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Review

Review

The Rapid Evolution of Continuous Blood Pressure Measurement: Future Considerations

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BACKGROUND: There exists an accelerating pace of availability and expanding variety of new blood pressure (BP) measurement technologies worldwide that seek to measure BP in entirely different ways than through the traditional "BP Cuff" commonly used for office and home measurements. A growing number of these devices are viewed by many clinicians and patients as potentially complementary sources of data when combined with office and home readings. However, wearable devices are intentionally designed to provide a more patient-centered experience and may have an important future potential to replace these traditional methods.

METHODS:BP is a continuous biologic variable (like body temperature, heart rate, blood oxygenation, etc.) that can now be measured much differently than by commonly used methods of obtaining random serial point in time BP measurements. For example, new technologies now exist that can combine beat-to-beat BP measurements (3,600 measures per hour on average) with additional complex physiologic data such as 24-h BP variability and real-time vascular biomechanical phenomena, including pulse wave amplitude, velocity, and contour analysis.

RESULTS: Such data could provide previously unavailable information for identifying potential new therapies for reducing modifiable vascular and endothelial dysfunction, thereby reducing the risk and progression of atherosclerotic cardiovascular disease.

CONCLUSIONS: Patients and their clinicians may soon be able to demystify extensive continuous personal BP measurement patterns from this evolutionary process through meaningful correlation with daily and life activities, and hence further achieve optimal cardiovascular health.

Keywords: ambulatory blood pressure monitoring; blood pressure; cardiovascular disease; hypertension.

There is a rapidly growing number of new blood pressure (BP) measurement technologies that seek to measure BP in entirely different ways than through the traditional "BP Cuff" that is commonly used for office and home measurements. Examples include different types of cuffless sensors at various arterial sites (e.g., chest, face, upper arm, wrist, finger) with continuous or "snapshot" monitoring of BP using a variety of direct or indirect recording and signal processing methods (e.g., reflectance pulse oximetry, radio frequency sensors, microstructure strain gauge fibers, opto-electronic, applanation tonometry, pulse transit time (PTT), smartphone based technology) over durations that may extend to weeks or months, and may incorporate software programs with clinical decision support functionality.[1] Yet, industry and regulatory standards for validation testing for clinical accuracy of these digital devices are currently lacking within the United States and European consumer markets.[2–4]

In response, the European Society of Hypertension has recently published comprehensive recommendations for the validation of cuffless "wearable" blood pressure measuring (WBPM) devices.[5] Some examples are listed in **Table 1**.

BP measurements are very often suboptimally performed despite extensive efforts to raise awareness on appropriate measurement techniques and the adverse consequences of inaccurate BP measurements.[6] In addition, 24-h ambulatory blood pressure monitoring (ABPM), a useful guideline-based method for diagnosing such conditions as "White Coat"(WCH) and "Masked" Hypertension and provide prognostic value, is rarely deployed by many practicing physicians.[7,8] However, Medicare's coverage

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of ABPM is restricted and subject to prior authorization requirements for patients with documented WCH who have no evidence of target organ damage.[9]

Our goal will be to provide an outline of the comparative utility between each of these methods for several important categories of use of WBPMs, including (i) BP measurement methods, (ii) Diagnosis of High Blood Pressure (HBP), (iii) Data collection and analysis of BP readings, (iv) current and future role in clinical decision-making for Guideline Directed Medical Therapy, (v) Patient-centered costs and benefits, and (vi) implications and considerations for current and future research.

Comparative features of BP measure methods

Table 2 displays the comparative features of OBPM, HBPM, ABPM, and WBPM.

Of note, consistent external international validation standards for WBPM devices currently do not exist, for example, with respect to reliability and accuracy of BP measurement, whereas many OBPM and HBPM (and a few ABPM devices) are included in Validate BP, an online list of validated BP measurement devices supported by the American Medical Association.[10] Measurements obtained from validated OBPM and HBPM devices provide only point-in-time samples of the continuous physiologic nature of BP. Hence, clinical decision-making-based samples of BP readings could lead to potential overtreatment or possible undertreatment. ABPM is considered the best and complementary BP cuff-based method for obtaining a reliable estimation of the true BP. Average values (typically obtained every 15–30 min while awake and 30–60 min while asleep) obtained during an entire 24-h period, or during daytime and nighttime periods, are better correlated with the risk of mortality and cardiovascular disease compared to OBPM or HBPM.[11] On the other hand, ABPM is relatively expensive, not easily available to patients, and can be uncomfortable, especially during sleep.[6] While the number of WBPM devices has rapidly increased across many developed countries, most are either arm or wrist "cuff based" devices and have not undergone rigorous validation against reference BP readings or "gold standard" validated OBPM and ABPM devices.[3,4] "Cuffless" BP devices have also become available, which can report BP readings at intervals of between every 1 and 30 s, but again, without adequate validation against traditional methods.[5,12] Figure 1 displays various cuffless BP technologies currently in use and under development which have had limited evidence of validation standards.

Table 3 further outlines the function and calibration of cuffless BP measuring devices.

Diagnosis

OBPM and HBPM are, of course, by far the most common methods used for diagnosis and management of HBP, while the use of ABPM is often also deployed in assisting the clinical diagnosis of more nuanced BP patterns that have important prognostic

Table 1. Common examples of wearable and "smartphone" devices by BP measurement method and calibration[5]

Device type	BP measurement method			Calibration method		
	Automated (wearable)	Manual (wearable or not)	Heart level (automated)	Calibration-free	Cuff-calibrated	Demographic-calibrated
Wristband, Smart Watch	+			+	+	+
Chest patch, Upper arm band	+		+	+	+	+
Smartphone, Smart Watch, Wristband		+		+	+	+

Each of these device types requires different methods for evaluation and validation of BP Measurement accuracy.

Table 2. Comparative features of BP measurement methods

Feature	Office BPM	Home BPM	24-h ABPM	Wearable BPMs
Widespread availability to clinicians	+	–	+/–	–
Availability to patients	+	+	+	+
Independent validation	+	+	+	–
Reliable measurements	+	+	+	–
Protocol for accurate measurements	+	+	+	–
Periodic 24-h measurements	–	–	+	+/–

+, common feature; +/–, inconsistent feature;–, uncommon/not a feature.
Abbreviations: BPM, blood pressure measurement; ABPM, ambulatory blood pressure monitoring; WBPMs, wearable blood pressure measurements.

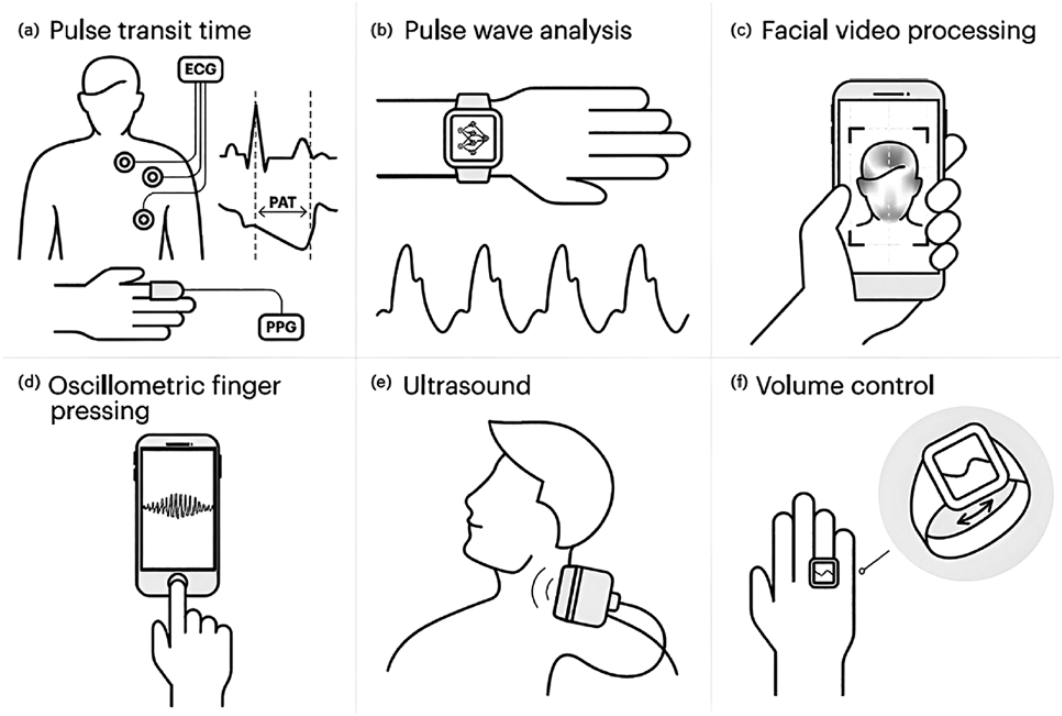

Figure 1. Wearable BP monitoring technologies.

Table 3. Function and calibration of cuffless BP measuring devices—terminology[11]

Device function/calibration		Definition
BP output frequency	Continuous	Obtains BP readings every 1–30 s
	Intermittent	Obtains BP readings every > 30 s (usually 30–60 min), or upon user's own will and initiation.
Measurement mode	Automated	Measures BP for days, weeks, or months without requiring any action by the user for each measurement via a wearable device.
	Manual	Measures BP in a single device position via user activation (e.g., user holds still a smartphone, smartwatch, or portable device at heart level)
Sensor	Wearable	Obtains BP with sensor fitted to user (e.g., wristband, smartwatch, ring) either automatically or manually
	Heart level	Obtains BP with sensor positioned at/near heart level
Calibration	Cuff-calibrated	Reports BP readings of one or more BP readings and requires periodic recalibration
	Demographic-calibrated	Reports BP readings after initial input of individual user variables (e.g., sex, age, weight, or other).
	Calibration-free	Reports BP readings without additional individual user information

Abbreviation: BP, blood pressure.

significance, such as HBP that may occur when supine or at night during sleep.[10,13,14] Both of these subtle but significant phenomenon are likely to go undetected in usual clinical practice but can certainly be directly observed by Hypertension specialists who commonly manage the ABPM process and then evaluate frequent sequential measurements with advanced data analytic methods. In addition, BP variability (BPV) patterns such as various forms of orthostatic hypotension (e.g., secondary to medications, age and as might occur postprandially or with micturition), BP "dipping" and "Morning Surge" can also be observed and evaluated for further clinical and shared decision-making, as will be subsequently discussed. **Table 4** displays the diagnostic features of the various BP measurement device categories.

Data collection and analysis

The comparative features of methods for data collection and analysis for each of the four BP measurement approaches are presented in **Table 5**. As previously noted, accuracy and reliability remain problematic for all four methods, which are most commonly obtained without patient proper preparation or correct measurement technique in accordance with standardized guideline-directed measurement protocols.[15] Clinicians and patients commonly rely on interpretation and analysis for OBPM and HBPM readings obtained during daily practice and self-monitoring for diagnosis, treatment decisions and atherosclerotic cardiovascular disease (ASCVD) risk assessments, whereas ABPM requires special expertise and analytic methods and potentially complex medical decision-making. However,

Table 4. Diagnostic features of the various BP measurement device categories

Feature	OBPM	HBPM	ABPM	WBPM
Diagnosis of HBP	+	+	+	–
Diagnosis of severe HBP[a]	+	+	+	–
Diagnosis of white-coat hypertension	+	+	+	–
Diagnosis of masked HBP	+	+	+	–
Evaluation of supine BP	–	–/+	+	+/–
Evaluation of waking "morning surge"	–	+	+	+/–
Nocturnal/sleep BP measurements	–	–	+	+/–
Orthostatic hypotension	+/–	–	+/–	–
Detection of BP "dipping"	–	–	+/–	+/–

+, common feature; +/–, inconsistent feature; –, uncommon/not a feature.
Abbreviations: OBPM, office blood pressure measurement; HBPM, home blood pressure monitoring; ABPM, ambulatory blood pressure monitoring; WBPM, wearable blood pressure measurement; HBP, high blood pressure; BP, blood pressure.
[a]As defined in the 2024 ESC Guidelines for the management of elevated BP and hypertension.[8]

Table 5. BP data collection and analysis

Feature	Office BPM	Home BPM	24-h ABPM	Wearable BPM
Accuracy of Measurements	+/–	+/–	+/–	+/-
Ease of Interpretation & Analysis	+	+	+/–	–
Adequate Availability of BP Data	–	+/–	+	+
Assessment of Variability	+	+	+	+
Easy Digital Data Transfer to EHR	+	+/–	–	–
Easy Digital Device/App Data Transfer	–	+	–	+/–
Standardized Digital Data Display	–	+/–	–	+/–
Other Clinical Data Easily Available	+	+	+	+/–

+, common feature; +/–, inconsistent feature; –, uncommon/not a feature.
BPM, blood pressure measurement; BPM, home blood pressure monitoring; ABPM, ambulatory blood pressure monitoring; BP, blood pressure; EHR, electronic health record.

how best to replicate these concepts with data obtained from WBPM has yet to be determined due to the absence of clinical trials or other evidence. Also, OBPM data is now commonly captured automatically and transferred to electronic health records, but not easily accomplished for the three other methods due to a variety of constraints, such as difficulties with interoperability and cybersecurity standards. Standard data display "apps" (for example, using staging classifications for HBP such as published by ACC/AHA) of serial readings have been developed for most self-monitoring devices, including the ability of the user to "download."[16] These features are relatively uncommon for the other three methods. The variety and complexities of common analytic methods for ABPM will be discussed in more detail later in this manuscript.

Clinical decision-making and quality measurement

Decisions for diagnosis, medication adjustment, lifestyle modification as well as ASCVD risk are made through BP measurement data obtained through OBPM, HBPM, and ABPM, but very uncommonly made with data obtained solely through WBPM readings. In addition, only data from OBPM and HBPM are required and allowed for quality and performance measurement, improvement, and reporting, for example to the Centers for Medicare and Medicaid Services[17] and the National Committee for Quality Assurance,[18] as well as quality improvement efforts such as Million Hearts,[19] AMA MAP™ HTN,[20] and Target BP.[21] Each of these features is summarized in **Supplementary Appendix 1**.

Patient-centered costs and benefits

Both HBPM and WBPM can be considered patient-centered, as both enable the end-user to self-monitor and track BP measurements, although accuracy and reliability remain problematic for both methods as noted in **Supplementary Appendix 2**. And these types of devices are often not covered by health insurers and therefore paid for out-of-pocket, especially if coupled with smartphones and other personal digital devices. A recent study found that compared to OBPM, HBPM or ABPM are cost-effectiveness, and potentially aid in detecting WCH and masked hypertension.[22] These researchers also suggest that ABPM and HBPM may be alternative approaches to office BP measurement, although evidence from randomized clinical trials to prove this hypothesis is lacking. They also speculate that the development of a standardized validation protocol for wearable BP monitoring devices might facilitate the clinical applicability of ambulatory BP monitoring.[21] For now, OBPM, HBPM, and ABPM remain the gold standard methods for many current and future clinical trials and population-based observational studies evaluating the overall costs and benefits of effective control of HBP. Future research questions and recommendations will be outlined further in this manuscript.

Methods for blood pressure variability and advanced analytics

Blood pressure variability (BPV) is an independent cardiovascular risk factor for patients with hypertension.[23] Substantial research has been published on multiple sequential BP measurements obtained through ABPM techniques. The most common method relies on the traditional statistical measures used in many published evaluations of BPV obtained from ABPM data, such as systolic BP mean, standard deviation (SD), weighted standard deviation (w SD), and coefficient of variance (CV). Generalized linear regression models can be used to evaluate statistical significance and hence guide subsequent inferential interpretations of research questions related to BP diagnosis and control. More

Table 6. Examples of evaluative measures of BPV[23–25]

From ABPM common analytic methods	Brief description of approach
1.Traditional statistical methods	1.Mean, Variance, SD
2.HBP Staging Classification	2.E.g. ACC/AHA or ESC Classification
3.Coefficient of Variation	3.Evaluates Overall BP Variability for 24 ABPM
4.Beat by Beat Oscillations	4.Sequential BP Reading Variation
5.ARV Index	5.Average Variation-Predicts CV Risk
6.Time Rate of BP variation	6.Steepness and Speed of Changes in BP
7.Weighted SD	7.Weighted Average of Day and Night SDs
8.Blood Pressure Variability	8.Evaluates Overall BP Variability
9.Pulse Wave Velocity	9.Analyzes Pulse Wave Configurations
10.Pulse transit time	10.Analyzes Pulse Wave Configurations
11.Reading-to-Reading Variability	11.Sequential BP Reading Variation
12.Circadian Rhythm Variability	12.Variation by time of day
13.Linear Mixed Model	13.For aggregate statistical analysis
14.Time in Target/Therapeutic Range	14.Sometimes deployed with ABPM

Abbreviations: ABPM, ambulatory blood pressure monitoring; ARV, average real variability; HBP, high blood pressure; ACC, American College of Cardiology; AHA, American Heart Association; ESC, European Society of Cardiology; CV, cardiovascular; SD, standard deviation; BP, blood pressure; TTR, time in therapeutic range.

widespread ABPM-related research has also opened the gates to advanced techniques of assessing BPV indices. For example, the average real variability (ARV) index appears to be (i) simple to compute, (ii) relatively insensitive to low sampling frequency, (iii) not strongly influenced by cyclic components, (iv) sensitive to the sequential order of BP readings, and (v) provides insight into BP changes.[24] Additional evaluation by these authors also suggests that elevated reading-to-reading 24-h BP variability confers a greater cardiovascular risk via inherent changes among consecutive BP measures independently of the BP level and/or repetitive hypertensive BP loads which is not independent of the BP level.[14] Dysregulation of the normal circadian BP rhythm observed with ABPM (i.e., "non-dipping" and "reverse dipping") might also assist in identifying subjects at increased risk for abnormal cognitive impairment and dementia, thereby facilitating timely diagnosis and early interventions.[25] Additional emerging examples of BPV measurement methods and strategies using ABPM data of analytic value include indirect measures of arterial stiffness, such as pulse wave velocity, differences between maximum and minimum systolic BP values (DSBP), averages of the absolute differences between consecutive ARV values and CV and time rate of blood pressure variation.[26,27] **Table 6** provides a summary overview of these various methods.

With the advent of WBPM, the rise of cuffless devices adds new signal processing approaches to assessing more complex forms of BP data. For example, PTT represents a potential "anytime, anywhere" approach for cuffless BP monitoring, which is determined by (i) measuring (a) electrocardiographic (ECG) and ear, finger, or toe photoplethysmography (PPG) waveforms or (b) two of these PPG waveforms and (ii) detecting the time delay between the waveforms.[28–30]

Continuous per-second ABPM: real world data

Such WBPM technologies now permit an exciting new method we define as Continuous Per-Second Ambulatory Blood Pressure Monitoring (CPS-ABPM). The commercially available Circul-VS device system, which includes a BP watch, Circul Pro Ring and Smart Cradle, was deployed to generate CPS-ABPM data. The ring was originally developed as an adjunct to monitoring continuous blood oxygenation (SpO_2) and heart rate (HR) tracking for sleep activity and relies on PPG with an infrared light-emitting diode sensor to continuously measure beat-to-beat BP. The watch is worn on the wrist on the same side as the ring and utilizes a pressure sensor and a bladder as actuator over the underlying radial artery. Both the ring and the watch have received FDA clearance. Together, the Circul-VS devices are designed to harvest and evaluate the extensive continuous per-second measurement data of systolic and diastolic BP, HR, and oxygen saturation for each biometric. A sample graphic summary of 8-plus hours of roughly 30,000 continuous per-second readings is presented in **Figure 2**.

Three important questions that are likely to arise immediately with such a new device are (i) "How is the accuracy of these devices and data externally validated?"; (ii) "How will the patient and clinician interpret this output for the purpose of accurately diagnosing HBP?"; and (iii) "How do we interpret the data output in order to make effective clinical decisions related to safe and effective control of HBP?"

The solutions to Question 1 are being developed in the US and Europe and will not be in scope for this manuscript. However, it is important now to address Questions (ii) and (iii).

The concept of "Time in the Therapeutic Range" (sometimes referred to as "Time in the Target Range" or "TTR") could well serve as a conceptual model for evaluating CPS-ABPM-generated data. TTR is by no means a new concept and has been applied to monitoring continuous glucose monitoring devices for people with diabetes. With respect to HBP, TTR has also been well documented to be of important clinical utility. For example, Systolic Blood Pressure TTR (SBP-TTR) was extensively deployed in the NIH Systolic Blood Pressure Intervention Trial (SPRINT) and found to be useful in predicting and preventing atrial fibrillation, and also associated with better cognitive outcomes in patients with hypertension with a higher SBP-TTR.[31,32] Additional studies have also demonstrated that higher SBP-TTR leads to fewer major adverse kidney and cardiovascular events that are associated with improved cardiovascular outcomes and considered significant determinant of all-cause mortality for patients with hypertension.[33–35] A recent scoping review demonstrated that variations exist in all factors used for the determination of SBP-TTR, including calculation method, BP target range, number of BP measurements, and duration. This heterogeneity can make it difficult to compare SBP-TTR across studies, but nonetheless, the

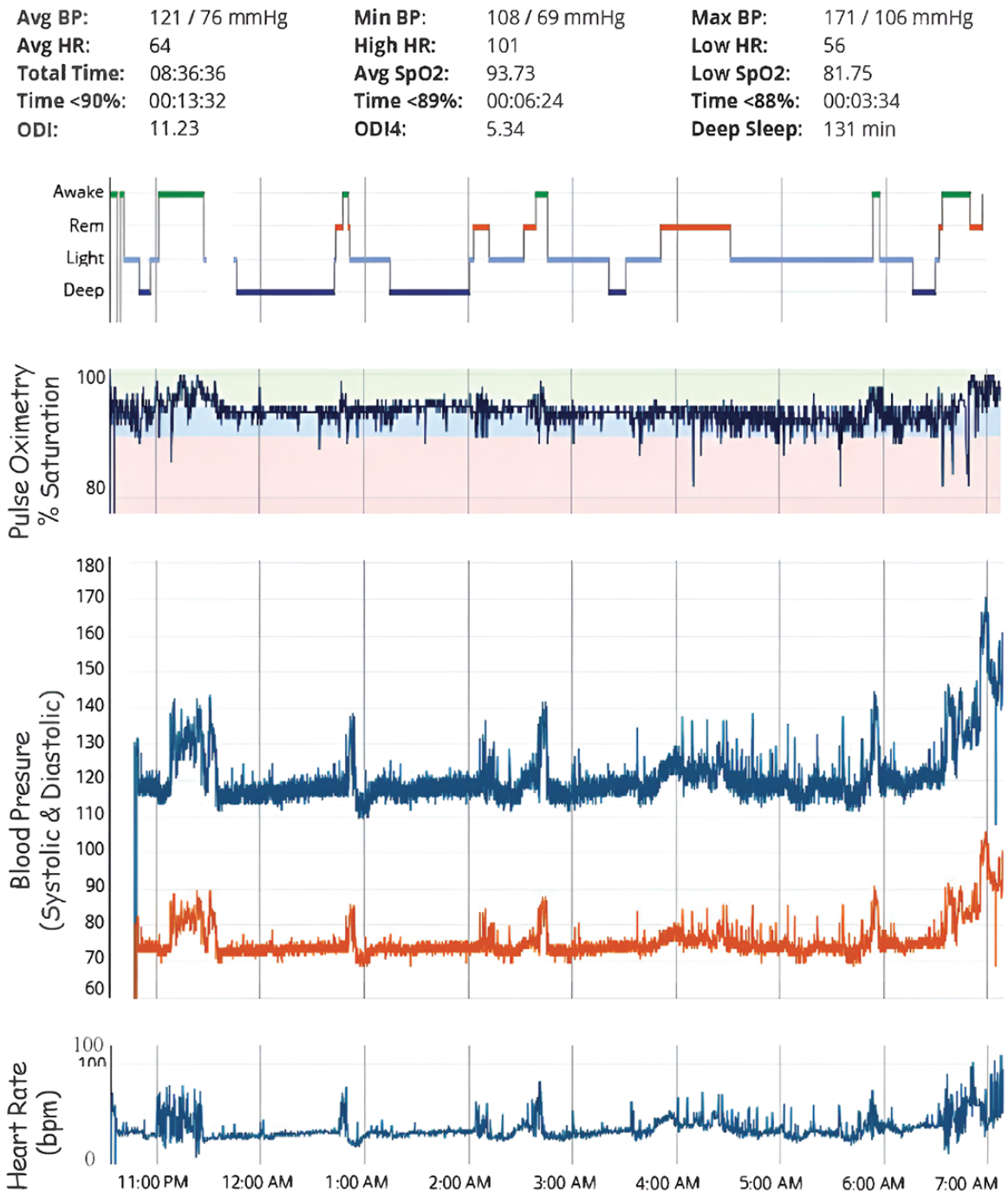

Figure 2. Sample data display for CPS-ABPM from Circul-VS device.

researchers confirmed that higher SBP-TTR was associated with reduced cardiovascular risk.[36]

Despite these limitations, TTR seems particularly appropriate for analysis and classification of CPS-ABPM data using the standard staging definitions in the 2017 American College of Cardiology/American Heart Association (ACC/AHA) BP guideline, as presented in Table 7.

The benefits of a more integrated and comprehensive assessment of CPS-ABPM can be realized by providing more informed diagnostic and treatment decisions when compared to traditional single-point in time OBPM and HBPM assessments. Integrating TTR assessments into the management of HBP can lead to better patient outcomes by ensuring that BP remains within the therapeutic range for a longer duration.[38] This can be achieved through ongoing continuous monitoring and appropriate adjustments to treatment. To illustrate CBPM in use, several case studies are presented.

Interpreting CPS-ABPM data

First, it is important to visualize some real-life data obtained from a willing volunteer in order to demonstrate this powerful feature. CPS-ABPM data were obtained from a single person without HBP (one of the authors) for two nights during sleep and 2 brief daytime episodes via the Circul-VS devices. Continuous per-second BP and HR data ingested and transformed from JSON files using

Table 7. 2017 AHA/ACC BP guideline staging classification for HBP[37,38]

Blood pressure category	SBP mmHg	DBP mmHg
Normal Blood Pressure	Less than 120	Less than 80
Elevated Blood Pressure	120–129	Less than 80
High Blood Pressure Stage 1	130–139	Or 80–89
High Blood Pressure Stage 2	140 or higher	Or 90 and higher
Hypertensive Crisis	Higher than 180	And/or higher than 120

Abbreviations: AHA, American Heart Association; ACC, American College of Cardiology; SBP, systolic blood pressure; DBP, diastolic blood pressure; mmHg, millimeters of mercury.

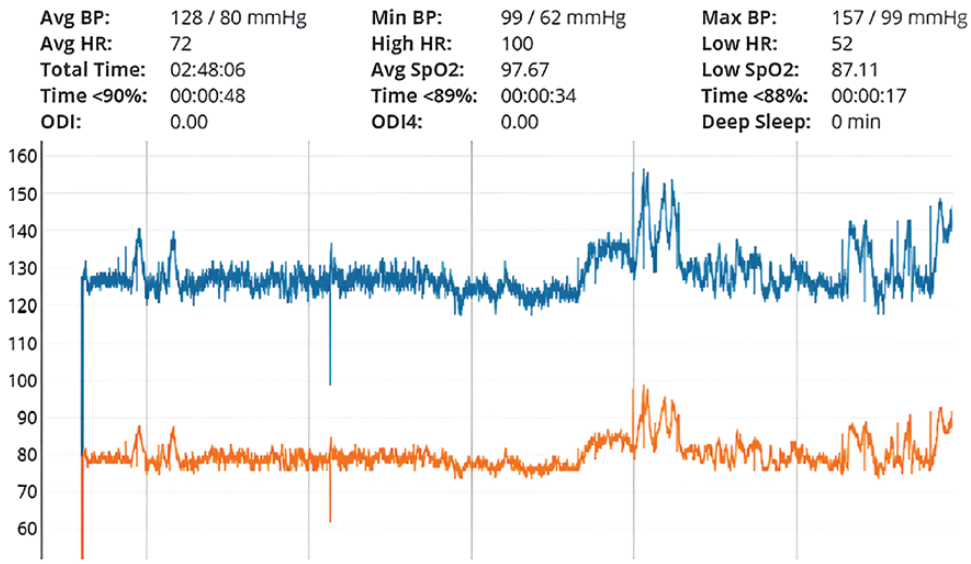

Figure 3. Circul-VS continuous per-second BP measurements 30 December 2024, 2 PM to 5 PM.

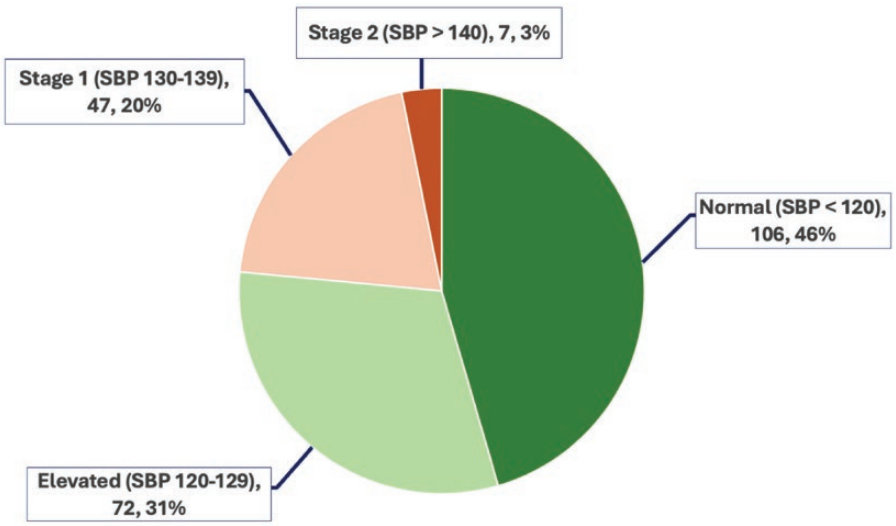

Figure 4. Distribution of ACC/AHA systolic BP stage 30 December 2024, 2 PM to 5 PM.

Python and Jupyter Notebooks, organized into Excel, and further processed for interpretation and analysis. Graphic displays initially created with Microsoft Excel. A more detailed description of the methods applied to collect, structure, and analyze these data are presented in Online Appendix 3

Figure 3 displays one of the standard Circul-VS + data platform displays of daytime of 10,800 continuous, sequential, and dynamic daytime per-second readings obtained over a 3-h period obtained from one of the authors of this manuscript.

The subject reported being seated and working at a desk for the first part of this tracing, followed by some vigorous city walking for much of the latter part, for which there is much more BPV.

Figure 4 then provides a visual summary of the observed ACC/AHA BP staging classification frequencies in accordance with a

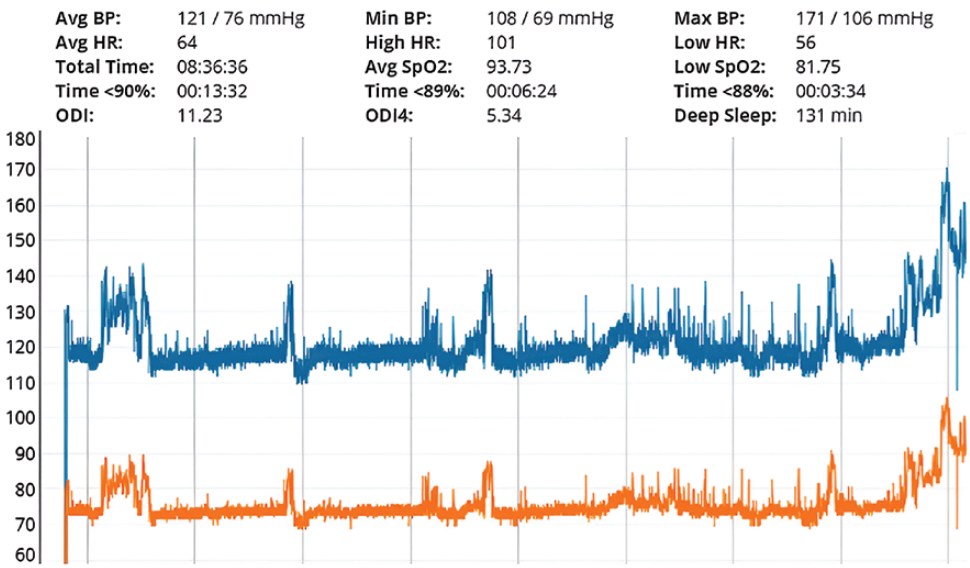

Figure 5. Circul-VS continuous per-second BP measurements 12/1–12/2 11:30 PM to 8 AM.

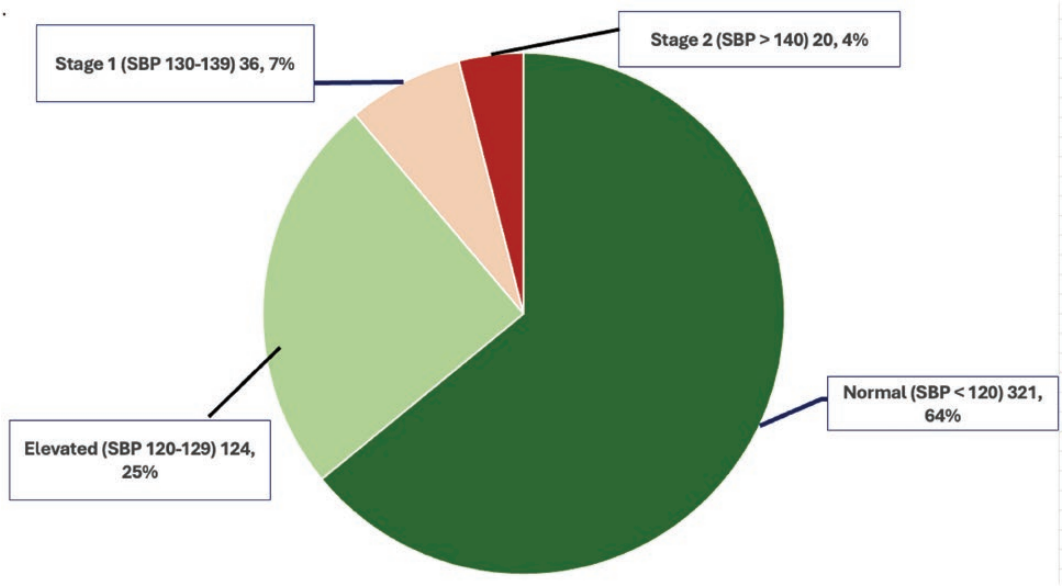

Figure 6. Distribution of per-second systolic BP frequencies for period 12/1–12/2/24 11:30 PM to 8 AM.

TTR of 77% for SBP < 130 and also consistent with the individual's historic trends of HBPM readings using a standardized device listed on Validate BP.

The next scenario was for an 8-h period of sleep, which is similarly displayed in **Figure 5**.

The subject reported that the initial readings were during getting ready and into bed, followed by relatively consistent periods of SBP readings of 120 mm punctuated by some brief spikes associated with nocturnal bathroom visits. BPV then increases for 2 hours, likely associated with REM sleep followed by a "morning surge" at the end of the tracing that included a several-minute ride on an exercise bicycle. **Figure 6** permits a summary visualization of 28,800 readings obtained over 8 h, this time categorized by relative frequencies of readings in 10mm "bins" between 90 and 160 mm as well as < 90 mm and > 160 mm. **Figure 7** does the same, but this time for "per hour" summarization.

Some potential and significant benefits arise from the insights obtained from these two evaluations, which are outlined in **Tables 8** and **9**.

Further illustration with 3 clinical vignettes

Initial development of a variety of hypothetical clinically meaningful use cases for future innovative design and implementation was also undertaken without the use of real CPS-ABPM but with the goal of highlighting 3 additional "Use Case" studies of different imaginary patient clinical vignettes. Case #1 (presented in Figure 8) is of a 67-year-old Female with Type 2 Diabetes, BMI = 32, A1C = 7.5, UACR = 100, LDL-C 90, CAC = 100 and HBP on insulin, ACEi, Thiazide, Statin, and chronic kidney disease (CKD) Stage 2.

This hypothetical patient clearly has a number of chronic illnesses that put her at major risk for future major acute cardiovascular events (MACE) as well as complications from Type 2 Diabetes and early signs of CKD. Assuming that the goal of control of the HBP is a TTR that is mostly within the Normal and Elevated stages, this brief sample of 10,800 CPS-ABPM readings from the Circul-VS device strongly suggests that this patient is far from achieving this goal with a TTR of only 25%. Further analysis as displayed in **Figure 9** provides the following additional valuable information by displaying the distribution of these readings into "bins" of 10 mm SBP that can be easily viewed by both the patient and her clinicians.

This brief sample may suggest a number of findings with potentially serious concerns including the possibility of a secondary cause of HBP as well as possible orthostatic hypotension, perhaps due to antihypertensive medications. This could also be further explored with a chart similar to what has been presented earlier in **Figure 7**, and various measures of BP variability as outlined in **Table 8** might provide additional risk assessment. Table 9 also lists some prognostics for future occurrence of MACE and CKD progression.

Case 2 is of a 35-year-old Male with documented Prediabetes, BMI = 28, A1C = 5.8, UACR = 0, LDL-C 110, on Metformin, PREVENT CKM Stage 0 and a Family History of HBP and CKD. A similar CPS-ABPM profile is presented in **Figure 10** for him:

Here, one might imagine that BP as usually measured a physician's office or at home might yield a reading that would be interpreted as "your BP is fine," or alternatively, that there might be evidence of "White Coat Hypertension." Either way, it will be imperative that he focus intently on implementing guideline-directed lifestyle modifications (GDLMs), all of which will have independent effects on lowering his higher readings and thereby improve his TTR (now only 25%) within the "Normal" Stage.

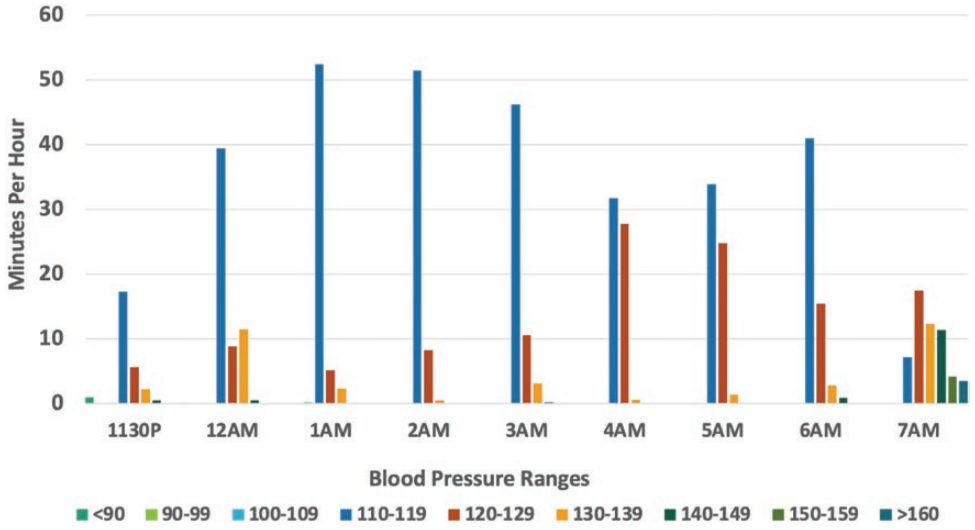

Figure 7. Distribution of systolic BP ranges per hour for period 12/2–12/3/24 11:30 PM to 8 AM.

Table 8. Some potentially useful classifications, time periods, and intervals for CPS-ABPM analysis and display

Common time periods /intervals for CPS-ABPM ACC/AHA High BP Classification Stage Reports:	•Hour, Sleep Time, Wake Time, Day (24-h period), Mult-day period (e.g., week, month) •Normal, Elevated, Stage 1, Stage 2, Severe, Uncontrolled
Time periods/intervals may also be useful for:	•SBP Range Reports (e.g., Intervals of 10 mmHg, less than 90, greater than 160) •Diastolic BP, Mean BP, BP Variability Analyses •Additional wearable device physiologic data such as SpO_2, HR, pulse wave contours
Examples of key analytic functionalities	•Easily compare between time periods (e.g., time of day, day of the week, month, seasonal) •Sample data from any selected time period duration into per-second graphs

Abbreviations: CPS-ABPM, continuous per-second ambulatory blood pressure monitoring; ACC, American College of Cardiology; AHA, American Heart Association; SBP, systolic blood pressure; BP, blood pressure; SpO_2, peripheral oxygen saturation; HR, heart rate.

Table 9. Potential valuable benefits of CPS-ABPM analysis

Improved detection and diagnosis of:	
Periodic hypertension	Secondary hypertension
Orthostatic hypotension	White-coat hypertension
Adequacy of pharmacologic management	Masked hypertension
	Sleep-related hypertension/hypotension
Uncontrolled hypertension	Supine hypertension
Pediatric-aged hypertension	

Abbreviations: CPS-ABPM, continuous per-second ambulatory blood pressure monitoring.

Table 10. Additional potential benefits of CPS-ABPM

Major improvements for patient-centered care such as:
Consistent alignment with Guideline-Directed Medical Therapies
Enhanced Patient and Caregiver empowerment
Reduction of uncertainty and apathy about self-management goals
Closer monitoring for effects of lifestyle modification interventions
Identifying synergies with other ASCVD risk reduction interventions
Facilitation of Precision and Personalized Medicine for Physicians
Facilitation of more effective Shared Decision-Making and Goal setting
New insights and feedback for management of personal stress
Easy customization to help guide a more effective care plan

Abbreviations: CPS-ABPM, continuous per-second ambulatory blood pressure monitoring; ASCVD, atherosclerotic cardiovascular disease.

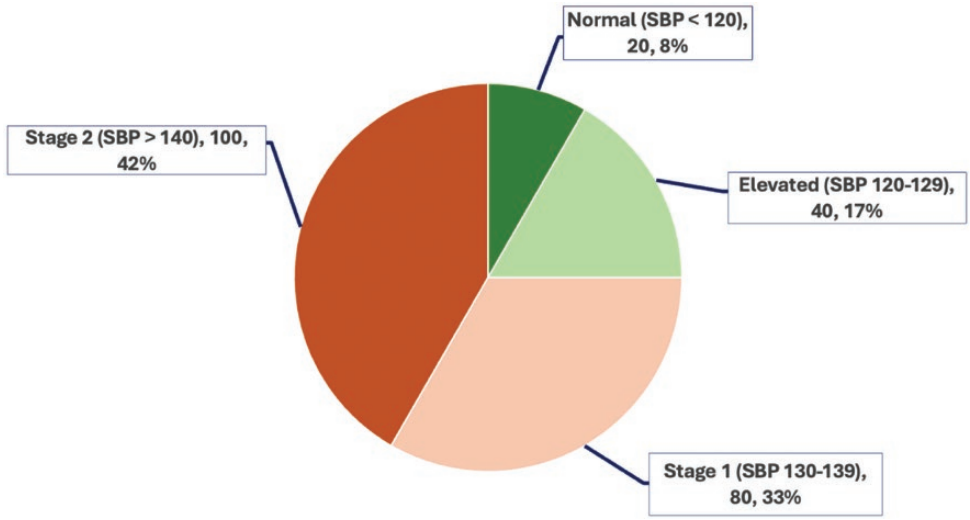

Figure 8. Case Study #1.

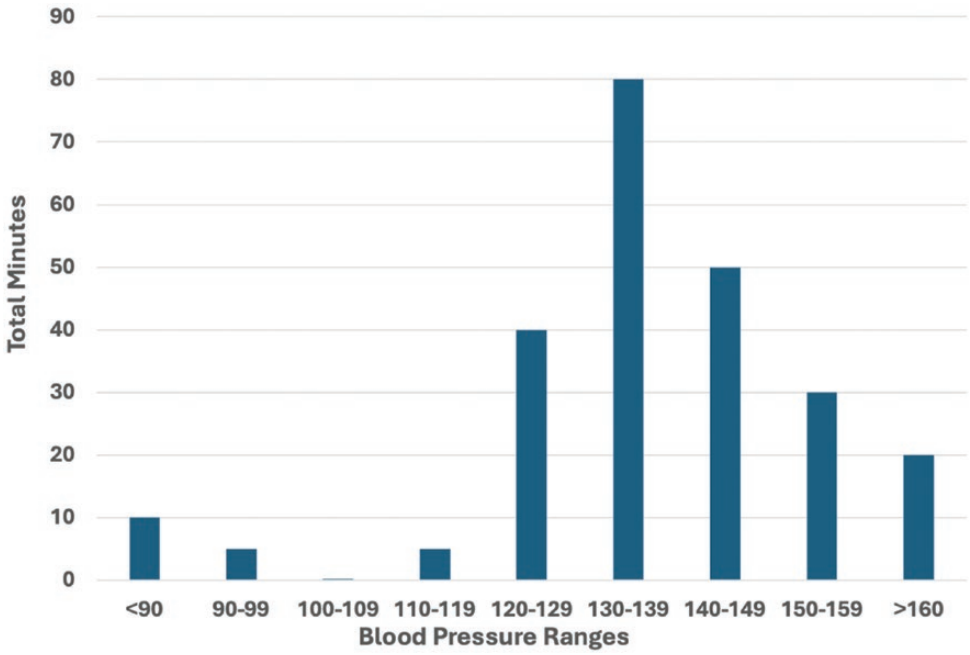

Figure 9. Case 1. Distribution of per-second systolic BP frequencies.

The third case (Figure 11) is of a 13-year-old female whose BMI = 25, and had labs recently done by her pediatrician of A1C = 5.0, UACR = 0, LDL-C 90, no Meds, PREVENT CKM Stage 0 because of a family history of HBP. This young woman also likes

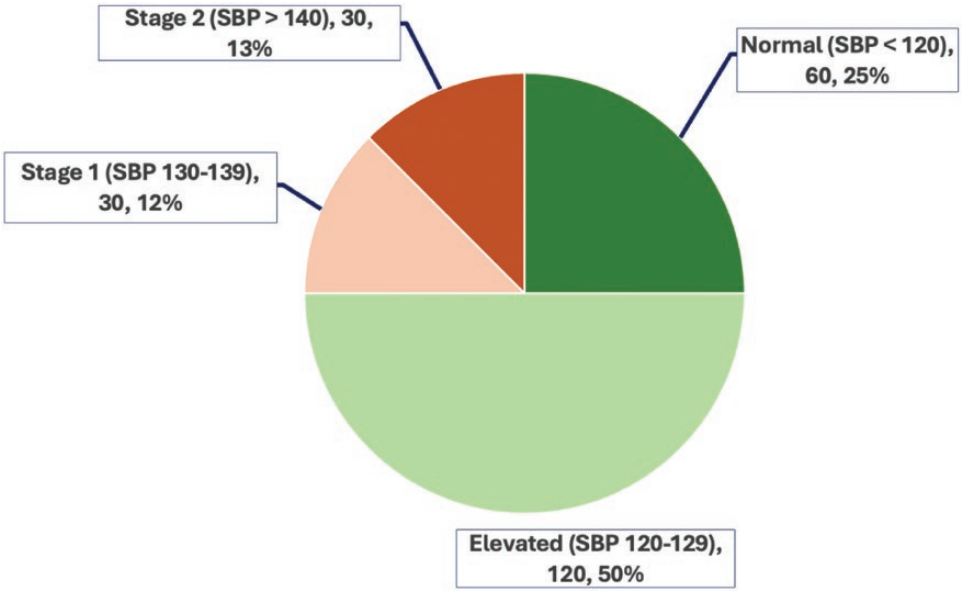

Figure 10. Case 2.

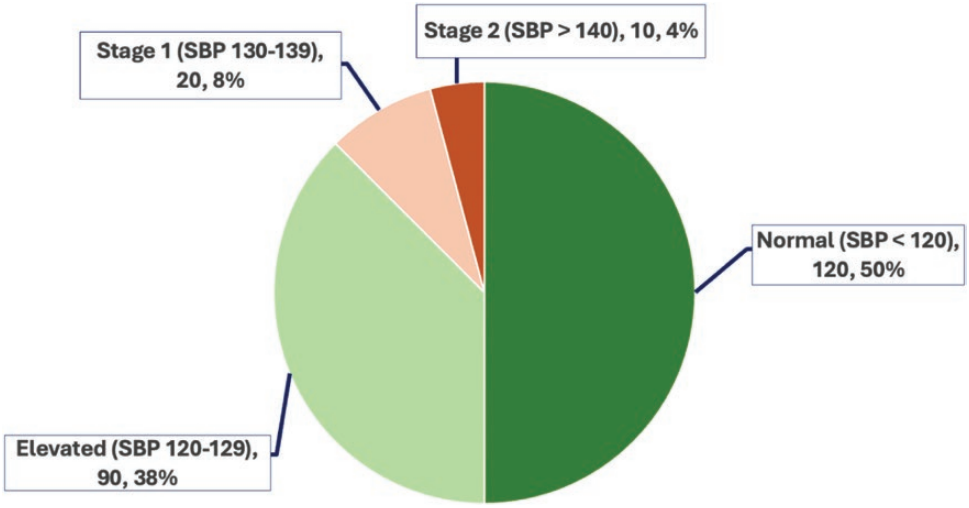

Figure 11. Case 3.

to play video games for several hours a day, especially on the weekends during the winter months (when the following CPS-ABPM data was obtained).

These data reveal some very concerning findings of a TTR of CPS readings that should be consistently below a SBP less than "Normal" (120 mm Hg) for her age, but is only 50%. Her pediatrician recommends further CPS-ABPM while encouraging her to participate in more physical activities, such as after-school sports and also to modify her eating habits by following a low-sodium, high-potassium, and reduced-calorie diet.

These few case studies presented summarize the additional potential benefits of using new and evolving WBPM devices, especially along with efficient, flexible data transfer, analysis and display methods such as are presented in this manuscript.

Summary and conclusions

BP is a continuous biologic variable (like body temperature, HR, blood oxygenation, etc.). Continuous BP measurement can be used to look beyond treating BP as a categorical variable based on OBPM and HBPM small sample of single-point in time BP measurements and help guide ASCVD risk assessment, pharmacologic treatments, and GDLM. Interpretation of BPV is complex and will require sophisticated data science techniques. Combining per-beat BP measurements (e.g., 86,400 measures per day) with additional physiologic data such as pulse wave amplitude, velocity, and contour analysis provides new insights for identifying potential new therapies for reducing modifiable vascular and endothelial dysfunction. Results of pattern analysis and BPV with a CPS-ABPM can potentially strengthen this person-centered approach, given that currently there are no standards that govern the absolutely essential ability for "sense-making." Interpretation of more continuous WBPMs must also be readily and consistently combined with other major ASCVD risk factors, such as those delineated in the Blueprint for Change,[39] to guide effective guideline-directed team-based care based on shared decision-making and identification of actionable adverse social

determinants of health. Some examples are listed further in **Supplementary Appendix 4**.

The pace of availability and expanding variety of WBPM devices is rapidly accelerating internationally. These devices are currently viewed by many clinicians as potentially complementary data when combined with OBPM, HBPM, and ABPM readings. However, WBPM devices are intentionally designed to provide a more patient-centered experience and hence have the near-term potential to replace these current traditional methods. Hence, patients and their clinicians would soon be able to demystify their personal BP measurements and meaningfully correlate with daily and life activities as well as more effectively achieve GDLMs. Clinicians need to be ready and equipped to educate and guide patients on this personalized medical information.

Evidence identified from clinical and prospective studies in support of the clinical accuracy of WBPM devices, as compared to measurements from traditional, standardized methods, would advance the take-up of the devices. Continued application of the time-honored baseline analytic methods and scientifically validated knowledge generated from traditional ABPM methods will help inform a growing variety of physiologically complex issues (e.g. those noted in **Table 8**), such as facilitating a more robust detection and contextual interpretation of circadian and positional BPV. In addition, consistent, evidence-aligned international industry and regulatory standards for these devices remain sorely lacking. Forthcoming evidence-based standards, with robust validation methods that closely align with HBP clinical practice guidelines, will ensure clear and consistent interpretation of aggregate data and provide meaningful guidance for patients, caregivers, and their healthcare teams in achieving improvement in cardiovascular health.

Supplementary material

Supplementary materials are available at *American Journal of Hypertension* (http://ajh.oxfordjournals.org).

Conflict of Interest

The authors declared no conflict of interest.

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