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Review

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The current state of blood pressure measurement and emerging technologies

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Abstract

Office blood pressure measurement has been the primary means of diagnosing and treating hypertension for almost a century. Increasingly, guidelines recommend out-of-office measurements (ambulatory or home blood pressure measurement) to confirm the diagnosis of hypertension and to follow treated patients. Ambulatory blood pressure measurement includes nocturnal measurement and provides a 24-hour blood pressure profile, enabling calculation of overall blood pressure, daytime mean, and nocturnal mean. Home blood pressure monitoring is a method of blood pressure measurement that is convenient and accessible. Blood pressure telemonitoring is a complementary and emerging technology that enhances the effectiveness of out-of-office blood pressure measurement and has the potential to improve the health of end users through engagement, efficiency, and enhanced communication with the care team. Blood pressure measurements can be obtained remotely, effectively transmitted to their health care team via telemonitoring for interpretation, and then a care plan can be developed and implemented. However, care must be taken to ensure that these emerging technologies record and transmit accurate blood pressure information in a secure and reliable manner.

Keywords: Blood pressure measurement, blood pressure telemonitoring, automated blood pressure measurement

INTRODUCTION

Hypertension is the leading cause of death and disability[1] and responsible for millions of deaths related to stroke, ischemic heart disease, and renal disease worldwide[2].The global prevalence of hypertension doubled from 1990 to 2019 and rates of (BP) control in those living with a diagnosis of hypertension are less than 25%[2]. Accurate and timely blood pressure measurement is an essential part of properly diagnosing and monitoring hypertension, such that control can be achieved.

AUTOMATED BLOOD PRESSURE MEASUREMENT

Blood pressure measurement has been performed in clinical medicine for over 100 years. Oscillometry was the first technique developed in 1876, followed by mercury auscultation[3]. Both techniques have been widely used, but oscillometry has increased in accuracy and automation, while BP auscultation has not significantly changed since it was first described. The auscultatory technique remains the reference standard in BP device validation studies (2-observer simultaneous auscultation with a mercury or calibrated aneroid device), but in clinical practice, due to the training, time and attention required to execute accurate auscultation, automated BPM is preferred.

Hypertension guidelines worldwide are increasingly recommending that diagnosis and treatment decisions be based on automated and out-of-office BPM[4-7]. Out-of- office BPMs include 24-hour ambulatory blood pressure measurement (ABPM) or self-measurement of home BP using an automated device (HBPM). Automated office BPM may be obtained using a single measurement (casual blood pressure measurements) or using an automated office blood pressure device (AOBPM) which can be activated to take repeated measurements with the health care provider out of the room (unattended BPM)[8] or with the health care provider present.

TYPES OF AUTOMATED BLOOD PRESSURE MEASUREMENT

Ambulatory blood pressure measurement

Hypertension is diagnosed by calculating mean BP over multiple clinic visits, a series of home measurements, or with ABPM[4,5]. Advantages of ABPM include: it provides multiple measurements throughout the day across differing physiologic and emotional states; the ability to assess full 24-hour control including during the night; it can diagnose masked hypertension and white coat hypertension; and it is a better predictor of cardiovascular events than office BPM[9,10]. However, expense, access and inconvenience limit the availability of this technique for many[11]. Furthermore, due to the disruption of sleep that may occur with ABPM, this test may not truly represent the BP during sleep[12]. One study looked at the reliability of office BPM, HBPM, and ABPM and their association with left ventricular mass index. HBPM was more reliable (on test-retest) than ABPM and more closely associated with left ventricular mass index[13]. Guidelines suggest that if high BP is identified by office BPM, ABPM and/or HBPM should be used to confirm the diagnosis of hypertension[4,11,6].

Home blood pressure measurement

There are also many advantages to HBPM. Home BP devices are less expensive than office or ambulatory devices; the privacy and flexibility of home use allow for frequent and opportunistic monitoring of BP by season, time of day[14], emotion, and pre/post medication use, to have a more personalized and complete assessment. The feedback from HBPM can empower patients to modify behaviors and lifestyle[15,16]. White coat hypertension, white coat effect, masked hypertension and masked effect can also be detected using HBPM[4]. One main disadvantage to HBPM is that, at least in the Australian market, most home devices sold are unvalidated, inaccurate, or both[17]. There are registries of validated BP devices that aim to guide consumers and clinicians to recognize and purchase only validated devices. Some examples of these are:

American Medical Association https://www.validatebp.org/

British and Irish Hypertension Society (BIHS) https://bihsoc.org/bp-monitors/

Hypertension Canada https://hypertension.ca/bpdevices

German Hypertension League (Deutsche Hochdruckliga) https://www.hochdruckliga.de/betroffene/blutdruckmessgeraete

Japanese Society of Hypertension https://www.jpnsh.jp/com_ac_wg1.html

STRIDE BP https://stridebp.org/bp-monitors

Medaval https://medaval.ie/

When using HBPM, it is also important to ensure that patients are educated on and using proper measurement techniques[4,11].

Office blood pressure measurement

Office BPM, which involves taking one or more readings in a clinical setting, has been the basis for much of the previous work on hypertension and anti-hypertensive medication[18]. Measurements conducted in a research setting, using strict protocols and taking the mean of multiple measurements typically taken two or more visits, are often 5-10 mmHg lower than the measurements done in busy clinical offices[19,20]. Due to patient finances, mobility, dexterity, living arrangements, and distance, sometimes office BPM is the only means of BPM. In these circumstances, office BPM provides a method of screening for hypertension and monitoring treatment effectiveness. If only office BPMs are used for clinical care delivery, white coat and masked hypertension/effect will be missed[21]. There is some work that suggests that the white coat effect can be minimized with unattended office BPM[22]. More recent work has shown little difference between attended and unattended automated office BPM[23]. Office measurements are a "snapshot" of the BP over a few minutes. Blood pressures fluctuate throughout the day and more measurements taken throughout the day (as is possible with HBPM or ABPM) and over many days (as is possible with HBPM) would certainly provide more data on the "usual" blood pressure[14]. For these reasons, when an office screening BP is elevated, most guidelines recommend confirmation with out-of-office measurements[4-7]. Comparisons of daytime ABPM average BP to automated office BP have shown poor agreement[24,25]. Furthermore, cardiovascular outcomes are better predicted with ABPM than OBPM[9].

The types of automated blood pressure measurement: AOBPM, HBPM, and ABPM are presented in Table 1.

While automated techniques of BPM have been in existence for many years, there are now available technologies to enhance the delivery and communication of BPM between patients and their care teams. Emerging technologies and their advantages and disadvantages are presented in Table 2. One overarching concern and question with this emerging technology is whether this movement will improve or widen the existing disparities in health care[26] when health literacy, cost and access may limit uptake in equity-deserving groups.

Table 1. Comparison of automated BP measurement techniques

	Daytime ABPM	Home BPM	Casual office BPM	Automated office BPM
Number of measurements	Every 15-30 min × 24 h	As able/indicated	Each visit	Each visit (3-6 measurements)
Timing of measurements	Infrequent 24-hour studies	As able/indicated	Each visit	Every 30-60 s
Remote monitoring	Possible	Yes	No	No
Acceptable for hypertension diagnosis	Yes	Yes	Over multiple visits, preferably in conjunction with out-of-office measurements	Over multiple visits, preferably in conjunction with out-of-office measurements
Able to detect white coat hypertension/masked hypertension	Yes	Yes (although ABPM preferable)[21]	No	No
Equivalent blood pressure	135/85 mmHg[5]	135/85 mmHg[5]	N/A	140/90[5]

Table 2. Comparison of established and emerging digital health enhancements to hypertension care

Technology	Advantages	Disadvantages
Remote patient monitoring	Effective, particularly with case management protocols	Relies on health and technology literacy
Cloud based ABPM	Protocolized with less health care time involved. Automated for patients.	Relies on effective and stable connectivity
Cuffless devices	Convenient, comfortable	Not validated
Artificial Intelligence, prediction and warning systems	May relieve health care provider time, may be able to prevent or warn of cardiac events	Not yet in mainstream practice, concept not yet proven effective
Digital therapeutics	Low cost, potential to have widespread use	Has not yet been shown to be effective in hypertension care

TECHNOLOGY ENHANCEMENTS

Remote patient monitoring for hypertension (self-measured blood pressure monitoring)

The Covid-19 pandemic accelerated the use of and need for virtual health care. This will be a legacy of the pandemic that will change the way care is delivered. During the pandemic, effective hypertension care was delivered remotely using virtual video or telephone visits[27]. A study in primary care indicated that patients found virtual visits to be convenient, and less expensive than taking time away from work for medical care; virtual visits were particularly effective for those with mental health or mobility challenges and reduced canceled visits[28]. Virtual visits can be enhanced by remote patient monitoring. Remote patient monitoring involves the transmission of health information from the patient's home or care environment to the physician or care provider in an alternate setting[29]. Remote patient monitoring can be accomplished using telemedicine (exchange of medical information between provider and patient at a distance) and/or m-health (telemedicine using a mobile phone) used in conjunction with a software platform that collects and presents patient-facing data to providers[30]. A recent international expert position paper suggests that the target populations for hypertension telemonitoring are: (1) those who would benefit from screening for hypertension and (2) those who have been diagnosed with hypertension and require follow-up and titration of pharmacologic and non-pharmacologic treatments[30].

The effect on BP has been null in some studies which have shown that telemonitoring is a safe and effective method of providing virtual care but does not result in improved BP control when compared with face-to-face visits or remote BP monitoring without a smartphone application[31,32]. However, in totality, the published literature supports a beneficial effect on BP control and cost-effectiveness. A quasi-experimental study in primary care found telemonitoring to be an effective way to control BP in large primary care practices without an increase in clinician workload, particularly when patient data was summarized in graphical/tabular format[33]. There is evidence that remote patient monitoring improves patient outcomes and reduces cost[34-37]. The cost of implementing a telemonitoring system with case management support in the UK was £ 25.56/mmHg reduction per patient in one study of 401 primary care patients in Scotland[38], a more recent study of patients from 76 general practices in the UK with one year follow up data from 552 patients reported a cost of £ 11/mmHg reduction per patient[37]. A Canadian study of BP telemonitoring with case management for secondary prevention in community-dwelling patients post stroke or transient ischemic attack showed a lifetime net healthcare saving of $1,929 CAD and increased per-patient quality-adjusted life years (QALY) by 0.83[39]. The TASMINH4 study, a study of patients with hypertension in a primary care setting in the UK, also showed the cost-effectiveness of telemonitoring compared to self-monitoring of BP alone with an incremental cost-effectiveness ratio of £ 17,424 per QALY[35]. A meta-analysis in 2013 showed that home BP telemonitoring was effective for BP control compared to usual care and resulted in a systolic/diastolic BP decrease of 4.71 mmHg (95%CI: 6.18, 3.24; $P < 0.001$)/2.45 mmHg (95%CI: 3.33, 1.57; $P < 0.001$) more than the control group[40]. The home BP telemonitoring interventions reported in this analysis were 662.92 (95%CI: 540.81, 785.04) euros per patient more expensive than usual care[40]. A 2019 meta-analysis supported that home BP telemonitoring improves BP control (mean change, systolic/diastolic: -3.99 mmHg; (95%CI: 5.06 to 2.93; $P < 0.001$)/-1.99 mmHg (95%CI: 2.60 to 1.39; $P < 0.001$) compared to usual care[41]. The decrease in BP was shown to be larger when counseling (mean change, systolic/diastolic: -5.85/-2.62 mmHg; $P < 0.001$/ $P < 0.001$) and education (-3.60/-2.21 mmHg; $P = 0.05$/0.008) were added to the telemonitoring[41].

Communication between the care team and patient may be improved with telemonitoring if both the patient and clinician are engaged, and if the technology is working and simple to use. Privacy and accuracy are challenges as new technology develops. Privacy challenges can be mitigated by ensuring that (1) software providers have established and follow security policies outlining how data are managed to maximize security; (2) software providers do regular penetration tests to ensure security is not being breached; (3) data are stored and transmitted in an encrypted and secure manner; and (4) both clinician and end user have password protected and/or two-factor authentication access to any software.

Essential considerations for BP telemonitoring are[42]:

A clinically validated BP device

A platform that is a repository for BP data and allows the clinician to view information

A system that is secure and conforms to health information privacy regulations

Features that further enhance the system:

Seamless integration with electronic medical record

Seamless ability to prescribe and easily transmit requisitions for tests

Protocolized case management

Cloud-based ABPM

Performing, interpreting, and sharing ABPM results can involve many steps and people. Typically, one clinic visit is required for patient orientation, device application by a technician or nurse and trial of BP measurements. The patient is provided with a paper diary to record activity and events that may have influenced their BP (exercise, work, stress, and sleep). The patient returns the following day for the removal of the device and to return the paper diary. The technician or nurse must then download the study and upload the data and send it to the physician for interpretation. The physician interpreter then reviews the data, generates a report and then the report must be distributed by another team member to the referring physician. The Heart Track ABPM software (A&D, Tokyo Japan) is an example of a seamless interface that is secure and protocolizes the instructions for the test (can be done on a tablet without the need for a health care provider to be present) and the interpretation (done by the software with approval/editing by the clinician). The software can integrate with EMRs and send reports without the need to print, then upload or send reports. This is an example of guideline-concordant care that is both patient- and clinician-centered, improving efficiency and decreasing the time to receive an accurate report[43].

Cuffless devices

Cuffless devices are an emerging technology. These devices are wearable and can provide even more information regarding the effect of emotions, activity, work, and rest on BP[44]. There is much work underway using this technology[45]. The devices come in many forms and include patches, watches, rings, scales, and smartphones[46]. The derivation of BP is different than oscillometry or auscultation and can include pulse transit time, pulse wave analysis, photoplethysmography, ultrasound[46], and tonometry[47]. Cuffless techniques do not represent a true pressure measurement; instead, BP is mathematically estimated from measured parameters. Accuracy is difficult to achieve because it is not presently possible to take into account all endogenous and exogenous factors that can influence BP levels at a moment in time when performing such mathematical estimations.

At present, there are no rigorous means of validating these devices, especially when used while the patient is active[48]. An advantage of these devices would be their unobtrusive BP derivation (less noise, less pressure disruption from inflation of a cuff) that would not wake wearers at night which is a drawback of ABPM and nocturnal home BP measurement. These wearable devices could provide frequent or even continuous BP measurements which would provide trends in terms of day/night, work/rest, emotion, and exercise effects on BP. At present, these devices may be reasonable (once calibrated against a validated cuff device) to demonstrate trends in BP but, until they are validated, would not be suitable to diagnose hypertension or to guide management decisions[14]. The Aktiia device has been tested against 2-observer auscultation in many positions but acknowledges that there is not yet a gold-standard comparator for this device based on pulse-wave analysis[49]. If cuffless BP devices can be validated and are shown to be accurate, there is much future research possible in terms of determining whether overall average BP, BP load, BP variability, daytime BP, nocturnal BP or some other construct best predict cardiovascular events.

Artificial intelligence, prediction, and warning systems

The future state of remote monitoring may be to predict and warn of health events[50]. Such a warning system has been developed which detects physical movements, pulse, and BP and has a thermometer and a barometer[50]. Results can be shared by patients and clinicians. The future state is considered where artificial intelligence could be used to predict future BP variability and potential cardiovascular events[51]. Artificial intelligence may ultimately be used to interpret ABPM data, interpret remote patient-generated data, make automated diagnostic and therapeutic recommendations, and guide lifestyle interventions.

Digital therapeutics

As defined by Digital Therapeutics Alliance, digital therapeutics are evidence-based software program therapeutic interventions that are used independently or in conjunction with other therapeutics to manage or prevent disease[52]. Digital therapeutics are potential management solutions for health objectives involving digital health and information and communication technology (ICT) applications[53]. The WHO recognized that digital interventions could strengthen healthcare delivery but also has the potential to divert resources from traditional approaches[53]. There has been significant activity toward applying digital therapeutics to hypertension with mixed results[51]. To date, the studies have been randomized but open-label studies with short-term follow-up (maximum 6 months). Even with positive results, this duration is not long enough to determine the effect on chronic disease. There have been some interventions designed by clinicians with some modest improvement in BP. One study randomized patients to use an application (app) that supported non-pharmacologic interventions (sleep, salt intake, alcohol reduction, exercise, body weight, and stress) versus usual care for patients diagnosed with hypertension but not yet on medications[54]. At the end of 12 weeks, the intervention group had a lower systolic BP on 24-hour ABPM of 2.4 mmHg[54]. Seemingly, this could be a low-cost intervention that could improve hypertension care; however, it is too early to tell whether the evidence will indeed support digital therapeutics in hypertension care.

CONCLUSION

Guidelines are increasingly recommending out-of-office BPM over office measurements. Home and ambulatory BPM are complementary methods of obtaining out-of-office measurements. These modalities can further be enriched by m-health and telemonitoring, which can add efficiency and cost-effectiveness and enhance communication between patients and members of the care team. Whether cuffless BP monitoring, artificial intelligence, and warning systems are additive contributions to standard hypertension care is an open question that will be clearer after the results of innovative, ongoing studies are known.

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Authors' contributions

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Reviewed and revised the manuscript: Ringrose JS, Padwal RS

Availability of data and materials

Not applicable.

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Conflicts of interest

JR is supported by an alternative funding plan from the Government of Alberta and the University of Alberta. JR and RP are cofounders of a digital health company, mmHg Inc.

Ethical approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

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