Wavelet denoising of vaginal pulse amplitude

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Abstract

Vaginal pulse amplitude (VPA) has been the most commonly analyzed signal of the vaginal photoplethysmograph. Frequent, large, and variable-morphology artifacts typically have crowded this signal. These artifacts usually were corrected by hand, which may have introduced large differences in outcomes across laboratories. VPA signals were collected from 22 women who viewed a neutral film and a sexual film. An automated, wavelet-based, denoising algorithm was compared against the uncorrected signal and the signal corrected in the typical manner (by hand). The automated wavelet denoising resulted in the same pattern of results as the hand-corrected signal. The wavelet procedure automated artifact reduction in the VPA, and this mathematical instantiation permits the comparison of competing methods to improve signal:noise in the future.

Descriptors: Sexual response, Normal volunteers, Vaginal photoplethysmography

The vaginal photoplethysmograph is often used to measure female sexual response for both research and clinical purposes, but its use faces many theoretical and methodological challenges (Prause & Janssen, 2006). One issue underlying several of the problems with the instrument is a lack of standardization for denoising the signal, especially the extraction or correction of artifacts thought to reflect movement. Manual data cleaning currently involves “an experienced researcher visually inspecting the data for outliers and deleting movement artifacts, which are defined as sudden and drastic changes in vaginal pulse amplitude” (Rellini, McCall, Randall, & Meston, 2005, p. 120). The procedure described in that study is typical (cf. Brotto, Basson, & Luria, 2008; Prause, Cerny, & Janssen, 2005) with no additional clarification or quantification of “drastic,” “sudden,” or similar descriptors. These procedures are especially troubling given that electromyographic activity in the vagina has been documented to increase tonically with clitoral vibratory stimulation (Gillan & Brindley, 1979, although see Laan & van Lunsen, 2002, for a possible exception), when participants report feeling threatened (van der Velde & Everaerd, 2001), and during increasing sexual arousal (Carmichael, Warburton, Dixon, & Davidson, 1994). This suggests that artifacts appear disproportionately during periods of sexual stimulation, so hand corrections of signals may systematically bias the vaginal pulse amplitude (VPA) during sexual arousal conditions due to their greater likelihood of occurrence during those conditions. Hand correction also is expected to increase variability in signals from laboratory to laboratory and across participants. This may decrease the signal:noise ratio (Gratton, 2007) by, for instance, reducing the epochs included in averages (Cutmore & James, 1999). A method that replaced, rather than deleted, artifacts would retain data to permit finer timescale analysis of sexual response. Further, hand correction limits the ability to make strong inferences about results across laboratories. An automated algorithm to systematically remove or reduce these artifacts would permit systematic examination of a correction process. In this study, a wavelet denoising algorithm is investigated for its ability to reduce artifacts by reproducing manual data cleaning and retain signal by a wavelet-fitting replacement strategy. Thus, the algorithm is expected to reduce processing time and improve data retention.

Attempts to characterize the VPA signal and its artifacts, which might guide development of an automated process, have been limited. The intravaginal device based on photoplethysmography principles used to measure cardiovascular responses by reflection typically has a sharp, symmetrical, sawtooth wave series. Researchers in one study attempted to quantify the impact of any signal pulse visually judged to be out of phase with 0.8 Hz (Prause et al., 2005). Twenty percent of the (10-s) epochs during a 3-min sexual film were impacted by artifacts, and 22% of the intervals with artifacts deflected the average in that interval by > 50% of the nearest interval without an artifact. When inspected visually, large artifacts appear to be highly prevalent in the VPA.

Others have attempted to use frequency-based signal processing approaches. Following fast Fourier transform (FFT) on 1-min signals judged (visually) to be artifact free, the highest peak in spectral tension at 0.75 Hz was used as the response index (Pras et al., 2003; Wouda et al., 1998). If an artifact was judged to be present, as occurred in 10% of the final minute intervals, the
minute just preceding the impacted interval was used. This procedure relies on the same variable interrater visual identification of artifacts, which may or may not accidentally include erroneous changes to the power spectra by any number of unidentified artifacts. It also does not account for variations in time between beats, which should have increased the spectrum (wider frequency band) included in an FFT analysis. For example, Figure 1 shows three VPA signals with potential artifacts. Because the signal power is greatest around 0.8 Hz for each signal, it is unclear whether the increased amplitude (Plot 1), dichrotic notch (Plot 2), or out-of-phase peak (Plot 3) would be identified by the "trained" raters in different laboratories. Leaving in the potential artifact would result in greater power at higher frequency bands in an FFT analysis that reduces signal frequency by about 70% for filtered bands.

Speculations abound regarding the possible etiology of signal artifacts, which could be helpful in isolating and characterizing the artifacts mathematically. Breathing has been described for years as contributing a slow wave present in some participants’ VPA (Palti & Berovici, 1967). This is consistent with respiration research that identifies breathing at laboratory baseline as between 0.2 and 0.25 Hz (Lorig, 2007). Researchers using electromyography (EMG) have documented increases in muscle activation during sexual stimulation in women not reporting sexual difficulties (Gillan & Brindley, 1979; van der Velde & Everaard, 2001). These may function to enhance sexual response, as documented in men (Oswald & Cleary, 1986), or may simply represent a reflex to cervical stimulation due to probe impingement (Shafik, 1996), or may even reflect the vaginal lengthening process concurrent with sexual arousal (Faix, Lapray, Callede, Maubon, & Lanfrey, 2002). Prause et al. (2005) requested that participants perform several exercises. Those that produced the greatest duration of artifact included (1) tensing pelvic muscles, (2) tensing abdominal muscles, and (3) scooting up in the testing chair. Although the free-dwelling nature of the probe can allow the orientation to change slightly, some claim to have rotated the probe intravaginally in participants and observed no signal change (Polan et al., 2003). In summary, some frequency-specific artifacts (e.g., breathing) are amenable to simple frequency filters, but artifacts that span frequencies (e.g., pelvic tensing, gross movement) require both frequency and time corrections.

Although many methods have been developed for artifact extraction and/or correction in other psychophysiological domains, wavelets appear best suited for further development of an algorithm for VPA denoising. More common artifact correction methods in other domains include regression-based approaches. Regression-based approaches measure activity thought to contribute to the generation of artifacts in the signal of interest, such as measuring electrooculograms to monitor eye movements to remove the artifacts that these eye movements generate in electroencephalographic signals. Values in the original signal are replaced based on some calculations using the second, artifact-monitoring signal (e.g., Semlitsch, Anderer, Schuster, & Presslich, 1986). However, these methods necessarily attenuate signal with noise reduction (Croft, Chandler, Barry, Cooper, & Clarke, 2005). For VPA, multiple filters would be necessary to attenuate the highly variable artifacts, and each filter also reduces the signal (Browne & Cutmore, 2002). Another option would be a components-analysis approach that relies on multitrial extraction of artifacts; however, these still require the subjective visual identification of artifact components that lead to data inconsistencies (Krishnaveni, Jayaraman, Anitha, & Ramadoss, 2006). Both windowed Fourier transforms and wavelets provide time-frequency information and have been applied to the study of non-

![Figure 1](image_url)  
**Figure 1.** Questionable artifacts in vaginal pulse amplitude signals.
Wavelet denoising of vaginal pulse amplitude

Wavelet transforms are the convolution of a signal with scaled and translated versions of a primary basis function called the “mother wavelet.” The mother wavelet can be selected from myriad published wavelet families, each of which enjoys certain mathematical properties appropriate for particular applications. Intuitively, one selects a mother wavelet based on its ability to serve (at some scale) as a representation of the underlying signal of interest. The mother wavelet defines a nested sequence of approximation/decomposition spaces, each having its own time-frequency window of resolution. Each of these spaces is spanned by “daughter wavelets,” which are dilated translates of the mother wavelet. This means that the daughter wavelets have the same morphology as the mother wavelet, but on different timescales. The resulting decomposition of a signal into these finer and finer timescales is implemented by a simple, recursive linear filter, known as the fast wavelet transform (FWT). By basing the FWT decomposition on translations and scalings of an individual, localized, waveform, the signal need not be cyclic or stationary, which permits obtaining a fit even when duration, amplitude, or latency vary (Gratton, 2007). Thus, the problems identified in using the FFT alone, including variability in the desired signal period and artifacts (although localized in time) that globally contaminate the desired frequency band, are corrected. The decomposed signal then can be reconstructed in time or frequency (e.g., Gurtubay et al., 2001) domains by reversing the FWT recursive filters. Signal components can be emphasized or deemphasized as desired by modifying coefficients of the wavelet decomposition at various levels. Brief, nontechnical introductions to wavelets are published elsewhere (e.g., Samar, Bopardikar, Rao, & Swartz, 1999).

Because wavelets use a pattern-matching approach applied to the entire signal affecting both time and frequency domains, the entire signal is transformed by this approach (not simply artifacts). Methods to compare manual cleaning and wavelet correction methods include signal:noise ratio calculation from signal simulation (cf. Iyer & Zouridakis, 2007), testing for the presence of theoretically expected outcomes from real psychophysiological data (cf. Houtveen & Molenaar, 2001), and descriptive assessment of visual changes (cf. Girton & Kamiya, 1973). The limitations of using a visual correction method as a gold standard are well known (Vialatte, Sole-Casals, & Cichocki, 2008). However, the raw, hand-corrected, and wavelet-corrected signals are compared in this study during a neutral and sexual film stimulus to test for the presence of theoretically expected differences by test conditions. The second approach to examine the efficacy of the wavelet correction method was descriptive to permit readers to examine the effects of the wavelet correction in the time domain.

Method

Participants

Participants were recruited through newspaper ads and flyers requesting volunteers for a study of alcohol and sexual response who were not experiencing problems becoming sexually aroused. Women were tested during the follicular phase. They were compensated financially for their participation. Twenty-two women volunteered (see Table 1 for demographic information). The data from 1 woman was excluded from additional analyses because of the vaginal photoplethysmograph (VP) becoming dislodged during testing.

Stimuli

The sexual film depicted a consensual, erotic, heterosexual encounter, edited to equal parts kissing/foreplay, oral sex being performed on the man and then the woman, and penile-vaginal intercourse. Low base rate content unlikely to be appealing to women (e.g., anal sex; Woodward et al., 2008) was excluded. The film shown was among the six for which women reported the strongest feelings of sexual arousal in a previous study (Janssen, Carpenter, & Graham, 2003). A documentary film about underwater creatures (National Geographic, 1995) was shown for 15 min before the start of the sexual film to establish a baseline. For these analyses 8,192 (or 213) data points were used from each condition, which reflected the last 102.4 s of the baseline and the first 102.4 s of the sexual film.

Vaginal Photoplethysmograph

The VP (Palti & Bercovici, 1967, refined by Sintchak & Geer, 1975) was a small cylindrical device made of clear acrylic plastic. An infrared light was embedded in the cylinder of the device and projected toward the vaginal wall. The light reflected back to a photosensitive cell within the body of the probe was recorded. It was assumed that more light returned to the phototransistor cell as the amount of blood in the vaginal blood vessels increased, although this interpretation has been challenged (Prause & Janssen, 2006). An acrylic plate was attached to the external cord to help stabilize it (Laan, Everaerd, & Evers. 1995). The VP was cleaned with Cidexplus, a glutaraldehyde-based antiseptic.

The VP output typically is filtered to yield two signals. The alternating current signal, referred to as the vaginal pulse amplitude, was used and is thought to reflect pressure changes within the blood vessels of the vagina’s vascular walls (Hoon, Coleman, Amberson, & Ling, 1981). The signal was bandpass filtered (0.5 to 30 Hz) and digitized (80 Hz) using a BIOPAC system (Model MP100). Although 80 Hz is well beyond the Nyquist frequency (around 0.8 Hz) for this signal, such oversampling maximized the processing approaches that could be attempted later at the minimal cost of larger file size. Signal processing is further discussed in the data analysis section below.

Table 1. Demographic and Sexual History Information about Participants

<table>
<thead>
<tr>
<th>Variable</th>
<th>Number (%)</th>
<th>Mean (SD)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age</td>
<td>23.5 (3.3)</td>
<td></td>
</tr>
<tr>
<td>Lifetime sexual intercourse partners</td>
<td>16.4 (27.8)</td>
<td></td>
</tr>
<tr>
<td>Years of education</td>
<td>15.3 (1.7)</td>
<td></td>
</tr>
<tr>
<td>Ethnicity</td>
<td></td>
<td></td>
</tr>
<tr>
<td>European American</td>
<td>18 (78.3)</td>
<td></td>
</tr>
<tr>
<td>African American</td>
<td>3 (13.0)</td>
<td></td>
</tr>
<tr>
<td>Asian</td>
<td>1 (4.3)</td>
<td></td>
</tr>
<tr>
<td>Hispanic</td>
<td>1 (4.3)</td>
<td></td>
</tr>
<tr>
<td>How important is religion?</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Very important</td>
<td>3 (13.6)</td>
<td></td>
</tr>
<tr>
<td>Important</td>
<td>8 (36.4)</td>
<td></td>
</tr>
<tr>
<td>Slightly important</td>
<td>4 (18.2)</td>
<td></td>
</tr>
<tr>
<td>Not important</td>
<td>7 (31.8)</td>
<td></td>
</tr>
</tbody>
</table>

Note: The VP output typically is filtered to yield two signals. The alternating current signal, referred to as the vaginal pulse amplitude, was used and is thought to reflect pressure changes within the blood vessels of the vagina’s vascular walls (Hoon, Coleman, Amberson, & Ling, 1981). The signal was bandpass filtered (0.5 to 30 Hz) and digitized (80 Hz) using a BIOPAC system (Model MP100). Although 80 Hz is well beyond the Nyquist frequency (around 0.8 Hz) for this signal, such oversampling maximized the processing approaches that could be attempted later at the minimal cost of larger file size. Signal processing is further discussed in the data analysis section below.
Procedure
The study was approved by the university institutional review board. Upon arrival at the laboratory, each woman completed an informed consent statement and demographic questionnaires on a computer. This analysis used the first neutral and sexual film presented from a larger study. Briefly, women placed the instrument themselves in a private room. They then viewed 15 min of a nature film that did not contain any sexual acts for which the last film segment (described below) was used as the baseline. Full details of the procedure are available elsewhere (Prause, Staley, & Finn, 2009).

Data Analysis
Signal cleaning and correction. The raw VPA signal was processed using two different methods to reduce artifacts. The first artifact-reduction method was the “typical” manual correction method, wherein two trained research assistants connected endpoints of the signal to delete visually identified artifacts. The first author trained research assistants to identify as artifacts any visual anomalies from the typical “sawtooth” shape of the signal, especially those that generated a peak or trough not consistent with the peak or trough interbeat interval from the absolute maximum immediately preceding or following the potential artifact.

The second artifact-reduction method was the wavelet signal correction method. The wavelet-based artifact removal methods (waveclean.m) used here is freely available at http://www.mathworks.com/matlabcentral under the first author’s name. This method removed all components of the signal’s transformation into the wavelet domain that did not correspond to the wavelength of the vaginal pulse signal, reduced the magnitude of the outlier peaks to visually resemble the rest of the signal, and transformed the modified wavelet decomposition back into a corrected signal in the time domain. The current study used a Coiflet mother wavelet with five vanishing moments for its visual resemblance to the signal of interest (see Figure 2), which is a common approach to initial selection of a mother wavelet. Among the many wavelets not selected, some were less symmetrical or had rounded peaks that do not resemble the VPA as strongly. The signal was transformed using a stationary wavelet transform, which allows the signal to be decomposed by the wavelet transform into discrete decompositions. For a signal of length $2^J$, where $J$ is some positive integer, there are $J$ decompositions. These components form periodic signals based on 1, 2, 4, 8, 16, ..., $2^J$ data points, with the different decompositions having increasing frequency. To retain wavelet decompositions corresponding to the desired frequency of the vaginal pulse (0.8 Hz), a wavelength of 100 data points was used (sampling $= 80$ Hz). Visual examination of many wavelet decompositions of different signals from these experiments suggested that the $(J-7)$th to $(J-4)$th wavelet decompositions corresponded to the wavelengths of the vaginal pulse signal. To remove the unwanted parts of the wavelet decomposition, all data points in the decompositions not within the $J-7$ to $J-4$ range were set to 0 (see Figure 3). The remaining signal was further processed to retain signal still affected by artifacts, which differs from traditional approaches that reduce data by deleting offending signal components in the time domain (see the Appendix for details). The inverse wavelet then was applied to reconstruct a corrected signal in the time domain. The threshold and multipliers were determined by iteratively visualizing the signal in the time domain using different multipliers until the replaced signal visually approximated the surrounding signal.

Amplitude extraction. The amplitude of each peak of the three signals then was extracted, binned, and averaged separately using Matlab (Mathworks, v. 7.4; FindVPAamp.m file available

![Figure 2. Coiflet mother wavelet selected for artifact reduction and sample wavelets not selected as mother wavelet.](image-url)
at http://www.mathworks.com/matlabcentral under the first author’s name). First, each signal was detrended to remove linear drift. Then, each time when the signal crossed the 0-mV threshold was recorded. The absolute maximum value between each zero-crossing time noted then was recorded, and each pair was added to form the amplitude per peak. The signal was binned into 10-s intervals. This means that some bins included different total numbers of peaks in their average, depending on the interbeat interval.

### Results

The $2 \times 3 \times 10$ repeated-measures ANOVA\(^1\) indicated main effects of Film, $F(1,19) = 14.95, p = .001$, $\eta^2_p = .44$. Signal, $F(2,38) = 139.75, p < .001$, $\eta^2_p = .88$, and Interval $F(9,171) = 5.91, p = .001$, $\eta^2_p = .24$. These were qualified by a Film $\times$ Signal, $F(2,38) = 4.52, p = .03$, $\eta^2_p = .19$, and Film $\times$ Interval, $F(9,171) = 8.03, p < .001$, $\eta^2_p = .30$, interaction. Contrasts indicate that the Film $\times$ Signal interaction was due to the wavelet-corrected signal exhibiting a slightly smaller absolute difference between the two test films, $F(1,19) = 11.61, p = .003$, $\eta^2_p = .38$ (see Figure 4), although it also resulted in a somewhat lower standard error in each condition. Polynomial contrasts indicated that the highest order (of linear, quadratic, or cubic) waveform had a significant effect.

\(^1\)Readers may question whether this means that an analysis of the wavelet signal alone would differ from patterns expected in similar research, especially given that the Film $\times$ Interval interaction seemed to indicate a smaller absolute difference between conditions for the wavelet-corrected signal. A $2 \times 3 \times 10$ repeated-measures ANOVA was conducted on the wavelet-corrected signal alone. As expected, there were main effects of Film, $F(1,20) = 17.88, p < .001$, $\eta^2_p = .47$, and Interval, $F(9,180) = 7.03, p = .002$, $\eta^2_p = .26$, and an interaction of Film $\times$ Interval, $F(9,180) = 15.02, p < .001$, $\eta^2_p = .38$. Contrasts indicated that the interaction was due to the linear increase observed in the sexual film that was not observed during the neutral film, $F(1,20) = 31.02, p < .001$, $\eta^2_p = .61$. 

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**Figure 3.** Example of wavelet decomposition coefficients before and after the smoothing calculation is applied (conducted on signal from Plot 3 in Figure 6).
responsible for the interaction of Film and Interval was a cubic pattern, \( f(1,19) = 4.51, p = .047, \eta^2_p = .19 \) (see Figure 5). This appears to reflect a slight plateau in response during Minute 2 of (the otherwise linear increase to) the sexual film.

Three sections of VPA were identified for the descriptive analysis (see Figure 6). The breathing is reflected in the slower wave that the faster waves typical of VPA appear to “ride.” Given the density of the signal, periodograms of the signal before and after wavelet signal correction also are provided (see Figure 7) to highlight the reduction in the slow-wave component. Each signal amplitude decreases with wavelet signal correction, but wave morphology and relative size is preserved. This supports the previous analysis, suggesting that the main effect of signal is due to a simple, monotonic transformation rather than some significant distortion of the pattern of response.

Discussion

This study supports the use of an automatic wavelet method of correcting the vaginal pulse amplitude signal component of the vaginal photoplethysmograph. The wavelet approach described to reduce artifacts preserves the large effect size of sexual arousal induction by visual sexual stimulation. Because wavelets affect both time and frequency, both slow-wave noise and nonperiodic movements were reduced in the signal consistent with existing manual data cleaning methods. Finally, artifact-free portions of the original signal are reduced proportionately in magnitude without increasing signal variability and preserving the frequency of interest.

Some may be concerned that wavelet correction changes both the artifacts and signal without clear artifact. As compared to other denoising strategies, wavelets tend to preserve peak amplitude (Singh & Tiwari, 2006). Because VPA is a relative signal, though, it also is only essential that relative contrast between conditions (within subjects) be preserved. The analysis presented here indicates that the expected relative differences between sexual and neutral stimuli were preserved after denoising by the wavelet correction algorithm. The effect size was slightly smaller than the effect size from the hand-cleaned signal, which could suggest that some important portion of the signal also was reduced. Although any denoising algorithm likely also reduces signal to some extent, the decreased variance suggests at least the effect size difference likely is not due to an increase of noise in the signal. It is possible that the smaller effect size reflects a true, smaller difference in the data or some decrease in the true signal component.

Another automated algorithm to clean the VPA is used by one laboratory and deserves mention (Laan & Everaerd, 1998). The routine identifies the strongest frequency component of the raw data (usually around 1 Hz) and generates a signal using a low-pass Butterworth filter based on this dominant frequency (B. Molenkamp, personal communication, 2009). Peaks and trough time locations are identified in this generated signal, and the corresponding values in the real signal at those time points are

Figure 4. Interaction of Film and Signal (± 1 SE) showing preservation of film condition difference across methods with overall amplitude reduction in wavelet method.

Figure 5. Interaction of Film and Interval (± 1 SE) showing the expected increase in response over time regardless of signal processing method.

Figure 6. Three representative artifacts in the raw signal and the same signals after wavelet correction.
Wavelet denoising of vaginal pulse amplitude

Figure 7. Periodograms of a signal contaminated with slow wave noise before and after wavelet correction.

Further processed. Further processing includes a low-pass filter to reduce dichrotic notch peaks and several comparisons that are trained to modify criteria that will identify extreme values in the signal. For example, if peak-to-peak time intervals exceed $-2.5\ SD$ or $+3.5\ SD$ from the immediately preceding interval, this peak will be excluded from further analysis. Future research may compare the resultant differences of this algorithm and the wavelet approach presented in this study.

The wavelet correction does not overcome the other limitations of the vaginal photoplethysmograph. The most serious of these is the lack of clarity regarding which of many physiological processes the instrument may reflect. For example, if recent vasomotion interpretations (Levin & Wylie, 2008; for general explanation of vasomotion, see Nilsson & Aalkjær, 2003) of VPA are supported, it is possible that amplitude would no longer be considered the important component of the signal. Briefly, vasomotion describes a sudden change in blood vessel diameter, such that blood flow increases might be better characterized by the number of vessels “open” rather than the gradual widening of all vessels in an area being perfused. The absolute amplitude of VPA signals would not directly reflect the level of perfusion in the vaginal tissue if vasomotion predominates in those tissues. Thus, wavelet denoising does not decrease the need for further investigation of the VPA signal or development of MRI (Maravilla et al., 2005), doppler (Kukkonen et al., 2006; Munarriz, Maitland, Garcia, Talakoub, & Goldstein, 2003), temperature (Prause & Heiman, 2009), or other alternate measures of female sexual response.

Mother wavelet selection in this study was based on visual resemblance (e.g., Krishnaveni et al., 2006). Although this is a common approach, there are many alternatives that could be used advantageously in future developments. Trial-and-error approaches testing a large number of wavelets from different families have the advantage that fit criteria can be used to establish a basis for selection. However, the fit may be specific to the data set that is used to “train” wavelet algorithms (Kurt, Sezgin, Akin, Kirbas, & Bayram, 2009) or lack face validity if visual resemblance to the signal under study is low. An alternate approach could be to better identify theoretically significant components of the original waveform and select wavelet families based on empirical characteristics (Ahuja, Lertrattanapanich, & Bose, 2005).

There are several additional ways to test for optimization of wavelet digital signal process parameters that were not used (see the review in the Introduction). Systematic characterization of VPA artifacts (cf. Benbadis & Rielo, 2009) would improve the ability to characterize them mathematically for future simulation tests. Additionally, simultaneous recording of VPA with other indices of known contaminants (e.g., vaginal electromyography as in van der Velde & Everaerd, 2001) would permit better characterization of the etiology of artifacts. This is unlikely to result in very effective means for removing artifacts, when considering the example of regression approaches used with EMG simultaneously recorded with EEG that are falling into disuse (Wallstrom, Kass, Miller, Cohn, & Fox, 2004). However, it may improve mathematical models of artifacts. Such characterization also would assist, most ideally, in reducing the introduction of artifacts into the signal.

This study presented probabilistic and descriptive evidence supporting the use of an automated, wavelet-based denoising algorithm for vaginal pulse amplitude, the primary signal analyzed from the vaginal photoplethysmograph. The algorithm appears to detect and treat artifacts in an effective manner consistent with manual data cleaning approaches. It also preserves the ordinality of the original signal across theoretically meaningful test conditions. Several alternate methods for developing an automated signal correction procedure and for assessing a correction algorithm were suggested. In addition to reducing processing time, the presented wavelet approach replaces artifacts with approximated signal to retain data. Normally, signals with artifacts are deleted, reducing the time series available for analysis. The algorithm is publicly available for continued development at publication.

REFERENCES


APPENDIX

Values in each decomposition were determined to artifact when
\[
\frac{2 \times \text{median}(|\text{decomposition}_j|)) + 23}{16} < \max(|\text{decomposition}_j|).
\]

These were multiplied by the constant
\[
\frac{2 \times \text{median}(|\text{decomposition}_j|))}{\max(|\text{decomposition}_j|)}
\]
at the maximum point with the multiplier decreasing quadratically from the center point to maintain the smoothness and continuity of the function (see Figure 3). (Maximum values identified on boundaries were smoothed only on the one, remaining side.)