18.3	43.8	42.2	3.7	797.3	56.6	798.6	59.7	0.2	

As a result, differenceΔNN(j) has slightly greater numerator and substantially smaller denominator than differenceNN(j). This explains the two orders of magnitude difference between differenceΔNN(j) and difference(j).

pNNtri values calculated from PPG can be misleading. For a young male, the more difficult balance tests (standing on a board-on-stone and on a rocking rocker board) resulted in a shift of NNppg interval differences toward longer values, falsely indicating that the more difficult tests decreased the regularity of heart rate that implies a decrease in stress level. The average total displacement of the back for 11 persons who performed both (a) and (b) and (c) tests in measurement situation B was calculated based on x-IMU measurements. For them the ratio of the average total displacements for the tests (a) : (b) : (c) was 1 : 4 : 17. Greater displacement means more intensive movement control expected to cause shorter ΔRR values.

pNNtri is able to reflect changes in stress level in situations when pNN50 alone would fail. In Fig. 4 pNNtri reveals the small changes while pNN50 is zero in all four measurements at rest. The shift of differenceNN towards longer (Fig. 5) and shorter (Fig. 6) values is obvious, while pNN50 alone would only show a negligible difference between the two measurements.

pNN50 decreases with age (see Table 2). The relaxation of a 65-old-year male causes almost negligible change in pNN50. On the contrary, the decrease in pNN0_20, in parallel with the increase in pNN20_50, reflects the change in momentary stress level (Fig. 5). Thus, pNNtri can characterize the momentary stress level of senior people much better than pNN50. Of the thirteen recordings (measurement situation A, test (e)) eleven indicated a shift towards longer NN intervals, two recordings showed negligible difference.

The increase in pNN0_20 together with the decrease in pNN20_50 and in pNN50 reflects the increase in momentary stress level with a better sensitivity than pNN50 alone (Fig. 6).

Figs. 4 – 6 demonstrate that pNNtri can characterize the change in stress level of an individual. Research work continues to assess the correlation of pNNtri with other HRV parameters.

5 Conclusions

HRV is applicable for estimating changes in an individual's actual stress level. The time domain characteristics of even very short (1-2 minute-long) recordings can be helpful. It is reasonable to qualify the differences between adjacent heart cycle lengths into three categories (pNNtri) instead of the widely used two (using pNN50).

pNNtri is able to detect changes in the stress level of a person. pNNtri values belonging to a person at rest are person specific. Before using pNNtri to express the actual stress level, recordings need to be taken when the person is at rest.

pNNtri is especially beneficial for senior people because their pNN50 values are close to zero, even at rest.

pNNtri values calculated from PPG may substantially differ from the gold standard calculated from ECG. Based on PPG, a good estimate can be given for the minimum, maximum, mean, and standard deviation of NN interval differences, especially for healthy young individuals.

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