

## SPECIAL ISSUE



# Don't Add or Miss a Beat: A Guide to Cleaner Heart Rate Variability Recordings

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Keywords: heart rate variability, respiration, biofeedback

*Heart rate variability (HRV) refers to the beat-to-beat variation in the time intervals between heart contractions. This phenomenon reflects physiological processes that are trained in many biofeedback applications. HRV is routinely monitored using an electrocardiograph (ECG) or photoplethysmograph (PPG), supplemented by a respirometer. This article explains the importance of inspecting raw signals, describes the effects of prescription medications and social drugs, identifies common sources of signal contamination, and recommends practical precautions to increase recording fidelity.*

Clinicians and researchers monitor heart rate variability (HRV) using electrocardiography (ECG) and photoplethysmography (PPG). The ECG sensor method is the gold standard for HRV recording because its sharp R-spike, which is the initial upward deflection in the ECG, can be more precisely identified by a software algorithm than the peak of the pulse wave (Berntson et al., 1997). The ECG allows a more accurate calculation of the interbeat interval, especially during psychological stressors (Schäfer & Vagedes, 2013).

### Strategies to Ensure the Integrity of Recorded Signals

Peper, Shaffer, and Lin (2010) recommended the following guidelines for ensuring accurate psychophysiological monitoring:

1. Understand the physiological mechanisms that generate the signal.
2. Always record and inspect the raw signal because this will allow you to identify artifact.

3. Question whether displayed values make sense. For example, heart rates of 10 or 180 beats/minute should be suspect in a client who is sitting quietly.
4. Recognize the appearance of common artifacts and how they alter derived measurements.
5. Intentionally create artifacts so that you can better recognize them. For example, rhythmically tap a finger attached to a PPG sensor and review both the raw signal and calculated heart rates (see Peper, Gibney, Tylova, Harvey, & Combatalade, 2008, for more complete instructions).

### ECG Recording

When monitoring HRV using the ECG signal, data acquisition software detects the sharp, upward R-spike of the QRS complex, which is produced by the depolarization of the contractile fibers in the ventricles (lower chambers) of the heart (see Figure 1). The QRS complex is comprised of an initial downward deflection (Q), sharp upward deflection (R), and a concluding downward deflection (S). Next, the software algorithm calculates the interbeat interval (IBI), which is measured in milliseconds (see Figure 2). An IBI of 1000 milliseconds corresponds to a heart rate of 60 beats/minute because there are 1000 milliseconds in a second and 60 seconds in a minute. IBI measurements allow us to calculate HRV time domain (e.g., standard deviation of the normal-to-normal heartbeat intervals [SDNN]) and frequency domain (e.g., low-frequency (LF) power) indices. HRV time domain indices estimate the degree to which the IBIs between successive heartbeats vary. A sampling rate of at least 256 samples/second is recommended to accurately detect the appearance of an R-spike (Task Force, 1996).

# Normal

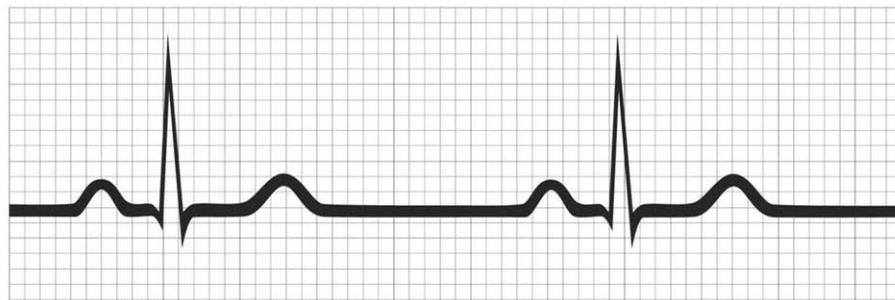
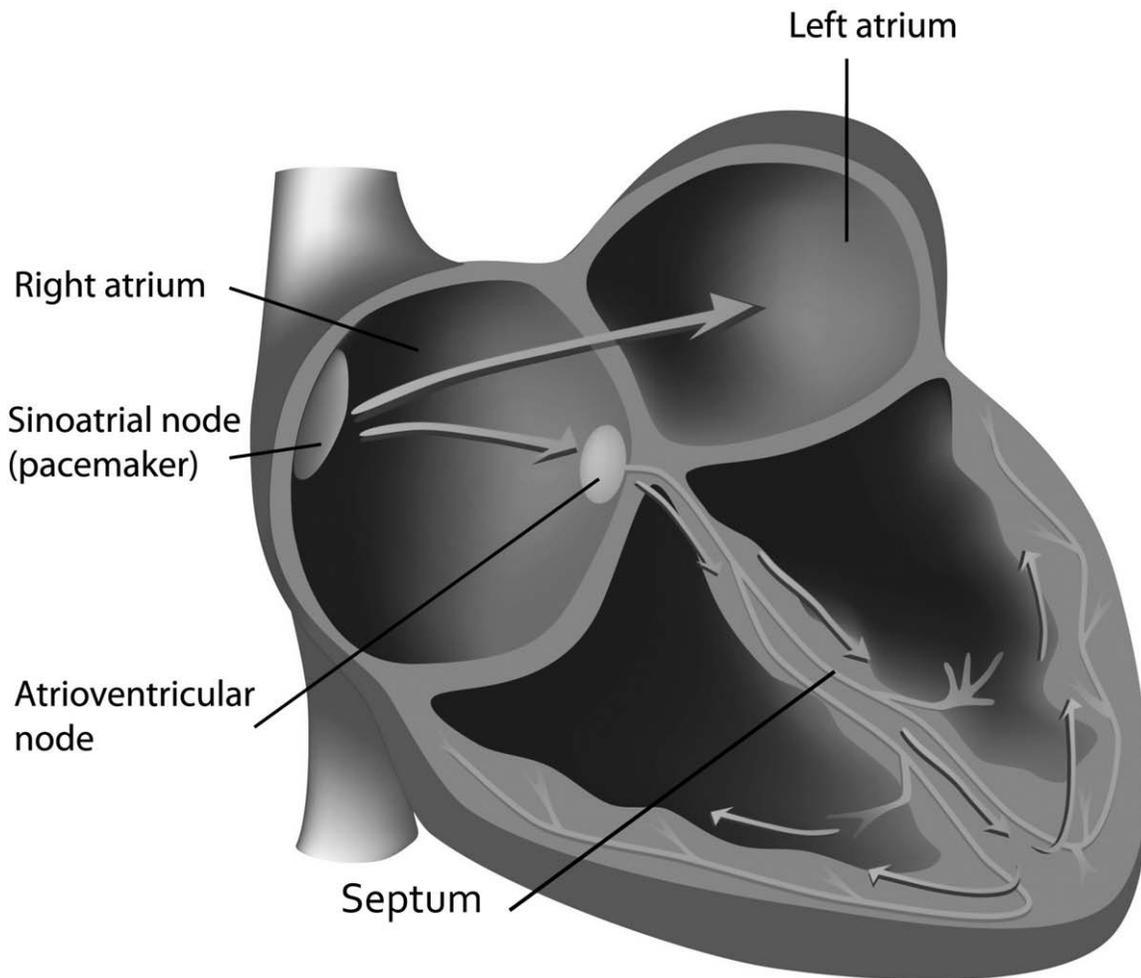
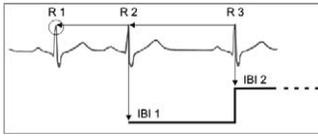


Figure 1. The generation of the electrocardiogram. Credit: Alila Sao Mai/Shutterstock.com



**Figure 2.** The interbeat interval (IBI) is calculated between the R-spikes of successive heartbeats.



**Figure 3.** Electrocardiograph (ECG) leads © Bork/Shutterstock.com

Frequency domain indices use power spectral analysis to determine the energy within four frequency bands: ultra-low-frequency (ULF), very-low-frequency (VLF), low-frequency (LF), and high-frequency (HF) bands. The minimum recording periods are 24 hours for ULF, five minutes for VLF, and five minutes or less for LF and HF (Shaffer & Venner, 2013; Task Force, 1996).

### ECG Leads and Electrodes

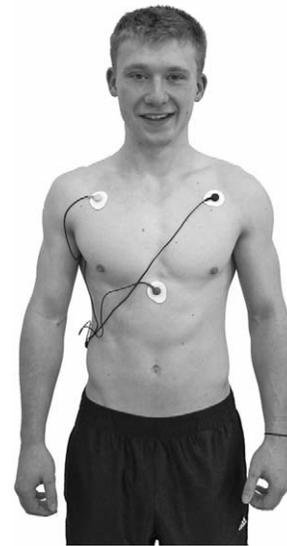
ECG leads include at least one reference and two active leads (see Figure 3). Standard lead cables have snap buttons onto which the electrodes are affixed. Dry or gelled electrodes can be used. Pre-gelled disposable ECG electrodes save preparation time and reduce the risk of infection (see Figure 4).

### Skin Preparation

Prepare the skin by rubbing the area where the electrodes will be applied with an alcohol wipe. Cleaning the skin of oil and dirt helps reduce impedance, which is opposition to AC current flow. For men, you may need to shave the chest and abdomen if body hair prevents satisfactory electrode contact with the skin.



**Figure 4.** Pre-gelled disposable electrocardiograph (ECG) electrode.



**Figure 5.** Chest placement.

### Placements

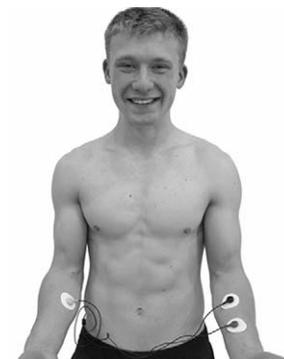
Four standard ECG electrode placements can be used. These include the chest, forearm, wrist, and lower torso. These placements differ in vulnerability to muscle (electromyography [EMG]) or movement artifact, speed of application, and degree of client comfort.

#### Chest Placement

A chest placement locates active and reference electrodes over the right and left coracoid processes, respectively, and a second active electrode over the xiphoid process (see Figure 5). This placement reduces the risk of arm muscle artifact, but exposes the chest area, which can be uncomfortable for female clients.

#### Forearm Placement

A forearm placement locates an active electrode on the right forearm and the reference and second active electrodes on



**Figure 6.** Forearm placement.



Figure 7. Wrist placement.

the left forearm (see Figure 6). Select an area with minimal or no hair. This placement is more vulnerable to contamination by arm and chest EMG artifact and movement artifact.

**Wrist Placement**

A wrist placement can use electrode straps instead of adhesive electrodes. One strap is used to attach an active electrode to the right wrist and the other to attach the reference and second active electrode to the left wrist (see Figure 7). While this is the easiest and most rapid ECG electrode placement, it is highly vulnerable to arm EMG artifact and movement artifact.

**Lower Torso Placement**

A lower torso placement suggested by Peper (personal communication, 2010) centers the reference electrode over the angle of the sternum and the active electrodes about 5 cm above the navel and 10 cm to the left and right of the midline (see Figure 8). This placement provides an alternative for clients who are uncomfortable exposing their chests (they can lift their blouse or shirt) and is less vulnerable to arm EMG artifact and movement artifact.

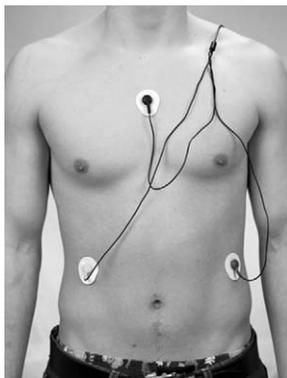


Figure 8. Lower torso placement.

Table. Drug effects on HRV measurements.	
Drugs That Affect Heart Rate Variability (Adapted from Gevirtz, 2011)	
Drug	Effect on HRV Measurements
Alpha-1 blocker (Carvedilol)	↑ RMSSD, pNN50, and HF
Benzodiazepines (Valium)	↑ SDNN and ↓ HF
Beta blockers	↑ SDNN, HF, and LF/HF ratio
Bupropion (Wellbutrin)	↓ SDNN
Caffeine	Minimal effect
Calcium channel blockers	Minimal effect
Clozapine (Clozaril)	↓ SDNN
Cocaine	↑ HR ↓ HF
Fanatrex (Gabapentin)	↑ SDNN, HF, LF/HF ratio
Flecainide (Tambocor)	↓ SDNN
Omega-3 fatty acids	↑ SDNN
Scopolamine (Atropine)	↑ SDNN and HF (low dosage) ↓ SDNN and HF (high dosage)
SSRIs (Prozac)	No effect
Thioridazine (Mellaril)	↓ SDNN
Tricyclics (Elavil)	↓ SDNN

*Note.* RMSSD = square root of the mean squared difference of adjacent normal-to-normal (NN) intervals, HRV = heart rate variability, SDNN = standard deviation of NN variables, HF = high frequency, LF = low frequency.

**Clinical Tips for ECG Sensor Placement**

Explain what the ECG sensor does and how it will be applied. Instruct the client to wear clothing that allows easy sensor placement. Snap the electrodes to the leads prior to applying them to the client's body. Ask for your female client's assistance in applying the sensors to her own body.

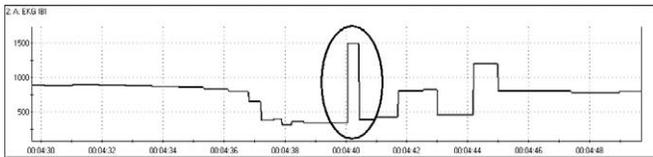


Figure 9. A missed beat.

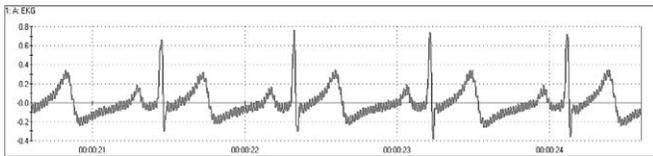


Figure 10. Line interference artifact.

## The Effects of Drugs on HRV Measurements

You should request a complete list of your client's prescription and social drugs because they can raise or lower ECG and PPG HRV measurements (see Table).

### ECG Artifacts

HRV artifacts can be produced by signal distortion or normal physiological events like premature ventricular contractions (PVCs). When distortion prevents software from detecting a heartbeat, this results in a missed beat and the calculation of a prolonged IBI. Conversely, when distortion causes software to detect an extra beat, this produces an artificially short IBI (see Figure 9). Missed and extra beats also affect PPG recording (Elgendi, 2012). Inspect the raw ECG signal for line interference, EMG, movement, direct-current (DC) offset, electromagnetic interference, and polarity artifacts.

### Line Interference (50/60 Hz)

Line interference artifact is the most frequent source of ECG signal contamination. It doesn't affect the blood volume pulse (BVP) signal as much, because it is based on back-scattered infrared light. Major sources of this artifact include computers, computer monitors, fluorescent lights, and power outlets. Line interference artifact looks fuzzy because HF fluctuations are superimposed on the signal (see Figure 10).

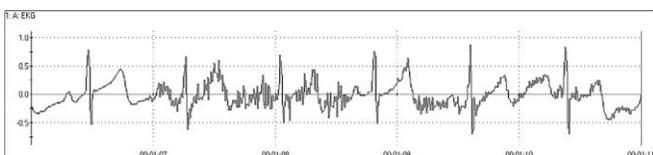


Figure 11. Electromyography artifact.

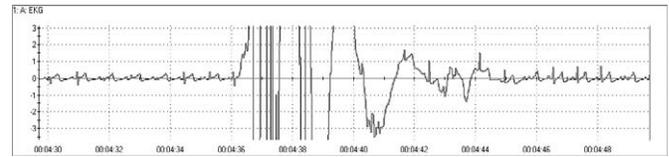


Figure 12. Movement artifact.

You can minimize 50/60-Hz artifact by using a 50/60-Hz notch filter, locating the encoder box three ft (1 m) from electronic equipment, using carbon-coated cables with active shielding, carefully preparing the skin and applying pre-gelled electrodes to achieve low and balanced impedances (approximately no more than 10 Kohms for each active-reference pair and 5 Kohms difference between measurements for both pairs), removing unused sensor cables from the encoder box, and choosing a well-designed electrocardiograph with high differential input impedance and common-mode rejection.

### EMG Artifact

Frequencies generated by the depolarization of skeletal muscles overlap with the ECG spectrum. The surface EMG ranges from 1–1000 Hz (Stern, Ray, & Quigley, 2001) while the ECG extends from 0.1–1000 Hz (Langner & Geselowitz, 1960). Muscle action potentials from large muscle groups travel to ECG sensors via the process of volume conduction (Shaffer & Neblett, 2010). Contraction of muscles in the arm can cause software to “see” many extra beats and calculate shorter IBIs (see Figure 11). You can minimize EMG artifact by using chest or lower rib placements, instead of forearm or wrist placements, and instructing your client to sit in a relaxed position and restrict movement.

### Movement Artifact

Client movement can pull the electrode cable so that the electrode partially (or completely) loses contact with the skin. This produces high-amplitude signal fluctuations that cause software to “see” many extra beats and calculate shorter IBIs as with EMG artifact (see Figure 12). You can minimize this artifact by firmly taping sensors leads to client clothing for

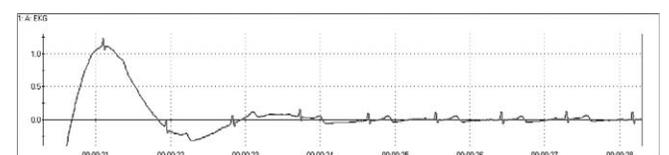
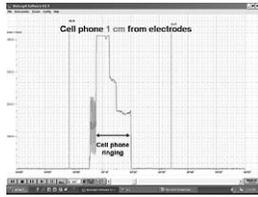


Figure 13. Direct-current (DC) offset artifact.



**Figure 14.** Surface electromyography recording showing the effects of a cell phone located 0.4 in. (1 cm) away from the electrodes (reproduced with permission from Erik Peper, PhD, BCB).

strain relief, using a lower torso placement, using pre-gelled electrodes to ensure strong skin-electrode contact, instructing your client to sit in a relaxed position and to restrict movement, carefully monitoring compliance, and examining the raw signal for artifact.

**Direct-Current (DC) Offset Artifact**

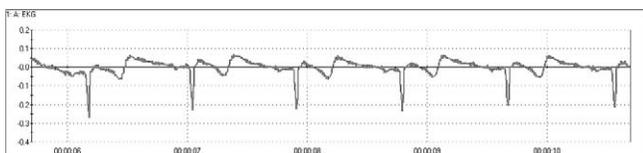
When the skin-electrode impedances of the three ECG electrodes differ due to poor skin-electrode contact, the ECG signal may drift up or down. DC offset artifact (signal drift) can cause extra beats or missed beats (see Figure 13). You can minimize DC offset artifact by cleaning the skin using an alcohol wipe and using fresh electrodes with sufficient gel.

**Electromagnetic Interference (EMI) Artifact**

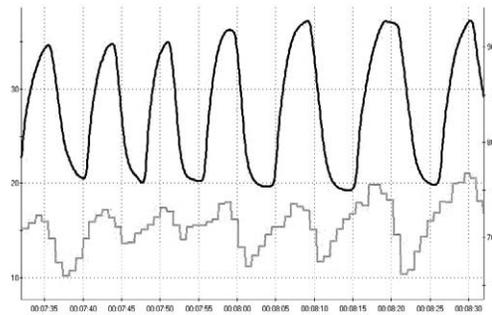
Cell phones can produce EMI artifacts when less than six ft (2 m) from ECG sensors or encoder boxes (Lin & Peper, 2009). The artifactual voltage is greatest when a cell phone located on the client receives a call (see Figure 14). You can prevent EMI artifact by ensuring that all cell phones are turned off before measuring HRV.

**Polarity Artifact**

The placement of the electrodes along the heart’s main axis affects both the direction and relative amplitude of the R-spike (see Figure 15). This artifact occurs when the active electrodes (yellow and blue) are misaligned with respect to the heart’s axis. A low-amplitude downward-oriented R-wave can cause software to miss beats and lengthen the IBI. You can prevent polarity artifact and maximize signal amplitude by correctly positioning the electrodes. For example, locate the yellow electrode (active) on the right shoulder and the



**Figure 15.** Polarity artifact.



**Figure 16.** Respiratory sinus arrhythmia. Heart rate (HR; lower tracing) increases as the abdomen expands during inhalation (upper tracing) and decreases as it contracts during exhalation.



**Figure 17.** Photoplethysmograph (PPG) sensor.

blue electrode (active) over the xiphoid process. Laterally adjust electrode position to increase R-spike amplitude. Finding the best location may require experimentation.

**Tracking Test**

You can determine whether the ECG signal responds to your client’s breathing by observing whether the instantaneous heart rate speeds during inhalation and slows during exhalation, a phenomenon called respiratory sinus arrhythmia (RSA; see Figure 16; see also Lehrer, 2013).

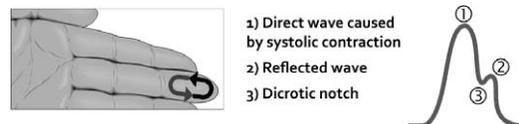
**PPG Recording**

A PPG sensor measures the relative amount of blood flow through tissue using a photoelectric transducer (see Figure 17). The BVP signal is the phasic change in blood volume with each heartbeat (Andreassi, 2007).

An infrared (7000°–9000° A) light source is either transmitted through or reflected off the tissue. Using the



**Figure 18.** Photoelectric transducer detection of relative blood flow.



**Figure 19.** The blood volume pulse (BVP) signal.



Figure 20. Attachment using an elastic band.



Figure 21. Attachment using Coban™ tape.

reflection technique, the light source and photodetector are placed on the same side of the tissue. The photoelectric transducer (phototransistor) detects the light and converts it into a positive DC signal. The intensity of the light reaching the sensor varies with brief shifts in blood volume (see Figure 18).

Blood appears red because it reflects red wavelengths. More light is reflected and the BVP signal increases when the volume of blood increases (Figure 19, phase 1). As the surge of blood ebbs, less light is reflected and the BVP signal declines as the volume of blood decreases. As the systolic pulse wave travels through the vascular tree, it is reflected back by the lower body and appears as a second peak (Figure 19, phase 2). The dicrotic notch (Figure 19, phase 3) is the gap between the direct and reflected waves.

### Skin Preparation

Unlike the ECG recording, no skin preparation is required since the PPG sensor detects back-scattered infrared light instead of an electrical potential. It is always a good idea to make sure that the client washes her hands so that dirt won't end up on the sensor's transducer window.

### Placements

PPG sensor attachment is critical because readings are sensitive to limb position, line interference artifact, ambient

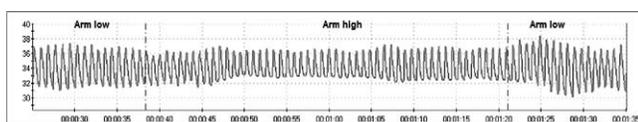


Figure 22. Changes in blood volume pulse (BVP) amplitude with hand placement below and above the heart.

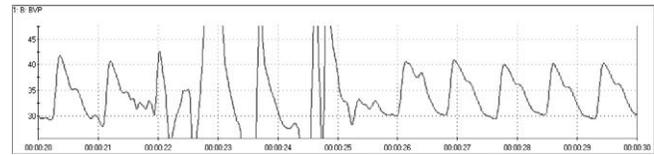


Figure 23. Movement artifact.

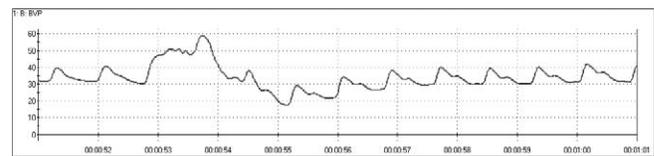


Figure 24. Blood pressure-mediated drifts.

light, movement, and pressure. For finger placements, attach the PPG sensor using an elastic band or Coban™ self-adhering tape to the palmar side of a larger finger and confine the sensor to only one finger segment. Use the thumb when the fingers are small or blood flow is compromised, such as when clients have cold hands (Peper, Shaffer, & Lin, 2010; see Figures 20 and 21). If your client is a manual worker, select the least callused finger, since thickened and hardened skin can impede infrared light transmission.

Sensor position relative to the heart strongly affects BVP. If the PPG sensor is placed on a limb below the heart, BVP signal amplitude increases. If the limb is placed above the heart, signal amplitude decreases (see Figure 22). These changes appear to reflect venous filling (Peper, Shaffer, & Lin, 2010).

### BVP Artifacts

Inspect the raw BVP signal for line interference, light, movement, pressure, and cold artifacts.

### Line Interference (50/60 Hz) Artifact

Line interference artifact appears as ripples during down-swings in the raw BVP signal (Elgendi, 2012). Take the precautions recommended for ECG recording.

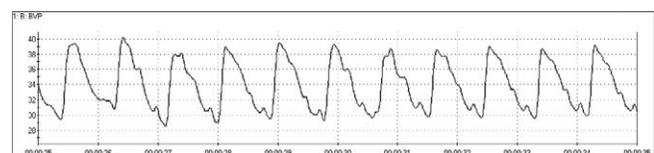


Figure 25. Movement artifact due to repetitive finger movements.

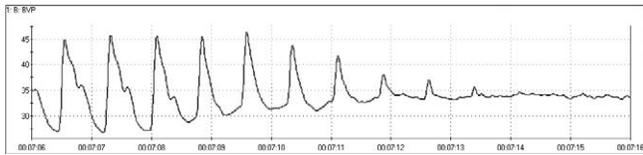


Figure 26. Pressure artifact.

### Light Artifact

When a PPG sensor is exposed to excessive direct light, baseline values are abnormally large. You can determine whether values are higher due to light artifact by covering the PPG sensor with a dark cloth. If values decline when covered, you have confirmed the presence of light artifact. The best strategy is to reduce direct light striking the sensor.

### Movement Artifact

Sensor movement artifact is the main cause of BVP signal distortion and can eliminate the signal or result in extra or missed beats (Elgendi, 2012). Sensor movement can interfere with infrared light transmission by the PPG sensor or allow contamination by ambient light (see Figure 23). Movement artifact assumes diverse shapes. Standing and sitting can produce blood pressure-mediated upward and downward drifts. Arm movement above or below the heart can also generate drifts (see Figure 24). Repeated movements like finger tapping can create waveforms with ripples that resemble multiple notches (see Figure 25).

You can minimize movement artifact by instructing your client to sit quietly, monitoring compliance, securing the sensor with an adhesive collar and a Velcro or stretch terry cloth band, firmly taping sensor leads to client clothing for strain relief, and covering the sensor with a dark cloth to minimize the entry of ambient light. The band should hold the PPG sensor in place without suppressing the pulse (Peper, Shaffer, & Lin, 2010).

### Pressure Artifact

Pressure artifact can be caused by wrapping a restraining band too tightly. Patients may report throbbing when a Velcro® band is wrapped too tightly around a finger. This reduces the amplitude of the raw signal, resulting in smaller values or a flat line, and may prevent detection of the peak

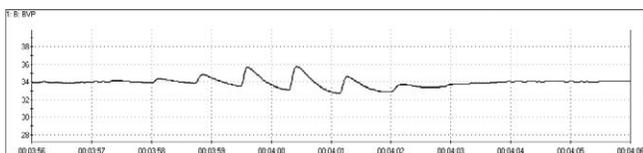


Figure 27. Cold artifact.



Figure 28. Respirometer.

of the pressure wave (see Figure 26). Excessive pressure can be caused by wrapping a restraining band too tightly or resting too much weight on the PPG sensor. Pressure artifact reduces the amplitude of the raw signal, resulting in smaller values. You can eliminate pressure artifact by readjusting the tightness of the restraining band (Peper, Shaffer, & Lin, 2010).

### Cold Artifact

Cold artifact is produced by cold exposure or sympathetically-mediated vasoconstriction that can reduce or eliminate a pulse wave. This prevents reliable detection of the peak of the pressure wave (see Figure 27). You can control cold artifact by maintaining at least a 74°F (23°C) room temperature. The thumb is an excellent site when a client's fingers are too small or have insufficient blood flow to detect a strong pulse (Peper, Shaffer, & Lin, 2010). Earlobe blood flow may produce an adequate BVP signal when you can't detect a signal from the fingers. Provide your client several minutes to relax if vasoconstriction is sympathetically mediated. Allow your client to place his or her hands in a sink filled with warm water or in front of a space heater for several minutes.



Figure 29. Abdominal respirometer placement.

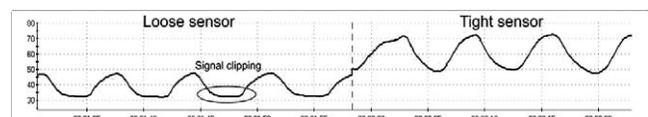


Figure 30. A loose sensor band results in clipping in the left half of the display.



Figure 31. Sinusoidal respirometer signal pattern.

## Tracking Test

You can determine whether the ECG or BVP signals respond to your client's breathing by observing whether his or her instantaneous heart rate speeds during inhalation and slows during exhalation.

## Respiration Recording

A respirometer is a flexible sensor band placed around the chest, abdomen, or both, that allows you to monitor respiration effort, pattern, and rate. A respirometer measures changes in expansion by detecting changes in electrical resistance (see Figures 28 and 29). A respirometer is required to measure the HRV time domain index HR Max–HR Min, which is calculated using the difference between the highest and lowest heart rates during each respiratory cycle. It is also used to determine the client's resonance frequency. The resonance frequency is the rate at which an individual's cardiovascular system can be stimulated by maneuvers like breathing or rhythmic muscle contraction to increase HRV (Shaffer & Venner, 2013).

To ensure adequate responsiveness, ask your client to completely exhale and then slightly tighten the sensor band during the postexpiratory pause. When the respiratory sensor is poorly attached and loosens or comes off during the middle of an inhalation, this can result in signal clipping and sharply change the signal's offset on the screen (see Figure 30). Respirometer amplitude (max-min) and peak (max) measurements are displayed in relative units, instead of absolute units as in °C or °F. You want to see a sinusoidal signal pattern with sufficient amplitude to detect both the peaks and valleys (see Figure 31). Since peak values depend on the exact placement of the band, stomach girth, the thickness

of the clothing under the band, and band tension, reliability can be very low and cannot be compared across sessions.

## Tracking Test

You can determine whether a respiratory sensor display mirrors your client's abdominal movement by performing a tracking test. Instruct your client to inhale and then exhale, and check whether the display of abdominal excursion mirrors actual stomach movement. You can verify the accuracy of respiration rate measurements, visually, by counting the number of oscillations (mountains and valleys) in the signal.

## Summary

Competent HRV monitoring requires familiarity with clean ECG, BVP, and respirometer signals, understanding of common sources of signal contamination, and precautions to minimize these artifacts. As with all biofeedback modalities, visual inspection of the raw signal is essential to ensuring measurement fidelity.

## Acknowledgments

This article draws heavily on Didier Combatalade's *Basics of Heart Rate Variability Applied to Psychophysiology*, published by Thought Technology Ltd. in 2010. Richard Gevirtz, PhD, BCB, graciously shared his table of drug effects on HRV, which was presented in 2011 at the Biofeedback Foundation of Europe conference in Munich. The authors thank Truman State University pre-med student Max McDermott for modeling ECG and respirometer placements.

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