Blood Pressure Measurement Methodologies
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Introduction
Blood pressure (BP), the pressure of circulating blood within the arteries, is one of the vital signs measured routinely to evaluate hemodynamics. It is expressed as systolic pressure over diastolic pressure and is measured in milliliters of mercury (mmHg) above the surrounding atmospheric pressure. Measurement allows for rapid triaging and determination of patient’s clinical condition. Accurate measurements and user-friendly interphases are, therefore, crucial to allow for ease of interpretation and for appropriate follow-up measures once BP values are obtained. There are various methods to obtain BP measurements (intermittent, continuous, invasive, and non-invasive), each come with their own advantages and disadvantages. With the advancement of medical science, the most commonly used method to date would be the oscillatory method through automated monitoring devices and further developments are underway to improve both accuracy and accessibility of BP measurement.

Abstract
Blood pressure (BP) is an important vital sign used to determine a patient’s clinical status and is applied in numerous settings such as clinics or hospitals, ambulatory, and self-monitoring. It not only serves to help medical professionals guide treatment but also assists patients in self-monitoring of their clinical condition. Accurate measurements and user-friendly interphases are, therefore, crucial to allow for ease of interpretation and for appropriate follow-up measures once BP values are obtained. There are various methods to obtain BP measurements (intermittent, continuous, invasive, and non-invasive), each come with their own advantages and disadvantages. With the advancement of medical science, the most commonly used method to date would be the oscillatory method through automated monitoring devices and further developments are underway to improve both accuracy and accessibility of BP measurement.

Key words: Blood pressure, methodologies, pseudoaneurysm

Techniques of BP Measurement
BP measurement can be invasive or non-invasive. While they produce similar measurements, the invasive method measures pressure while the non-invasive method uses flow as a surrogate estimate of pressure. Invasive Arterial BP (IABP)
The gold standard of arterial pressure measurement is directly through an intra-arterial catheter. It is useful for beat-to-beat measurement of BP, an alternative when non-invasive methods of BP measurement are challenging (for example, in the cases of impaired skin integrity, obesity, or anatomical limitations - such as previous lymph node excision, limb amputation, and arteriovenous fistulas), superior in accuracy at extremes of BP or in the presence of cardiac arrhythmias and allow for frequent arterial blood gas sampling. There are no absolute contraindications to IABP monitoring; however, caution must be taken to avoid placement of an intra-arterial catheter in extremities with pre-existing vascular insufficiency. Complications which usually arise from misuse of the equipment include distal ischemia from resultant thrombosis, hematoma, pseudoaneurysm, damage to surrounding structures, infection, and erroneous intra-arterial drug administration. As IABP monitoring is not without risk, it is usually reserved for patients on vasoactive medications and unstable patients being managed in an intensive care setting or intraoperatively where scrupulous BP monitoring is vital to the patient.

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Received 07-04-2018; Accepted: 09-06-2018
Non-IABP

There are several methods of NIBP measurement, all of which involve the use of a sphygmomanometer composed of a pneumatic cuff connected to a manometer for measurement. BP measurement is obtained by occlusion of a major artery with an external cuff. The cuff is inflated to a pressure higher than the BP inside the artery which collapses it. The pressure in the cuff is then slowly released allowing gradual blood flow through the artery. The pressure in the cuff when blood flow first returns through the artery is taken as an estimate of the systolic pressure, while the pressure in the cuff when the blood flow becomes continuous is taken at the diastolic pressure.\(^5\)

The palpatory method estimates pressure through palpation of the radial pulse. The BP cuff is inflated until the radial pulse is not palpable and further inflated another 30 mmHg above that, as the BP cuff is deflated, systolic pressure is taken at the point where the radial pulse becomes palpable again. During deflation of the cuff, as the radial pulse becomes palpable again, there is also an accompanying pulsatile thrill, and the disappearance of this pulsatile thrill is taken as the diastolic pressure.\(^3\) This method is useful in the absence of a working automatic BP monitor or a stethoscope as it only requires a sphygmomanometer. The major disadvantage of this method is that the measurement of diastolic pressure subjects to a high interobserver variability. This method is also inaccurate in severe hypertension as the radial pulse may not even be palpable then.\(^3,4\) With the advancement of medical science, this method has largely been replaced with the auscultatory or automated BP measurement, and hence, there are very few studies validating the accuracy of this method.

The auscultatory method relies on the detection of Korotkoff sounds from inflation and deflation of the BP cuff for accurate measurement of systolic and diastolic pressure. The Korotkoff sounds are detected through a transducer over the brachial artery.\(^5,6\) The main drawbacks to this method are movement artifacts obscuring the true Korotkoff sounds.\(^7\) The mercury sphygmomanometer has been regarded as the gold standard for office BP measurement; however, its role has diminished greatly after the widespread ban of its use due to the known toxicities of mercury.\(^5\) Newer hybrid sphygmomanometers combining oscillatory and manual auscultatory methods have now replaced mercury devices and have also been validated by studies to be reliable alternatives.\(^9\) Regardless, the mercury sphygmomanometer still remains as a reference and standard against any new developments or validations in BP measurement.\(^9\)

The oscillatory method detects air volume variations or oscillatory amplitudes in the BP cuff during deflation and the maximal oscillation point corresponds to mean arterial pressure.\(^5,4\) As the oscillations begin around systolic pressure and continue below diastolic pressure, BP is estimated through an algorithmic interpretation of the oscillatory amplitudes and the heart rate. This, therefore, allows for automated devices to be programmed for rapid and consistent BP measurements.\(^5,10\) There is, however, no standardized method of measurement and different brands of recorders use different algorithms. Its main disadvantages are movement artifacts which will affect the bandwidth of the oscillatory signals, and variations in BP measurements depend on the type of algorithm used.\(^7\) This method has been validated against the intra-arterial and auscultatory methods with good correlation.\(^11\) Virtually, all automated BP devices, nowadays, employ this method for BP measurement for portability and self-measurement of BP which has greatly improved the accuracy of diagnosing hypertension, allowed for better monitoring of BP control, and most importantly increased patient’s compliance with antihypertensive therapy.\(^12\)

The ultrasound technique incorporates the use of an ultrasound probe over the brachial artery to detect Doppler phase shifts from the movement of the arterial wall during deflation of the BP cuff. Systolic pressure is recorded when a Doppler phase shift is detected and diastolic pressure is recorded at the point where there is a reduction in arterial wall motion.\(^2,13\) Few studies have validated this method of measurement and mostly studied measurements in infants and young children with inconclusive results.\(^14,15\)

The finger cuff method of Penaz first developed in the 1980s is a method that allows for non-invasive continuous BP monitoring by recording arterial waveform indirectly from a finger using plethysmography. The output of the plethysmography is connected to a servo system and dynamic setpoint adjuster that ensures full transmission of finger arterial BP to cuff air pressure by employing the principle of arterial unloading.\(^16\) In essence, the diameter of a finger artery is kept constant by “clamping” it with the cuff, and this is done by dynamically applying a counter pressure to the finger artery through the cardiac cycle keeping it at a volume between collapsed and fully extended allowing internal pressure to equal external pressure, also termed unloading.\(^17\) The plethysmogram is then analyzed and BP is determined during the short periods of steady cuff pressure. This method has since been adapted to show brachial pressures reconstructed from finger pressures. Some examples of such devices include the Finometer (Finapres Medical Systems, Amsterdam, The Netherlands) and the Nexfin (BMEYE, Amsterdam, The Netherlands). Some studies have validated the Nexfin device against non-invasive (namely, the auscultatory method) and invasive methods with good correlations to either method with adherence to the Association of the Advancement of Medical Instrumentation (AAMI) criteria.\(^18\) Bearing in mind, however, that the other non-invasive methods and the AAMI protocol are not intended for continuous BP monitoring and hence cannot directly be applied for comparison. The major disadvantage of the method is that it cannot be used in cases with insufficient blood flow or severe vasoconstriction to the extremities as in peripheral vascular disease or patients on high doses of vasoactive drugs.\(^19\) So far, this method has mainly been employed for research purposes.

Technical Aspects of BP Measurement from the Arm

There are significant potential sources of error or inter-operator variability with BP measurement from the upper arm. Firstly, the
cuff size in relation to the patient's arm circumference. A small cuff size will lead to overestimation of BP. As suggested by the American Heart Association (AHA), the bladder length should be 80% of the patient’s arm circumference with the ideal width being 40%.[20] [Table 1].

Secondly, the patient's position in relation to the BP cuff. The AHA recommends for the patient to be seated with legs uncrossed and back as well as arms supported. Ideally, the patient should be seated 5 min before measurement with all clothing covering the arm to be removed. The arm should be at the level of the heart such that the middle of the cuff corresponds to the level of the right atrium. The readings will be overestimated if the arm is too high and conversely underestimated if the arm is too low.[2,20] Thirdly, the rate of inflation and deflation of the BP cuff. Rapid inflation or over inflation can cause discomfort and erroneously overestimated BP readings as a result. Rapid deflation tends to underestimate systolic BP and overestimate diastolic BP. It is recommended again by AHA that the cuff be inflated to 30 mmHg above the point at which the radial pulse disappears and be deflated at a rate of 2–3 mmHg/s.[2,20] Lastly, the number of BP measurements taken to obtain mean BP values. At least two readings should be taken at intervals of 1 min or more. The average of the two readings represents the patient's BP. If the readings differ by >5 mmHg, an additional one or two more readings should be taken and the average of all the readings obtained is used.[2,21]

Table 1: Recommended cuff sizes by AHA[21]

<table>
<thead>
<tr>
<th>Adult patients (arm circumference, cm)</th>
<th>Recommended cuff size (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>22–26</td>
<td>12x22</td>
</tr>
<tr>
<td>27–34</td>
<td>16x30</td>
</tr>
<tr>
<td>35–44</td>
<td>16x36</td>
</tr>
<tr>
<td>45–52</td>
<td>16x42</td>
</tr>
</tbody>
</table>

AHA: American Heart Association

Table 2: BHS grading criteria

<table>
<thead>
<tr>
<th>Grade</th>
<th>Absolute difference between standard and test device (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>≤5 mmHg</td>
</tr>
<tr>
<td>A</td>
<td>60</td>
</tr>
<tr>
<td>B</td>
<td>50</td>
</tr>
<tr>
<td>C</td>
<td>40</td>
</tr>
<tr>
<td>D</td>
<td>Worse than C</td>
</tr>
</tbody>
</table>

BHS: British hypertension society

Devices for BP Measurement

Devices must go through a validation process before they are recommended for use in the general population. Two protocols, AAMI and British hypertension society (BHS), have been formulated for this purpose and are used in most validation studies [Table 2]. A device is recommended for use if it fulfills the AAMI criteria for systolic as well as diastolic pressure and receives a Grade A or B under the BHS protocol for systolic and diastolic pressure. Conversely, a device is not recommended for use if it fails either AAMI criteria for systolic or diastolic pressure and receives a Grade C or D under the BHS protocol for systolic or diastolic pressure.[22] A questionable recommendation is made when the device fulfills one of the two criteria. That device should not be recommended clinical use until a confirmatory study has been performed.

Grades denote the total percentage of readings within 5 mmHg, 10 mmHg, and 15 mmHg of the mercury standard. Criteria in all three respective groups must be fulfilled before the grade is bestowed.[23]

Arm Cuff Monitors

Arm cuff is used to measure BP from the brachial artery. There are various monitors that utilize an arm cuff. The mercury sphygmomanometer measures BP using a column of mercury (liquid). This also means that the BP monitor must be placed on level ground for accuracy. The aneroid sphygmomanometer consists of a spring mechanism and a metal membrane that transduces pressure from the cuff to the needle gauge. The absence of liquid in the device permits portability and measurement on uneven or even vertical surfaces such as walls. Due to its convenience and ease of use, the most widely used automated sphygmomanometer employs oscillometry to detect pressure waves.[22]

Wrist Cuff Monitors

Wrist cuff monitors utilize automated devices (oscillometry technique) to measure BP from the radial artery. This technique was developed facilitate self-BP monitoring. However, it is subjected to several areas of inaccuracies as a result of peripheral vasoconstriction or incorrect limb placement. Although it is not yet fully established, desk support position that allows the wrist to be at heart level provides the best correlation to mercury BP measurement.[24] Further advancements such as the addition of position sensors to the wrist device which only allow BP measurements when the device is at heart level has helped to mitigate the issue of limb placement. With this development, a select few devices have since been successfully validated in research settings. Nonetheless, this technique has not been validated for use as an alternative to brachial BP measurement.[25–27]

BP Measurement in Special Populations

A validation study of BP device measurement typically includes adults from the general population who are normotensive or hypertensive. However, there are always groups of individuals who fall out of the normal population, in whom where BP measured with standard protocol devices could be inaccurate. Special populations as defined by the 2018 collaborative statement from the US AAMI, the European Society of Hypertension (ESH), and the International Organization for Standardization for a universal standard for the validation of BP measuring devices are those with theoretical and clinical evidence...
of different accuracies of BP measurement on BP monitors.\textsuperscript{21,26}\ A study by Stergiou \textit{et al.} highlighted some of these individuals such as young children, pregnant women (including those with eclampsia), those with high arm circumference (>42 cm) as well as patients with arrhythmias, namely atrial fibrillation (AF). Separate validation studies are recommended for individuals in the special population after the device has gone through a successful validation in the general population.\textsuperscript{24} As per the ESH-International Protocol, evaluation and validation studies for device suitability in special populations require an additional 35 subjects with the exception of pregnant women which requires 45 subjects after a full validation study of 85 subjects has been done in the general population.\textsuperscript{30} If a device is only meant for special population use, a full 85 subject study must be done. Elderly individuals with end-stage renal failure or diabetes have also been considered as special populations; however, there is inadequate evidence of significant variation in their BP from the general population.\textsuperscript{28}

**BP Measurement in Children**

Children have different physiological and anatomical characteristics compared to adults. They have smaller arm circumferences, significant differences between brachial and aortic BP values as well as low amplitude and consequently difficult to detect Korotkoff sounds.\textsuperscript{30} To date, normative data on BP in children are still standardized on BP readings using a mercury sphygmomanometer.\textsuperscript{31} Currently, it is recommended that hypertension in children be diagnosed by the auscultatory method with ambulatory BP monitoring (ABPM) being the gold standard for diagnosis. Since automated oscillatory BP monitors are widely used, nowadays, it is prudent to know if it is a reasonable alternative to the auscultatory method. Although limited studies for the oscillatory method in the pediatric population exist, they show fair correlatability between the auscultatory and oscillatory methods.\textsuperscript{33} In addition, home BP monitoring though more accessible and practical for long-term BP monitoring has not yet been established for the diagnosis of hypertension in children.\textsuperscript{32} Nonetheless, a noteworthy point is that day ABPM is higher than home BP, whereas there is no difference in adults.\textsuperscript{33} This is attributed to their high level of physical activity in the daytime.

**BP Measurement in Pregnancy**

Due to physiological changes during pregnancy, the Korotkoff sounds are more reproducible and reliable. As such, the auscultatory method is recommended for BP monitoring in this population. The oscillatory method tends to underestimate BP in this population.\textsuperscript{23} Moreover, oscillatory signals are affected by factors such as increased peripheral vascular resistance, peripheral edema, and reduced intravascular volume which are associated with pre-eclampsia where BP is vital for diagnosis.\textsuperscript{28} Automated oscillometric BP monitors may be used as an alternative to the auscultatory method, especially in diagnosing hypertension; however, the devices must have been successfully validated in pregnancy.\textsuperscript{24} BP pressure during pregnancy depends on gestation, but largely BP >140/90 is considered to be abnormal and systolic BP >150 is considered a medical emergency, and treatment is necessary to prevent a subsequent stroke.\textsuperscript{34}

**BP Measurement in Patients with AF**

The difficulty of BP measurement in the presence of AF stems from fluctuation in ventricular filling, stroke volume, and cardiac contractility. These directly influence beat-to-beat variability of BP and contribute to large inter- and intra-observer variability compared to patients in sinus rhythm. As such, there are no standardized guidelines for BP monitoring in AF.\textsuperscript{35} The accuracy of the auscultatory method is largely unknown and automatic oscillatory measurement is uncertain.\textsuperscript{36} However, studies are starting to show a good correlation of auscultatory and oscillatory methods with IABP.\textsuperscript{37} Thus far, the best recommendation for office BP determination is still through the auscultatory method but with triplicate measurements to make up for the expected significant variations in BP. Validation studies for automated oscillatory devices when compared to auscultatory method have shown reasonable accuracy for systolic pressure but a slight overestimation of diastolic BP.

**Conclusion**

BP can be measured through different methods; however, with the growing demand for medical attention, it must be measured accurately and effectively to facilitate swift clinical judgment. Furthermore, patients play an important role in managing their own condition and their help with self-monitoring at home is critical to guide further medical management. As such, BP measurement should also be user-friendly and designed for independent or self-measurement. Thus far, the oscillatory method through an automated measurement device has allowed for this. However, we do recognize that it may not be enough in certain clinical settings, especially, when continuous BP monitoring is required. Although invasive BP monitoring provides the most accurate measurement, it is not without risk and cannot be applied in an ambulatory or outpatient setting. Development of a non-invasive continuous BP measurement method or refining of the finger cuff method of Penaz could suffice as a reasonable alternative.

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How to cite this article: Sia CSM, Hong WZ, Leo CCH. Blood Pressure Measurement Methodologies. Hypertens 2018;4(1): 72-77.

Source of support: Nil, Conflict of interest: None