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Pearls and pitfalls of cuffless blood pressure monitoring devices

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ABSTRACT

Cuffless blood pressure measuring devices are emerging as alternatives for out-of-office assessment of patients with hypertension. This novel technology promises to deliver continuous or beat-to-beat blood pressure measurement and resolve some of the inconveniences associated with conventional cuff-based devices such as improper cuff fit, discomfort, low adherence to monitoring, and technical challenges. Blood pressure can be estimated based on phenomena related to cardiovascular activity: pulse wave velocity, pulse wave analysis, tonometry, and volume clamping. In this narrative review, we seek to summarize current approaches for nontraditional measurement of blood pressure and discuss some of the benefits and limitations of this technology.

Keywords: Blood pressure, cuffless device, ambulatory blood pressure monitoring, blood pressure monitors, hypertension

List of abbreviations (in alphabetical order):

ABPM – Ambulatory Blood Pressure Monitoring
BI – Bioimpedance
BP – Blood pressure
CL-BP – Cuffless blood pressure
ECG – Electrocardiography
HBP – High blood pressure
HBPM – Home blood pressure monitoring
IPG – Impedance plethysmography
PAT – Pulse Arrival Time
PEP – Pre-ejection period
PPG – Photoplethysmography
PTT – Pulse Transit Time
PWA – Pulse Wave Analysis
PWV – Pulse Wave Velocity

INTRODUCTION

High blood pressure (HBP) is a common modifiable risk factor for a significant number of conditions such as cardiovascular disease, kidney disease, and stroke [1]. Evidence has shown that there is a difference between in-office and out-of-office measurements of blood pressure (BP) and that continuous monitoring could better outline blood pressure variance, and augment treatment recommendation and patient adherence [2]. Out-of-office blood pressure monitoring can be achieved through intermittent 24-hour ambulatory BP monitoring (ABPM) or home BP monitoring (HBPM) using automated devices based on oscillometry [3]. Single measurements are typically well tolerated by patients, but the need for repeated evaluations produces discomfort and may pose significant challenges to patients in their daily activities. The human factor is an important error source as incorrect placement and improper cuff size lead to false readings. There is a

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growing body of literature to support new techniques for BP measurement. New technologies have emerged that offer the possibility of noninvasive BP measurement without cuff-dependent devices. This narrative review explores the different measuring principles utilized for cuffless BP monitoring, their benefits, and pitfalls.

MATERIALS AND METHODS

We have performed a comprehensive PubMed database search to identify novel technological developments for cuffless BP measurement to determine their benefits and limitations. Key terms used for this survey were: cuffless blood pressure, cuffless device, blood pressure measurement, and blood pressure monitoring.

Why cuffless devices?

The term "cuffless blood pressure device" (CL-BP) refers to any noninvasive measurement technology used for BP assessment that does not require an inflatable cuff [4]. Conventional assessment of blood pressure is classically done by methods such as arterial catheterization and the auscultatory method, or by electronic means using oscillometry [5]. Direct arterial catheterization is rarely available and invasive [6]. Oscilometry has several additional benefits comparable to previously mentioned techniques, such as ease of use, lack of observer bias, low cost, and reliability [4]. Yet these methods have several limitations related to the use of cuffs such as inadequate cuff fit, patient discomfort and low tolerability, low adherence to monitoring, and in some instances technical challenges [6]. A significant drawback is the limited information they provide as these methods characterize a moment in time of the variable BP of patients' daily activity and usually it captures only the resting BP value [7]. Continuous measurements of blood pressure might be the future of hypertension evaluation as it can capture a complete picture of circadian variability and in emergency cases, it can provide immediate information about heart health status. Benefits are summarised in Table 1.

Populational strategies for BP control have shown little progress as many patients with elevated blood pressure are still frequently undiagnosed and due to the hardship that monitoring these patients presents over time [8]. Phsician-centered evaluation of hypertensive patients has additional issues because patients have been shown to have elevated blood pressure as a result of stress related to doctor-patient interaction ("white-coat hypertension") [9]. Phone applications and smartwatch devices are widely available to the general population. Integrating BP monitoring technology into ubiquitous devices can increase the pool of patients suitable for therapeutic intervention, facilitate tracking of therapeutic response, and ease the stress associated with BP monitoring.

TABLE 1. Pearls of cuffless blood pressure measuring devices

Pearls
Continuous or beat-to-beat assessment of blood pressure
Provides immediate information about health status
Registers blood pressure during physical activity and throughout the circadian cycle
Facilitates tracking of medication response
Readily available in ubiquitary devices
Alleviates discomfort associated with blood pressure monitoring
Increases adherence to monitoring
Decreases human error
Increases awareness about cardiovascular disease

Principles of measurement for cuffless BP devices

There has been an increased interest in the development of sensor technology for BP measurement such as photoplethysmography (PPG), ultrasound imaging, electrocardiography (ECG), bioimpedance (BI), mobile phone sensors, and microelectromechanical applications [10,11]. These sensors take advantage of several physiologic changes that happen during cardiac electric and mechanical activity and register an appropriate signal. The signals can be determined either by the pulse wave and its recoil during ejection faze, body vibrations due to mechanical movement of the heart or vessel wall, blood volume variations in the chest, or sounds produced by the opening and closing of the valves and cardio-vascular activity [11]. The information they provide is used to calculate an estimation of patient blood pressure using proprietary algorithms based on two main approaches: (1) Pulse Wave Velocity (PWV) which can be assessed from Pulse Transit Time (PTT) or Pulse Arrival Time (PAT), and (2) Pulse Wave Analysis (PWA) [5].

1. Pulse wave velocity

Pulse wave velocity is the speed at which an arterial pressure wave travels between two measurement points of the vascular system and it relates to arterial wall stiffness [12]. For its calculation two variables are required: the time it takes the pulse wave to travel from point A to point B and the distance between the measuring points [13]. Blood pressure can then be calculated using the logarithmic relation between two equations, the Moens-Kortweg equation and the Hughes equation respectively [11]. The assumption is that an increase in arterial stiffness is proportional to BP increase and the increase of pulse wave velocity [14]. However, arterial stiffness is also dependent on the intrinsic elasticity properties of the arterial wall which is unique for each individual, as such an initialization of the device and then calibration is required to adjust to an absolute measurement, typically performed by cuff-dependent devices [5].

Pulse transit time

The pulse transit time method of PWV computation uses signals related to the pulse wave and the information carried by it to measure the time elapsed between two measuring points [15]. There are multiple systems and sensors utilized in signal collection for this model such as PPG, impedance plethysmography (IPG), or a combination of the two (IPG-PPG) [11]. Photoplethysmography is a common sensing technique that assesses the absorption of the specific wavelength which varies with the changes in blood volume determined by the pulse wave [16]. The change in volume triggers the sensor announcing the arrival of the wave. Two PPG sensors can be positioned proximal and distal to an artery or in different parts of the circulating system in a noncontinuous approach [14]. Bioimpedance-based devices have also been developed such as the prototype developed by Huynh and col. that has incorporated 2 sets of bioimpedance sensors in a smartwatch that are positioned in a small area along the radial artery of the patient's wrist and has shown satisfactory accuracy of BP prediction [17]. In the same manner, Sel et. al. have recently developed a ring-like bioimpedance device that is inserted on the patient's finger and is backed by an artificial intelligence algorithm that provides a linear continuous estimation of BP and promises to resolve the skin tone contrast problem associated with PPG devices [18].

Pulse arrival time

PAT is another approach for PWV measurement that evaluates the time passed from the electric activation of the ventricle (peak of the R-wave) using an ECG chest lead and the onset of the pulse wave signal at a distant arterial site [4]. As such, it sums up the PTT and the time passed from the depolarization until the mechanical ventricular action coined the pre-ejection period (PEP) [19]. Fewer sensors are needed as the proximal sensor is always an EGC lead, and the distal sensor can be either a PPG or an IPG [14]. PB estimation algorithms based on PAT make assumptions about PEP which can have individual variability and can be influenced by vasoactive drugs, stress, emotion, and physical activity which can be a source of measurement error [19].

2. Pulse wave analysis

Pulse wave analysis works by measuring different aspects of the waveform of a typical pulse wave such as amplitude or reflection wave [20]. This method uses PPG sensors and records a graph dependent on the absorption of the wavelength of projected light [14]. It offers additional advantages such as simultaneous determination of cardiac output, stroke volume, and peripheric vascular resistance [21]. Interpretation is usually done by machine learning technology and can easily be integrated into cotidian devices such as smartwatches [11].

Facial video processing advancements have made possible the extraction of information about pulse waveform features and the development of noncontact monitoring [22]. This development can be integrated into ubiquitous devices such as smartphones, and the collection of data can be made without patient interaction [4]. A softwer with integrated face recognition identifies a skin patch of interest, averages spatially the wavelength for red blue, and green signals, and then uses the data to reconstruct a PPG waveform [23].

Applanation tonometry is a semi-occlusive technique in which partial pressure must be applied on an artery (such as the radial artery) until all tangential forces in the arterial wall are dissipated such that the remaining pressure is exerted by the outward force of the BP. This force is then measured by a pressure sensor and an arterial waveform is constructed [24]. Recently Siemasz et. al. developed an autocalibrating device based on this principle using a pneumatic sensor placed on the radial artery that promises to resolve some of the issues related to the cuffless monitors [25].

Volume clamping, also known as Penaz-method, uses a finger cuff and an integrated PPG sensor on the artery of the finger [4]. The cuff is inflated until the pulse wave reflects mean blood pressure. Spikes are registered as positive and negative transmural pressure which are used for BP calculation. These are operating in clinical settings and are not available for out-of-office monitoring [5].

Pitfalls of current cuffless technology

Some concerns have emerged about these devices. (Table 2) The measured signals have interindividual variability thus initialization and frequent calibration are needed. The calibration is done by oscillometry which has a measurement error that gets incorporated in the calculation of CL-BP devices [11]. Conditions related to steady-state regarding vasomotor actions, and autonomic nervous system involvement changes in motion, and thus the assumption that the device was calibrated for is inadequate [14]. The position of the arm is also important as signals are influenced by the hydrostatic effects of gravity [4]. Also, there is a need for a noise-free signal for the proper functioning of the EGC and PPG sensors and motion produces interference [26].

TABLE 2. Pitfalls of cuffless blood pressure measurement

Domains	Details
Calibration	Dependent on initialization for each patient Dependent on cuff-based devices Need for frequent calibration Calibration is performed in resting state
Proprietary algorithms	No calibration standard issued Incorporates error during calibration "Drift" phenomenon away from calibration "Zero-out" phenomenon around calibrated value or demographic Makes assumptions about certain conditions and variables Dependent on heart rate which is influenced by medication Does not account for peripheral artery disease and other obstructions of blood flow Does not account for arrhythmia, heart failure, coronary disease, and pregnancy that alter pulse wave morphology and frequency
Motion and position	Assumptions calibrated for are not true in physical activity Need for noise-free signals
Sensing technology	PPG sensors do not account for skin tone Ambient light interference Sensor placement assumes artery accessibility
Ethics	Can create a disparity between social classes Could record without patient consent Data can be used to track emotional responses to ads and social contexts

Signal detection is continuously difficult for all measuring techniques. Light sensors face difficulties in signal detection with the variation of skin tone, and most technologies based on PPG sensors do not control for this variation [14]. There are current efforts to reduce calibration dependency, and noise, and improve contrast sensing [25,27,28].

The devices must make assumptions about other variables such as PEP or blood viscosity, vascular compliance, and position of the measured artery which are influenced by certain conditions, and autonomous nervous system involvement, and the assumptions don't hold true in specific population groups [19,26]. Algorithms do not account for certain conditions such as peripheral arterial disease that can obstruct blood flow to the peripheric sensor, and are dependent on heart rate which can be influenced by medication like beta-blockers [5]. There are several other populations misrepresented in studies such as pregnant women, patients with arrhythmias, heart failure, and coronary artery disease in which the morphology of the pulse wave may differ and the intervals between the waves may vary [14]. Artificial intelligence algorithms tend to paradoxically "zero out" the mean of the measurement around the calibrated value or average of the population [29].

Finally, there are ethical concerns. Availability of technology is dependent on the financial status of the targeted audience, and thus this has the potential to create disparity between social classes regarding access to medical services. If the intention is to increase awareness about cardiovascular disease and offer monitoring capabilities to vulnerable populations and thus increase the number of patients with high BP adequately controlled through medication, then the cost may work against it. Fortunately, research efforts are directed toward the inclusion of these technologies into ubiquitous devices such as smartphones. However, this resolution raises additional concerns as noncontact monitoring via smartphone camera can be maliciously used to track emotional responses to ads and social contexts and can acquire information without user consent [4].

CONCLUSION

Cuffless blood pressure monitoring is a novel prospect for future clinical practice and management of BP that promises to resolve some of the issues of conventional assessment techniques. These devices estimate blood pressure by either a PWV or PWA approach. They can deliver a continuous or beat-to-beat assessment of BP variability during daily activity with minimal discomfort and could be used for out-of-office monitoring. However, some limitations have emerged in recent literature regarding dependency on calibration, the need for making assumptions of some physiologic conditions, motion involvement, signal detection capability of current technology, and ethical concerns that have made implementation and validation for public use not possible. More research and technological development are needed to resolve these issues.

Conflict of interest

The authors declare no conflict of interest.

Author's contributions

Conceptualization, I.R.A. and C.A.E.; writing-original draft preparation, I.R.A. and F.B.D; writing-review and editing, F.B.D., D.A.M., and C.L.E.; supervision C.A.E. All authors have read and agreed to the published version of the manuscript.

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