White paper
MDSP™ ECG Processing Technology
Capabilities and Principles of Operation

Interval and arrhythmia analysis of ambulatory ECGs is often problematic due to noise and artifact. Noise has been a long-standing barrier to expanding the range and utility of information that can be extracted from ambulatory recordings. Beyond masking detail in the recordings, noise results in both false positive arrhythmia detections and reduced sensitivity. When measuring intervals, noise introduces measurement variability, renders a significant portion of beats uninterpretable, and may introduce a heart rate dependent bias when computing individualized QT correction. VivaQuant Multi-Domain Signal Processing (MDSP™) technology nearly eliminates the impact of noise when extracting information from ambulatory ECGs. This opens the door to powerful new non-invasive diagnostics and enables other diagnostics that have been impractical to use in the past due to expense and difficulty. This paper provides an overview of the technology and reviews results obtained to date for detecting arrhythmias and measuring intervals.

Technology Overview

MDSP represents a significant advance in ECG analysis. Traditional template-based approaches proved to work quite well for analyzing ECGs from sedentary subjects, but when noise is present or morphology changes occur due to posture changes in ambulating subjects, a large number of templates may be needed. When a large number of templates are used to accommodate morphology changes, inappropriate template switching can occur, resulting in interval measurement jitter when noise is present. The conventional approaches require a significant number of assumptions: e.g. QRS amplitude is relatively stable from one beat to another; QRS complexes must be relatively narrow; and T-wave amplitude is significantly lower than QRS amplitude. The only assumptions required for MDSP are that the signal is pseudoperiodic and the noise and cardiac signal emanate from different sources (e.g. heart and skeletal muscle).

MDSP removes noise without distorting ECG morphology by dividing the cardiac cycle into two windows – a first window surrounding the QRS complex and a second window that includes the remainder of the cardiac cycle. Since the information content in the QRS complex is quite different than the information contained in the remainder of the cardiac cycle, spatially selective filtering can be applied to remove noise. Conventional filtering techniques would run into limitations imposed by the Heisenberg uncertainty principle, which dictates that there must be a trade-off between time and frequency resolution. This would result in “smearing” of information between the windows (e.g. between the first and second windows) where the character of the signal changes rapidly. MDSP circumvents the Heisenberg limitation by decomposing the ECG signal into subcomponents in multiple mathematical domains. Subcomponents are then manipulated to separate those associated with noise from those associated with the desired ECG signal. Once the subcomponents associated with noise are identified, they are removed and the remaining subcomponents are reconstructed into a noise-free signal. Seven patents have issued and 10 more are pending on MDSP technology and features it enables for remote monitoring.

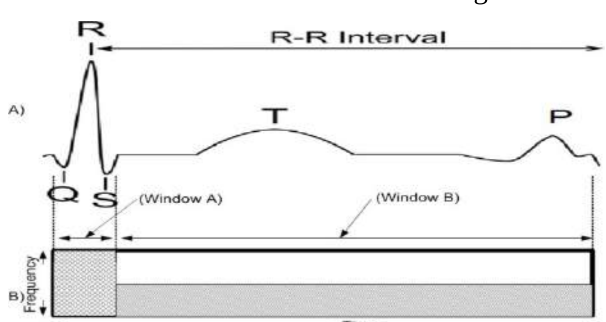

Figure 1. The cardiac cycle of the ECG is divided into two windows, one containing the QRS complex and a second window containing the remainder of the cardiac cycle. Spatially selective filtering is applied to take advantage of the drastically different character of the information in the two windows to remove noise without distorting morphology.

There are a number of side benefits to this approach, one of the most significant being that noise can be measured on a sample-by-sample basis. This is especially useful when identifying T-wave offset for the purpose of QT interval measurement. Determining the precise location of T-wave offset is difficult due to its flat morphology. The presence of even a small amount of noise near the location of T-wave offset often results in a bias in identifying its location, usually a bias toward shortening the QT interval [Malik, 2000]. When using conventional algorithms for QT interval measurement, a manual review process is used whereby an operator discards measurements when noise is present in the vicinity of T-wave offset. Because MDSP can very accurately measure noise in the vicinity of T-wave offset, a confidence metric can be computed from the noise that automates the process that would otherwise be performed manually by an operator. In addition, because MDSP removes nearly all of the noise, far fewer cardiac cycles are discarded.

Another side benefit of this approach is the ability to perform signal source separation. An assumption made by MDSP is that the sensed signal emanated from multiple sources. For example, the atrial and ventricular waves in the ECG emanate from different chambers of the heart, muscle noise emanates from a source different than the heart, and movement artifact emanates from the tissue-electrode interface. The signals from all these sources present at the sensing electrodes as a sum of the parts. The various subcomponents generated by MDSP carry information about each of these signal sources. Subcomponents can hence be manipulated in mathematical space to generate atrial and ventricular activity independently. Likewise, the respiratory component of the ECG can be derived separately and used to compute respiratory rate from ECG. Lastly, signal source separation can be used to isolate repolarization activity of the heart. Once isolated, T-wave alternans and other information can be derived to provide additional diagnostic/clinical information.

Noise Reduction Performance

MDSP reduces noise in human recordings by up to 25 dB (95%) for noisy ECGs (Brockway and Hamlin, 2011). Quality of Signal Reconstruction (QSR), a metric commonly used to evaluate fidelity in signal processing algorithms, ranges from 97% to 100% depending on the level of noise in the recording. Figure 2 shows the results of a controlled study whereby white noise of varying levels was added to a clean ECG using the standard methodology prescribed by the ANSI/AAMI EC-57 standard. Test recordings were generated with SNR ranging from 0 to 40 dB. The noise-corrupted signal was then processed with MDSP to remove noise. SNR of the output signal was then measured per EC57 and QSR was computed on the filtered vs. original signal on a point by point basis to assess mean squared point-to-point difference between the original and filtered ECG.

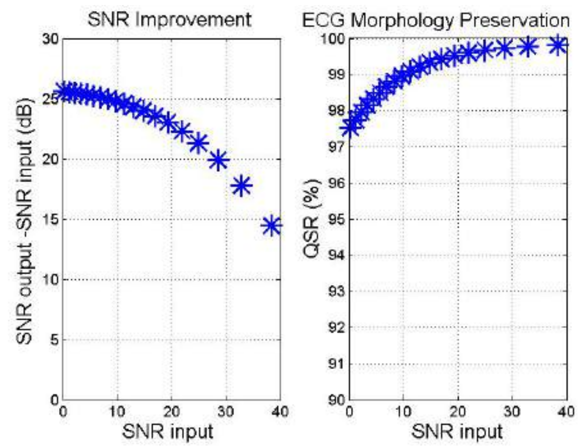

Figure 2. Results of a controlled study showing Signal-to-Noise Ratio (SNR) improvement and QSR vs. input SNR. Note that the noisier the signal, the greater the improvement in SNR.

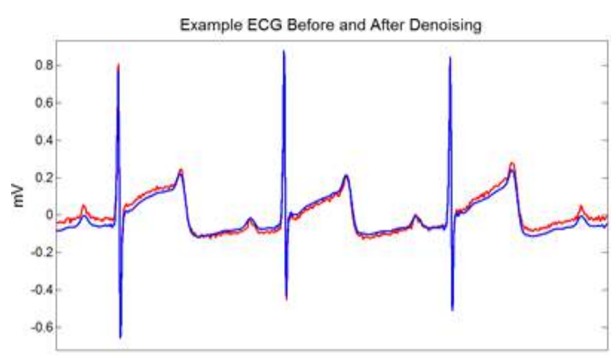

Figure 3. Clean ECG before (red) and after (blue) processing with MDSP to demonstrate that MDSP does not introduce distortion in the noise removal process.

Performance is Maintained as Noise Increases

Figure 4 below provides insight into how well MDSP performance with increasing levels of noise. Conventional algorithms perform very well when ECG signals are clean, but performance falls quickly as noise increases. Figure 4 demonstrates that MDSP maintains performance consistent with a noise-free ECG until signal-to-noise ratio (SNR) reaches about 12 dB. Data used to generation the MIT-BIH arrhythmia data base. Noise was added per the EC57 standard. None of the commercialized algorithms publish information on how performance is impacted by noise, so no comparative data are available. However, evidence from prior experience and from published results would indicate that performance of existing algorithms drops off quickly just below 20 dB. For reference, the recording on the left of Figure 5 is about 0 dB SNR.

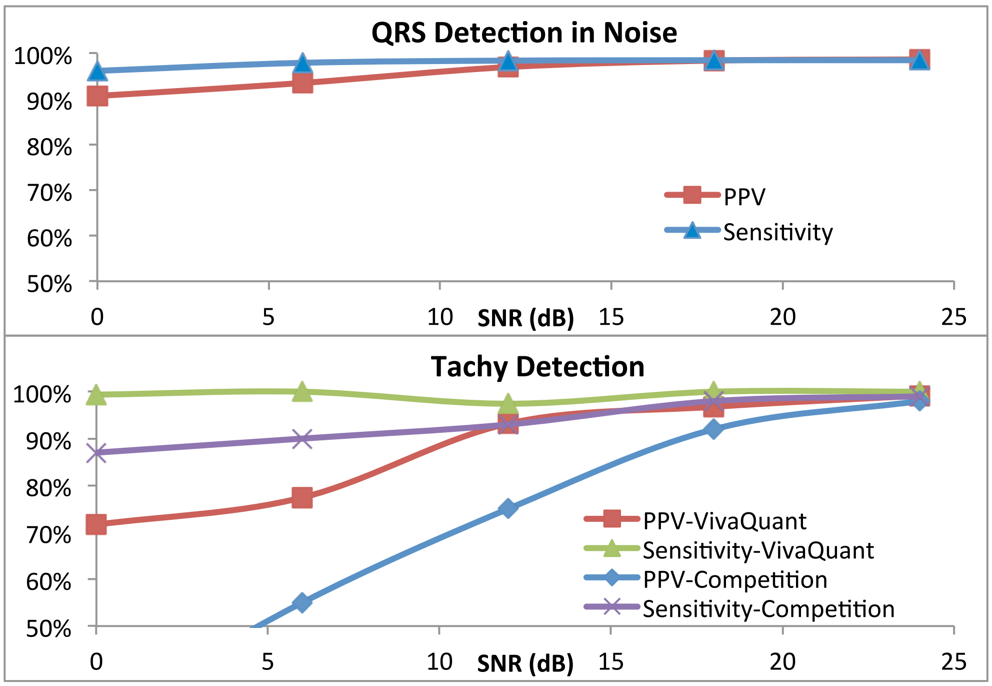

Figure 4. QRS detection and tachyarrhythmia performance vs. noise.

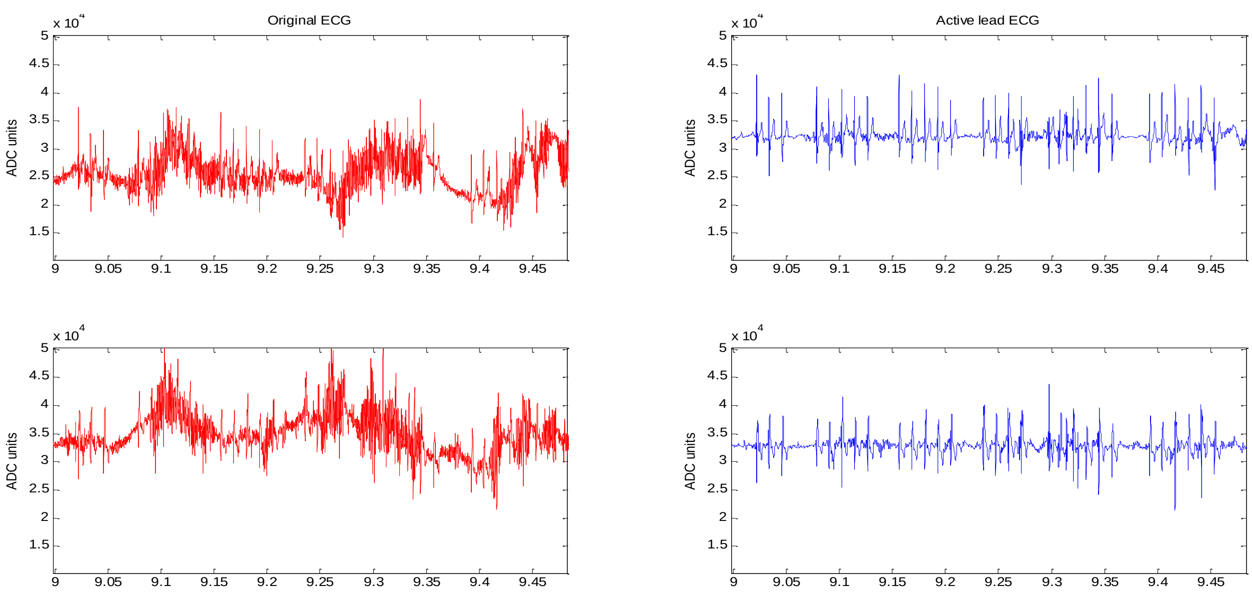

Figure 5. MIT-BIH recording with noise added per EC57 standard before (left) and after filtering with MDSP. This record contains cardiac pauses that would likely be missed prior to noise removal.

Heart Rate Variability (HRV) Measurement

High QRS detection accuracy, as enabled by VivaQuant's MDSP technology, is critical when HRV measurements are required. It has been shown that even a few errors in QRS detection or missed beats can have a significant impact on the accuracy of HRV computations (Malik, 1992, Mateo & Laguna 2003). Further, computation of an accurate HRV measurement also depends on the ability to identify and exclude beats that are part of an atrial fibrillation episode, ventricular and atrial premature contraction, or other arrhythmias. High accuracy of QRS detection and arrhythmia discrimination that are demonstrated with MDSP are instrumental in providing robust HRV analysis.

Interval Measurement Performance

MDSP has been shown to accurately measure intervals in ECGs recorded from surface electrodes using jacketed telemetry in freely moving subjects. JET recordings were analyzed by an expert operator using the DSI Ponemah system to obtain beat-to-beat (B-B) PR, QRS, QT, and RR interval measurements. The VivaQuant MDSP algorithm was used to automatically derive beat-to-beat measurements from the same recordings. Results shown here are unedited and are presented exactly as output from the algorithm.

MDSP and Ponemah results were compared by evaluating: a) Accuracy of beat-to-beat measurements, b) Accuracy of 60-second mean values, c) Consistency and spread of the 60-second standard deviation (SD) of the mean, and d) Density of measured values.

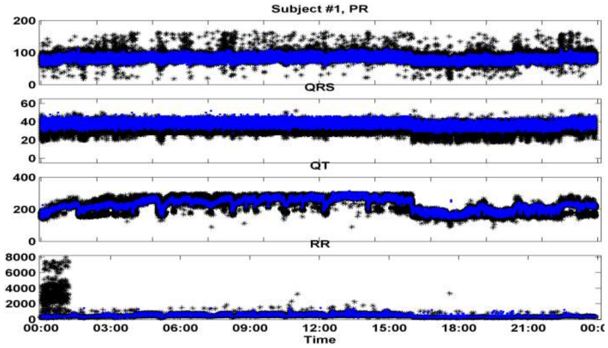

Figure 6. Beat-to-Beat intervals for 24-hour recording of subject M1 for MDSP (blue) and Ponemah (black).

Note that there is considerably more variability in measurements obtained from the further demonstrated with the box plots of Figures 7-9. In these plots, the Y-axis represents SD of 60 second mean values. Note that variability of measurements obtained with the Ponemah system is highly inconsistent, whereas SD of measurements obtained with MDSP is consistently between 3 and 5 msec.

The average SD for MDSP-derived PRi, QTi, and QRSi was 2.6, 2.9, and 1.6 msec, respectively. SD for Ponemah was 4 to 30 msec for PR, 8 to 18 msec for QT, and 3 to 5.5 for QRS. Note that SD for MDSP is 2X to 5X lower than that for Ponemah and is highly consistent vs. highly variable for Ponemah. SD for Ponemah measurements is highly dependent on the noise level in the recording. This translates to a 2X-5X lower minimum detectable difference for a typical study design.

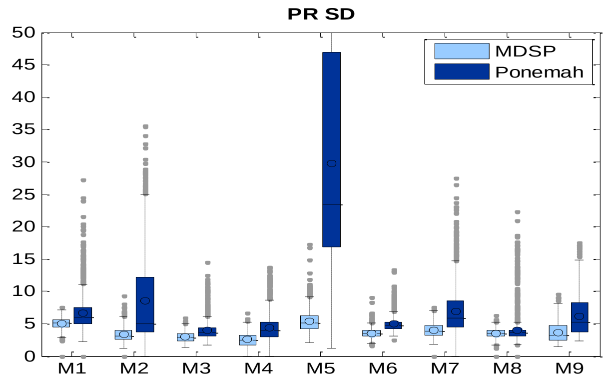

Figure 7. Box plot of PR interval (PRI) showing SD of 60-sec mean for 9 subjects. Note that recording M5 was somewhat noisy and P-wave amplitude was small, resulting in extraordinarily high variability in Ponemah PR measurements.

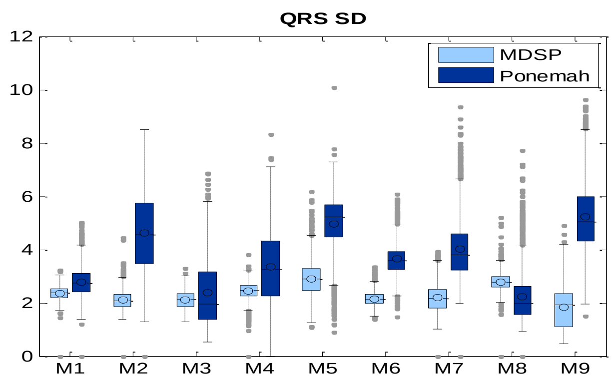

Figure 8. Box plot of QRS (QRSI) duration showing SD of 60-sec mean for 9 subjects.

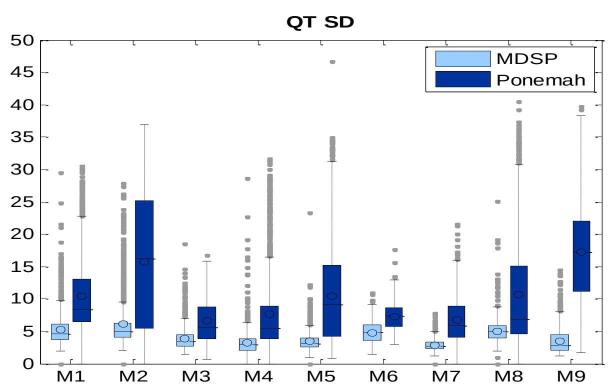

Figure 9. Box plot of QT interval (QTI) showing SD of 60-sec mean for 9 subjects. Note that SD varies with the level of noise in the recording. M2, M5, M8 and M9 are quite noisy while M3, M4, M6 and M7 are relatively free of noise.

Summary

MDSP provides a number of benefits vs. conventional algorithms for analyzing arrhythmias and intervals in ECGs. These include:

- MDSP processes recordings more than 100X faster than competing systems and the AE1000 software provides efficient tools for review and editing of the analysis results.
- MDSP automatically provides accurate interval measurements with low variability, even when noise is high. The high accuracy of interval measurements enables study of beat-to-beat interval dynamics, such as restitution and possibly TWA in ambulatory recordings for risk stratification purposes.
- MDSP significantly improves sensitivity to detecting a test article effect on cardiac intervals by reducing minimum detectable difference by 2-5 X.
- MDSP may facilitate better insight into QT response to a test article that impacts heart rate or autonomic balance and may mitigate a heart-rate-dependent bias in individualized QT correction that can result in higher inter-subject variability.
- MDSP combined with VivaQuant's AF detection algorithm provides exceptionally high sensitivity and PPV for atrial fibrillation, including recordings with a high prevalence of PACs as verified on VivaQuant proprietary data. High PPV translates into low false positive event rate.
- The only setup parameters required by the MDSP algorithm is species and sampling rate. This contrasts to other algorithms where as many as 45 setup parameters are used. This greatly simplifies validation required for regulatory bodies.
- MDSP performance has been field tested on more than 3000 days of recordings from multiple species representing a broad range of drug-induced effects on morphologies and pathologies.

Literature

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