Heart Rate Variability (HRV) validation

Introduction

Heart rate is the number of heartbeats per minute. Heart rate variability (HRV) is the fluctuation in the time intervals between adjacent heartbeats.[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 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 Heart Rate and HRV algorithm uses the photoplethysmography (PPG) signal recorded from facial skin tissue (remote PPG - rPPG) or, if light conditions are challenging, from a fingertip placed on the camera's lens (PPG). 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 RR intervals is known as the **Heart Rate Variability (HRV)**.
Binah.ai's HRV measurements are based on various parameters calculated from RR interval values:

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

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

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

SD1, SD2 [in milliseconds] are derived from a scatter plot of every RR interval 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 RR interval, and it is defined as the ellipse's length.

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

Methods

In validation experiments, RR intervals were measured in healthy participants and patients who suffer from hypertension. Binah.ai's RR interval measurements were validated in comparison to the Polar H10 Heart Rate Sensor™. 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.

For rPPG measurements, 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.

For PPG measurements, a mobile device was placed on the participant's hand, with the participant's finger covering the entire area of the camera lens (in iOS devices, the finger covered the torch, while in Android devices, the finger did not cover the torch). The participant's hand rested comfortably on a soft pillow at heart level, with the wrist aligned with the forearm.

rPPG and PPG experiments were conducted simultaneously. Participants were looking at the mobile device positioned in front of them, while an additional mobile device was on their hand, recording the PPG signal from their finger.

Participants were instructed to avoid any movement (including talking) and to avoid changing finger pressure on the lens during the recordings. Each recording lasted approximately 60 seconds.

For this report, the Binah's SDK 4.4.2 version was used.

The measurements were recorded by the mobile device models listed below.

Models used for rPPG measurements -

iOS: iPad 6th gen, iPhone 11 Pro, iPhone 13, iPhone 13 Pro Max

Android: Samsung s10, Samsung S21, Samsung S21 Ultra, Sony Xperia, Huawei P30 Lite

Models used for PPG measurements -

iOS: iPhone 8, iPhone 11 Pro, iPhone 13 Pro, iPhone 13 Pro Max

Android: Samsung Note 9, Samsung s10, Samsung S21, Samsung S21 Ultra, Huawei P30

Results

Tables 1-4 include demographic data for each HRV parameter, for each operating system (iOS and Android), and for each mode (PPG and rPPG).

iOS:

Vital Signs	Number of Participants	Age Range (average)	Sex	Fitzpatrick Skin Tone*
RRi (ms)	26	25-57 (36)	F (35%), M (65%)	2 (26%), 3 (54%), 4 (20%)
SDNN (ms)	26	25-57 (36)	F (35%), M (65%)	2 (26%), 3 (57%), 4 (17%)
rMSSD (ms)	25	25-57 (36)	F (35%), M (65%)	2 (26%), 3 (57%), 4 (17%)
Baevsky's SI ($1/sec^2$)	25	25-57 (36)	F (33%), M (67%)	2 (25%), 3 (57%), 4 (18%)
SD1 (ms)	25	25-57 (36)	F (34%), M (66%)	2 (26%), 3 (57%), 4 (17%)
SD2 (ms)	26	25-57 (35)	F (38%), M (62%)	2 (25%), 3 (57%), 4 (18%)

Table 1: Demographic data for rPPG experiments using phones with an iOS operating system.

Vital Signs	Number of Participants	Age Range (average)	Sex	Fitzpatrick Skin Tone*
RRi (ms)	29	25-57 (36)	F (30%), M (70%)	2 (28%), 3 (59%), 4 (13%)
SDNN (ms)	28	25-57 (34)	F (34%), M (66%)	2 (32%), 3 (52%), 4 (16%)
rMSSD (ms)	30	25-57 (35)	F (33%), M (67%)	2 (33%), 3 (55%), 4 (12%)
Baevsky's SI ($1/sec^2$)	29	25-57 (36)	F (31%), M (69%)	2 (29%), 3 (56%), 4 (15%)
SD1 (ms)	30	25-57 (35)	F (33%), M (67%)	2 (30%), 3 (55%), 4 (15%)
SD2 (ms)	28	25-57 (35)	F (34%), M (66%)	2 (29%), 3 (54%), 4 (17%)

Table 2: Demographic data for PPG experiments using phones with an iOS operating system.

Android:

Vital Signs	Number of Participants	Age Range (average)	Sex	Fitzpatrick Skin Tone*
RRi (ms)	23	25-57 (36)	F (31%), M (69%)	2 (23%), 3 (58%), 4 (19%)
SDNN (ms)	22	25-57 (36)	F (29%), M (71%)	2 (27%), 3 (61%), 4 (12%)
rMSSD (ms)	21	25-57 (36)	F (30%), M (70%)	2 (27%), 3 (59%), 4 (14%)
Baevsky's SI ($1/sec^2$)	23	25-57 (35)	F (28%), M (72%)	2 (23%), 3 (60%), 4 (17%)
SD1 (ms)	23	25-57 (35)	F (33%), M (67%)	2 (29%), 3 (57%), 4 (14%)
SD2 (ms)	21	25-57 (35)	F (31%), M (69%)	2 (28%), 3 (59%), 4 (13%)

Table 3: Demographic data for rPPG experiments using phones with an Android operating system.

Vital Signs	Number of Participants	Age Range (average)	Sex	Fitzpatrick Skin Tone*
RRi (ms)	22	25-53 (34)	F (32%), M (68%)	2 (24%), 3 (68%), 4 (8%)
SDNN (ms)	22	25-53 (34)	F (29%), M (71%)	2 (25%), 3 (67%), 4 (8%)
rMSSD (ms)	22	25-53 (34)	F (29%), M (71%)	2 (25%), 3 (71%), 4 (4%)
Baevsky's SI (1/sec^2)	24	25-53 (34)	F (27%), M (73%)	2 (23%), 3 (65%), 4 (12%)
SD1 (ms)	24	25-53 (34)	F (27%), M (73%)	2 (23%), 3 (65%), 4 (12%)
SD2 (ms)	20	25-53 (35)	F (27%), M (73%)	2 (18%), 3 (73%), 4 (9%)

Table 4: Demographic data for PPG experiments using phones with an Android operating system.

* Fitzpatrick skin tones are: 1- Pale white, 2- white, 3- Darker white, 4- Light brown, 5- Brown, 6- Dark brown or black.

Accuracy and persistency:
Tables 5-8 include statistical information (RMSE, MAE, MAE SD, 95% CI) for each HRV parameter, for each operating system (Android and iOS), and for each mode (PPG and rPPG).

iOS: **Table 5:** RMSE, MAE, MAE SD, and 95% CI for rPPG experiments using phones with an iOS operating system. Abbreviations: RMSE - Root Mean Square Error, MAE -Mean Absolute Error, MAE SD -Mean Absolute Error Standard Deviation, CI - Confidence Intervals.

Vital Signs	Number of measurements	RMSE	MAE	MAE SD	CI 95%
RRi (ms)	46	1.95	3.79	3	[2.9, 4.68]
SDNN (ms)	44	1.94	3.78	3.41	[2.73, 4.85]
rMSSD (ms)	42	2.44	5.96	4.69	[4.69, 7.69]
Baevsky's SI (1/sec^2)	48	1.77	3.15	3.5	[2.16, 4.23]
SD1 (ms)	46	2.19	4.78	3.82	[3.7, 6.05]
SD2 (ms)	41	2.19	4.82	3.8	[3.58, 6.04]

Table 6: RMSE, MAE, MAE SD, and 95% CI for PPG experiments using phones with an iOS operating system. Abbreviations: RMSE - Root Mean Square Error, MAE -Mean Absolute Error, MAE SD -Mean Absolute Error Standard Deviation, CI - Confidence Intervals.

Android:

Vital Signs	Number of measurements	RMSE	MAE	MAE SD	CI 95%
RRi (ms)	48	2.09	4.38	3.87	[3.26, 5.51]
SDNN (ms)	41	2.29	5.25	3.76	[4.06, 6.43]
rMSSD (ms)	37	2.32	5.39	4.1	[4.03, 6.76]
Baevsky's SI (1/sec^2)	53	1.54	2.39	2.01	[1.83, 2.94]
SD1 (ms)	42	2.34	5.46	4.46	[4.07, 6.85]
SD2 (ms)	39	2.57	6.63	4.44	[5.19, 8.07]

Table 7: RMSE, MAE, MAE SD, and 95% CI for rPPG experiments using phones with an Android operating system. Abbreviations: RMSE - Root Mean Square Error, MAE -Mean Absolute Error, MAE SD -Mean Absolute Error Standard Deviation, CI - Confidence Intervals.

Vital Signs	Number of measurements	RMSE	MAE	MAE SD	CI 95%
RRi (ms)	25	1.76	3.1	2.13	[2.23, 3.98]
SDNN (ms)	24	2.07	4.27	3.97	[2.59, 5.95]
rMSSD (ms)	24	2.14	4.6	4.1	[2.87, 6.33]
Baevsky's SI (1/sec^2)	26	1.68	2.83	3.19	[1.54, 4.12]
SD1 (ms)	26	1.8	3.25	3.21	[1.96, 4.55]
SD2 (ms)	22	2.22	4.92	4.77	[2.81, 7.04]

Table 8: RMSE, MAE, MAE SD, and 95% CI for PPG experiments using phones with an Android operating system. Abbreviations: RMSE - Root Mean Square Error, MAE -Mean Absolute Error, MAE SD -Mean Absolute Error Standard Deviation, CI - Confidence Intervals.

Pearson correlations between Binah.ai's RR interval estimations versus the Polar H10 Heart Rate Sensor™ measurements were calculated (Figure 1). Pearson correlation coefficients (R values) were very high for both operating systems (Android and iOS) and both modes (rPPG and PPG).

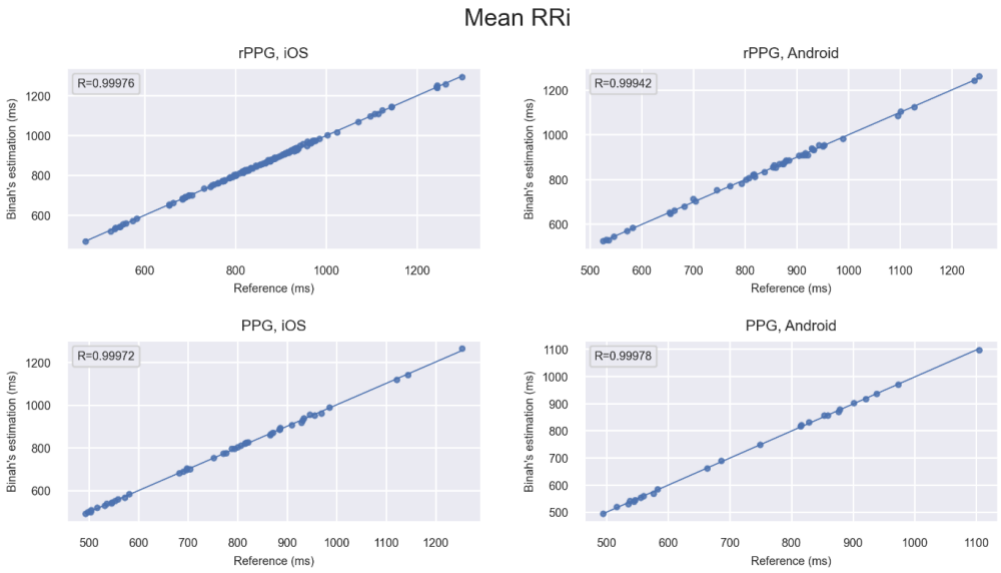

Figure 1: Binah.ai's RR interval (RRi) estimation vs. reference device measurements. Pearson correlation was calculated, and correlation coefficients are presented on each plot (R). Plots describe measurements conducted in both modes (rPPG and PPG) and both operating systems (iOS and Android).

Conclusions

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

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