Computer Evaluation of Exercise Based on Blood Volume Pulse (BVP) Waveform Changes

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Abstract: - It is well established that the benefits obtained from exercising are enhanced if a sufficiently strong cardiovascular response is achieved as result of the exercise sessions. Frequently, the achievement of that critical exercise level is gauged by estimation of the subject's heart rate and comparison to an appropriate "target rate". This paper explores the use of computerized algorithms to assess the changes in the Blood Volume Pulse (BVP) waveform recorded using an infrared finger photoplethysmograph (PPG) at different points in an exercise session, as an alternative (and more comprehensive) evaluation of the cardiovascular response due to physical exercise. The paper focuses on the quantification of a feature of the BVP waveform called the "Dicrotic Notch", which has been observed to reduce its depth as exercise progresses. This paper reports on the comparison of three computerized approaches designed to reflect the BVP waveform changes through a single parameter, which could be obtained automatically from the digitized BVP signal.

Key-Words: - Exercise Evaluation, Photoplethysmograph, PPG, Blood Volume Pulse, BVP, Dicrotic Notch, Non-invasive monitoring

1 Introduction

Most individuals who exercise are faced with the need to gauge the intensity of their exercise sessions, and adjust this intensity to obtain a maximum of benefits, with a minimum risk of negative consequences. This must be an individualized process, since the appropriate level of effort that should be involved in an exercise session must be appropriate to the age and fitness level of the subject [3]. A practical method to quantify the intensity of exercise is by monitoring of the subject's heart rate (HR) during the session. [1][4]. The measured heart rate, compared to the estimated maximum heart rate for the individual, is often used to label the intensity of the exercise session as "moderate" (60% - 70%), through "high" (85%) [7]. Heart rate, however, reveals only a facet of the complex cardiovascular changes that take place during exercise. In addition to the changes in heart rate and stroke volume, exercise brings about specific changes in the peripheral resistance of the cardiovascular system [8]. In contrast with the measurement of heart rate, dynamic measurements of perfusion in the periphery of the cardiovascular system will not only reflect changes in the rhythm of the cardiac cycle, but, they will also reveal peripheral changes. Specifically, finger photoplethysmography (PPG) is a non-invasive technique for the monitoring of peripheral perfusion, which does not require costly equipment or specialized personnel. The Blood Volume Pulse (BVP) signal obtained with a PPG transducer has been used in the past to determine the heart rate [6]. However, a more detailed analysis of photoplethysmographic BVP variations may indicate peripheral circulatory changes that take place in an individual due to exercise. Further research has shown that the changes in the single BVP signal through an exercise session (before exercise, immediately after exercise, and after a recovery period) can be measured, characterized, and quantified through signal processing methods that can be implanted in a personal computer [5]. In this paper we present and analyze three such methods, as applied to data collected in a controlled exercise session.

2 Data Gathering Protocol

The recording procedure used consisted of three measurements: A, B and C, through a total time of about 18 minutes. Ten healthy volunteers with ages between 22 and 40 participated in the recordings.

Each subject was requested to sit comfortably, resting the right arm on a table. At this point, the first photoplethysomgraphic Blood Volume Pulse record was obtained from the tip of the right index finger (Stage "A", "Before exercise"). After recording for about 30 to 60 seconds, the subject was asked to begin performing continuous lifting of a 6.6-pound dumbbell with the left arm. At the end of 1-minute intervals, the subject was asked to switch the arm used to lift the dumbbell. This process lasted for 8 minutes. Then a second BVP measurement was taken (Stage "B", "Immediately after exercise"). After this, the subject was asked to rest, allowing for his or her cardiovascular system to recover, for 8 more minutes. After the recovery period, one last BVP measurement was taken from the right index finger (Stage "C" or "After recovery").

All of these measurements were obtained with a Model 1020FC infrared finger clip photoplethysmograph, manufactured by UFI, Morro Bay, CA (Figure 1). The signal obtained from the phototransducer was amplified by a gain factor of 100 V/V. The DC component was removed and a low-pass filter with a corner frequency of 10 Hz was used to remove high-frequency interference components. The resulting analog signal was sampled at 500Hz, with a 12-bit resolution for a range of -5.0 V to +5.0V.

FIG1. Use of the UFI 1020FC infrared finger clip photoplethysmograph

Figures 2 through 4 show the BVP waveforms recorded from one of the subjects (S3) at stages A, B and C, respectively. As we can see, in stages A and C, the dicrotic notch is very pronounced, while in stage B the Dicrotic Notch is less obvious, because of the changes in the cardiovascular system caused by the exercise. This is probably due to a combined effect of the increased cardiac output and decreased peripheral resistance associated with exercise [8]. Our objective is to find methods to derive a single numerical parameter from the BVP signal, which will reflect those cardiovascular changes.

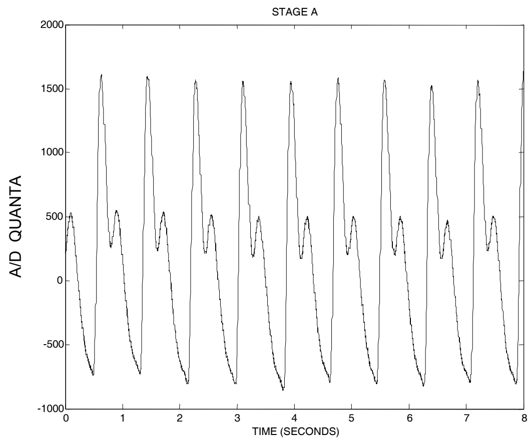

FIG 2. BVP waveform from Subject S3 at stage A

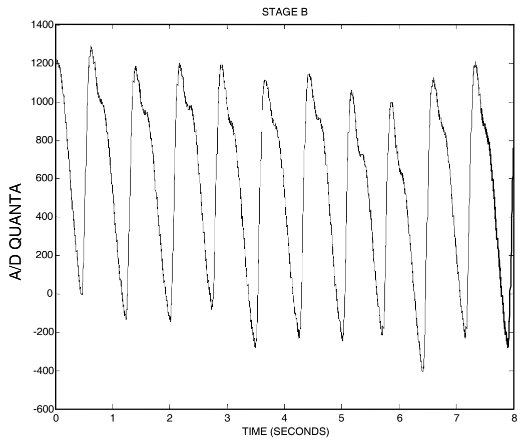

FIG 3. BVP waveform from Subject S3 at stage B

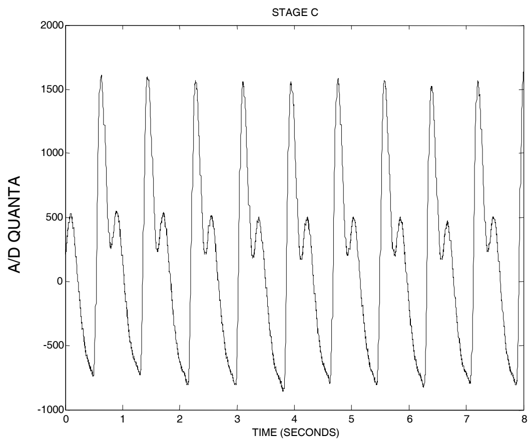

FIG 4. BVP waveform from Subject S3 at stage C

3 BVP Quantification Methods

3.1 Data Processing Methods

Three approaches were tested to quantify the changes introduced in the photoplethysmographic Blood Volume Pulse waveform by exercise. The first approach attempted to summarize the changes in depth and position of the Dicrotic Notch immediately after exercises by averaging histograms of pre-aligned individual beats from the BVP signal and comparing the area under the histogram in different amplitude ranges. A second method was tried, by which the changes were observed in the frequency domain. A peridogram from each selected segment was obtained and the amplitudes of the fundamental and second harmonics in the signal were compared at the three recording stages in the protocol. Lastly, the dicrotic notch depth was measured and used to characterize the changes in the BVP waveform. A more detailed explanation of each one of these approaches, as well as a summary of the results obtained for each, follows.

3.1.1 Average Beat Histogram Analysis

Preliminary observation of the records obtained for the study indicated that the dicrotic notch tends to be less pronounced in the measurement taken right after the exercise (Stage B). This led us to implement a processing scheme that separates individual beats in the signal, aligns them according to their maxima and computes a normalized histogram for each of them. In this histogram the full amplitude range of each beat is divided into 100 bins and the number of values within each amplitude bin is found. Before the exercise session (A) and after the recovery period (C), the presence of the dicrotic notch results in a large number of samples detected in the range R1: (40% - 70%) of the total amplitude of the beats, which tends to predominate over R2: (70% - 100%). On the other hand, immediately after the exercise session the Dicrotic Notch is normally less pronounced. So the ratio of the histogram accumulation for range R1 and the histogram accumulation for R2 was selected as the single index to summarize the changes in the histogram [2]. Examples of the normalized histograms for signals measured at stages A and B are shown in Figure 5. The following table indicates the ratios found for the ten subjects at the 3 different stages of the procedure, normalized to the value found in stage A, for each subject. Figure 6 shows these results in graphical form.

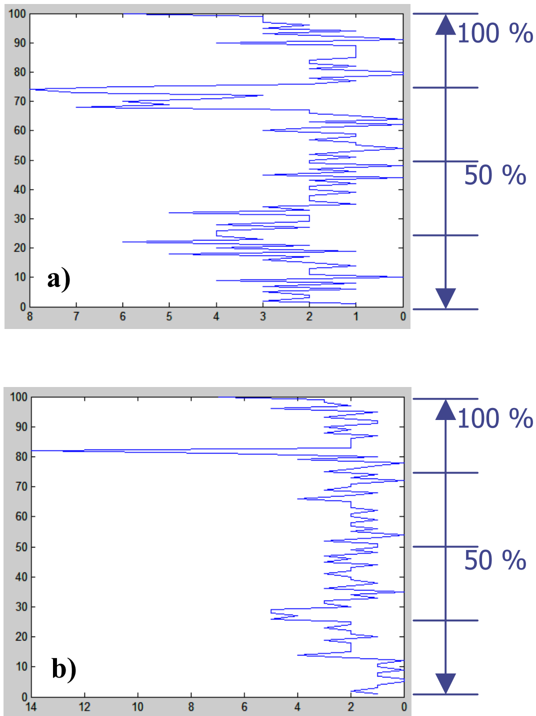

FIG 5. Typical normalized histograms for BVP waveforms recorded at stages a) A and b) B.

TABLE I. HISTOGRAM METHOD RESULTS (R1 / R2 RATIO)

Subject	*Stage A*	*Stage B*	*Stage C*
S1	1.00	0.7294	0.9132
S2	1.00	0.3839	0.9089
S3	1.00	0.2013	1.0873
S4	1.00	0.5365	1.0215
S5	1.00	0.7838	0.7962
S6	1.00	0.8422	0.8879
S7	1.00	0.4042	0.5712
S8	1.00	0.9264	0.9182
S9	1.00	1.1282	1.3340
S10	1.00	0.5276	0.8639

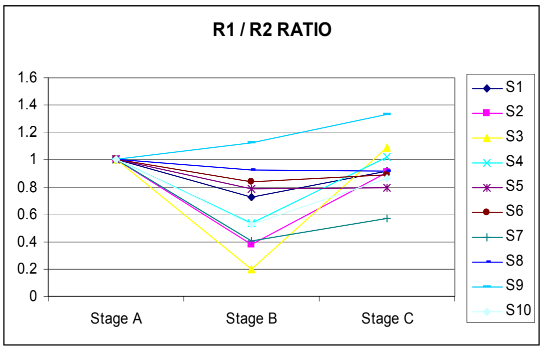

FIG 6. Histogram method results

3.1.2 BVP Harmonic Composition Changes

The presence of the Dicrotic Notch in the BVP waveform is represented in the frequency domain as a significant component corresponding to the second harmonic of the fundamental BVP frequency. This second harmonic component is normally very significant in comparison with the fundamental in stages A and C (i.e., at rest or after recovery). In contrast, the second harmonic contribution is small at stage B (right after the exercise session), since the Dicrotic Notch is less well defined. To detect these changes we propose the determination of the ratio Pf2/Pf1, where Pf2 is the amplitude of the second harmonic and Pf1 is the amplitude of fundamental in the averaged periodogram of the BVP segment recorded at each stage of the procedure. The two spectral peaks measured for this approach are labeled in the sample BVP periodogram (from stage A) shown in Figure 7. The experimental values of this ratio, normalized to the ratio measured in stage A for each subject are shown in Table II and Figure 8.

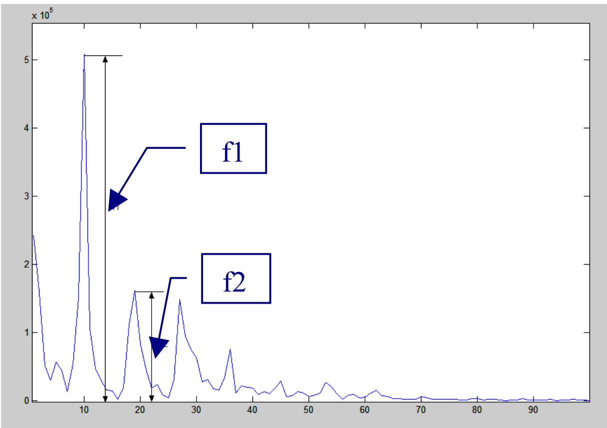

FIG 7. Typical periodogram of a BVP waveform collected at stage A. The first two harmonic components (f1 and f2) are indicated.

TABLE II. HARMONIC METHOD RESULTS (Pf1 / Pf2 RATIO)

Subject	*Stage A*	*Stage B*	*Stage C*
S1	1.00	1.2965	0.9408
S2	1.00	1.1722	0.8228
S3	1.00	1.6172	0.9418
S4	1.00	1.0162	1.0092
S5	1.00	0.6991	0.8178
S6	1.00	0.9147	1.6994
S7	1.00	1.4692	1.3159
S8	1.00	1.1322	1.4105
S9	1.00	1.9591	1.7746
S10	1.00	1.3119	0.7448

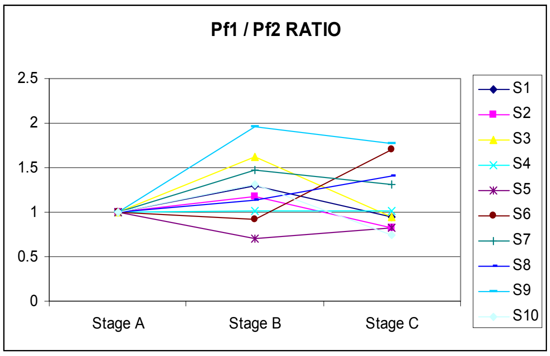

FIG 8. Harmonic method results

3.1.3 Dicrotic Notch depth method

The algorithm for this approach isolates each individual BVP beat and identifies the local minimum and local maximum associated with the presence of the Dicrotic Notch. The difference between these two levels is used as the estimation of the Dicrotic Notch depth for a particular beat. The ratio of the Dicrotic Notch depth to the total amplitude of each beat is found and an average of this ratio is calculated for all the beats in the BVP segment under study. Figure 9 illustrates the measurement of both the Dicrotic Notch depth and the estimated total amplitude of the BVP beat. Table III and Figure 10 show the results for the 10 subjects studied, at the 3 stages of the protocol, normalized to make stage A for every subject 1.0.

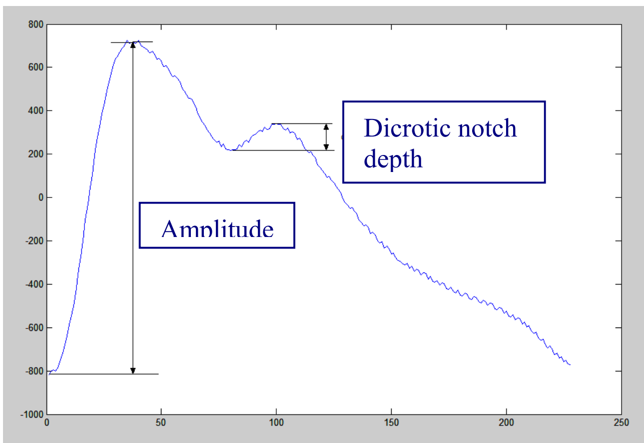

FIG 9. Measurements of the Dicrotic Notch Depth normalized with respect to the BVP waveform amplitude.

TABLE III. NORMALIZED DICROTIC NOTCH DEPTH METHOD RESULTS

Subject	*Stage A*	*Stage B*	*Stage C*
S1	1.00	0	0.0984
S2	1.00	0.0550	0.4990
S3	1.00	0.0084	2.3933
S4	1.00	0.0351	1.0879
S5	1.00	0.0905	0.2032
S6	1.00	0.0263	0.0088
S7	1.00	1.00	1.00
S8	1.00	1.00	1.00
S9	1.00	0.0056	0.5506
S10	1.00	0.4069	1.1176

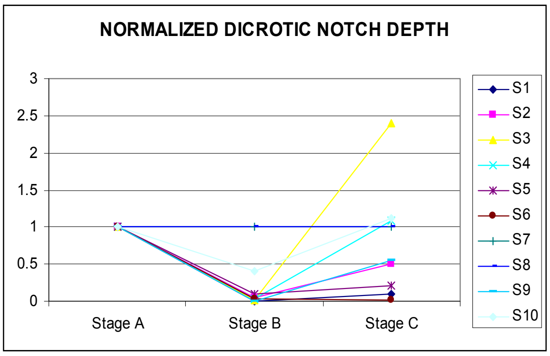

FIG 10. Dicrotic notch depth method results

4 Discussion

The traces shown in Figures 2 through 4 reflect the expected increase of heart rate immediately following the 8-minute period of exercise. In addition, stage B shows a lessening of the Dicrotic Notch that may be due to the selective readjustment of the arteriolar tone associated with the performance of exercise [9].

Tables I – III and Figures 6, 8 and 10 show that there is significant variability in the BVP responses recorded from different individuals through the exercise protocol used in this study. It is important to assess if these differences are primarily due to the methods used to evaluate the changes in BVP waveforms or whether they arise because the waveforms themselves varied in different ways through the 3 recorded stages (A, B and C) for different individuals. By visual inspection of the waveforms recorded, we realized that for eight of the ten experimental subjects the waveforms at the different stages showed the anticipated changes very clearly. However, the waveforms from two of our subjects (S8 and S9) showed much less pronounced changes.

In order to compare the efficiency of each one of the signal processing approaches used in the study to represent the changes in the BVP waveform induced by exercise, we will focus on the records obtained from the eight subjects for whom BVP waveform changes were consistent and clear, i.e. we will exclude from consideration the results from subjects S8 and S9. Looking at this subset of the data, we appreciate that the histogram method (Table I and Figure 6) provides results that are consistent with our expectations. For this method the lessening of the Dicrotic Notch observed immediately after exercise (stage B), is represented by a reduction of the resulting numerical index, with respect to the values obtained at stages A and C. For the Histogram method this pattern is only disrupted for subjects S8, which has a lower value for stage C than for stage B and for S9 whose value for stage A is lower than for stage B. These are, however, two subjects with non-representative BVP waveforms.

The calculations for the Dicrotic Notch depth method are sometimes complicated by the fact that the waveform may not show a typical notch in the downward slope, but just a lessening of the slope. This phenomenon is most likely to occur in Stage B, right after exercise. In such cases, the Dicrotic Notch depth was assessed as zero. Subjects S7 and S8 displayed this kind of irregular Dicrotic Notch in all three of their BVP measurements. Therefore, their indices in the three stages are zero, yielding the same values across Table III, in their corresponding rows.

The harmonic ratio method displayed the lowest consistency of results across subjects. Even restricting the observations to the eight subjects whose BVP waveforms seemed to follow a typical pattern from stage A to stage B, and then to stage C, the traces in Figure 8 display inconsistent trends. It is speculated, at this point, that the re-distribution of the BVP energy that takes place from stage A to stage B, which is typically reverted from stage B to stage C, may involve more than just the first and second harmonics in some cases. That is, it is possible that the BVP waveform at stages A and C may be complex enough so that substantial components are present at several harmonic frequencies, not only the first and second harmonics. This may be the reson why monitoring the relative changes of just the first and second harmonics could, in some cases, fail to capture the overall BVP waveform change.

5 Conclusion

Photoplethysmographic BVP records obtained from 10 healthy volunteers confirm that the BVP waveform changes as the subject performs exercise. In our study eight of the 10 subjects studied displayed clear and consistent BVP waveform changes of the type that we had originally expected. That is, the resting BVP displays an identifiable Dicrotic Notch in its downward slope, which is lessened or even disappears right after exercise, reappearing after the recovery period. In the remaining two subjects the BVP changes were subtler.

The Histogram method was successful in consistently representing the BVP changes of the eight subjects whose data was typical. The results from the Dicrotic Notch depth method were particularly consistent showing a reduced index at stage B for most subjects. This method, however, cannot be properly applied to subjects whose BVP signals lack a fully formed Dicrotic Notch even at rest. In addition, this method seems to be the one that is most strongly affected by the presence of noise in the BVP signal. The results from the Harmonic Ratio method were the least consistent of the three methods considered. Overall, the Histogram seems to be the most promising for the computer-based quantification of the BVP waveform changes that will provide a more comprehensive assessment of the cardiovascular response elicited by exercise.

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