Signal Processing Quantification of Changes in the Blood Volume Pulse (BVP) Waveform due to Exercise

Chao Li [1], Jing Zhai [1] and Armando Barreto [1,2]
[1]Department of Electrical and Computer Engineering,
[2] Biomedical Engineering Institute
Florida International University
Miami, FL, 33174, USA

Abstract— **Observations made in the past by our group confirmed that the Blood Volume Pulse (BVP) waveform recorded using an infrared finger photoplethysmograph (PPG) undergoes changes as the subject performs physical exercise. In particular, the Dicrotic Notch of the BVP waveform has been observed to become less prominent in connection with the performance of exercise. There is an interest in characterizing those changes through a single parameter to measure the level of exercise the subject has reached, at any time during an exercise session. This paper reports on the comparison of three Digital Signal Processing approaches designed to reflect the BVP waveform changes through a single parameter, which could be obtained automatically from the digitized BVP signal. For this study BVP measurements were taken from 10 subjects, as they engaged in upper-body exercises and rested afterwards.**

Keywords— **Photoplethysmograph, PPG, Blood Volume Pulse, BVP, Digital Signal Processing, Dicrotic Notch, Non-invasive monitoring**

I. INTRODUCTION

Finger photoplethysmography (PPG) is a non-invasive monitoring technique, which does not require costly equipment or specialized personnel. Traditionally, the Blood Volume Pulse (BVP) waveform obtained from PPG sensors has been used to determine the heart rate [1]. However, a more detailed analysis of photoplethysmographic BVP variations, which consider the features of this signal beyond its basic periodicity, may reflect additional 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 [2]. The so-called "Dicrotic Notch" in the BVP waveform seems to be one of the features of the signal most strongly affected by the performance of exercise. The Dicrotic Notch is also observable in the arterial pressure record, where it is considered to be the representation of the pressure transient produced when the aortic valve closes at the end of left-ventricular ejection [4].

The evaluation of the BVP waveform change by a simple numerical index is of interest as a potential objective, individualized measure of the level of exercise that a subject has achieved with respect to a baseline status, prior to the beginning of the exercise session.

II. METHODOLOGY & RESULTS

II.1 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 photoplethysmographic 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. The subject was asked to switch the arm used to lift the dumbbell at intervals of 1 minute. This process lasted for 8 minutes overall. 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. 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.

Figures 1 through 3 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 [5]. Our objective is to find methods to derive a single numerical parameter from the BVP signal, which will reflect those cardiovascular changes.

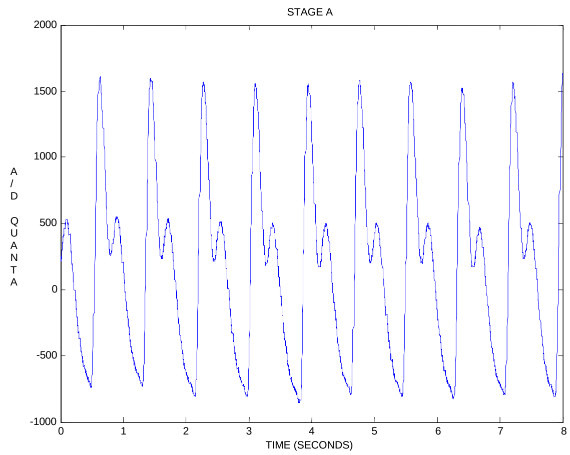

Fig. 1. BVP waveform from Subject S3 at stage A

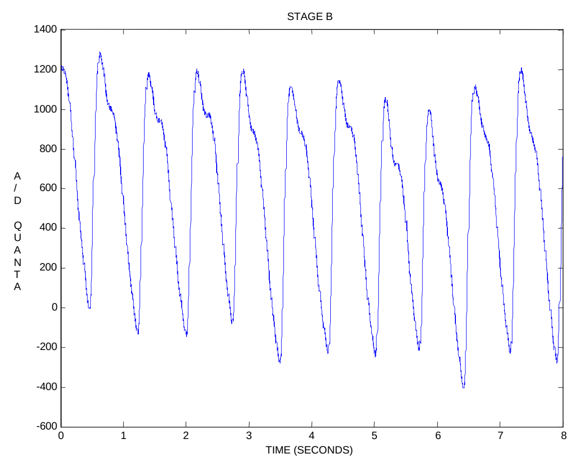

Fig. 2. BVP waveform from Subject S3 at stage B

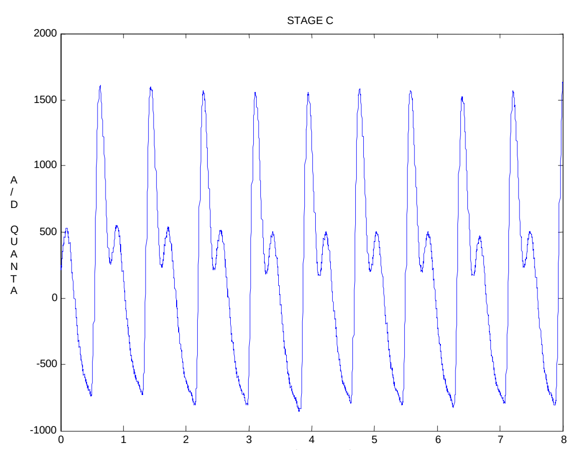

Fig. 3. BVP waveform from Subject S3 at stage C

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 periodogram 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.

II.2 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 signal 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 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 [3]. 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:

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

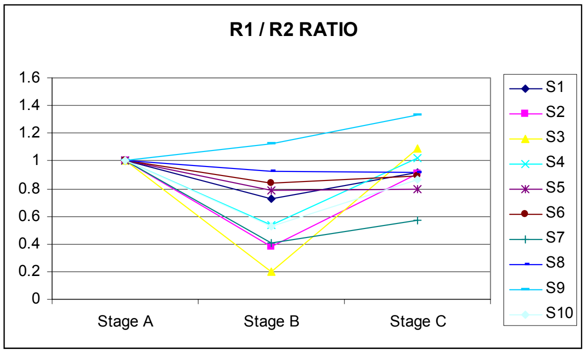

Fig. 4. Histogram method results (R1 / R2 Ratio)

II.3 BVP Harmonic Composition Changes:

The presence of the Dicrotic Notch in the BVP waveform is associated with the presence of a strong second harmonic component in the BVP spectrum. This second harmonic component is normally very significant in comparison with the fundamental for 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 and the waveform more closely resembles a single sinusoidal. To detect these changes we propose the determination of the ratio Pf1/Pf2, 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. These ratios, normalized to the ratio measured in stage A are shown in Table II and Figure 3.

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

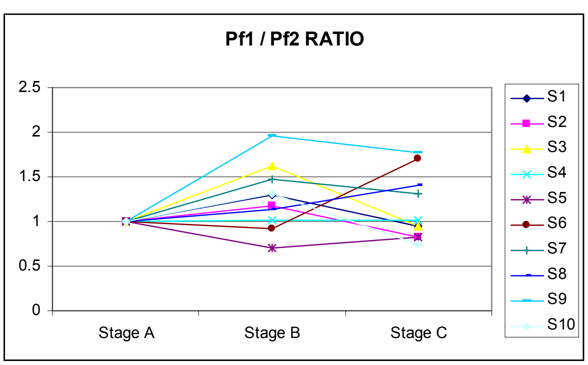

Fig. 5. Harmonic method results (Pf1 / Pf2 Ratio)

II.4 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. Table III and Figure 4 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:

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

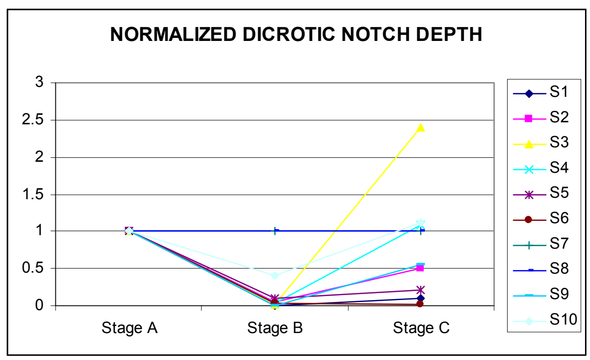

Fig. 6. Normalized Dicrotic Notch depth method results

III. Discussion

The traces shown in Figures 1 through 3 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 [6].

Tables I – III and Figures 4- 6 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 4) 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 5 are seen to 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 harmonic s 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.

IV. 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 intended application, due to the consistency of the results obtained and its relatively robustness to noise components in the BVP signal.

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