GARMIN®
HEALTH

GARMIN ENHANCED BBI

An Example Night

November, 2023

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INTRODUCTION

Heart rate variability (HRV) is a very broad term that refers to variations in the time intervals between heartbeats. It was discovered years ago that HRV yields much information about the functioning of the cardiac autonomic nervous system. There are many ways to measure HRV, both in the time domain and frequency domain.[1]

The basic measurement used to compute every HRV metric, such as the root mean square of successive differences (RMSSD) and the standard deviation of NN intervals (SDNN), is a time series of inter-beat intervals (IBI). Two ways to measure IBI are using electrocardiogram (ECG) and photoplethysmography (PPG) signals. ECG measures the electrical signals that drive the functioning of the heart, while PPG relies on measuring the waveform of the arterial pressure wave. IBIs obtained using ECG measurements are called R-R Intervals (RRI) as they are measured by obtaining the time interval between the R wave of the QRS complex in two successive beats. IBIs obtained using PPG measurements are called Beat-to-Beat Intervals (BBI) in that the PPG signal measures the time interval between two successive pulse pressure waves of the capillary arterial blood flow in the sensor field of view (which in the case of Garmin wearables, is the wrist). *Figure 1* illustrates the basic ECG and PPG measurements and how RRI and BBI are derived thereof.

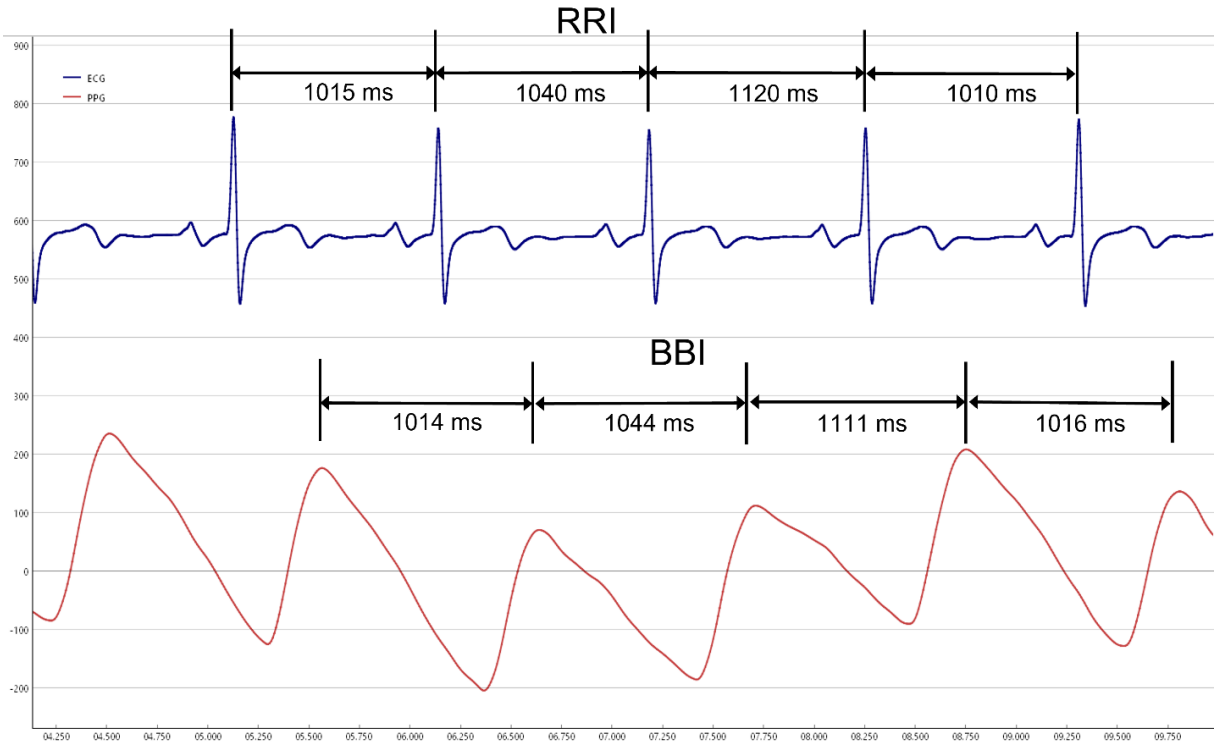


Figure 1: *Illustration of ECG and RRI, and PPG and BBI*

Compatible Garmin wearable devices measure the BBI directly using the PPG sensor on the bottom of the device. Garmin makes the time series of BBI measurements available to select partners via the Garmin Health Standard SDK as well as through the Garmin Health API.

WEARABLES, BBI, AND DIGITAL HEALTH

Wearable devices and their accompanying sensor data are driving rapid change in digital health and digital therapeutic industries. Garmin devices, with their superior battery life and highly accurate biosensor data *, are at the forefront of this revolution. Garmin wearables can go up to five to seven days without charging and have flexible interfaces to make biosensor data such as Heart Rate** and BBI available to partners and researchers, who can then apply this information to their particular area of expertise.[3,4]

Users who wear a compatible Garmin device overnight help support the accuracy of the BBI information collected. The availability of high quality BBI unlocks many applications such as stress, body battery, recovery, sleep analysis, and more without the need to wear a portable ECG device such as a chest strap.[5,6,7]

WHAT IS GARMIN ENHANCED BBI?

In Garmin's legacy implementation of BBI, a design decision was made to emphasize availability even during periods of marginal signal quality. This decision necessitated extra filtering of the PPG signal which, in turn, limited the bandwidth with the consequence of sometimes affecting the accuracy of higher frequency HRV markers such as RMSSD.[8]

Garmin Enhanced BBI uses a different signal processing chain which preserves the bandwidth of the signal and provides higher accuracy for high BBI variations. In addition to this higher bandwidth, a confidence metric (a binary indicator of ONE for high confidence and ZERO for low confidence) was added to the BBI time series to indicate to the researcher whether any particular beat might be of higher error due several reasons (described further below). Garmin Enhanced BBI is unique in the industry in that Garmin is providing a confidence metric for every heartbeat (outside of areas of extremely high motion or poor signal, where no beat information is provided) to the researcher or partner, not aggregated HRV statistics like SDNN or RMSSD where the device algorithm has applied arbitrary outlier rejection logic.[10] This allows the researcher or partner to interpret the data and perform outlier rejection as they see fit and compute as many HRV metrics as they wish.[1,8] More importantly, researchers or partners can use the data to look for other important physiological signals in the BBI time series. *Figure 2* provides the general idea of how BBI with confidence works (with ECG derived RRI also plotted).

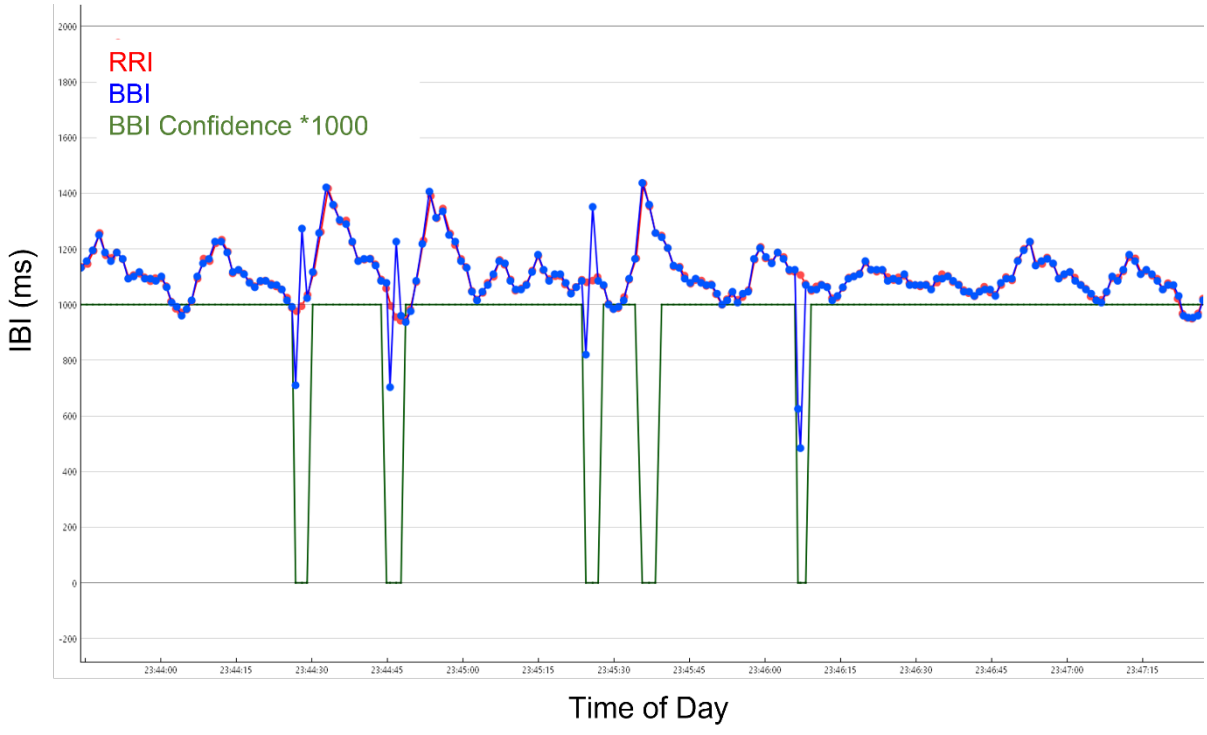


Figure 2: *Garmin Enhanced BBI with Confidence. Representative Plot*

Note the confidence value is multiplied by 1000 to make it visible on this y-axis scale. Actual BBI confidence is either a 0 or a 1.

BBI CONFIDENCE EXPLAINED

Generally speaking, beats can be marked as low confidence for three reasons:

Motion: By far the most common reason to mark a beat as low confidence is due to motion artifact. Garmin wearables contain a three-axis accelerometer sampled simultaneously with the PPG signal. When the accel detects motion above a predetermined threshold, the beat is marked as low confidence. If device motion exceeds an even higher threshold, the device will decline to provide a beat measurement at all, and the time series will indicate a gap until the motion falls beneath the threshold again.

Signal Quality: There are many reasons for low signal quality. The most common is simply a fit issue. If the optical sensor is not seated against the skin on the back of the wrist, there may be no signal. Low blood perfusion in the tissue in the field of view of the optical sensor can also create reduced signal quality. Further, the signal can be almost extinguished if the wearer lays on the limb and puts a lot of pressure on the watch.

Abnormally High HRV: Even in cases where the sensor signal quality is good, the PPG signal can still occasionally contain errors for a variety of reasons. To combat this, Enhanced BBI contains an algorithm to estimate the BBI variance in real time, and mark as low confidence any beats that are thought to be unlikely due to being abnormally short or abnormally long. A large amount of data was processed to tune the Enhanced BBI algorithm, including many recordings of heart rhythms besides sinus rhythm, including atrial fibrillation and frequent PVCs.

Referring to *Figure 2*, it is clear that BBI confidence does a good job of bracketing beats of poor accuracy. However, BBI confidence is not 100% specific, and sometimes marks accurate beats with low confidence (see the beats at approximately 23:45:35 in *Figure 2*). Many times, the abnormally high HRV test is responsible for marking an accurate beat with low confidence. Importantly, the researcher has the ability to inspect low confidence beats and decide whether to include them in their analysis or not as Garmin makes information available at the beat level, not at an aggregate statistic level like RMSSD or SDNN.[9]

HOW ACCURATE IS GARMIN ENHANCED BBI?

Garmin Enhanced BBI is measured during the user's sleep interval. The sleep interval is presumably a period of low motion and good blood perfusion, which provides the best PPG signal for measuring of BBI. As shown below, Garmin Enhanced BBI approaches the accuracy of an ECG-based RRI measurement system with far less user friction – all a user has to do is wear a Garmin watch or band properly on either wrist. Below is an analysis of a single sleep interval (i.e. one night) using Garmin enhanced BBI.

BBI METHOD

This analysis compares Garmin Enhanced BBI against RRI obtained from a reference ECG monitor. In this case, the subject wore a Garmin Venu 2 Plus on the left wrist, and a Firstbeat Bodyguard 2 ECG monitor was worn as the reference.[10] The subject's sleep interval was set to 10:00pm to 6:30am. However, the interval analyzed was somewhat shorter as the subject was not in bed and in low motion for the entire sleep interval. Information about the data collection is listed in Table 1.

DATA COLLECTION INFORMATION	
Age	56
Gender	Male
BMI	25.9
Sleep Interval Analyzed	10:06:44 pm to 5:56:00 am
Total Number of Beats	26,248
Number of High Confidence Beats	24,468
Percent High Confidence Beats	93.13%

Table 1: *Descriptive Information About the Data Collection*

RESULTS

Figure 3 provides a broad view of the entire night. Generally, there is very good agreement between the RRI (red trace) and the BBI (blue trace). Also of note is the BBI confidence (green trace). It is noteworthy that the RRI reference device itself is subject to motion artifact and other errors as seen by the outliers in the red trace.

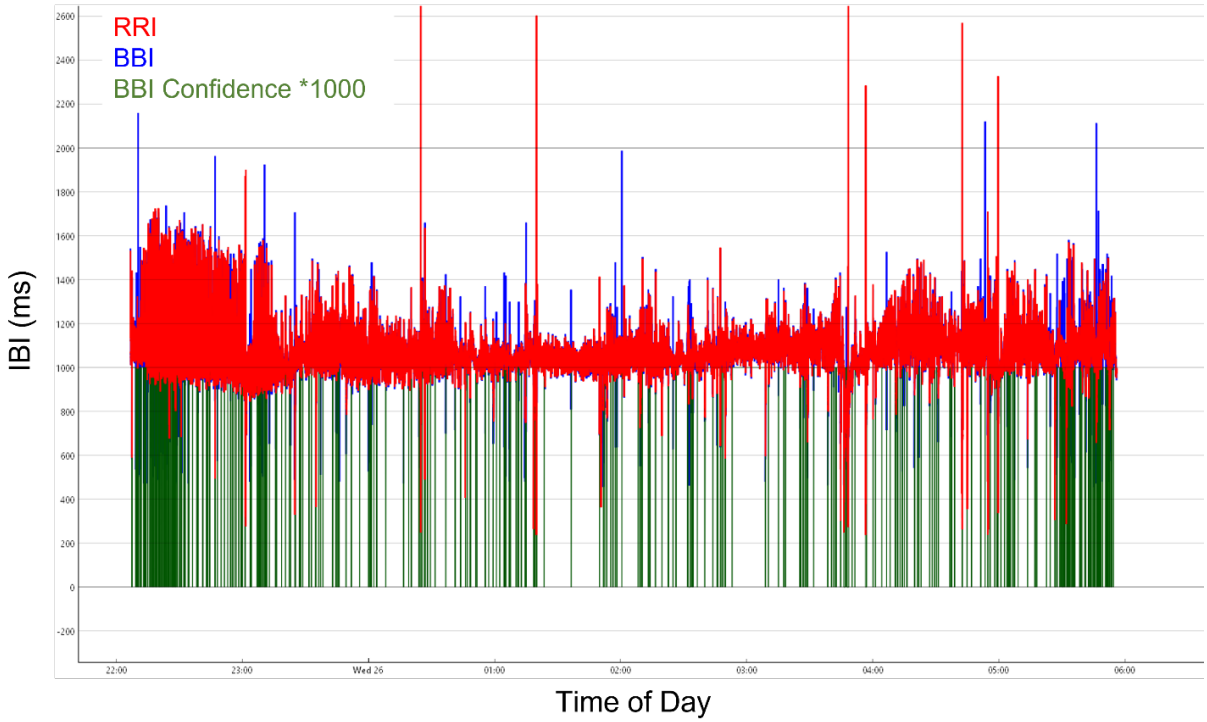


Figure 3: *Entire Night, All Beats, RRI, BBI, and Confidence*

Figure 4 shows an enhanced view of the entire sleep interval with low confidence beats removed (as well as some obvious RRI outliers).

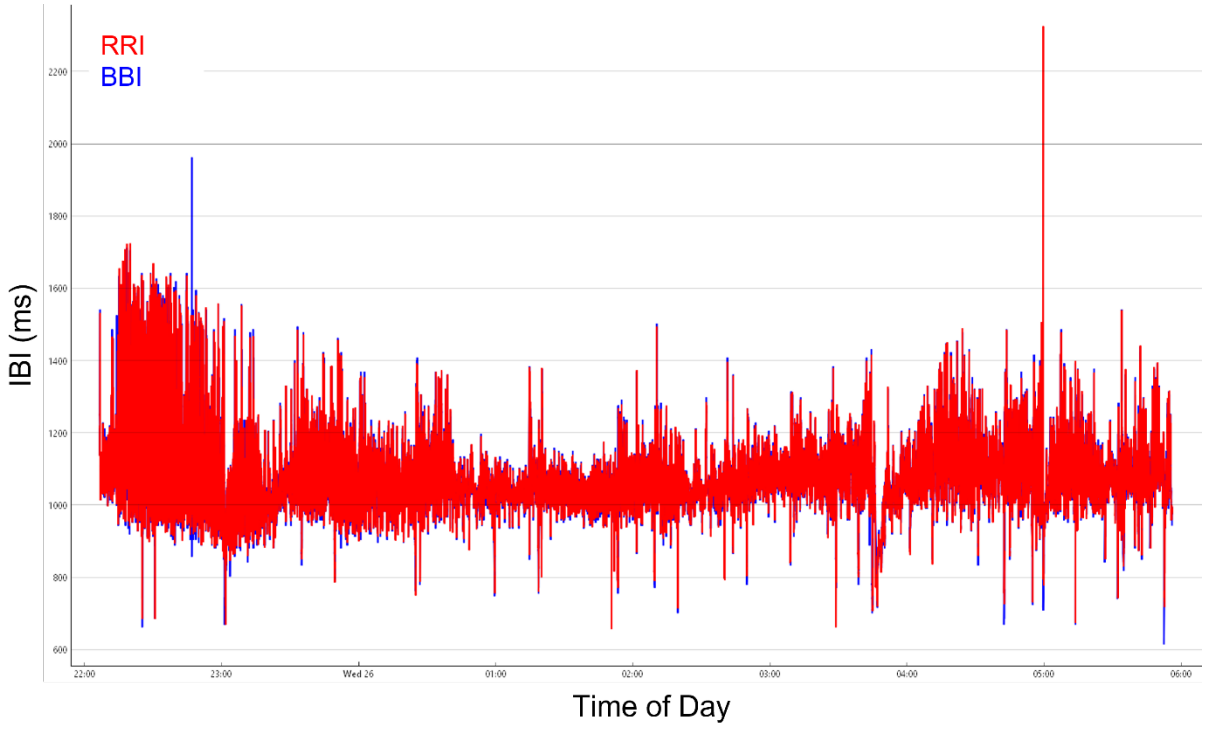


Figure 4: *Entire night, high confidence beats only*

Note the near absence of BBI outliers. One RRI outlier remains at about 5 am. The BBI and RRI time series, when only high confidence beats are included, are extremely similar. Table 2 illustrates the mean and standard deviation of both time series.

	RRI	BBI
Mean	1078.6 ms	1078.0 ms
Standard deviation	92.90 ms	93.99 ms

Table 2: *Mean and standard deviation high confidence beat time series, RRI and BBI*

When only high confidence beats are compared to the reference beats, a high level of accuracy is attained. The histogram of beat errors is shown in *Figure 5*. It indicates that the beat error is nearly zero mean (0.506 ms) and has a standard deviation of 8.55 ms. With a mean BBI of 1078 ms, this means that 68.2% of the beat errors are on average less than 0.79% of the magnitude of the BBI.

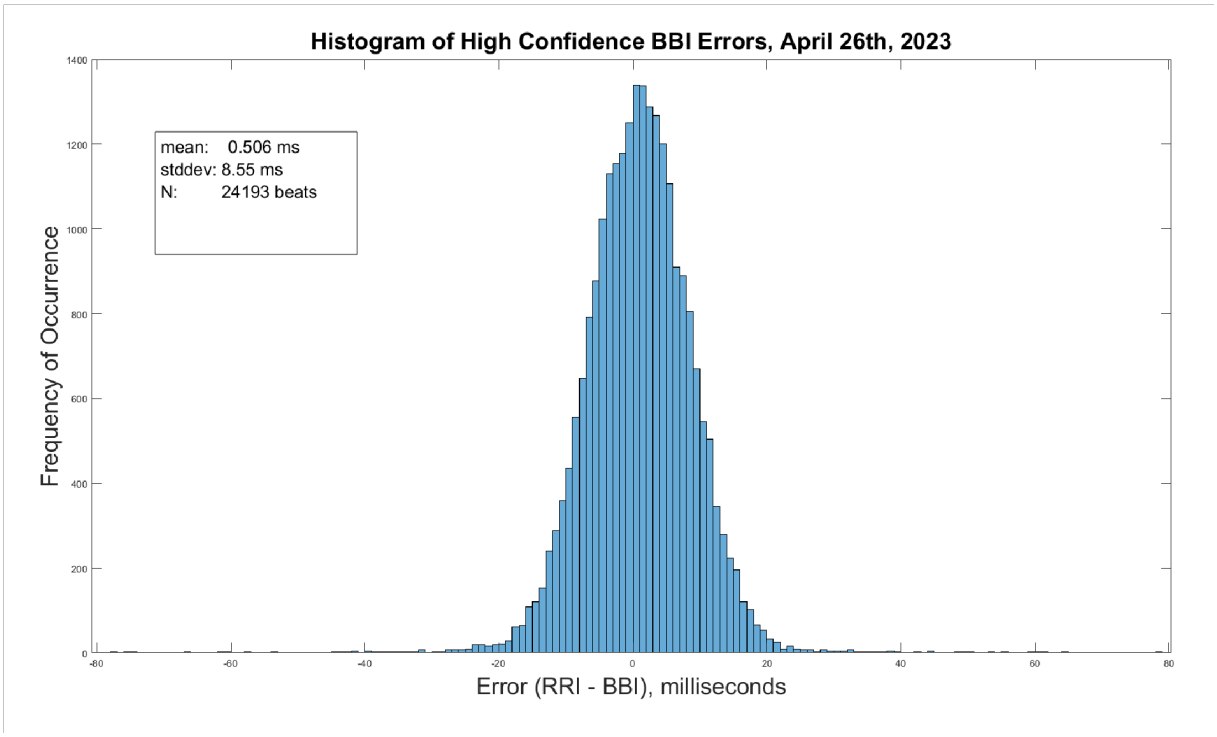


Figure 5: *Histogram of BBI Errors compared to RRI ECG Reference, high confidence beats*

As another illustration of the accuracy of Enhanced BBI, *Figure 6* shows a scatter plot of high confidence BBI vs RRI. The Pearson correlation coefficient is a remarkable 0.975. This illustrates an extremely high concurrence between the RRI reference beats and the BBI beats when only high confidence beats are analyzed.

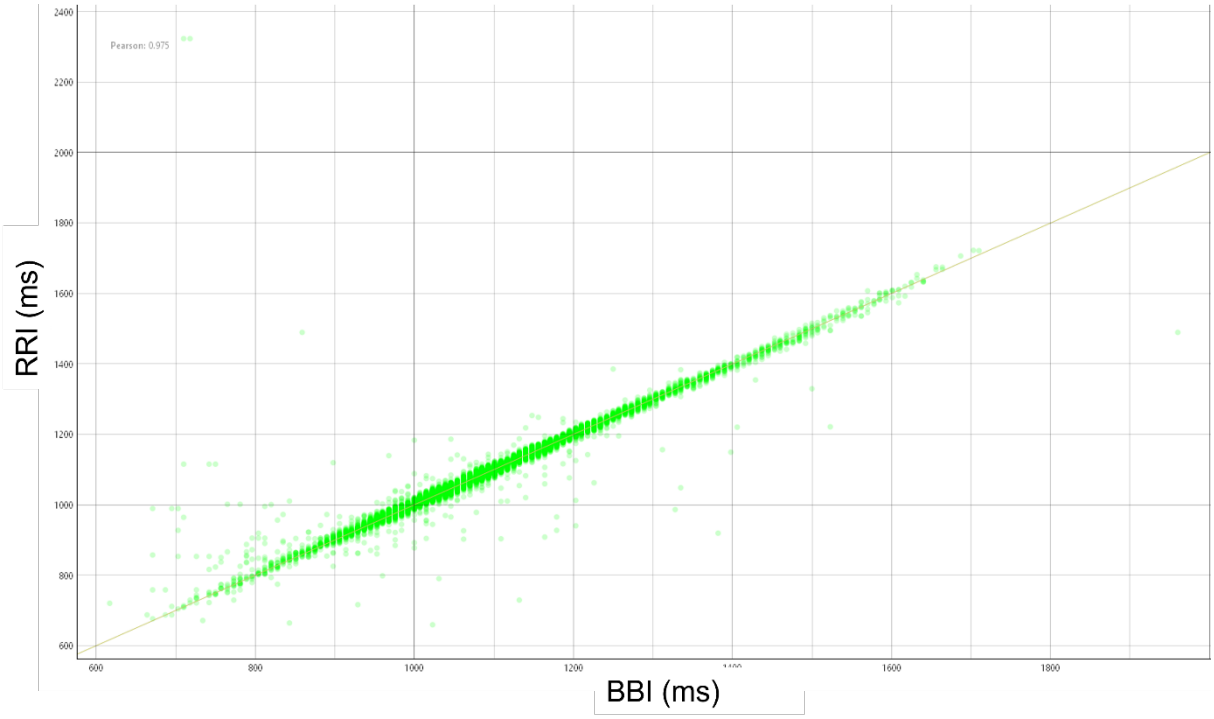


Figure 6: *Scatter plot of BBI (x axis) vs RRI (y axis)*

A very commonly used aggregate statistical measurement of HRV is RMSSD. A five-minute RMMSD measurement is typically computed. It is of note that RMSSD is very susceptible to outliers due to the squaring operation. *Figure 7* plots RMSSD of both RRI and BBI for the entire sleep interval. By only including high confidence beats in the RMSSD calculation, nearly perfect agreement between the RRI truth and the BBI is obtained. The RMSSD outlier at 5 am is due to an RRI outlier, not due to inaccurate BBI.

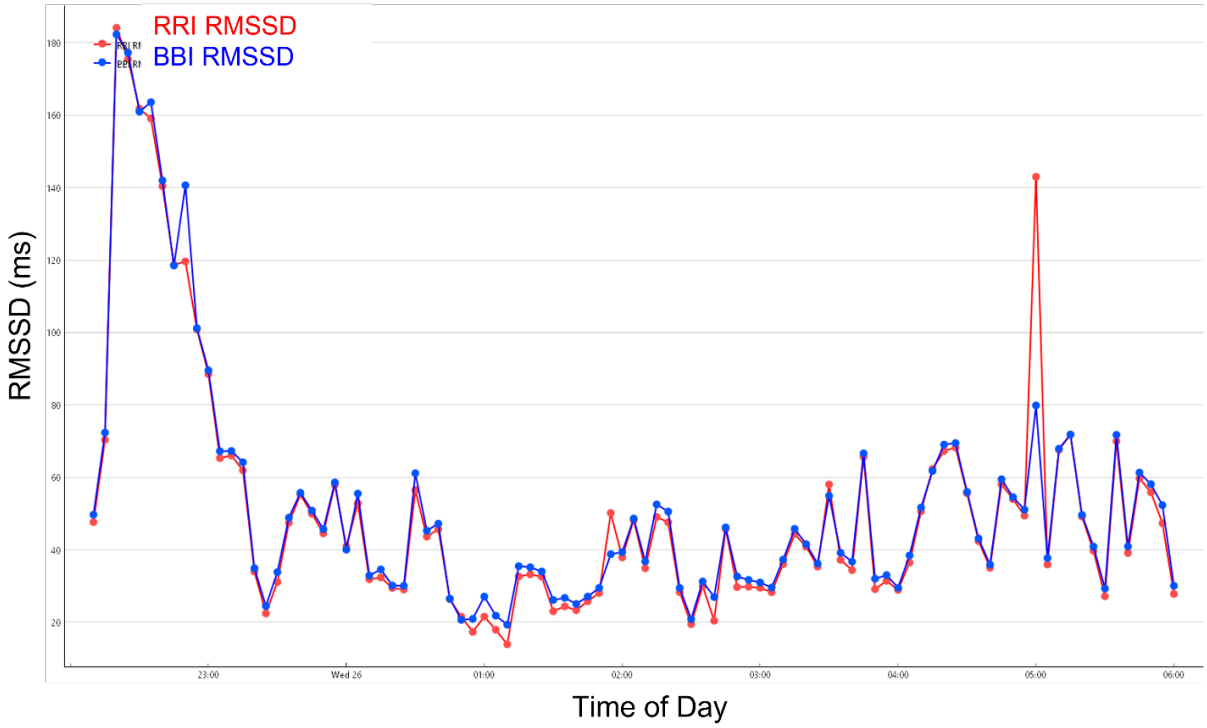


Figure 7: *Five minute RMSSD comparison between BBI and RRI (note RRI outlier at 05:00)*

Another very commonly used method to analyze HRV is known as the Poincaré plot.[11] The Poincaré plot illustrates the variation of a particular beat compared to the next beat. *Figure 8* is a Poincaré plot where the X axis is IBI_n, and the Y axis is IBI_{n+1}. In *Figure 8*, the Poincaré plot of the BBI is nearly identical to the Poincaré plot of the RRI.

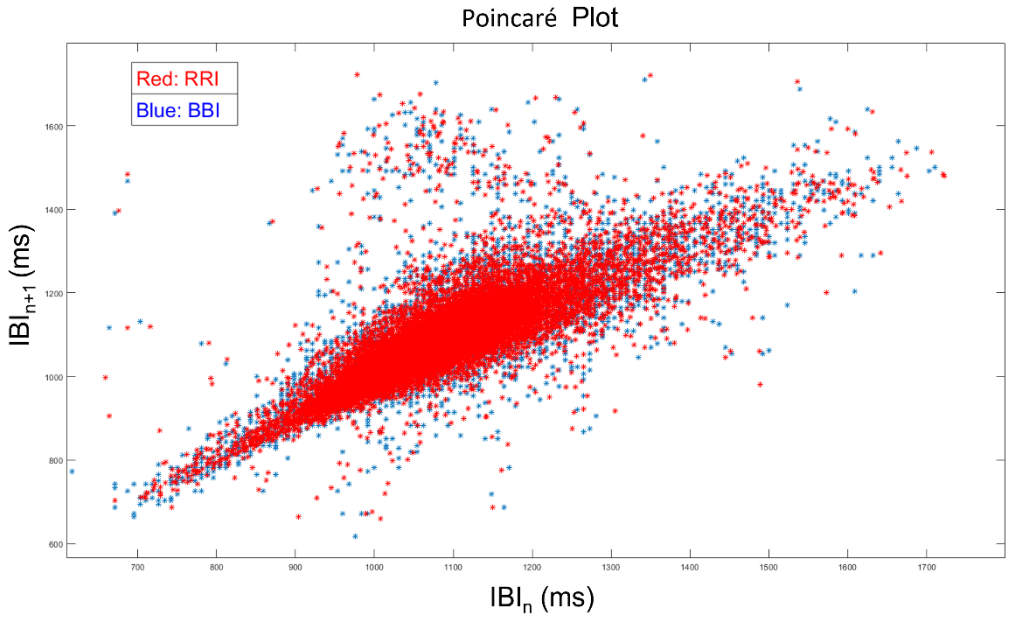


Figure 8: *Poincaré Plot, BBI and RRI, High Confidence Beats*

Table 3 further illustrates this, comparing the SD1 and SD2 of the BBI and RRI time series.

	RRI	BBI
SD1	124.38 ms	125.88 ms
SD2	42.32 ms	42.65 ms

Table 3: *SD1 and SD2 of RRI and BBI Poincaré plot*

DISCUSSION

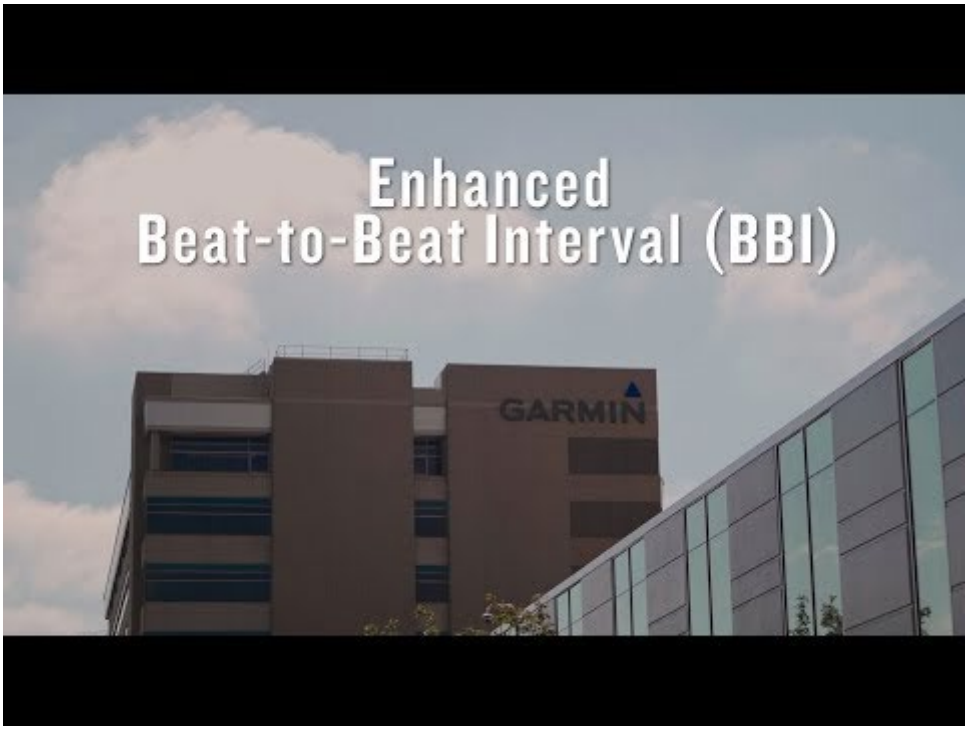
Enhanced BBI is a powerful tool for partners and researchers. It provides highly accurate BBI information at a beat level, not at an aggregate statistical level. This unlocks many avenues of analysis and research into HRV that were not available without this high-resolution data (such as Poincaré analysis). Further, the addition of BBI confidence at a beat level provides researchers additional vital information for data cleansing and data curation that is not available with other wearables.

Enhanced BBI is revolutionary as it unlocks long term data recording in Garmin wearables at a very high resolution, but still compact enough to offload the recorded data wirelessly via low bandwidth data links such as Bluetooth Lower Energy (BLE). Beat-level confidence is a powerful tool that gives more information to researchers about the quality of a BBI measurement without the need to access the raw PPG or raw accelerometer data streams, as these create very large files that are problematic to offload from the wearable using wireless data links.

* See Garmin.com/ataccuracy.

** Garmin wearable devices are not medical devices and are not intended for use in the diagnosis or monitoring of any medical condition.

Learn more about Garmin Enhanced BBI in following video:



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