Heart Rate Variability (HRV) Validation

Introduction

Heart rate (HR) is the number of heartbeats per minute. **Heart Rate Variability (HRV)** is the fluctuation in the time intervals between adjacent heartbeats (**RR intervals – RRi**).[1] HRV is generated by heart-brain interactions and autonomic nervous system processes. HRV helps the body adapt to environmental and psychological challenges. It reflects regulation of autonomic balance, blood pressure, blood vessel diameter, gas exchange, gut, and heart.[2] A healthy heart is not a metronome, and heartbeats do not occur at constant intervals, but rather with a small variance between them.[3] This variability in heartbeats provides the flexibility to rapidly cope with an uncertain and changing environment. [4]

Physical or emotional stress results in faster, monotonic heartbeats, causing HRV to decrease. Relaxation results in slower, less regular heartbeats, and higher HRV.[5] Normal HRV is associated with a lower risk to develop depression and post-traumatic stress disorder.[6,7] Moreover, decreased HRV has been identified as an independent predictor of cardiovascular and overall mortality.[8–10] Thus, HRV is a noninvasive method that can be used to evaluate autonomic nervous system activity and physical and emotional status in a variety of clinical situations. [11,12]

Binah.ai's HRV algorithm uses the photoplethysmography (PPG) signal recorded from facial skin tissue (remote PPG - rPPG). The algorithm identifies the heartbeat peaks, which represent the contraction of heart ventricles (R peaks of the QRS complex of the ECG wave).

Definitions:
RR intervals (RRi) are defined as the difference between successive R peaks.
RR intervals are calculated as:
$RR(n) = R(n)-R(n-1)$, where n is the beat index number.

The variability of RRi is known as the **Heart Rate Variability (HRV)**.
Binah.ai's HRV measurements are based on various parameters calculated from RRi values:

HRV SDNN [in milliseconds] represents the standard deviation of RRi.

RMSSD [in milliseconds] is the root mean square of RRi.

Baevsky's Stress Index [in 1/sec2] is a well-known index for stress evaluation based on HRV measurements. It is calculated using RRi data (median, min, max, and histogram).

SD1, SD2 [in milliseconds] are derived from a scatter plot of every RRi against the next interval (Poincare' plot) and by fitting an ellipse (curve which resembles a squashed circle) to this Poincare' plot. SD1 is the standard deviation (SD) of the distance of each point from the y = x axis, and it is defined as the ellipse's width. SD2 is the standard deviation of each point from the y = x + average RRi, and it is defined as the ellipse's length.

This report describes the results of a validation experiment, that compares Binah.ai's HRV measurements with the measurements of an accurate reference device.

Methods

Binah.ai's HRV measurements were validated in comparison to the Polar H10 Heart Rate Sensor™ in healthy participants and patients who suffer from hypertension. The Polar H10 is a chest strap sensor that collects 1-lead ECG signals.

Measurement set-up:

Each participant was instructed to sit as stably as possible. A Polar H10 Heart Rate Sensor™ was placed around the user's chest. Recordings were conducted in a testing room located in Binah.ai's offices, with controlled and fixed artificial ambient light.

A mobile device was placed on a stand in front of the participant. The participant's face filled over 20% of the frame's area (distance of 30-40 cm) and was positioned in the center of the frame. The camera was set at the level of the forehead and positioned perpendicular to the face. Participants were instructed to look at the screen during the whole recording and to avoid any movement (including talking). Each recording lasted approximately 60 seconds.

Statistical analysis:

Accuracy was calculated using the following parameters:

$$AE\ (Absolute\ Error) = App_i - Ref_i$$

$$RMSE = \sqrt{\frac{\sum_{i=1}^{N}(App_i - Ref_i)^2}{N}}$$

$$MAE = \frac{1}{N}\sum_{i=1}^{N}|App_i - Ref_i|$$

When,
N is the number of data points.
App is the measurement of the Binah.ai's application.
Ref is the measurement of the reference device.
i is the index number of the measurements.

Confidence intervals (CI) were calculated using the bootstrap method and indicate where the estimator (i.e., RMSE) would fall, with 95% confidence, for future samples.
Participants with outlier AE (defined as 3 standard deviations or more above the mean) and participants with invalid reference device values were excluded from analysis.

For this report, the Binah's SDK 4.10.1 version was used.

The measurements were recorded by the mobile device models listed below.
iOS: iPhone 8, iPhone 11 Pro, iPhone 13 Pro Max.
Android: Samsung S10, Samsung S21 Ultra, Pixel 6 Pro, Samsung Note 9, Huawei P30.

Results

Demographic Data:

Table 1 includes participants' demographic data for each operating system (iOS and Android).

Operating System	Number of Participants	Age Range (average)	Sex	Fitzpatrick Skin Tone *
iOS	32	25-57 (36)	F (35%), M (65%)	2 (26%), 3 (56%), 4 (17%)
Android	35	25-57 (36)	F (26%), M (74%)	2 (36%), 3 (52%), 4 (12%)

Table 1: Demographic data for experiments using phones with an iOS and Android operating systems.
* Fitzpatrick skin tone classifications are: 1- Pale white, 2- white, 3- Darker white, 4- Light brown, 5- Brown, 6- Dark brown or black.

Accuracy Data:

Table 2 includes accuracy data for iOS and Android (RMSE, RMSE CI 95%, MAE±SD) for each HRV parameter.

Operating System	Vital Signs	Number of measurements	RMSE	RMSE CI 95%	MAE±SD
iOS	**mean RRi (msec)**	121	4.4	[3.7, 5.1]	3.2±3.0
	SDNN (msec)		6.6	[6.0, 7.3]	5.5±3.7
	rMSSD (msec)		10.1	[9.0, 11.2]	8.5±5.6
	Baevsky's SI ($1/sec^2$)		2.5	[2.1, 2.9]	1.9±1.6
	SD1 (msec)		7.3	[6.5, 8.1]	6.0±4.1
	SD2 (msec)		7.4	[6.5, 8.3]	6.0±4.4
Android	**mean RRi (msec)**	77	6.1	[4.7, 7.3]	4.3±4.3
	SDNN (msec)		7.1	[5.7, 8.5]	5.1±4.9
	rMSSD (msec)		10	[8.0, 12.0]	7.4±6.8
	Baevsky's SI ($1/sec^2$)		3.2	[2.7, 3.7]	2.4±2.1
	SD1 (msec)		8	[6.4, 9.6]	5.9±5.5
	SD2 (msec)		7.6	[5.9, 9.3]	5.4±5.4

Table 2: RMSE, RMSE CI 95%, and MAE±SD for measurements using phones with an iOS and Android operating systems, when compared to the reference device. CI were calculated using the bootstrap method. Abbreviations: RMSE - Root Mean Square Error, CI - Confidence Intervals, MAE -Mean Absolute Error, SD - Standard Deviation.

Pearson correlations between Binah.ai's mean RRi and SDNN estimations versus the Polar H10 Heart Rate Sensor™ measurements were calculated and presented in **Figures 1-2**. Pearson correlation coefficients (R values) were very high for both operating systems (Android and iOS).

The Bland-Altman plots for comparison between measurements of the two methods (Binah's and the reference device) are presented in **Figure 3** (for mean RRi) and **Figure 4** (for SDNN).

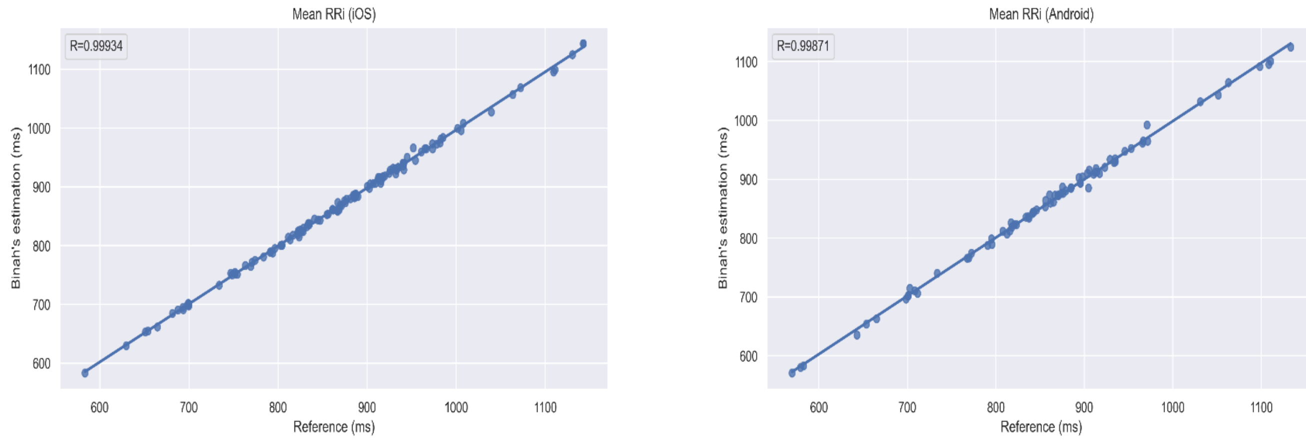

Figure 1: Mean RRi - Binah.ai's mean RRi estimation vs. reference device measurements. Pearson correlation was calculated, and correlation coefficients are presented on each plot (R). Plots describe measurements conducted in both operating systems (iOS and Android).

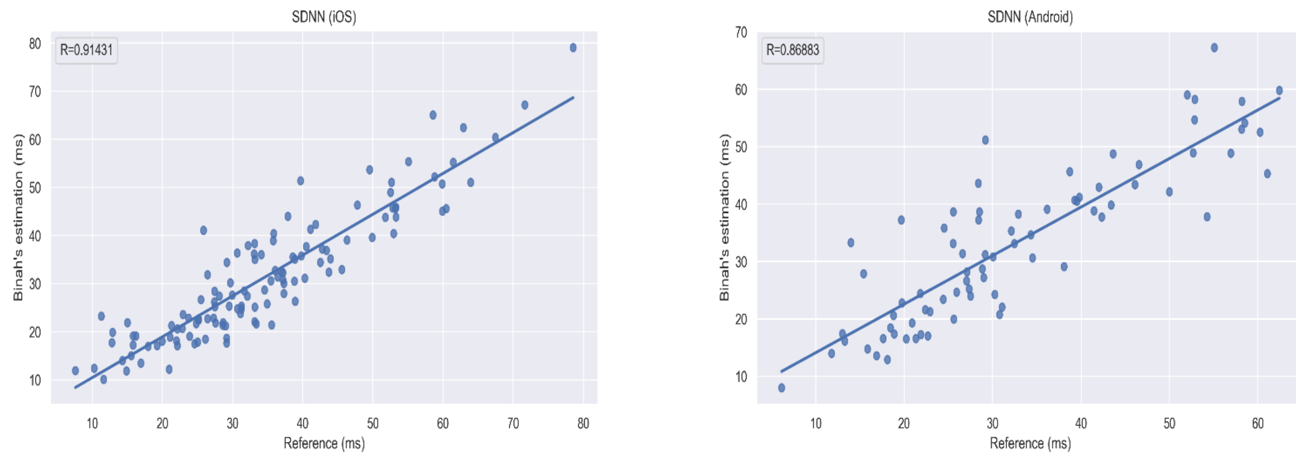

Figure 2: SDNN - Binah.ai's SDNN estimation vs. reference device measurements. Pearson correlation was calculated, and correlation coefficients are presented on each plot (R). Plots describe measurements conducted in both operating systems (iOS and Android).

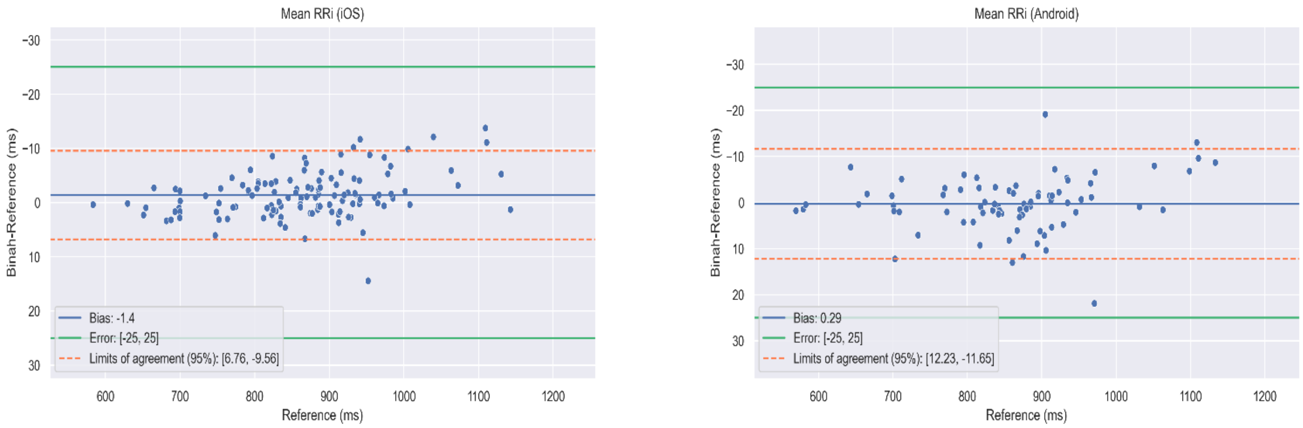

Figure 3: Mean RRi - Bland-Altman plots for comparison between mean RRi measurements of the two methods (Binah's and the reference device). Plots describe measurements conducted in both operating systems (iOS and Android). The "Bias" line stands for the mean difference between measurements of Binah.ai and the reference device, the "Error" lines represent the value of the accuracy criterion, the "Limits of agreement" lines mark the limit of 95% of the samples.

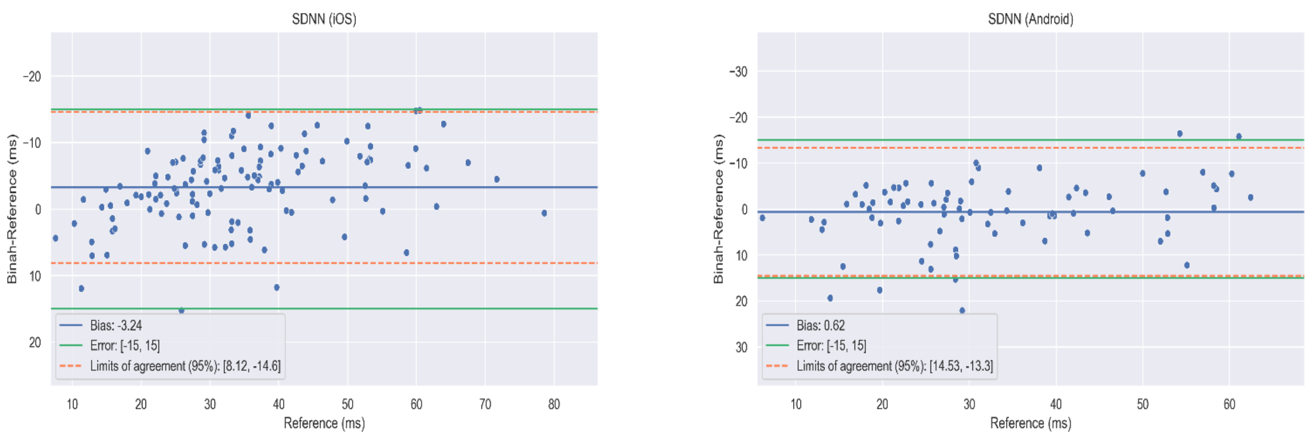

Figure 4: SDNN - Bland-Altman plots for comparison between SDNN measurements of the two methods (Binah's and the reference device). Plots describe measurements conducted in both operating systems (iOS and Android). The "Bias" line stands for the mean difference between measurements of Binah.ai and the reference device, the "Error" lines represent the value of the accuracy criterion, the "Limits of agreement" lines mark the limit of 95% of the samples.

Conclusions

This report summarizes the results of validation experiments in which Binah.ai's HRV measurements were found to be highly correlated with the reference device.

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