Blood Pressure Beyond the Clinic: Rethinking a Health Metric for Everyone

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ABSTRACT

Blood pressure (BP) is typically captured at irregular intervals, mostly in clinic environments. This approach treats BP as a static snapshot for health classification and largely ignores its value as a continuously fluctuating measure. Recognizing that consumers are increasingly capturing health metrics through wearable devices, we explored BP measurement in relation to everyday living through a two-week field study with 34 adults. Based on questionnaires, measurement logs, and interviews, we examined participants' perceptions and attitudes towards BP variability and their associations of BP with aspects of their lives. We found that participants modified their use of BP devices in response to BP variability, made associations with stress, food, and daily routines, and revealed challenges with the design of current BP devices for personal use. We present design recommendations for BP use in everyday contexts and describe strategies for re-framing BP capture and reporting.

Author Keywords

Personal informatics; blood pressure; self-monitoring.

ACM Classification Keywords

J.3. Life and medical sciences: Health.

INTRODUCTION

Blood pressure (BP) is an important and widely used indicator for assessing cardiovascular health. One in five hypertensive individuals are not even aware they have high BP and overall public understanding of BP is poor [3,11]. Young adults in particular are less likely to be aware of their blood pressure. However, recent longitudinal studies have shown that capturing blood pressure at an earlier age and evaluating it over a lifetime provides valuable data for understanding and predicting cardiovascular risk [1].

Limited awareness and understanding of blood pressure is due in part to the fact that BP measurement is typically situated in the clinic. However, metrics typically captured in this context or through cumbersome devices are becoming more accessible to consumers through noninvasive, wearable sensors designed to support personal monitoring. The success of consumer devices like the Fitbit demonstrates deep interest in leveraging sensor data to learn about, reflect upon, and inform lifestyle choices. In particular, the ubiquitous nature of these sensors creates a shift from ad hoc measurement towards continuous capture within the context of normal daily activities. For a health indicator like blood pressure, continued advancement of tools such as wrist-worn, cuffless, continuous BP monitors [22] suggest a future in which cardiovascular metrics are captured as easily as the activity data dominating the current wearable technology market.

For this study, we explore the concept of ubiquitous health sensing in relation to BP monitoring by evaluating how people use and relate to their BP measurements outside of a typical medical context. To explore this potential future state for personal health sensing, we first describe related work on home BP measurement, its relationship to personal health informatics, and challenges with communicating measurement uncertainty. Second, we describe our study design and descriptive findings. Third, we outline the themes elicited from questionnaires, participants' BP logs, and semi-structured interviews conducted with each study participant. We conclude with a discussion of design opportunities to enhance the experience of BP measurement for personal health and well-being.

Based on participants' experiences, we provide three main contributions in this paper: (1) we improve understanding of a healthy population's attitudes and motivations toward BP variability and monitoring, (2) we identify aspects of everyday living that people associate with their BP measurement, and (3) we recommend design strategies to make this metric intelligible and relevant for personal monitoring.

BACKGROUND AND RELATED WORK

Fundamentals of BP and BP variability

A BP measurement is a snapshot of the force of blood pressing on the arteries as the pressure rises and falls with each heartbeat. BP is measured in units of millimeters of mercury (mmHg), typically using an inflatable cuff that exerts pressure on the outside of a part of the body to obtain the arterial pressure. Optimal BP is clinically defined as less

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than 120/80 mmHg, where the upper value is systolic pressure (SBP) and the lower value is diastolic pressure (DBP).

BP is frequently discussed as a static snapshot of SBP and DBP, however it is a dynamic process with natural fluctuations over the course of days, weeks, and months. People usually experience changes throughout the day such as a nighttime dip in pressure in accordance with one's circadian rhythm [14]. Systolic BP typically varies by approximately 10-15 mmHg during the daytime and 5-10 mmHg at night [27]. BP can also fluctuate dramatically due to short-term influences that affect cardiac output and vascular resistance. Caffeine significantly increases SBP by 5-10 mmHg and psychological stress and physical exertion can cause an increase of 20-60 mmHg [16,21,27]. Sleeping, eating, and a variety of other activities are also correlated with dynamic changes in BP yet occur sporadically, making the changes difficult to identify without continuous monitoring [27].

Value of BP measurement outside the clinic

These short-term fluctuations in BP are important because significant variation may cause subtle arterial damage that raises average BP over long periods [20]. However, clinic-based measurement, considered the standard for BP classification, is how most people assess their BP. The clinic setting may not be optimal due to limitations in its capacity to accurately measure BP in certain contexts [26] and the fact that 15% of adults do not visit their providers annually [23]. Instead, studies show that BP monitoring at home is better at predicting cardiovascular risk than measurements in the clinic [19,24]. Though automated ambulatory monitoring is becoming more widespread, it is cost-prohibitive, requires clinical guidance, and necessitates wearing a cuff that auto-inflates every 30-60 minutes for at least 24 hours.

As a result, home BP devices have become a preferred alternative for BP assessment. Yet home devices are still designed based on clinical needs and not with personal use in mind. In a study focused on elderly adults, researchers described usability challenges with patients reliably measuring their BP, interpreting the results, and integrating measurement into daily routines [12]. Despite these challenges, home monitoring has the potential to positively influence quality of life and empower individuals when it is integrated successfully into everyday living [5].

Growth of personal health monitoring

Challenges with user-device interaction for health monitoring are not limited to elderly or at-risk populations despite the research emphasis on these groups. Increasingly cheap sensors have encouraged rapid growth in the personal health sensing market in the US [9]. Tracking health metrics enables people to learn more about their specific context and motivate lifestyle changes. Li et al. described how collecting behavioral information along with physiological metrics helps foster insight and promote positive behavior [17]. Choe and colleagues build on this work, noting a strong interest in health metrics among self-trackers, but highlighting breakdowns that may inhibit tracking behavior [4]. Other research highlights how perceptions of personal monitoring devices for general living, wellness, or illness affect how people use them in the home [13]. Epstein et al. identified how various data representations supported users to make discoveries about their behavior and identify opportunities for change [8]. These conclusions align with the observations of Bentley et al. regarding the importance of promoting self-reflection and linking multiple streams of data to promote meaningful personal monitoring [2]. As BP becomes easier to capture, it can serve as a key metric supporting lifestyle monitoring and personal health.

Measurement uncertainty with BP devices

BP measurement also introduces variability due to signal noise and lenient validation protocols. Devices that meet current validation criteria may still be inaccurate by more than 5 mmHg in a given measurement for more than half of users [10]. This level of error introduces challenges to interpreting singular snapshots of BP and can lead someone to classify their blood pressure and health risk incorrectly.

How users understand and accept this type of variability reflects a common challenge with sensing tools that must provide reliable feedback despite measurement uncertainty. Lim and Dey introduce the concept of intelligibility to describe how well context-aware systems communicate reasoning or uncertainty [18]. In the health domain, Kay et al. explored the intelligibility of scales in communicating weight fluctuations. Importantly, Kay et al. found that a person's understanding of weight fluctuation was associated with their trust in the scales' capabilities [15]. Similar to scales, displaying BP as a static snapshot without communicating measurement uncertainty may impact user perception of BP devices over time.

Based on this related work, we assert there is an opportunity to reframe BP for a broader audience, motivated by personal monitoring outside of the clinic. Brief, infrequent clinic visits limit the ability of providers to assess short-term changes in BP or to account for in-clinic measurement variation. Individual use of BP devices outside the clinic more accurately encapsulates BP as dynamic variable, however, the way users respond to this variability is poorly understood. Moreover, BP's sensitivity to environmental variables shows promise as a metric for self-tracking and linking with aspects of daily living. Our study illuminates the value and challenges of BP capture for personal informatics use among a population not familiar with BP monitoring.

STUDY OVERVIEW

Participants

Since monitoring has been studied extensively in populations with high BP, we excluded persons who were actively taking BP medication or had been diagnosed with hypertension or other cardiovascular diseases. This increased the likelihood that our participants had limited experience with

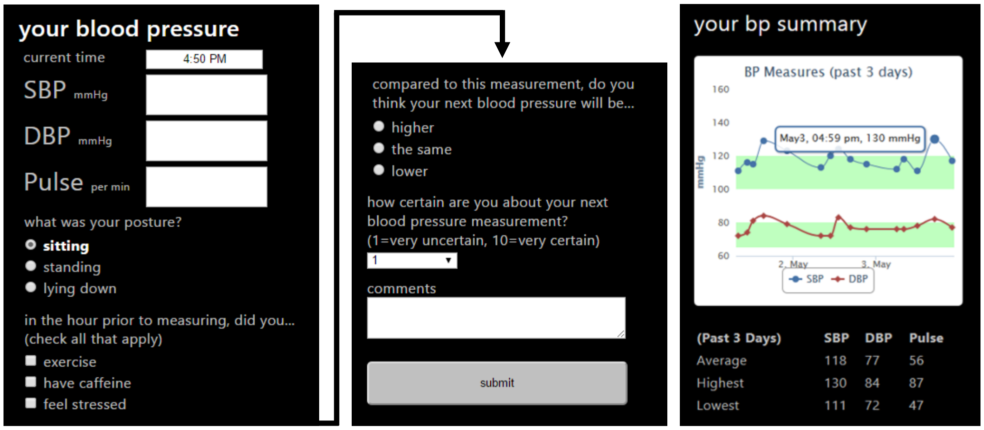

Figure 1. Screenshot of a mobile web app used by participants to collect each blood pressure measurement. For the second week of the study period, participants could see a 72 hour visual summary of their BP data.

monitoring their BP. We also required that participants own a smartphone or tablet so that they could use our web-based logging tool (Figure 1) regardless of their location.

Using purposeful sampling based on age and gender to ensure representation from an adult population, we recruited participants from a large volunteer database. Thirty-four (17 female) persons, aged 23 to 53 (mean=36.6, SD=7.8), participated in the study. All participants had some college-level education, with 27 holding a college degree or higher. Participants indicated a high level of physical activity, with 79% reporting exercising outside of work on a daily basis. Also, 68% of participants stated that they had previously measured their BP outside of a clinic, such as at a pharmacy kiosk or at home with a personal BP device.

Study protocol and analysis

At the beginning and end of the study, participants completed a questionnaire covering demographic details and knowledge, beliefs, and attitudes about BP. For evaluations of changes in responses pre- and post-study, we used paired Wilcoxon Signed-Rank tests. We also collected and summarized a brief follow-up survey distributed 60 days after the end of the study. Each participant received a gratuity and kept their BP cuff after finishing the study. To encourage adherence to our protocol, participants who averaged at least four recordings daily received an extra gratuity.

At baseline, participants received a MicroLife BP3MC1-PC portable upper-arm BP monitoring cuff that has been validated for clinic and home use [7]. The investigators also reviewed standard protocol for BP measurement with each person and had them take their baseline BP reading. Participants then measured their BP daily at five points spread throughout the day for 14 days. This served as an experimental surrogate for a future of more continuous, cuffless measurement for which technology is already emerging. Our study design differs from clinic-defined home protocols to give participants the opportunity to see their BP as a continuously fluctuating variable and not just a means for diagnosis and monitoring. All participants opted in to receive text and/or email reminders sent periodically during the day to support adherence. After each measurement, participants completed a mini-questionnaire delivered through a web-based app that assessed contextual data known to influence BP—caffeine intake, stress, or exercise—based on activities in the hour preceding the BP recording (Figure 1). The questionnaire also provided space for participants to comment on each measurement. For the final week, participants were given access to a 72-hour visual summary of their BP trends and a table summary of their average, highest, and lowest values for SBP, DBP, and pulse.

n=2,181	Mean	Median	Min	Max	SD
SBP	127	126	90	170	13.1
DBP	81	80	42	145	10.2
Pulse	74	72	28	145	15.5

Table 1. Descriptive summary of BP measurements recorded by participants during the 14 day study period.

Summarized in Table 1, over the course of the study period, participants recorded 2,181 BP measurements (mean 4.6 per day per participant) and entered brief structured information about each measurement. Figure 2 shows the distribution of measurements by time of day with peaks at 8am, 12pm, and 9pm. Across the BP recordings, 84% were measured while sitting, 11% standing, and 5% while lying

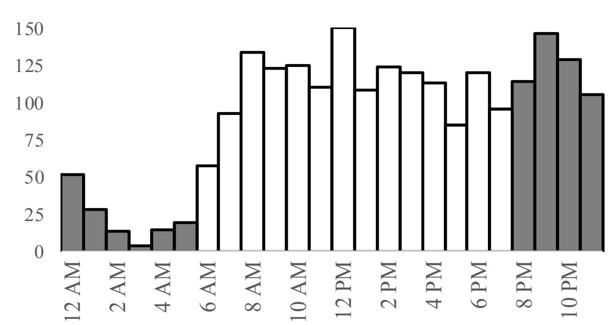

Figure 2. Overview of the number participant recordings by time of day. Evening hours are shaded in gray.

down. For more than half of the entries (56%), participants made brief, open-ended notes about the measurement they had just taken. The three authors independently coded a subset of the participants' logs entries to identify common themes that were then used to code all of the entries.

At days 7 and 14, we conducted a semi-structured interview with each participant during which we provided them with a summary of their BP log and reviewed the data with them. We conducted 68 interview sessions totaling 45 hours. Each session averaged 40 minutes (range: 26–61 min) and focused on the participant's recent experiences with using the BP device. All interviews were transcribed and reviewed for preliminary themes. The authors organized the emerging concepts into an affinity diagram to help identify higher-level concepts and relationships among terms. They iterated on codes through several rounds in order to focus in on the core themes used for this article. One author used these themes to analyze each interview using Atlas.ti 7. Finally, the remaining authors each coded a subset of the interviews to validate the themes and ensure reliability.

RESULTS

Based on interviews, BP logs, and questionnaires, we review participants' attitudes toward their use of BP devices in terms of accuracy, relevance to daily living, and impact on their sense of well-being. We also highlight challenges this cohort associated with using a BP device every day.

Participant response to BP variability

Prior research has established measure-to-measure variation at clinics between 10 and 20 mmHg [27]. Our analysis of participant recordings that were measured while sitting showed within-person variation of ±5 to ±15 SBP during the study (Figure 3). We found that participants were very sensitive to the variation that they experienced over the study period and demonstrated a variety of behaviors and strategies when they noticed deviations from their usual BP.

Evaluating measurement accuracy and consistency

Measurement variability, whether from the device or a natural change, challenged participants' level of trust in a given measure. When the device reported a value outside of an expected range, participants would take extra steps such as taking repeat measures to evaluate its accuracy. If the results appeared consistent over time, they seemed reassured:

> *"I wouldn't bet on those numbers with my life, but I would say that they are within a range that works, because I can literally sit down and sometimes I do just take my blood pressure three times in a row just to see how accurate it is. And the numbers will fluctuate plus or minus 5 to 10 on the blood pressure [device]." (P18)*

Recognizing consistency in the measurements was an important consideration for many of the participants. They mentioned challenging settings such as being on a boat or in a car where they questioned the numbers because, "*taking it in places with me in different variables and environments and stuff, I feel like you have to kind of baby it or it's going to give you some crazy reading" (P27).* However, finding a comfortable location and the appropriate amount of time to sit down and take the measurement was often a challenge.

Comparing to other sources

In the interviews, participants often compared the study-provided BP device with other sources of BP measurement. They visited their primary care clinic to compare with their doctor, went to pharmacy kiosk machines, and also tested their device relative to other BP devices that family members or friends owned. One person (P14) seemed satisfied with the device used in the study, *"because one of the days I actually went to the doctor and it was only like—the number is only like one or two different."*

Within the questionnaire, participants indicated what sources of BP measurement they trusted the most. Methods that involved multiple measurements were ranked highest. Although the overall order of rankings across participants did not change over the study period, more participants

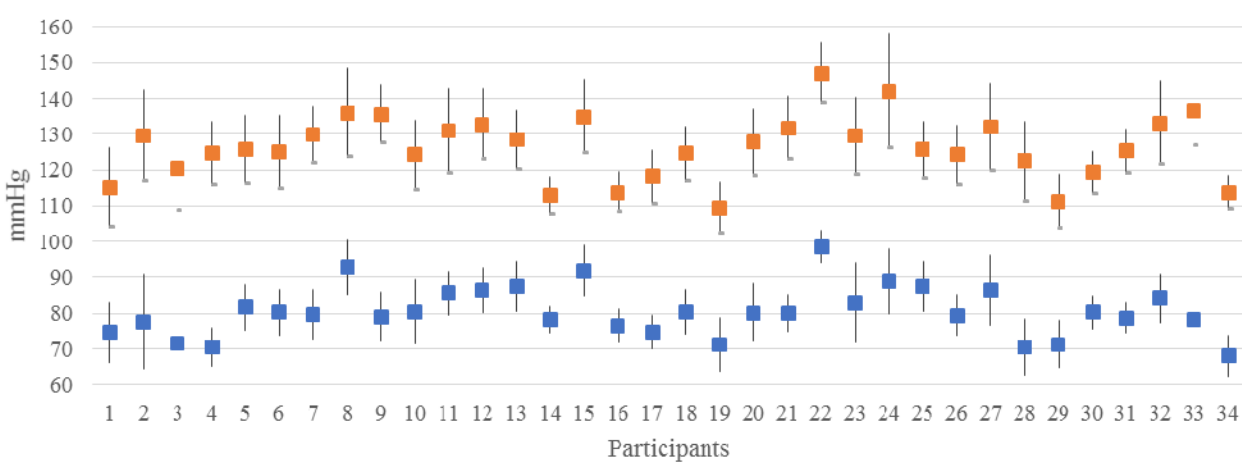

Figure 3. Overview of within-person variation between participants. The top (orange) indicates the average and range for each participant's SBP, the bottom (blue) for each person's DBP. Overall within-person variation ranged from ±5 to ±15 SBP.

gave a lower ranking to single-point measurements at the end of the study (one-tail, $p<0.025$ after Bonferroni correction). This suggests that our study cohort placed greater value on having multiple measurement points to assess BP versus casual, ad hoc approaches (Table 2).

Using heart rate to gauge validity

In the interviews, participants commented that they paid attention to specific values within a given BP reading, especially heart rate, as a way of deciding if the measurement seemed reasonable or not. When this relationship broke down, participants expressed greater doubt in the measurement. P34 had a normal BP reading but was skeptical because of what seemed like an inaccurate hear rate. "*I don't know why my heart rate was so elevated. I wasn't doing anything, I felt fine but that's what I read on the machine. I don't know. Maybe it's accurate, maybe it wasn't" (P34)*.

Understanding counter-intuitive fluctuations in BP

The variability that participants experienced occasionally ran counter to their expectations in relation to level of activity during the day. Participants expected their BP to be lower in the mornings as, *"that's going to probably be my most relaxed part of the day" (P16)*. In contrast, the afternoons are when, *"you would expect it to be a little higher because that's the more 'active" portion of the day" (P30)*. Participants intuitively expected their BP to be low at times when they felt relaxed or when they had not recently been active, such as after sleeping. Similarly, they believed that the greater amount of activity during the day or immediately after exercising would lead to higher measurement values.

In the questionnaire, 47% of participants both pre- and post-study selected the afternoon (defined as 2-5pm) as the highest BP point of the day. Moreover, there was an increase from 18% to 38% of participants that selected the morning as the lowest BP point of the day. Their intuition seemed to influence their expectations for BP despite a lack of evidence in the recordings or in the literature supporting this. Within a typical sleep-wake cycle there are natural oscillations in BP levels—a rise in BP that begins before waking, peak BP in the late morning, and a drop in the early afternoon [14]. P08 was also surprised by this trend at first, but then she recalled an article about women who have heart attacks in the morning because *"it has something to do with something rising in their bodies.*" She was able to adjust her expectations with greater understanding of BP variability.

Adjusting behavior to achieve desired BP

Participants also described how they learned over the course of the study factors that might influence their BP level and then altered their behavior to achieve a desired BP target. P09 explained, *"I would know that from what I had been looking at, that my pressure would be jacked up at certain times,"* so he avoided caffeine and took his BP at times when he thought it would be lowest, *"because I want to see my overall average go down"*. P09 framed his BP monitoring as a competition that he wanted to win. Other participants used their observations of BP variability and avoided stressful settings that they linked to elevated pressure, reduced their caffeine intake, and made other changes to their behavior to affect measurements.

Measure	Rank
Measured continuously by a cannula (small tube) that is inserted into an artery in the body.	1
Average of measurements automatically recorded every hour for 24 hours by an auto-inflating device.	2
Average of self-measurements taken at home 3 times a day for 3 days using an automated BP cuff.	3
Measured once by a doctor using a manually inflated cuff with a stethoscope.	4
Measured once by a nurse using an automated blood pressure cuff.	5
Self-measured once at home using an automated blood pressure cuff.	6
Measured once at a kiosk machine with auto-inflating cuff commonly found in drug stores.	7

Table 2. Participant ranking of the most trustworthy sources for measuring blood pressure at baseline. Order did not change when re-evaluated at the end of the study.

Correlating BP with daily living

Using structured fields in the web application, we asked participants to mark if they exercised, felt stressed, or drank caffeine in the hour prior to each measurement. At least 1 out of 8 recordings was linked to one of these three variables (Table 3). In the free-text log notes, participants made connections with other aspects of their lives including emotion, food intake, and physical state. These same themes appeared throughout the interviews as well, suggesting a desire to relate daily activities with their BP levels.

	Descriptor	Count	%
Structured from web app Total log entries=2,181	Caffeine	353	16
	Stress	291	13
	Exercise	279	13
Author coded from participant comments in web app Total comments=1,225	Context: activities	549	45
	Context: part of day	340	28
	Context: location	99	8
	Intake (food, drink)	209	17
	Commentary on BP	180	15
	Emotional State	106	9
	Physical State	72	6

Table 3. Participant descriptors for BP measurements. Caffeine, Stress, and Exercise were structured options; other themes were coded from comments in log entries, where there were multiple descriptors possible for a given entry.

BP's relationship to patterns of everyday living

The most common annotation (45% of all comments) from participants was to provide context about a recent or upcoming activity, the part of the day (e.g. bedtime), and their location when they captured their BP. Participants reported taking measurements in a wide variety of settings outside the home including in vehicles and in public spaces. However, having a routine setting, "*was probably the most relevant to me because it was the most controlled environment. Same time of the day, I'm doing the same type of work. I'm interacting with the same type of people... It's so more relevant to me to see during that time because I think more factors are controlled" (P07).* Participants described work and home as stable places through which to capture a meaningful set of measurements. Participants also explained how a change in pattern, *"shows that our weekends are totally different than the weekdays. I guess keeping that in mind, I'm not too surprised but it is surprising that the blood pressure is so sensitive to I guess routine versus whatever ad hoc thing we're doing" (P01)*. Throughout the logs and interviews, participants stated that their BP data heavily reflected their recent activities and routines.

BP's relationship to food and drink

Food and meals were an important contextual factor that participants associated with BP, despite the fact that there is no clear evidence supporting this type of acute effect. Beyond having caffeine, 17% of the notes included comments about other forms of consumption, including recent meals, alcohol, and cigarettes. Further reflecting this belief, participants responded in the questionnaire about whether different scenarios would lead to an acute increase, decrease, or no change in an average person's BP. More than 75% of participants at baseline and 85% post-study believed a high-sodium meal would increase BP. Though popular discussion about the link between sodium and heart disease is a possible reason for participants' focus on meals, they felt it added relevance and meaning to highlight instances where they either consumed food or drink or had missed a meal.

BP's relationship to emotional and physical states

In the interviews, participants rationalized a given BP reading based on whether they were feeling stressed, anxious, or unwell at the time. P13 mentioned how, *"Stress is a big thing and I know that that definitely raises blood pressure because when I feel stressed and I take it, it's up."* Participants marked 13% of their entries as feeling stressed. In addition, noting physical states, such as feeling tired or unwell, was another way for participants to give more context to BP readings. Ultimately, our study cohort expressed how a given BP value helped them realize how their emotional or physical state was affecting them. Seeing their BP measurement brought attention to, *"my surroundings, my intake, my stress intake and wanting to know more about that and what the triggers are, and how to stop those" (P27).* Monitoring provided a reflection of their current state and validated periods where they felt stress or excitement.

Hypotheses and experiments to understand BP

The process of incorporating more contextual data alongside the BP measurements helped participants to triangulate possible causes for the fluctuations. Fifteen percent of the log entries included comments about participants' reactions to a particular reading where they often provided explanations for why they recorded a particular BP value. After getting an unusual reading, P33 explained, *"I am wondering if it was the shirt fabric I had on. I will experiment with that tomorrow."* In response to confusion or questions about a given reading, participants began to hypothesize and test out how their BP behaved in relation to a certain activity or aspect of their lives. P27, for example, expressed a desire to set up an experiment where, *"One day for lunch, I would eat a whole bunch of pizza and take it and the next I would eat salad, and see if that was different, and it would make you feel good if you could see a big change in it."* Participants would take their BP before and after climbing stairs, after coming out of a meeting, or in other contexts to see how the activities affected their BP.

Impact on Perceptions of Well-being

BP is a widely used health indicator for clinic diagnosis and treatment. Accordingly, participants framed their experience of measuring BP in relation to health and well-being.

Classifying blood pressure risk

Although participants had heard of hypertension, pre-hypertension, and normal BP prior to this study, most were not able to correctly identify the corresponding numerical thresholds of these categories when asked in the questionnaire. At baseline, 35% and 26% of participants selected the correct thresholds of hypertension and normal BP respectively. We observed an increase to 44% correctly answered for hypertension ($p=0.366$) and 53% correctly answered for normal BP ($p=0.020$) by the end of the study.

We also asked participants to self-describe their BP as normal, pre-hypertensive, or hypertensive (Figure 4). Prior to the study almost all participants (91%) self-identified as having normal BP and only one participant stated they were pre-hypertensive. However, after the study, 24% and 6% classified themselves as pre-hypertensive and hypertensive, respectively ($p=0.003$). This change is corroborated by the calculated average of all sitting measurements that participants recorded in their BP logs. Using clinic-based thresholds for classification, 62% had normal BP and 38% were

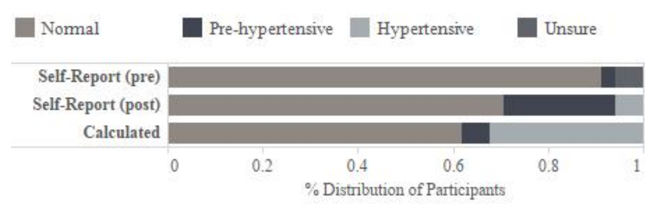

Figure 4. Participants' self-reported classification as either normal, pre-hypertensive, or hypertensive (pre/post), and calculated classification of measurements taken while sitting.

pre-hypertensive or hypertensive. The reason for this change pre- to post-study is unclear, but factors such as enhanced knowledge of BP definitions, greater awareness of their typical BP, or possibly increased anxiety from the readings could have affected participants' classification.

Defining BP beyond "clinical" normal

The change in how participants perceived their BP-related risk reflects a larger interest among participants in understanding how their BP compared to others. During the interviews, participants made comparisons to friends, family, or other groups. They expressed a desire to know, *"is what I'm seeing typical from other people? That was what I'm just trying to figure out" (P30).* How participants defined normal varied. Some simply wanted to know whether they were "healthy". However, many wanted to compare their measurements to individuals that were in a similar age group, the same gender, and a similar lifestyle in terms of physical activity, smoking, and diet. This discussion also led several of the participants to hypothesize that comparisons to others that are younger or healthier might be an effective way to stay motivated around health goals:

> *"So I would like to see not only for my age group because I think the medical community tends to have lower expectations as we age…I want to compare to younger people not—it's the whole thing why people think, 'Oh, we're older so it's okay to have 25 lbs. on.' No it's not." (P08)*

Challenges to BP use in everyday contexts

Prior work has revealed measurement and interpretation challenges with using BP devices [12,13], however, participants in this study also discussed the emotional impact of measurement, concerns about the stigma of using a BP device, and their interest in continuing to measure their BP.

Emotional impact and reactions to BP readings

When the participants measured their BP, the health implications associated with blood pressure would create strong positive and negative emotional reactions. As P27 explains, *"I think subconsciously even looking at it, I would get a little stressed or kind of little anxious because I would be scared it would be really high again."* P10 commented how the process of the cuff inflating was "anxiety-inducing" as it cut off circulation in his arm. Feelings of apprehension about future measurements or the discomfort of using the device put off some participants. Others that had an atypical measurement described feeling panicked and obsessed, taking repeated measurements well beyond the 5 requested per day in order to make sure the readings were correct.

Conversely, participants had positive reactions to their data when they focused less on individual readings. For example, after seeing a graphic visual of his data, P10 explained that, *"Once I thought I was in the norm I was like, 'Yeah, I'm good, nothing to worry about,' and then I just go on with my life."* Another participant actually felt more secure over time while taking measurements at home because, *"You get like an emotional attachment to the thing… it's a little buddy because it's with you and so it feels like it's protecting you, that might sound so funny" (P09)*. Participants' framing and association with the BP data and devices influenced their emotional experience.

Associations of BP with illness

Framing is important, as participants described challenges with using the device in an open setting. They felt uncomfortable with how others would perceive them and were concerned about how the device attracted attention and was disruptive to others. Participants described instances where co-workers, friends, or family expressed concern or asked if they were unwell because they were capturing their BP.

> *"This isn't exactly a device that you go for and buy it—you relate this to sickness. So you try to avoid those devices…The design, it does not attract me and it's an aisle that I just try to avoid. It's something with health issues…You never relate this design to I just want to be healthy and I want to keep it there. Versus the [fitness] watch, when I keep it there, I want to be healthy and I want to track it. The design helps to inspire you." (P26)*

P26's experience reflects a current challenge with existing perceptions of BP. The stigma of its association with having a disease or being unwell was a concern across participants.

Continued use of BP device

During the interviews, participants commented on their motivation to continue using the device after the study ended. Regularly monitoring BP helped some to *"understand the readings better. That it does fluctuate. And one reading at the doctor once a year is not going to tell the whole story. Which I thought it did. I really thought that's all you needed" (P31).* Not everyone identified immediate value from using the BP device, however. P10 expressed a desire for additional context to add value or significance to the BP results. He preferred that, *"if the program could be designed that was like—you just had this amount of calories or this kind of food and you'll see this bump in your blood pressure. Yeah, maybe I would be more intrigued to keep up with that kind of data and learn."*

At the study end, seventeen participants stated that they would continue to measure their BP at least once per day. Another thirteen mentioned an interest in capturing their BP periodically, such as, *"one to two times a month just to see. That's about it. And I think that would be sufficient just to kind of—and I would do my three [measurements]—get my average because I think that that's important" (P34).* Four mentioned they were unlikely to continue measuring it regularly, *"because I know I'm more or less in the healthy range—I mean yes I do go into the 120's, but whatever—so I wasn't as concerned about it" (P30).*

We also followed up with participants 60 days after the study to assess their continued use. Twenty-six (76%) of the participants responded. Even though several people continued to measure their BP at least once a week, most respondents reported less frequent measurement than during their final interview (Table 4).

DISCUSSION

Based on the experiences of our participants, there is an opportunity for redesigning future BP devices for a general audience that addresses issues of stigma, measurement variability, and the lack of meaningful, actionable, feedback with current devices. The themes discussed in the previous section are especially relevant as we shift from ad hoc BP measurements in the clinic to more frequent measurement at home by consumers seeking to track and understand general well-being based on their data. Our participant experiences demonstrated that a BP value means little in isolation.

For our participants with limited knowledge of BP, the variation that they experienced influenced their attitudes and understanding of blood pressure. In some cases their intuition of BP during the mornings or after exercise broke down. In other cases, participants associated BP with moments of stress or factors related to their environment. Increased interaction with their BP led many participants to alter their behavior, experiment with how their BP responded to stimuli, and reflected a desire for greater knowledge of how BP links with different aspects of their lives.

Importantly, measuring BP and experiencing variation had an emotional impact on many participants. Observing unusual values caused confusion, frustration, and anxiety that influenced their interest in using the BP device. They discussed their use in terms of normative social influences that aligns with the findings in the autoethnography reported by O'Kane et al. [25]. Participants expressed a desire to situate their BP relative to others—to motivate change or establish a sense of what is normal BP and normal variation. However, some participants started to measure their BP well beyond the study requirements after becoming concerned with a particular elevated reading. This contributed to feelings of stress and may have led to even more elevated readings. Because measuring BP has such strong connotations with illness, devices designed for personal use should consider how this metric will be accepted and interpreted—both positively and negatively—as it becomes more pervasive.

Envisioning future BP devices for personal use

Many participants expressed an interest in regular measurements to ascertain their BP and gain an intuitive understanding of BP variability through introspection. Others wanted to explicitly test the acute impact of certain activities on their BP. To support this need, we envision an unobtrusive, wearable BP device that can capture BP as a dynamic variable throughout the day. This type of device should link with other data such as stress measures and food logs that many of the participants highlighted as relevant to their BP variation. We also know that the relationship between BP and risk of cardiovascular disease is continuous and short-term changes can be meaningful indicators of health risk. Capturing these changes in real-time can provide immediate feedback to users regarding trends and help them to reflect, review, and engage with their BP data.

Post-Study Use	Count	%
More than once/week	4	12
Once/week	4	12
Once/month	9	26
Haven't used device	9	26
No response	8	24

Table 4. Follow-up survey of average self-reported measurement frequency 60 days after the end of the study.

Other participants described the value of BP measurement in terms of a periodic check-up, such as monitoring for preeclampsia for a short duration of time. As an alternative to a device built for continuous monitoring, we envision a system that reimagines the pharmacy BP kiosk. However, unlike a kiosk, our participants did not want a snapshot of their BP at a single point in time, but preferred a way to temporarily capture their BP for a period of time—such as monitoring several days to capture an average and evaluate longitudinal trends. They also did not want to manage or find a place for a cumbersome, infrequently used device in the home, nor have to go to a fixed location like a pharmacy. The users of this new system do not need to monitor their BP every day, but are interested in a momentary, repeated measure assessment that reports their health status and how they compare to others. They prefer measuring their BP in an environment that is convenient and comfortable using a system that is either disposable or can be integrated unobtrusively into their home environment.

Design recommendations

Even though our participants strongly desired to track their BP at home, they were dissatisfied with the capabilities of typical home devices. Here, we consider the implications of short-term fluctuations and an audience new to BP monitoring. We suggest several design considerations that can improve the relevance, actionable value, emotional impact, and intelligibility of BP data captured for generalized use.

Making BP data relevant and context-sensitive

The importance of situating BP in context is evident with the variety of environmental and situational variables that participants highlighted in the study. Participants did not discuss their BP values independently, but often connected readings with their workplace, stress, food and drink, exercise, or other activities. Bentley and other researchers have argued that for longer-term personal monitoring, a multifaceted, holistic outlook on what to track can enable more nuanced and personalized feedback from sensor data [2]. BP devices should have greater integration with sensors that detect location, movement, stress, and other physical metrics to help individuals understand changes in blood pressure in relation to relevant aspects of their lives.

Participants also described adding context to BP data by comparing their numbers to other groups to get a sense of what is "normal". This desire for having a certain BP status is a clear opportunity to leverage crowd-sourcing to provide an individual with an understanding of their data relative to others with similar age, gender, or lifestyle. Participants also wanted to compare to others' BP in order to set goals for self-improvement. Based on data from younger or healthier users, devices could even infer and recommend activities and lifestyle changes that would help users attain health goals. Having a personalized history of BP changes in combination with other persons' data can provide users with valuable trajectories for predicting health risks [1] and help motivate behavior changes in a person's life.

Making BP data meaningful and actionable

The manner in which BP data is presented seemed to have a large impact on participants' interpretations and perceived value. The typical device's display of a snapshot of SBP, DBP, and pulse values provides little sense of the form or shape of their blood pressure over time. In cases of strong variation this may have hindered pattern recognition, and participants' prior experience influenced their assumptions and expectations. For example, many participants expected their lowest BP reading in the morning and were often confused by the rise and fall of BP throughout the day. The participants also cited the order that the numbers are presented and their relative magnitude as why they focused on SBP or DBP. Recognizing these situations where expectations break down or when the data display directs user attention provides an opportunity to focus design to educate users about meaningful BP variability and trends.

Blood pressure devices can also move beyond supporting reflection toward providing actionable information. Systems should flexibly handle diverse representations of BP data such as binary (healthy or not), categorical (health risk), ordinal (population comparisons), or continuous (trends, correlations with everyday living) to not only answer user queries but support active decision-making aligned with personal goals. A continuous monitoring tool that can recognize patterns, learn baselines, and identify meaningful trends can support real-time decisions through contextually aware feedback. Instead of placing a burden on the user or a third party to analyze a large, complex dataset, the device can produce an appropriate data representation that helps evaluate actions relative to changes in BP.

Making BP data desirable

Even though participants expressed interest in evaluating correlations between their current mental state and their BP, atypical BP readings among some participants increased their anxiety in a manner similar to the white coat effect observed in clinics. The way that individuals perceive BP devices and how BP results are communicated to them can affect this type of emotional response. We suggest that future designs frame BP data in terms of averages and ranges to reflect measurement uncertainty and mitigate the psychological impact of a single high reading. Framing measurements this way also offers an opportunity to incorporate better visual displays that emphasize patterns, trends, and deviations from the mean rather than single-point measures.

Making BP data trustworthy and intelligible

Most home BP devices, including the one used in this study, will provide a clinical stratification of BP based on a single measurement. Yet within person variation, environmental stimuli, and device inaccuracy create significant measurement variability [10]. Even clinical guidelines recommend incorporating additional factors such as comorbidities and lifestyle behaviors in order to classify cardiovascular risk [19]. A single reading provides a misleading understanding of an individual's BP. In a home setting, participants have the ability to capture regular measurements of their BP. Therefore, classification of a person's health status may be more relevant and representative as an average or visualization of BP trends. Devices could begin with typical variance as ascertained from other users or based on existing literature and slowly personalize this to the individual, emphasizing their BP as a range. The devices can also improve their intelligibility by providing an indication of confidence in a given reading depending on factors such as deviation from an average BP or awareness of the possible influence of environmental variables.

Limitations

Because our study was primarily qualitative, and because our participant sample skewed slightly towards a physically active and educated demographic, we caution against overgeneralizing our findings. Moreover, although participants were exposed to their BP repeatedly during the study period, a two-week interval might be inadequate to fully reflect and understand their blood pressure. However, we believe the open log entries and the multiple interviews provide insight into how non-hypertensive individuals begin to understand and relate to BP as a personal health metric. This type of real-time in situ data capture is a well-recognized approach to understanding ubiquitous technologies [6].

CONCLUSION

BP is a valuable metric to incorporate as part of personal informatics systems for health. We identified self-tracking needs including responding to BP variability through repeated or continuous measures and supporting personal discovery of BP fluctuations linked to everyday living. Reframing BP devices away from disease management toward well-being can help reduce the stigma and emotional anxiety associated with BP and stimulate greater adoption and use of these devices. Future designs should consider more casual use contexts in addition to health maintenance.

Through our analysis of participant experiences with tracking their BP, we illuminate how individuals collecting more frequent at-home BP measurements perceive BP variability and make associations with activities and aspects of daily living. We also demonstrate the impact and relevance that measurement of BP had on a young, healthy population. Finally, we discuss opportunities to improve the design of BP devices through better support of individual reflection, diverse data representations, transparency around BP variability, and integration with other sensor data. Many BP devices currently on the market are still designed for clinical needs and uses. The shift towards sensor-based personal health monitoring provides an opportunity to innovate on this metric and make blood pressure measurement more accessible and relevant to a broader audience.

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