Twenty-Four-Hour Ambulatory Blood Pressure Measurement Using a Novel Noninvasive, Cuffless, Wireless Device

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BACKGROUND
Ambulatory blood pressure monitoring (ABPM) using cuff-based devices is used for diagnosis and treatment of hypertension. Technical limitations, low compliance, and complex procedures limit their use. The aim of the present study was to test the accuracy of a new photoplethysmography-based, wearable device (Wrist-monitor) as compared with the standard cuff-based ABPM device.

METHODS
Twenty-four-hour (24H) ABPM was performed in parallel for both devices on volunteers aged 18–65 years, while documenting their daily activities. Level of comfort and activity disturbance of both devices were recorded. Linear regression and Bland–Altman were used to evaluate the agreement between devices. Receiver operating characteristic (ROC) curve analysis was used to classify hypertension based on the average Wrist-monitor measurements as compared with a cuff-based ABPM device.

RESULTS
The study included 28 subjects (18 men) mean age 41.5 ± 16.2 years. Bland–Altman analysis resulted in 24H bias of −1.1 mm Hg for both diastolic blood pressure (DBP) and systolic blood pressure (SBP). Mean daytime bias was −1.9 mm Hg for DBP and SBP, while nighttime bias was smaller (0.7 and 0.4 mm Hg for DBP and SBP, respectively). ROC curve analysis yielded a mean area under the curve (AUC) of 1 for SBP and 24H blood pressure measurements. AUCs of 0.994 and 0.955 were found for the daytime DBP and night DBP, respectively. 24H ABPM with the Wrist-monitor caused significantly less inconvenience compared with the cuff-based device (*P* < 0.001).
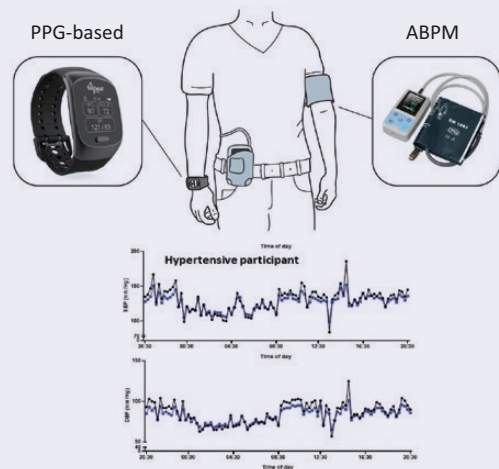
CONCLUSIONS
The cuffless device provides comparable measurements to those obtained with the currently used cuff-based ABPM device, with significantly less inconvenience to the subject.

CLINICAL TRIALS REGISTRATION
Trial Number NCT03810586.

GRAPHICAL ABSTRACT

Keywords: ambulatory blood pressure monitoring; blood pressure; cuff manometry; hypertension; noninvasive blood pressure monitoring; photoplethysmography

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Hypertension is a major risk factor for cardiovascular and cerebrovascular morbidity and mortality, yet its diagnosis can be delayed due to lack of overt symptoms and reliance on blood pressure (BP) measurements for diagnosis. Ambulatory blood pressure monitoring (ABPM) has become a frequently used method for the diagnosis of hypertension,[1,2] as it provides a more comprehensive assessment of BP during daytime and nighttime, and allows identification of patients with distinct BP profiles, such as masked or white-coat hypertension.[3–5] There is increasing evidence showing that ABPM may score the severity of hypertension and predict the cardiovascular risk of a patient more accurately than office-based BP measurements.[6,7] The recent National Institute for Health and Care Excellence (NICE) guidelines recommend using 24-hour (24H) ABPM to confirm the diagnosis of hypertension.[8]

In spite of all the advantages, the currently used ABPM devices have several setbacks that complicate their use and influence the accuracy of BP measurement. These include discomfort from using the cuff, inappropriate cuff size, and inaccuracies in measurements during sleep and daily activities.[9–14] Moreover, it was recently shown that the US hypertension control rates are now declining rather than improving.[15] Thus, there is a need for comfortable, precise, and user-friendly techniques for long-term BP measurement, helping with monitoring hypertension treatment dosing and medication compliance.

The purpose of the current study was to test the capability and compare measurements obtained using a wearable, noninvasive, cuffless photoplethysmography (PPG)-based remote patient Wrist-monitor to measurements obtained using a gold standard 24H oscillometric cuff-based ABPM device.

MATERIALS AND METHODS

Study design and ethical considerations

This prospective, comparative clinical trial was approved by the Institutional Review Board of the Hadassah Medical Center, Jerusalem, Israel (0671-18-HMO, NCT03810586).

Population

Thirty participants between the ages of 18–65 years of both genders were recruited for 24H BP monitoring. Included were both healthy subjects and subjects with stable chronic diseases on medical treatment. Excluded were individuals undergoing medical evaluation, subjects with arrhythmia, pregnant women, individuals with lack of judgment/mental illness, and those employed by the recruiting center. Each participant signed an informed consent form prior to the beginning of the study.

The PPG-based device

PPG is commonly applied for pulse oximetry, transmitting light which is absorbed by a detector on the other side of relatively thin body parts such as fingers, ear lobes, etc. While passing through the tissue, the light wavelengths show a unique absorbance pattern. The detector can measure the changing absorbance at each of several wavelengths, determining the absorbance resulting from the pulsating arterial blood. The currently used sensor (BB-613WP, Biobeat Technologies, Petah Tikva, Israel, Figure 1) is based on reflective PPG, in which part of the transmitted light is reflected from the tissue and detected by a photodiode detector positioned near the light source transmitter. The high resolution of the PPG wave combined with advanced algorithms allows the sensor to capture changes, as well as to track vital signs, derived from the pulse contours. Tracking the changes of BP is achieved after a preset baseline calibration process, and is based on pulse wave transit time technology combined with pulse wave analysis. The baseline calibration measurement is patient-specific and is performed using an approved noninvasive, cuff-based device with the average value of 3 consecutive measurements entered into the device's management application. Calibration is needed once every 3 months, which increases its clinical usability. Within the context of this study, calibration was conducted only once, at the beginning of the study. The algorithms used to analyze the PPG signal provide values that reflect the values within the large vessels/aorta, as was shown previously.[16] The
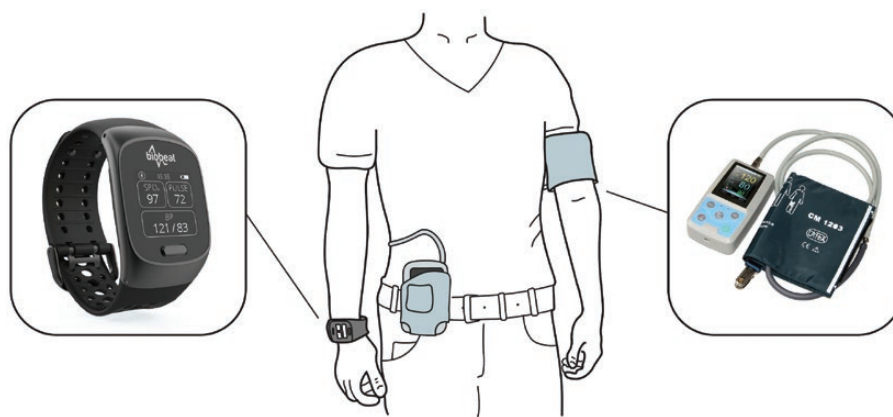

Figure 1. The PPG-based Wrist-monitor and the ABPM device. Each participant wore both for a 24H period, each was attached on the opposite hand. First measurements with the ABPM device before starting the comparison study were used as the baseline/calibration measurements for the PPG-based device. Abbreviations: 24H, 24-hour; ABPM, ambulatory blood pressure monitoring; PPG, photoplethysmography.

measurement is not influenced by arm position with relation to the heart level. The data were collected and transmitted in real-time to a web application available both to the user and the health care provider, thus providing a remote patient monitoring capability. The PPG-based sensor is integrated in a Wrist-monitor device, and can be worn on any wrist size (Figure 1). The device is FDA cleared for BP measurements.

Study protocol

On the morning of the study the subjects completed a demographic and past medical history questionnaire, after which both devices were placed, one on each arm—the ABPM was placed on the left arm with the cuff size adjusted as needed, and the Wrist-monitor was attached to the right arm's wrist.

The FDA and CE certified oscillometric ABPM [ABPM50 by CONTEC medical systems (People's Republic of China)] measured BP every 20–30 minutes for a 24H period, as further detailed below. The collected data were transferred to a designated computer program for further analysis.

We have previously shown that the PPG-based device is comparable to a cuff-based sphygmomanometer device.[17] This device is able to measure BP every 5 seconds. Initial calibration measurements were taken and entered into the PPG-based device's web application, and from that moment on, the PPG-based devices were continuously monitoring the BP at a 5-second measurement rate. The programmed ABPM BP measurements were recorded every 20–30 minutes, for up to a 24H period, each having an exact timestamp of when it was recorded. From 07:00 to 23:00 measurements were taken every 20 minutes, and from 23:00 to 07:00 measurements were taken every 30 minutes, as accepted in the clinical practice. With each participant, at the beginning of the study, the research team synchronized the PPG-based device inner clock with the time as it appeared in the ABPM app. This allowed us at the end of the study, to pair a parallel measurement taken at the same time in the PPG-based device and in the ABPM device, and compare the two, even if the ABPM measurement time intervals were not precisely as programmed. During this 24H period, participants kept an activity diary which included items such as sleeping, eating, and exercising activities. Nighttime period was defined individually based on the data obtained from the diary. The 24H data were directly transferred from the ABPM device and collected from the PPG-based device's data cloud for further analysis.

Questionnaire

After 24H of measurements, participants answered a final questionnaire, which included feedback on the use of both devices. This questionnaire included questions about the comfort level and compliance of both devices. Participants were asked the following questions[1]: How comfortable was the device? (with the score of 1–5, where 1 indicates not comfortable at all and 5 indicates very comfortable)[2] How much did the device disturb your daily activities? (1 indicating substantial disturbance and 5 indicating no disturbance)[3]

Rate your level of willingness to use the device for long-term BP monitoring (with the score of 1–5, where 1 indicated not willing and 5 indicates very willing).

Statistical analysis

Clinical characteristics and BP values are presented as mean and SD. Paired sample t-test was used to compare between the mean BP values obtained by the cuff-based device and the Wrist-monitor. The level of absolute agreement between the cuff-based device measurements and those obtained from the PPG-based Wrist-monitor for daytime, nighttime, and 24H systolic BP (SBP) and diastolic BP (DBP) were evaluated using Bland–Altman plots. Results of the Bland–Altman analyses are reported as mean biases ± 95% limits of agreement (LOA). Linear regressions were preformed to test the relationship between the BP measurements recorded by the cuff-based device and the Wrist-monitor. These analyses were performed for 24H, daytime, and nighttime SBP and DBP. The ability of the Wrist-monitor to identify abnormal BP values as the cuff-based device was tested with receiver operating characteristic (ROC) curve analysis and calculation of the area under the curve (AUC). Similarity between methods was tested using TOST test, in order to assess equivalence of 5 mm Hg for 24H, daytime, and nighttime BP.[18] All other results are presented as means ± SD. Statistical analyses were considered significant if $P < 0.05$. Data were analyzed using SPSS 23.0 (SPSS, Chicago, IL) and GraphPad Prism 8 (GraphPad Software, San Diego, CA).

RESULTS

Characteristics of the study population including daytime, nighttime, and mean 24H BP recorded by the 2 devices are shown in Table 1. Two of the initially recruited participants were excluded from the analysis due to low rate of data collection in the ABPM device. Among participants, 18 (64.3%) were men, with mean age of 41.5 ± 16.2 years and body mass index of 26.3 ± 5.2 kg/m². Six participants (21.4%) had a diagnosis of hypertension. BP was obtained simultaneously every 20 minutes for approximately 24H, with both techniques. When measurements from all time-points and participants ($n = 2,381$) were analyzed, 87.6% (DBP) and 81.5% (SBP) of all measurements obtained by the Wrist-monitor were in the range of ±5 mm Hg from those obtained by the ABPM device, while 95.3% (DBP) and 94.2% (SBP) were in the range of ±10 mm Hg (Table 2). Table 3 summarizes the rate of measurements in the hypertension range with both devices during daytime, nighttime, and 24H.

Next, we analyzed the level of agreement between the 2 devices, using the Bland–Altman plots (Figure 2). Mean 24H measurements were marginally underestimated (−1.1 mm Hg for both DBP and SBP) with the PPG-based remote patient Wrist-monitor, with narrow 95% LOA (−4.1, 1.8, and −4.2, 1.9 mm Hg for DBP and SBP, respectively; Figure 2a). When comparing the measurements obtained during the daytime or nighttime separately, average daytime bias was −1.9 mm Hg for DBP and SBP (Figure 2b), while nighttime bias was smaller (0.7 and 0.4 mm Hg for DBP and SBP,

Table 1. Characteristics of the study population including mean blood pressure values with both devices

Characteristics	n = 28	
Age	41.5 ± 16.2	
Sex (m/f)	18/10	
BMI (W/H^2)	26.3 ± 5.2	
Known hypertension	6	
Regularly exercise	25	
Currently smoking	3	
Moderate alcohol consumption	4	
Blood pressure	ABPM	PPG-based device
24H		
SBP (mm Hg)	119.9 ± 11.3	118.8 ± 11.3*
DBP (mm Hg)	73.0 ± 9.8	71.9 ± 10.0*
Daytime		
SBP (mm Hg)	125.2 ± 11.5	123.3 ± 11.1*
DBP (mm Hg)	77.2 ± 9.7	75.3 ± 9.7*
Nighttime		
SBP (mm Hg)	106.0 ± 11.1	106.5 ± 11.5*
DBP (mm Hg)	61.9 ± 9.4	62.6 ± 9.8*

Values are mean ± SD. Abbreviations: 24H, 24-hour; ABPM, ambulatory blood pressure monitoring; BMI, body mass index; PPG, photoplethysmography. Hypertension defined as systolic blood pressure (SBP) ≥130 mm Hg and/or diastolic blood pressure (DBP) ≥80 mm Hg or treatment for hypertension.

*Significant ($P < 0.001$) equivalence between devices by TOST test within 5 mm Hg.

Table 2. Agreement of blood pressure measurements between the 2 devices

Total measurements	2,381	
Measurements/participants	84.6 ± 8.5	
	DBP	SBP
BP differences (24H), mean ± SD	1.1 ± 7.1	1.1 ± 8.3
Differences <±5mm Hg	2,086 (87.6%)	1,940 (81.5%)
Differences <±10mm Hg	2,270 (95.3%)	2,244 (94.2%)
	ABPM	PPG-based device
24H		
Above 125/75 mm Hg	729 (30.7%)	684 (28.8%)
Above 125 mm Hg	869 (36.6%)	821 (34.5%)
Above 75 mm Hg	949 (39.9%)	939 (39.5%)
Daytime		
Above 130/80 mm Hg	501 (21.0%)	438 (18.4%)
Above 130 mm Hg	640 (26.9%)	566 (23.8%)
Above 80 mm Hg	640 (26.9%)	585 (24.6%)
Nighttime		
Above 110/65 mm Hg	232 (9.7%)	254 (10.7%)
Above 110 mm Hg	212 (8.9%)	229 (9.6%)
Above 65 mm Hg	166 (7.0%)	187 (7.8%)

Abbreviations: 24H, 24-hour; ABPM, ambulatory blood pressure monitoring; BP, blood pressure; DBP, diastolic blood pressure; PPG, photoplethysmography; SBP, systolic blood pressure.

Table 3. Comparison of levels in the hypertension range between the 2 devices

	ABPM	PPG Wrist-monitor
24H		
Above 125/75 mm Hg	729 (30.7%)	684 (28.8%)
Systolic above 125 mm Hg	869 (36.6%)	821 (34.5%)
Diastolic above 75 mm Hg	949 (39.9%)	939 (39.5%)
Daytime		
Above 130/80 mm Hg	501 (21.0%)	438 (18.4%)
Systolic above 130 mm Hg	640 (26.9%)	566 (23.8%)
Diastolic above 80 mm Hg	640 (26.9%)	585 (24.6%)
Nighttime		
Above 110/65 mm Hg	232 (9.7%)	254 (10.7%)
Systolic above 110 mm Hg	212 (8.9%)	229 (9.6%)
Diastolic above 65 mm Hg	166 (7.0%)	187 (7.8%)

Abbreviations: 24H, 24-hour; ABPM, ambulatory blood pressure monitoring using cuff-based devices; PPG Wrist-monitor, photoplethysmography-based, wearable device.

respectively; Figure 2c). As expected, 95% LOA for the average daytime (SBP: −7.0, 3.3; DBP −6.3, 2.5 mm Hg) was greater as compared with the average nighttime (SBP: −1.7, 2.6; DBP −1.5, 2.9 mm Hg) measures compared with the average 24H values. We have also analyzed the level of agreement for each measurement during daytime, nighttime, and 24H (presented in Supplementary Figure S4 online). Comparison of average BP measurements throughout the longitudinal monitoring show high precision and accuracy (LOAs for each panel in Figure 2: from −4.2 to 1.9 for 24H SBP, from −6.9 to 3.3 for daytime SBP, from −1.7 to 2.6 for night SBP, from −4.1 to 1.8 for 24H DBP, from −6.3 to 2.5 for daytime DBP, and from −1.5 to 1.8 for night DBP), with a relatively narrow 95% LOAs, as shown in Figure 2. Comparison at the level of specific measurements show wider LOAs for daytime and 24H measurements while those for night are narrower (Supplementary Figure S4 online).

We found a slight under and over estimate of the agreement between the PPG-based device and the cuff-based ABPM device (Figure 2 and Supplementary Figure S4 online). However, under estimate was present in less than 2% of the total number of measurements for both SBP and DBP (38 and 50 out of 2,377 measurements, respectively), and over estimate was present in less than 1% of the total number of measurements for both SBP and DBP (19 and 17 out of 2,377 measurements, respectively).

Mean values obtained by both devices were highly correlated ($R^2 > 0.95$, $P < 0.0001$) for both DBP and SBP, during the 24H measurement period, and during the daytime and nighttime separately (Figure 3a–c).

In Supplementary Figure S5 online, we present the BP graphs of both the ABPM and the PPG-based devices of all participants.

We used ROC curve analysis to determine the differences obtained between devices for the acceptable abnormal threshold. Thresholds for the ROC were determined according to the 2017 ACC/AHA Guideline's definition for hypertension: the cutoffs for SBP were 130, 110, and 125 for daytime, nighttime, and 24H, respectively, and the cutoffs for DBP were 80, 65, and 75 for daytime, nighttime, and 24H, respectively.[19] ROC curve analysis of the average BP measurements yielded a mean AUC of 1 for SBP and 24H BP measurements. AUCs of 0.994 and 0.955 were found for the daytime DBP and night DBP, respectively. When analyzing all BP measurements ($n = 2,381$), AUC for both SBP and DBP were >0.94 for all means of 24H, daytime, and night BP.

We then compared the average of all the 24H measurements taken using the PPG-based devices with the average of the 24H measurements of the PPG-based devices excluding those taken in parallel with the cuff-based ABPM device; with the average of measurements taken by the PPG-based device in parallel to the cuff-based ABPM device; and with the average of measurements of the cuff-based ABPM device. We found that the average measurements taken with the cuff-based ABPM device and with the paralleling PPG-based device measurements were significantly higher than the average taken during the rest of the day (mean of differences (MOD) of 24H measurements of the PPG-based devices—114/68; MOD of measurements of the cuff-based ABPM device—120/73; MOD of measurements of the PPG-based devices excluding those taken in parallel with the cuff-based ABPM device—114/68; MOD of measurements of the PPG-based device taken in parallel to the cuff-based ABPM device—119/72) (Supplementary Figure S6 online).

In 10 participants, the static BP measurements taken by the cuff-based device and used for baseline calibration were above the threshold regarded as hypertensive. In 2 of them, average 24H measurements show normal BP. In the other 18 participants, baseline calibration static BP measurements were normotensive, yet in 3 of them the average 24H measurements are consistent with hypertension.

The participants reported the Wrist-monitor was significantly ($P < 0.0001$) more comfortable (Supplementary Figure S7A online), was less of a disturbance for their daily routine (Supplementary Figure S7B online), and had a significantly ($P < 0.0001$) higher rating for long-term adherence/responsiveness (Supplementary Figure S7C online).
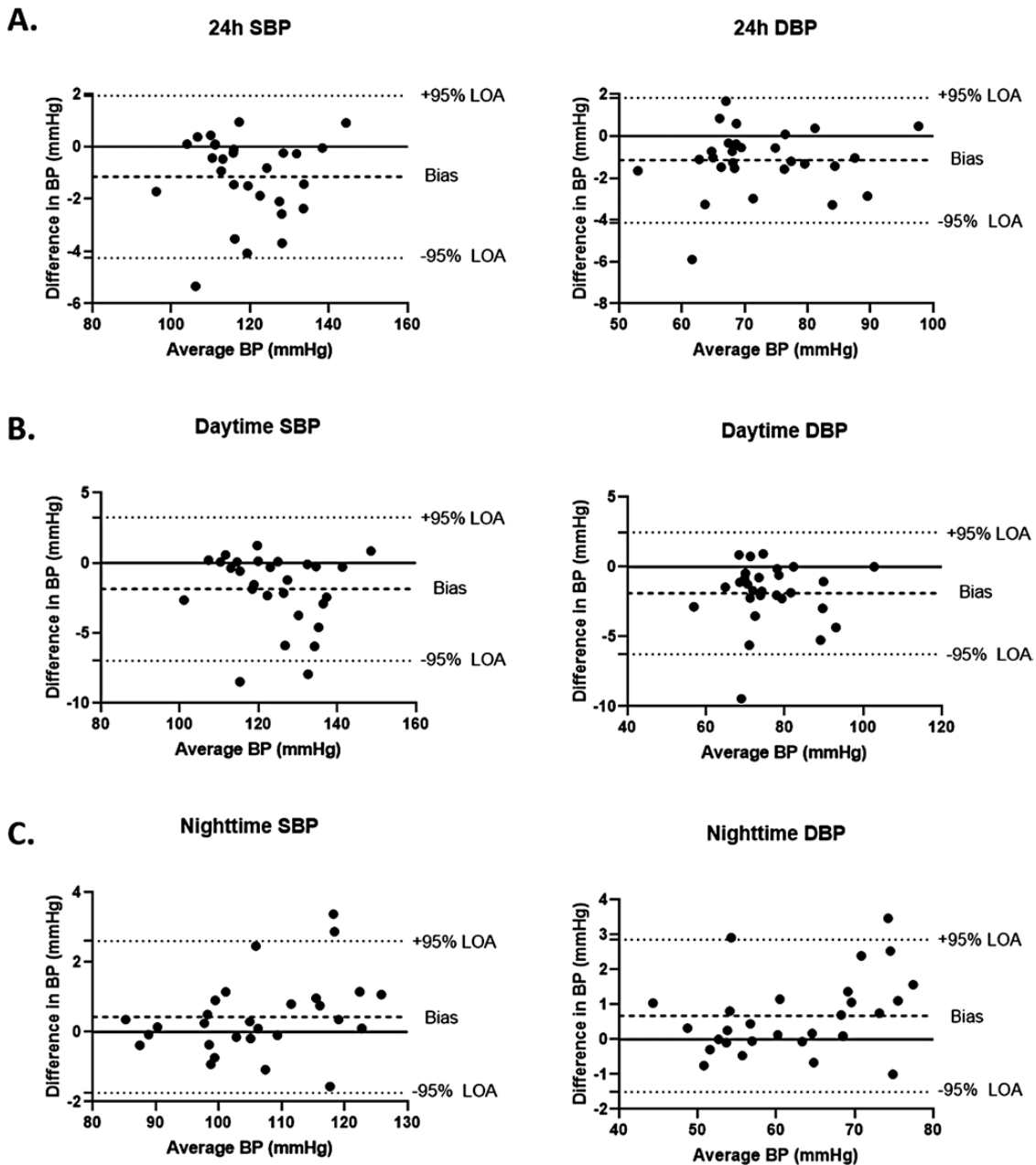
Figure 2. Bland–Altman plots of the limits of agreement between the Wrist-monitor and the ABPM measurements for 24H ambulatory blood pressure (BP) monitoring. Systolic BP (SBP; left panels) and diastolic BP (DBP; right panels) for the entire 24H measurement period (panel **a**), daytime measurements (panel **b**), and nighttime measurements (panel **c**). The dashed horizontal lines represent the mean difference between the 2 measurements (bias) and the dotted horizontal lines represent the 95% limits of agreement (LOA). Abbreviations: 24H, 24-hour; ABPM, ambulatory blood pressure monitoring.

DISCUSSION

In this observational study, we tested the capability of a novel remote patient monitoring device to repeatedly measure BP during a 24H period and compared it with a gold standard commonly used oscillometric ABPM device. No significant differences in average measurements between the 2 devices were found. High correlations were observed between the BP levels recorded by the 2 devices even when looking at individual measurements throughout the 24H period, and when looking at daytime and nighttime separately,

as seen in the Pearson correlation test and Bland–Altman analysis. Moreover, ROC analysis has shown that the difference between measurements is within the high correlation, in more than 80% of the measurements the difference between the devices was less than 5 mm Hg, and in ~95% of the measurements the difference between the devices was less than 10 mm Hg, for both SBP and DBP values. These findings suggest that the PPG-based device might be used for 24H BP recording and can potentially replace the gold standard sphygmomanometer-based BP ABPM device. The
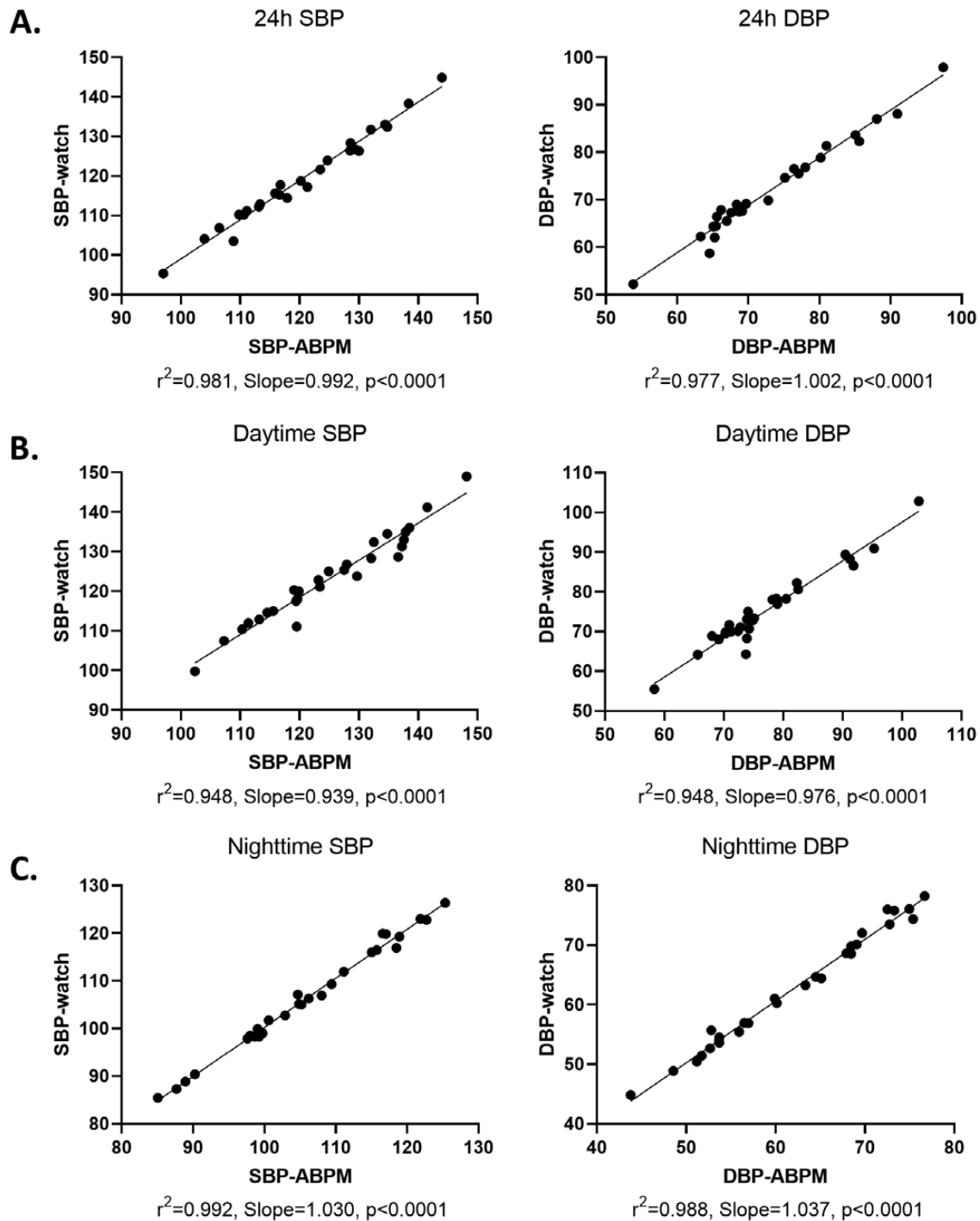
Figure 3. The association between the measures obtained by the Wrist-monitor and the ABPM for 24H ambulatory blood pressure (BP) monitoring. Systolic BP (SBP; left panels) and diastolic BP (DBP; right panels) for entire 24H measurement period (panel **a**), daytime measurements (panel **b**), and nighttime measurements (panel **c**). The solid line is the best fit linear regression and the dashed line is the line of identity. Panels **d** and **e** show an example of a normotensive participant and a hypertensive participant, respectively, as an example to the accordance between the devices. Abbreviations: 24H, 24-hour; ABPM, ambulatory blood pressure monitoring.

recording with the new device is much more convenient and can be used for more than 24H and therefore might give much more reliable information. Our results suggest continuous BP measurement with the novel device causes less disturbance in daily activities and therefore may become a routine method to diagnose hypertension and to follow patients with hypertension.

The obvious clinical need to improve BP recording resulted in several attempts to develop noninvasive, wearable devices for continuous BP measurement. These include,

among others, the applanation pulse tonometry, in which the pressure wave is continuously measured in the radial artery, from which the BP is extrapolated following calibration with a standard cuff-based BP device[20]; the vascular unloading time, in which the pulse wave is recorded using PPG and compared with an induced and changing pressure that keeps the amplitude constant, enabling to calculate the BP from the required change in pressure[21]; and pulse wave transit time, in which the BP is calculated from the delay in the pulse wave compared with an electrocardiogram signal recorded in parallel.[22] In all, preliminary theoretical and small clinical studies have been conducted, but there is still a need to have more information from well-established clinical validation studies.[10,22–25] Here, we present a clinical study of a PPG-based device, using the pulse wave transit time and pulse wave analysis techniques unique by the fact that there is no need to combine electrocardiogram signals, allowing a less cumbersome method to continuously record BP.

ABPM has several advantages over a single BP measurement either in the clinic or at home, as it allows a more accurate characterization of the BP pattern of an individual throughout the day and night, and during activities of daily living.[2,12] However, as the currently used ABPM devices are cumbersome, the users' compliance is relatively limited.[14,26–28]

When looking at the cuff-based BP repeatability and aiming to reduce BP measurement errors, several recommendations were issued so far in different guidelines, including the use of validated upper-arm oscillometric devices in place of auscultation, training of medical assistants, monitoring compliance with BP protocols, and having several measurements taken to reduce standard errors.[29,30] All of these issues are easy to comply with when using the PPG-based device.

The high precision and accuracy of average BP measurements throughout the longitudinal monitoring with a relatively narrow 95% LOAs (Figure 2) further shows the value of the PPG-based devices for ambulatory BP monitoring. When comparing all BP measurements (*n* = 2,381, Supplementary Figure S4 online), a wider LOA can be noticed during daytime. This is expected due to the dynamic nature of everyday living, as measurements were taken while the participants were ambulatory and in a dynamic real-life setting, unlike measurements taken in a static laboratory setting. This is further strengthened when we see a higher level of agreement in the night measurements, collected mostly during sleep. As neutralization of hydrostatic effects during the night might also be involved as a mechanism, this should be addressed and included in future studies.

It is important to emphasize that clinically, the diagnosis of hypertension, as well as treatment and outcome measures, are based on the average measurements. Thus, since the aim of this study was to test whether the PPG-based device can be used for ambulatory BP monitoring, comparing the average measurements is more relevant than comparing all measurements. Despite the higher LOAs of all measurements, ROC analysis of over 94% during daytime, night, and 24H measurements demonstrates high level of accuracy at the individual measurement level.

As shown in Supplementary Figure S6 online, we found that BP values are influenced by the cuff-based device in comparison to the optical-based Wrist-monitor device, perhaps indicating a cuff-related bias. Though this might have a profound effect on future BP monitoring, we think that the current study should be repeated with larger numbers of participants before definite conclusions could be drawn.

When comparing the static baseline BP levels with the measurements taken during the 24H monitoring we found that in 5 participants out of the 28 there were discrepancies, further emphasizing the advantage and the importance of having a 24H monitoring period and not relying on single measurements for the diagnosis of hypertension.

Outliers or unreliable measures could potentially influence such comparison studies. Indeed, in our hands, we found that out of the thousands of measurements collected, less than 1% were either outliers or unreliable measures, leading to the mean ± SD values described in Table 2 and shown in Supplementary Figure S5 online. Despite these outliers, we still show that 94.2% of SBP measurements and 95.3% of DBP measurements fall within 10 mm Hg (Table 2).

Our study has limitations. We studied a relatively small group of subjects and we did not include enough hypertensive subjects, very elderly subjects, obese subjects and patients with very high or very low BP levels. Therefore, we are unable to estimate the accuracy of the device in these subpopulations. Nevertheless, it is important to note that we compared more than 2,800 measurements between the 2 devices, that the average age of the participants was within the range of people diagnosed with primary hypertension, and that the average body mass index fits the definition of overweight.

We did not take BP measurements from both arms before starting the test in each individual, and thus may have missed individuals with a substantial BP difference between arms. None of the participants knew of any such difference before joining the study.

Finally, the PPG-based device is under validation for other inpatient settings, such as in pregnant women during labor, in postsurgery patients, and in COVID-19 patients, helping in all of these clinical settings by remote patient monitoring.[31]

In conclusion, the wearable, wireless, noninvasive PPG-based device is more comfortable, user-friendly, and offers accurate and continuous BP monitoring. This device could provide a 24H ABPM for hypertension diagnosis and treatment, with high compliance and without reducing the sensitivity of the test. Moreover, this device offers a longer period of continuous monitoring, potentially enabling better adjustment of treatment of hypertensive individuals. Further studies are needed to confirm the accuracy of the device in hypertensive patients and in other subpopulations.

SUPPLEMENTARY MATERIAL

Supplementary data are available at *American Journal of Hypertension* online.

Supplementary Figure S4. Bland–Altman plots of the level of agreement between the Wrist-monitor and the ABPM measurements for each measurement. Systolic BP (SBP; left panels) and diastolic BP (DBP; right panels) for the entire 24H measurement period (panel **A**), daytime measurements (panel **B**), and nighttime measurements (panel **C**). The dashed horizontal lines represent the mean difference between the 2 measurements (bias) and the dotted horizontal lines represent the 95% limits of agreement (LOA).

Supplementary Figure S5. Graphs showing the 24H systolic and diastolic blood pressure measurements of both the ABPM and the PPG-based devices of all 28 participants.

Supplementary Figure S6. Comparison between the average of all 24H measurements, daytime measurements, and nighttime measurements taken using the cuff-based ABPM device (black bars) with the average of measurements of the Wrist-monitor excluding those taken in parallel with the cuff-based ABPM device (white bars); with the average of all measurements taken by the Wrist-monitor (dark-gray bars); and with the average of measurements of the Wrist-monitor taken in parallel with the cuff-based ABPM device (gray bars). (**A**) Systolic blood pressure (SBP) and (**B**) diastolic blood pressure (DBP). ***$P < 0.0001$, *$P < 0.05$.

Supplementary Figure S7. Participants' feedback regarding the ease of use of the noninvasive PPG-based Wrist-monitor and the ABPM device. The level of comfort (**A**), daily activity disturbance (**B**), and willingness for long-term use (**C**) in a scale of 1–5.

FUNDING

DISCLOSURE

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