Garbage In; Garbage Out—Identify Blood Volume Pulse (BVP) Artifacts Before Analyzing and Interpreting BVP, Blood Volume Pulse Amplitude, and Heart Rate/Respiratory Sinus Arrhythmia Data

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Blood volume pulse is a popular method for monitoring the relative changes in peripheral blood flow, heart rate, and heart rate variability. This article stresses the danger of blindly interpreting measures like heart rate, which are derived from blood volume pulse, without close inspection of the raw blood volume pulse signal. The authors identify common sources of signal contamination and recommend practical precautions and treatment of artifacts.

This article is part of a series that reviews artifacts that often arise while recording major physiological signals. Artifacts are unwanted signals that are not generated by the biological systems being monitored (Peper, Tylova, Gibney, Harvey, & Combatalade, 2008). Although artifacts are not the signals we intend to record, they may provide a wealth of information, such as covert movement, which could indicate psychological stress. Data are only valid and meaningful if the analyzed signals and derived statistical data are taken from artifact-free recordings. For a detailed understanding and analysis of artifacts, we recommend reviewing the procedures described in the book Biofeedback Mastery (Peper et al., 2008) and in the multimedia CD Biofeedback Tutor (Shaffer, 2009).

Blood volume pulse (BVP) is measured using a photoplethysmograph (PPG) and indicates dynamic changes in blood volume underneath the sensor. The BVP signal indicates relative changes in the vascular bed due to vasodilation or vasoconstriction (increases or decreases in blood perfusion) as well as changes in the elasticity of the vascular walls, which may be correlated with changes in blood pressure. BVP is commonly used to monitor heart rate, heart rate variability (HRV), and relative blood volume underneath the sensor. PPG sensors can be placed anywhere on the body, from the earlobe to the vaginal wall, and measure relative changes in the perfusion of the blood through the tissue underneath the sensor. The index finger is the most common location for recording a BVP signal due to the ease of placement (Peper, Harvey, Lin, Tylova, & Moss, 2007).

The volume of blood in the arteries and capillary beds increases with each arterial pulsation. Heart rate can be estimated from the BVP signal. Heart rate, or the number of heartbeats per minute, is calculated by measuring the time interval between the heartbeats, which is called the interbeat interval (IBI). The time of the IBI is divided into 60 seconds to calculate the beat-by-beat heart rate as shown in Figure 1.

The time between each beat can vary, and thus the estimated beat-by-beat heart rate can vary also. Two estimates of the variability of the heart rate are the standard deviation of the average normal-to-normal beats (SDNN) and the standard deviation of average beat-by-beat heart rate (SDHR). The raw BVP signal must be artifact-free before the SDNN and SDHR measures of heart rate variability may be meaningfully interpreted.

Inspecting the Raw BVP Signal for Artifacts

Heart Rate

When analyzing average heart rates, it is important to eliminate artifacts before calculating estimates of HRV or changes in pulse amplitude. Heart rate averages calculated from the data may not be reliable if artifacts exist, as illustrated in the following vignette:

What happened? He reported increased arousal during the stressful imagery, yet his heart rate was lower than during the...
initial baseline condition. It was only when I inspected the raw BVP signal from which the heart rate was calculated that I realized that the averaged signal was incorrect.

This dialogue illustrates issues related to artifacts in the BVP data. The data were contaminated by movement artifact, as shown in Figure 2. After eliminating this artifact, the heart rate was nearly 5 beats per minute lower, as shown in Figure 3. Also, a slight increase in heart rate during the stressful imagery rehearsal was revealed once the contaminated data segments were removed.

The identification and elimination of movement artifact can significantly increase the accuracy of heart rate measurements obtained in clinical practice.

Blood Volume Pulse Amplitude

Blood volume pulse amplitude (BVPA) measures the relative blood volume under the sensor. When analyzing BVPA, it is important to eliminate artifacts before calculating BVPA. Averages calculated from contaminated data may be invalid, as illustrated in the following vignette:

What happened? During the neutral and anger recall task, there was significant increase in BVPA as compared with the initial baseline condition, as shown in Figure 4. It was only when I inspected the raw volume pulse (BVP) signal from which the amplitude was calculated that I realized the average signal amplitude was incorrect, as shown in Figure 5.

The computer-calculated averages of BVPA were incorrect. Only after inspecting the recorded raw data was it clear that the pulse was not detected and that the apparent
increase in BVPA amplitude was an artifact. Most likely the person covertly moved the monitored fingers so that the signal was lost.

General Rules to Identify the Integrity of the BVP Recorded Signal

- Understand the basis of the signal. The BVP signal is a photoplethysmographic recording and measures relative changes in tissue perfusion. The amount of light transmitted, diffracted, and reflected through the skin depends upon skin quality. Thus, this measure is only accurate for an individual and cannot be used as an absolute measure between individuals. It can be used as a relative change measure between conditions.

- Signal amplitude depends on placement of the sensor. Thus, positioning the sensor at a slightly different location will change BVPA.

- Record the signal at the appropriate time scale and signal amplification to best inspect the raw signal. Display the signal in no more than 60-second segments with sufficient amplification to show the heartbeat's deflection, as shown in Figure 6.

- Check whether the BVP signal passes a behavioral test. For example, confirm that the upward BVP deflection on

Figure 5. The same recording as Figure 4 except that the time scale was changed to display 10 seconds of data. Visual inspection showed an absence of blood volume pulse waveforms (see the middle blood volume pulse raw tracing) in the anger condition. The blood volume pulse amplitude measure was most likely produced by movement artifact.

Figure 6. Effects of different amplification range settings (appropriate, too small, and too large) on the blood volume pulse raw signal.

Figure 7. The effect of temperature on blood volume pulse signal recorded from the left index finger. The amplitude of the blood volume pulse signal decreases as the finger is colder. If the signal is too low, heart rate cannot be derived from the interbeat intervals.

Figure 8. The effect of wrapping the tape loosely, snugly, or very tightly around the photoplethysmograph sensor and index finger. When taped loosely, the blood volume pulse amplitude is decreased and prone to movement artifacts. When taped very tightly, blood flow is occluded and the blood volume pulse signal cannot be recorded. Optimum signal is recorded when sensor is taped snugly.
the raw signal recording corresponds with a palpated pulse or electrocardiogram (EKG) signal.

- Always record the raw biological signal from which averages or other signals are derived. Without the original signal, it is impossible to know whether the signal is the intended biological signal or an artifact. For heart rate and HRV derived from BVP, the BVP signal should show a clear upward deflection with every pulse.

- Analyze the raw signal. Are you amplifying beyond the limits of recording? Is the raw signal too small? The recorded signal may be too noisy.

- Ask yourself, "Does the signal or the derived signal make sense?" A pulse of 10 or 180 is highly unlikely if a person is sitting quietly. A very rapid instantaneous change in BVPA is also unlikely. If the display significantly departs from expected values, first assume that it could be caused by an artifact.

- Know what artifacts look like and how they affect derived signals. Purposely create every possible artifact so that you can identify them during recordings. See the instructions in Peper et al. (2008).

Most common BVP artifacts are the absence of rhythmic fluctuations produced by the heartbeat or rapid transient changes such as

- Reduced blood flow underneath the PPG sensor. This most often occurs when the fingers are cold (<80°F) or when tape or Velcro® are applied so tightly that they constrict blood flow as shown in Figures 7 and 8. The colder the fingers, the less blood flow and the more likely that the raw amplified signal is distorted by artifacts. Possible solutions include recording from the thumb, warming the person’s hands, loosening the tape or Velcro® wrapping, or recording the heart rate with EKG sensors.

- Light leakage into the PPG sensor. The wrapping allows extraneous light to enter the PPG sensor. A possible solution is to better wrap the sensor. We usually recommend using elasticized self-adhesive wrapping such as Coban Tape Self-Adherent Wrap™ (3M, St. Paul, MN).

- Incomplete contact with sensors. This frequently occurs if the fingers are small, thin, or narrow, such as in children or petite adults. Possible solutions include recording from the thumb or using a smaller sensor.

- Sensor movement. Any movement of the sensor over the skin induces numerous artifacts. In most cases, the movement artifacts appear as sharp deflections in the raw signal (see Figures 3, 4, and 7). Possible solutions...
include recording surface electromyography from the forearm extensors and flexors as an independent measure of finger muscle activity. Also, remind the participant to keep his or her hands and fingers relaxed.

**How to Extract Meaningful Data When Artifacts Are Present**

Always monitor the raw signal and if artifacts are observed, if possible, eliminate them before continuing. Then, after finishing the recording, inspect the BVP raw signal for artifacts. If there is a sufficiently long artifact-free segment, use those segments to analyze the heart rate signal and delete the artifact-contaminated segments. When calculating HRV frequency components such as low-frequency percentage of power, deleting data points can distort the temporal relationship between data points. Instead, use HRV analysis software to replace contaminated values with interpolated ones. If 30% or more of the record is contaminated and there are no clean segments of sufficient length, redo the recording. In clinical settings, it is sometimes not possible to redo the session or segment. In such a case, select the artifact-free segments and compute the necessary statistics.

Without removing the artifacts, incorrect conclusions may be drawn from the data. This is illustrated by comparing the data of a 1-minute artifact-included and artifact-eliminated recording from a client who had premature ventricular contraction (PVC), as shown in Figures 9 and 10. A PVC is a “skipped beat” in which the ventricles of the heart contract before the atria contracts to fill the ventricles. When this occurs, the ventricles pump very little to the body and lungs, which results in a skipped beat (Gomella & Haist, 2003, p. 390). Thus the peripheral recording of BVP shows an absence of a pulse and a doubling of the IBI, which results in a decrease of the calculated heart rate. Although this type of arrhythmia is usually not dangerous, it would be unhealthy to increase PVCs. The high HRV of 12.79 beats per minute could indicate health; however, this was actually due to the cardiac disorder (PVC) of skipping a beat. When these skipped beats were eliminated, the standard deviation decreased to 3.28 beats per minute. Without analyzing the actual BVP recording, the high HRV would be interpreted as a sign of health and it would have been possible to have the client increase his or her displayed HRV, which in this case would mean increasing the number of PVCs.

**Summary**

BVP allows noninvasive and convenient measurement of peripheral blood flow, heart rate, and HRV. Because PPG sensors are vulnerable to diverse artifacts, we must carefully select a monitoring site and attach the sensor, give instructions to minimize movement, administer a behavioral test, observe client behavior, inspect the raw signal, and exclude artifact-contaminated data. Blind acceptance of BVP-derived measurements without examination of the raw BVP signal threatens the validity and interpretation of these readings.

**References**


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