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Hypertension Diagnosis: A Review on Techniques to Measure Blood Pressure

Wai Ti Chan*

***Abstract* – Hypertension is both a symptom and a cause of health complications. The consequences of long-term hypertension are more documented than short-term hypertension, so detection methods emphasize the presence of long-term hypertension. These methods require confirmation of consistently high blood pressure. Thus, established methods require long-term observation of the patient, which poses the risk of starting treatment too late for effective mitigation. These methods are also not portable enough for long-term observation to be comfortable. The goals of on-going research into detection of hypertension are the confirmation of hypertension with shorter durations of observation, and comfortable and convenient methods of frequent blood pressure checks. Future methods that are promising include wearable non-auscultatory sensors, AI-assisted comparisons of short-term observation data against databases of readings, and small implants.**

Keywords— High Blood Pressure, Blood Pressure Measurement, Hypertension, Hypertension Detection, Long-term Observation.

I. Introduction

The laymen description of hypertension is blood pressure that is higher than normal. This is both a symptom of health complications and a cause of other health complications too [1]. Due to its significant contribution to health complications, e.g. as a morbidity factor of health, there have been and still are efforts to determine its presence, cause, and effect [2].

Hypertension generally has a compounding effect on health complications, i.e., worsening hypertension is certain to worsen health further in other ways. For example, sympathetic activity of hypertension includes poor blood flow to organs, which in turn cause deterioration of those organs [3].

According to clinical observations, less than half of people that have hypertension are aware of their complication [1]. As a health complication, hypertension is estimated to have caused the cumulative loss of over 140 million years of potential lifespans among the world's population as of 2015, i.e., the loss of productivity due to hypertension is significant [2].

Therefore, there is research and development (R&D) into methods of detecting hypertension, with the goal of estimating the severity of hypertension, any associated health complications (caused or caused by) and any potential treatment [5].

This article is specifically about techniques to measure blood pressure. It is not about treatment methods, or the mechanisms of hypertension.

II. Methodology of Review

Where relevant, specific entries in the references will be cited in the following sub-sections; the numbering of

* Corresponding author. Email: wtchan@mmu.edu.my ORCID: 0000-0002-2366-1851
Wai Ti Chan is with the Faculty of Engineering and Technology (FET), Multimedia University (MMU), Jalan Ayer Keroh Lama, Bukit Beruang, 75450 Melaka, Malaysia. (Phone: +606-2523185; fax: +606 - 231 6552; e-mail: wtchan@mmu.edu.my).

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citations in this section will be based on the numbering of citations as they appear in other sections.

A. General Medical Journals

General science journals, e.g. *Nature Reviews: Disease Primers*, are the source for the research on the background of hypertension and hypertension diagnoses. This is so that there can be opening statements about hypertension against the backdrop of other scientific studies into other health complications, such as statements about the need for convenient and reliable diagnosis methods for them.

B. Medical Journals Specifically about Hypertension

Medical journals that specialize in hypertension, such as the name-sake *Hypertension*, are the main sources of information for this review. These journals provide specific and/or technical information such as the mechanisms of methods for measuring blood pressure.

This step in the review methodology also reveals that the main finding for the diagnosis of hypertension, which is long-term high blood pressure, has not changed since the establishment of its definition. Henceforth, the review effort focuses on blood pressure measurement.

C. Literature Research into Mechanisms of Measuring Blood Pressure

The next procedure in the review methodology is the literature review of the mechanics of measuring blood pressure, starting with direct-contact methods like CVC. This procedure happens concurrently with the following procedure, so that revisions of statements in the review can be made to emphasize realistic limitations of blood pressure measurement.

D. Risks and Limitations of Methods to Measure Blood Pressure

This procedure in the review methodology happens concurrently with the previous one. This is so that current trends in R&D of blood pressure measurement can be identified, together with the practical limitations of novel methods and their advantages compared to established methods.

III. Background & Problem Statement

The ensuing passages are a brief history of hypertension awareness and methods to detect it.

A. Brief Statement on the Terminology of Hypertension

"Hypertension" is the term that describes consistently high blood pressure; this description precludes any condition that causes imminently reversible high blood pressure [6]. Consequently, dissertations about hypertension, including this review article, generally emphasize methods on confirming the presence of long-term high blood pressure [7].

B. Awareness of Hypertension

Incidentally, one of strategies in confirming the occurrence of hypertension is maintaining public awareness of hypertension [8]. This strategy is applicable to any common health complication, but in the case of hypertension, the effectiveness of this strategy is limited by different health systems and clinical guidelines for the detection and treatment of hypertension [8].

These differences are due to differences in the affordability of treatment for hypertension [8]. Since observation of hypertension generally occurs alongside treatment [7], the differences in affordability also resulted in different comprehensiveness in detecting and confirming hypertension [9].

Ongoing R&D of diagnosis methods for hypertension implements the strategy of reducing the inconvenience of testing for hypertension; this can also theoretically address the issue of affordability [10].

In summary, efforts in raising awareness of hypertension must occur together with improving the convenience and affordability of persistent and consistent blood pressure measurement.

C. Hypertension Diagnosis, in General, and Problems

(For the purpose of text brevity in this review article, the phrases "blood pressure measurement" and "blood pressure checks" are used interchangeably. Which exact phrase is used depends on the context of the passage, e.g. "measurement" is used if operation of a device is part of the topic.)

Understandably, diagnosis of hypertension involves checking blood pressure. However, confirmation of hypertension requires frequent checks and informing medical practitioners of the results of these checks [11]. Thus, this requires regimentation of patients' lifestyles, which they might not be able to implement due to conflicting schedules [11].

Without regular checks and reports of these checks, not enough data can be collected and studied by medical practitioners to reliably confirm hypertension [12]. The current general solution for this is to have patients undertake checks on their own, i.e. "out-of-office" checks, and record the results, but the results of these are not readily acceptable for reliable diagnoses. This is because the veracity of these results is always challengeable because they are not necessarily performed by certified medical practitioners [12].

The solution for this is that the results of "out-of-office" must be confirmed by the practitioners after studying these results and agreeing that the results corroborate checks that are performed by the practitioners [13]. However, this does not address the concern about patients not being able to regiment such checks in their schedules. Furthermore, there is the risk of apathy on the part of patients that discourages them from continuing checks, especially when they are aware that they cannot afford treatment if they are diagnosed with hypertension [14].

Present R&D of diagnosis methods work around this major limitation of data from regular checks and gather evidence that these work-arounds can be as reliable as diagnoses from long-term tracking of high blood pressure [15]. For example, hypertension may be a symptom of other health complications, so the presence of these other health complications is determined; if these other health complications are diagnosed, confirmation of hypertension is likely [15].

The approaches of these methods will be described in later sections of this article.

D. Comorbidity of Hypertension

As described earlier, hypertension may be the cause or symptom of other health complications, or both. Thus, hypertension can be classified according to their association, or lack thereof, with other health complications [16]. For example, if the patient has heart or blood vessel diseases, any confirmed hypertension is investigated for comorbidity with these diseases and will be classified as being associated with cardiovascular complications if the comorbidity is confirmed. Incidentally in these cases, treatment of such hypertension happens in parallel with treatment of other associated health complications [16].

There are cases where hypertension is not readily associated with other health complications. There is still ongoing debate in communities of medical practitioners about the classification of such hypertension, though the generally accepted term is "primary hypertension" [17]. Proposals for further classification include terms that associate the hypertension with the mechanics of their causes, where determined [17].

E. Hypertension Treatment, in General

As mentioned already, this article is not about hypertension treatments. The main topic of this review article is hypertension detection methods. However, in the case of hypertension, diagnosis and treatment are intertwined. To clarify, the effect of a treatment on hypertension can only be confirmed to be effective if further blood pressure monitoring shows improvement, meaning that the conditions that the treatment addresses are the likely cause of hypertension [18].

IV. Diagnosis Approaches

The following passages are not necessarily categorization of methods. Where relevant, the subheadings indicate categorization.

A. Blood Pressure Measurement

(For the purpose of text brevity, the phrase "blood pressure" is abbreviated to "BP" when blood pressure measurements and blood pressure checks are mentioned.)

Established methods to diagnose hypertension involve BP measurement. There is R&D into reducing the amount of BP checks, but there is no known reliably confirmed results from R&D efforts into forgoing these checks entirely [19].

Consequently, this means that diagnoses of hypertension must involve the means and devices for BP measurement. The reliability of the diagnoses depends on the diligence of their execution and the conditions of the devices involved. An example of the risks that are posed by this limitation is the uncertain reliability of out-of-office BP checks, i.e. checks done by patients instead of certified medical professionals [13].

The "gold standard" method of hypertension diagnosis is ambulatory BP monitoring (ABPM), which involves blood pressure readings and reports of these readings to a medical practitioner over a 24-hour period in the patient's otherwise usual daily life; the goal is to detect periods of high blood pressure and correlate these with the corresponding circumstances of the patient [20]. Yet, this "gold standard" is not feasible for every patient, depending on the complexity of and complications in their daily lives. Thus, there is R&D into diagnosis that are not as intrusive as ABPM but are comparably reliable [20].

B. Technique-related Methods

The most common technical procedure of BP measurement is the auscultatory method. It involves cuffing the patient's arm and increasing pressure on the cuff, thus constricting blood vessels there. Subsequently, the pressure is eased. Meanwhile, the patient's pulse is read. Parameters of the pulse, such as the difference between when the cuff is tightened and when it is eased, are used to estimate blood pressure. The estimation of blood pressure from the parameters of the pulse is the technical concept of this method [21].

In this article, "technique-related methods" is the term for the methods that follow this technical concept. However, they may differ in the techniques to measure the pulse of the patient. The standard technique utilizes cuffing, but others, as will be described later, may not use cuffing.

B. Parameter-related Methods

Auscultatory methods estimate blood pressure from pulse readings, as mentioned earlier. There are methods that estimate blood pressure from other bodily processes, i.e. other physiological and/or anatomical parameters. In this article, "parameter-related methods" is the term for these methods.

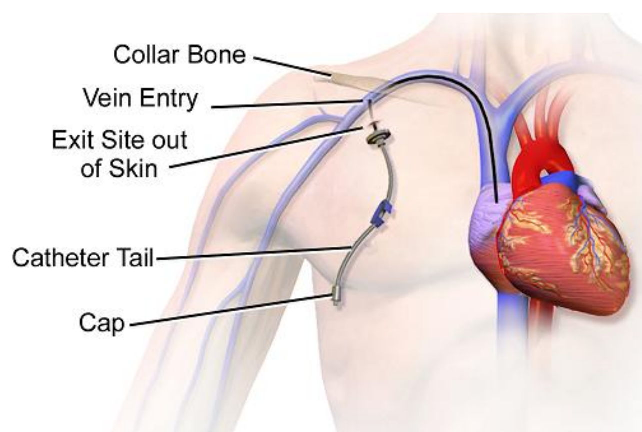

FIGURE 1. The CVC method measures blood pressure via direct contact with blood; this method is neither convenient nor portable.

One of these methods happens to define blood pressure as a quantifiable health factor. This is the insertion of a catheter into a blood vessel of a patient, usually a vein, as shown in Figure 1; this method is thus named the central venous catheter (CVC). CVC can then provide blood to support a visually obvious column of fluid, i.e., fluid head, or otherwise have the blood exert force on a pressure-sensitive sensor for the namesake BP measurement. Conveniently, the catheter also accommodates blood sampling and administration of intravenous medicine. However, this method is invasive, poses significant concerns and risks, and thus is only practical for hospitalized patients [22].

Present R&D efforts into both types of methods focus on non-invasive methods; these methods are described in later sections of this article. However, they generally require the placement of sensors somewhere on the person of the patient, so the patient may experience discomfort and/or inconvenience from having to wear the equipment. R&D efforts to mitigate discomfort and improve portability are ongoing [23].

V. Present-Day Technique-Related Methods

As mentioned earlier, the prevalent principle of BP measurement is the auscultatory method; this is usually performed with cuffing of the patient's arm. However, this technique can inflict discomfort on the patient, generally due to the tightening sensation in the patient's arm [24]. Thus, there is R&D into alternatives for cuffing.

Otherwise, these alternatives still follow the principle of the auscultatory method, e.g. they measure the pulse and estimate blood pressure from the pulse readings. Hypertension is then diagnosed from these estimates.

A. Photoplethysmography

An alternative to cuffing is photoplethysmography (PPG). PPG involves the illumination of the skin of a person. The theory behind this technique is that the different tissues and fluids within human skin would absorb, emit, and reflect light differently when they are illuminated. Thus, when blood pulses through skin, the changes in the light that it gives off can provide information for pulse readings, such as pulse wave velocity. Thus, PPG fulfills the principle of auscultatory methods [25].

The practical results of R&D into PPG are pulse oximeters. These miniature devices provide both illumination via LED arrays and have photosensor arrays to capture the illumination from the skin. These devices are placed on the fingers like clips. Incidentally, fingers are the most optimal locations for PPG due to the diffusion of blood vessels in the subcutaneous tissues of fingertips [25]. Pulse oximeters also make use of electrocardiography, which will be described later.

However, having clip-like devices on one's fingers is not conducive to daily life because of the obstruction that is posed by these devices in dexterous matters, e.g. handling objects. Consequently, the use of pulse oximetry is scheduled in the same manner as BP-measuring cuffing, i.e. pulse oximetry could not be used for convenient real-time monitoring [26].

Ongoing R&D efforts into PPG for BP measurement focus on the portability of the devices. For example, there is development of a wrist-worn device by Marinari et al., but the calibration of this device must be performed for each individual patient using other BP measurement methods because of different skin and subcutaneous conditions among patients; this calibration requires comparisons with cuffing-based BP measurements [27].

Although a person's pulse may change the dimensions of blood vessels such that these changes can be detected with PPG, the exact timing of the pulse coming and going is not so readily measured with PPG [28]. Electrocardiography is used to supplement PPG to address this, as will be described shortly.

B. Electrocardiography

Incidentally, a person's pulse also carries electrical energy from the heart. Electrocardiography (ECG) can detect this electrical signal from a person's pulse. ECG measures the pulse rate by detecting the electrical signal from the coming and going of the person's pulse, e.g. measurements like pulse transit time (PTT) [28].

However, ECG is not able to directly measure any kinetic energy brought by a person's pulse, or directly sense any changes in dimensions of blood vessels due to a person's pulse [29]. Consequently, ECG is generally used together with PPG to improve the measurement of the timing of a person's pulse [25][28]. On the other hand, there is ongoing R&D into using ECG on its own for BP measurement, as will be described later [29].

C. Peripheral Arterial Tonometry

Peripheral arterial tonometry (PAT) has its basis in PPG. PPG on its own does not apply pressure to the body part that is being measured, but the signals from the PPG sensor may be altered by pressure that is applied to other body parts that are adjacent to the measured body part [30].

PAT is implemented similarly to PPG, but with the addition of application of pressure to the body part that is being measured. In other words, it includes a procedural element of cuffing, namely the application of pressure. Since PPG is generally applied on fingers, PAT involves putting fingers into sheaths that can apply a uniform field of pressure [30]. This application of pressure mitigates any alteration of the signals from the sensors due to the pressure from adjacent body parts [30].

This means that PAT reintroduces the concern of discomfort due to the application of pressure. Although this experience is different from the discomfort of upper arm cuffing, there are still people who find the application of pressure in PAT procedures to be notably uncomfortable, such as school-going children [31].

(a) (b)

FIGURE 2. Typical appearances of commercially available blood pressure measurement devices that use (a) arm cuffs, and (b) PPG and ECG.

VI. Present-Day Parameter-Related Methods

Auscultatory methods rely on listening to the patient's pulse to estimate blood pressure, and then repeating the procedures to determine the consistency and persistency of high blood pressure that would confirm diagnoses of hypertension. The parameter-related methods that are described in this article deviate from this principle, either in their estimation of blood pressure or other means of confirming hypertension, as will be described in the following sub-sections.

A. Oscillometric Methods

Oscillometric methods were discovered in the same era as auscultatory methods when the cuffing of upper arms for BP measurement is developed [32]. Instead of taking readings according to the timing of the patient's pulse, as per auscultatory methods, oscillometric methods tabulate the oscillations (e.g. peak-to-peak changes) of pressure readings as detected by sensors in the cuffing [33]. Not having to track the timing of the pulse meant that the BP measurement device does not need a stethoscope or equivalent component, thus reducing hardware design complexity [34].

However, without the timing data provided by tracking the pulse, systolic and diastolic blood pressure estimations must be performed with mathematical algorithms that are applied on the pressure fluctuations. The outputs of these algorithms can differ significantly, depending on variables other than cuff pressures that are used in these algorithms (including individuals with different health circumstances), even if they have been calibrated with auscultatory methods [33].

Nonetheless, development of devices of oscillometric methods continue in the present-day, due to the convenience of automating them and developing consumer-ready BP measurement devices from these. The proliferation of these devices is made possible through validation of the reliability of their readings by medical professionals and associations, such as in the case of OMRON's products [35].

B. Electrocardiography Only

ECG has been described earlier as a companion procedure to PPG [25][28]. There is R&D into using ECG on its own, with the intention of simplifying the procedures for BP measurement to just ECG readings [29]. The incentive for this R&D is that ECG sensors are more portable than PPG devices and cuffs [36].

However, ECG lacks the means for measuring the physical forces from blood pressure. Thus, ECG-only methods must be developed by correlating reading patterns with those from known cases of hypertension that are confirmed by auscultatory BP measurements [36]. Presently, there is no reliable statistical correlation between ECG patterns and auscultatory BP measurements [37]. Yet, R&D efforts continue along the idea of statistical correlation, because of the goal of developing portable BP measuring devices [38].

C. Statistical Comparisons

As described earlier, the established method of diagnosing hypertension is a sequence of persistently high blood pressure readings. However, there is research into other potentially quicker means of diagnosing hypertension, i.e. substituting the long-term observation that is necessary for established methods of diagnosis with relatively faster methods.

The current trend of such research is finding correlation between sets of measurements and the measurements from confirmed cases of hypertension [39]. For example, a smaller set of PPG readings taken from a suspected case can be compared with larger sets of PPG readings of known cases to predict the occurrence of hypertension in the suspected case [39].

Another example is the comparison of BP measurements that are made during specific activities, such as cardio exercises, with the measurements from normal individuals that are performing the same sort of activities; the latter measurements are referred to as "thresholds" in such studies [40]. The theory of this method is that BP measurements that are above the thresholds are indicators of hypertension, but confirmation by medical practitioners are still needed [40].

D. Ultrasound

Hypertension is a co-morbid condition, so there can be other health complications. Theoretically, complications that are known to be caused by hypertension can be detected using methods that are not typically used to diagnose hypertension, thus confirming hypertension indirectly [41].

There are cases of cardiovascular diseases that are caused by prolonged hypertension, such as hypertrophy, i.e. thickening muscles, of the heart. Ultrasound checks can confirm such hypertrophy, hereby indirectly diagnosing hypertension, or corroborating the diagnosis of hypertension [42].

E. Blood Tests

Hypertension can cause cardiovascular issues, among other health complications, which in turn can change the composition of blood away from normal. For example, inflammation and cell damage from persistently high blood pressure may release particles such as cell membrane fragments and proteins, which can be identified through spectroscopy, centrifugation and/or chemical tests [43].

This is of course an invasive technique that is not suitable for round-the-clock monitoring. However, blood tests, and other tests of bodily fluids, can diagnose for the causes of secondary hypertension, i.e. hypertension caused by other health complications [44][15].

The main setback of ultrasound and blood checks to diagnose hypertension, as mentioned earlier, is that hypertension has already developed alongside other health complications. In other words, these methods will not be suitable for early diagnoses of hypertension, before other health complications have developed.

F. Summary

The common similarity of the methods that have been described in this section is that they do not track the pulse, i.e., unlike what is necessary for auscultatory methods. They also do not apply pressure on the patient's body. In other words, these methods intend to avoid the common complaints about auscultatory, e.g., the inconvenience and discomfort of having one's pulse being tracked. However, the trade-offs are either different kinds of discomfort, or lack of reliable measurements.

Among these methods, ECG is the most promising; expected future R&D into ECG is described later under section VIII.

VII. Conclusion

Table 1 provides a summary of problems with hypertension diagnoses and their potential solutions, as have been described in earlier sections. The overall thematic statement of Table 1 is that R&D efforts have yet to produce a reliable substitute for the gold standard of auscultatory method of upper arm cuffing for BP measurement.

However, R&D efforts for alternatives to established auscultatory methods have been going on for decades, e.g. as early as 1982 for oscillometric methods [45], and continue to today. Reliable substitutes that are more portable and convenient for long-term observation of blood pressure is still a significant goal in R&D of hypertension.

TABLE 1. Problems and potential solution(s).

Problems	***Potential Solution(s)***
Long-term observation of persistently high blood pressure is needed to diagnose hypertension	• Data from short-term observation is compared with databases of long-term observation for any patterns that indicate hypertension, with verification from medical practitioners. • Alternative diagnosis parameters, but see the entry just below.
Diagnosis parameters that are alternative to persistently high blood pressure are diagnoses for hypertension that has advanced to be comorbid with other health issues.	• These alternative parameters do not contribute to early diagnosis of hypertension, but they can still be used to determine which type of hypertension is occurring, followed by the appropriate type of treatment.
Established BP measurement methods require interruption of patients' daily activities, i.e. require rescheduling of lifestyles.	• Research and development of methods that are more portable, but these methods require study, verification, and certification by medical practitioners; see entry below.
Methods to be developed according to the auscultatory principle must have techniques that measure both the magnitudes of forces from the pulse and their timing; either on its own is not enough.	• The techniques that would be implemented must be complementary, e.g. PPG, which measure pulse magnitudes, and ECG, which measure pulse timings, and can be contained within the same device, e.g. pulse oximeters. • If a single technique is used, the variations within the readings can be analyzed to determine the coming and going of the pulse. However, there must be reliable correlation; see two entries below.
Methods that do not track the timing of the pulse do not have reliably consistent BP measurements.	• Algorithms are applied to determine the coming and going of the pulse from the variations in pressure readings; this R&D approach has yet to reach reliable results at this time of writing.
Methods that do not measure the force from the pulse do not have reliably accurate BP measurements.	• R&D efforts for this solution attempt to correlate readings that do not measure force or pressure, e.g. the electrical signals from ECG, with those that do. At this time of writing, reliable correlations have yet to be achieved.

VIII. Upcoming Innovations

Although these R&D efforts have yet to achieve their goal at this time of writing, they have produced notable results on the side.

For example, studies into PPG suggest that in addition to BP measurement, PPG has the potential to contribute to diagnoses of other diseases such as diabetes, from details such as abnormal pulse oximeter readings when they are used on diabetic individuals who otherwise have normal BP readings from upper arm cuffing [46].

Likewise, studies into ECG for use in diagnoses of hypertension have documented that ECG readings can reveal the onset of health complications that are comorbid with hypertension, especially cardiac disorders [47] and even neurological complications [46]. On the other hand, these discoveries also suggest that PPG and ECG BP measurement may need to be recalibrated in the case of patients with multiple health complications.

Although R&D efforts into BP measurement generally focus on portable and non-invasive means, there is attention on implants, which fulfill the need for long-term observation. These sensors pose the risk of interfering with the patient's physiology and have the problem of needing reliable power sources, but advances in the physical miniaturization of electronic components and wireless have been gradually addressing these [48].

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Wai Ti Chan: Writing – Original Draft Preparation;

CONFLICT OF INTERESTS

No conflict of interests were disclosed.

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Our publication ethics follow The Committee of Publication Ethics (COPE) guideline. https://publicationethics.org/

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