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Sources of automatic office blood pressure measurement error: a systematic review

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Keywords: blood pressure (BP), automatic office BP measurement (AOBPM), Sources of measurement error, systolic and diastolic blood pressure (SBP and DBP)

Abstract

Objective: Accurate and reliable blood pressure (BP) measurement is important for the prevention and treatment of hypertension. The oscillometric-based automatic office blood pressure measurement (AOBPM) is widely used in hospitals and clinics, but measurement errors are common in BP measurements. There is a lack of systematic review of the sources of measurement errors. *Approach*: A systematic review of all existing research on sources of AOBPM errors. A search strategy was designed in six online databases, and all the literature published before October 2021 was selected. Those studies that used the AOBPM device to measure BP from the upper arm of subjects were included. *Main results*: A total of 1365 studies were screened, and 224 studies were included in this final review. They investigated 22 common error sources with clinical AOBPM. Regarding the causes of BP errors, this review divided them into the following categories: the activities before measurement, patient's factors, measurement environment, measurement procedure, and device settings. 13 sources caused increased systolic and diastolic BP (SBP and DBP), 2 sources caused the decrease in SBP and DBP, only 1 source had no significant effect on BPs, and the other errors had a non-uniform effect (either increase or decrease in BPs). The error ranges for SBP and DBP were −14 to 33 mmHg and −6 to 19 mmHg, respectively. *Significance*: The measurement accuracy of AOBPM is susceptible to the influence of measurement factors. Interpreting BP readings need to be treated with caution in clinical measurements. This review made comprehensive evidence for the need for standardized BP measurements and provided guidance for clinical practitioners when measuring BP with AOBPM devices.

1. Introduction

Hypertension is a major global public health problem. It is estimated that 1.4 billion adults worldwide suffer from hypertension and 10 million people die from it every year (Mills *et al* 2016, Padwal *et al* 2019). In addition, hypertension is positively correlated with the incidence of other cardiovascular diseases (CVDs) and is a major threat to human health (Brady *et al* 2020, Alvarez *et al* 2021, Beime *et al* 2021). The risk of death from stroke, ischemic heart disease, or other CVD doubles for every 20 mmHg increase in systolic blood pressure (SBP) and 10 mmHg increase in diastolic blood pressure (DBP) (Lewington *et al* 2002). The overall global adult prevalence rate is 31% and hypertension is highly prevalent in all major regions of the world (Mills *et al* 2016, Padwal *et al* 2019). As the prevalence of hypertension has increased year by year, the health expenditures of various countries have increased. This phenomenon is most common in low- and middle-income countries and has caused a substantial economic burden (Kulkarni 2021).

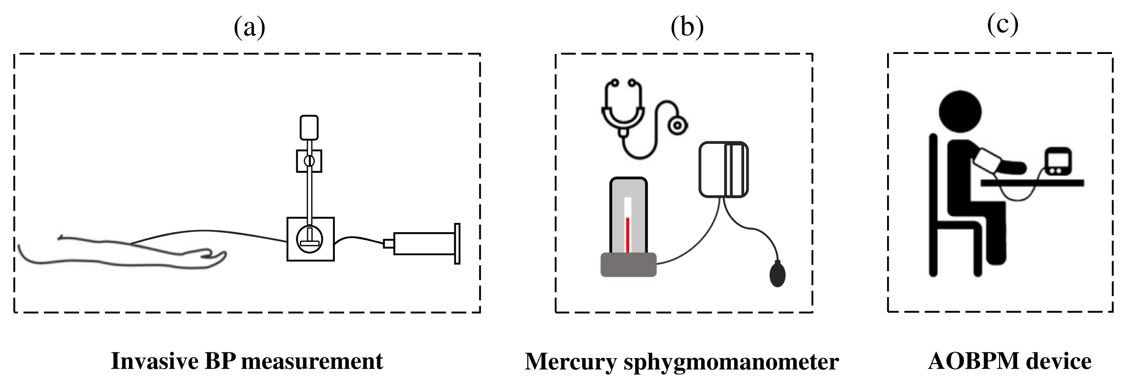

Figure 1. The evolution of BP measurement. (a)–(c) represent invasive BP measurement, mercury sphygmomanometer, and the automatic office BP measurement device, respectively.

Many countries have begun to focus on BP measurement to develop appropriate healthcare policies. Blood pressure (BP) measurement has a history of more than one hundred years (Chen *et al* 2017). Over time, the measurement method has evolved from invasive BP measurement to mercury sphygmomanometer, and automatic office BP measurement (AOBPM) (Argha *et al* 2021). Figure 1 shows the evolution of BP measurement technologies. The manual auscultatory method of using a stethoscope to listen to Korotkoff sounds for BP determination has been regarded as the gold standard for non-invasive BP measurement (Liu *et al* 2016, Argha *et al* 2021). However, the auscultatory technique requires a trained operator to estimate BP by listening to Korotkoff sounds (Pan *et al* 2017). In addition, the conventional auscultatory technique requires mercury to display the pressure change in the cuff. Mercury contamination is another major reason why mercury sphygmomanometers are gradually being replaced by AOBPM devices (Ma *et al* 2009, Buchanan *et al* 2011, Liu *et al* 2015).

The AOBPM device is widely used because of its convenience and accuracy. In most hospitals or clinics, BP measurement with the AOBPM device is a simple procedure that takes only 1–2 min (Campbell *et al* 2020). However, the BP value recorded clinically is usually affected by factors such as the measurement environment, the procedure, the patient's pre-measurement activities, and device settings (Williams *et al* 2004, Kurtz *et al* 2005, Sheppard *et al* 2019). It is estimated that an error of 5 mmHg in BP measurement will cause 84 million people to be misdiagnosed worldwide (Padwal *et al* 2019).

It has been widely agreed that accurate and reliable measurement is essential for the diagnosis and treatment of hypertension (Muntner *et al* 2019, Padwal *et al* 2019). Many international organizations, including the American Heart Association (AHA), the European Society of Cardiology (ESC), and the European Society of Hypertension (ESH) have issued detailed guidelines to improve the accuracy of AOBPM (Williams *et al* 2018, Muntner *et al* 2019). These guidelines require that BP should be recorded in a quiet and thermostatic room with subjects sitting in a chair with a supported back, without crossing legs, smoking, or exercising before the measurement. In addition, some guidelines make recommendations associated with factors such as cuff size. Unfortunately, these recommendations are not well followed and implemented in clinical practice, and the accuracy of AOBPM is often overlooked (Siddique *et al* 2021). Some previous studies have quantified the effects of different measurement conditions on the measured BPs, such as cuff size and the number of repeated measurements (Naqvi *et al* 2018, Plumettaz *et al* 2020). Despite significant efforts by many organizations to raise awareness of the consequences of inaccurate AOBPM, the problem of non-standardized AOBPM persists. However, there is a lack of a systematic review of the source of errors and the resulting BP variability.

The aim of this study is to systematically review the literature and summarize the existing evidence to describe the effect of different factors on BP measurement results and provide comprehensive evidence to support the need tab for standardized BP measurements and for updating recommendations for accurate BP measurements in clinical settings.

2. Methods

2.1. Design

A systematic review was performed with the aim of capturing potential sources of AOBPM measurement errors and summarizing the effects of different factors on BP measurement values. This review only discusses the recording of BP in the upper arm by an oscillometric-based AOBPM device in a clinical setting. Therefore, ambulatory BP measurement, wrist BP measurement, and mercury sphygmomanometer were not discussed.

The AOBPM is simply referred to as 'Blood pressure measurement' or 'BP measurement' in the following text and tables. The measurement errors were classified according to when compared to the formal measurement (before or during measurement) and the object that caused the error. In this study, all sources of error were divided into five categories: the activities before measurement, patient's factors, environment, measurement procedures, and device settings.

2.2. Search strategy

In this search strategy, the term corresponding to the error in each BP measurement is described. The literature was searched in the six online databases: Chinese Science Citation Database (CSCD), Web of Science Core Collection (WOSCC), KCI-Korean Journal Database, MEDLINE, Russian Science Citation Index (RSCI), and SciELO Citation Index. Non-English literature, animal studies, non-original articles (letters, comments, reviews), and not on upper arm BP measurements were excluded from the search process. Each measurement error and the term used to describe it are shown in table 1. The search was performed in October 2021. Figure 2 shows the flow chart of literature selection and exclusion.

2.3. Selection criteria

Two researchers (Jian Liu and Yumin Li) searched the literature in the same database simultaneously using the same search strategy. In case of discrepancies in the literature, the decision was made by discussion between the two researchers. The search strategy is shown below:

(1) English Literature.

(2) All BP results were recorded from the subject's upper arm with a cuff.

(3) Each paper included the effect of one or more measurement errors on BP values.

(4) Letters, comments, reviews, and other non-original studies were excluded.

(5) The results of all studies were publicly available.

(6) The studies were published from January 1980 to October 2021.

2.4. Literature collation and exclusion

After all the literature was completed, they were classified according to the five categories of error sources. After reviewing the abstract and conclusion of each article, the papers that did not meet the inclusion criteria were excluded. This exclusion criterion is as follows:

(1) The influence of the error source on the BP value is not given in the literature;

(2) The results of the study were unavailable or unpublished;

(3) Not belonging to any of the above error sources.

At least two researchers were responsible for each screening stage. If there is a difference in the number of studies from a particular source of error, the conclusion was determined by two researchers through consultation.

2.5. Literature supplement

Relevant studies from the reference lists of the above studies were included in this review (duplicate studies were excluded).

2.6. Data analysis and synthesis

After the above selection and screening, all literature that meets the requirements was extracted. Since this study involved the effect of multiple error sources on BP, meta-analysis is not appropriate.

3. Results

In clinical AOBPM, the accuracy of the results is affected by many factors. These factors come from the environment, the standardization of the measurement procedure, etc The measurement error was classified according to the time when it occurred and the object that caused the error. In this study, all sources of error were divided into five categories: the activities before measurement, patient's factors, environment,

Table 1. Each source of error and its search term.

Classification of error sources	Sources of error	Search terms	Paper numbers	Number of papers selected
The activities before measurement	*Stimulant drinks*	Blood pressure AND (alcohol OR energy drinks OR coffee OR water)	138	24
	Drinking water	Blood pressure measurement AND (water OR bladder distension)	15	10
	Exercise before measurement	Blood pressure measurement AND exercise	71	22
	Smoking	Blood pressure AND smoking	161	6
	Rest period before measurement	Blood pressure measurement AND period OR (rest OR wait)	90	6
Patient's factors	*White-coat effect & Masked Hypertension*	Blood pressure measurement AND (mood OR white-coat effect OR masked hypertension)	104	16
	Atrial fibrillation	Blood Pressure Measurement AND atrial fibrillation	33	6
Environment	*Measurement room temperature*	Blood pressure AND cold exposure	25	19
	Supported back	Blood pressure AND back	33	2
Measurement procedures	*Clothing*	Blood pressure measurement AND (bare arm OR clothes OR clothing OR sleeve)	12	9
	Difference between left and right arms	Blood pressure AND inter-arm	75	10
	Respiration	(Blood pressure AND breath) OR (blood pressure measurement AND (respiration OR respiratory)	29	10
	Body movement	Blood pressure AND movement	49	5
	Arm position	Blood pressure AND (arm position OR unsupported arm)	30	7
	Crossed legs	Blood pressure AND (crossed leg OR leg crossing)	14	8
	Body posture	Blood pressure AND (body position OR sitting OR supine OR standing)	190	19
	Talking	Blood pressure AND talking	24	8
	Number of repeated measurements	(Blood pressure measurement OR blood pressure reading) AND (number OR first OR single OR third OR fourth)	88	16
	Short interval between repeated measurements	(Blood pressure measurement OR blood pressure reading) AND interval	25	4
Device settings	*Excessive deflation rate*	Blood pressure AND deflation AND (speed OR rate)	6	3
	Inflation versus Deflation	Blood pressure AND deflation AND inflation	7	6
	Cuff size	Blood pressure measurement AND cuff	146	12

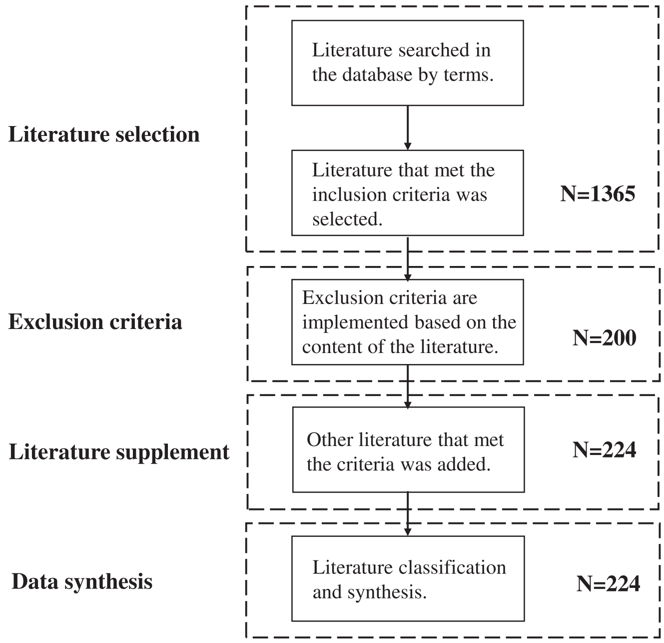

Figure 2. The flow chart for literature selection.

measurement procedures, and device settings. Based on this classification, this review included 22 error sources from 224 studies and summarised each error source on BP values.

3.1. The activities before measurement

3.1.1. Stimulant drinks

Eight studies have shown that drinking has an acute effect on BP (Dai *et al* 2002, Fazio *et al* 2004, Bau *et al* 2005, Carter *et al* 2011, Karatzi *et al* 2013, Buckman *et al* 2015, Nishiwaki *et al* 2017, McDonagh *et al* 2018). It was found that SBP increased significantly in healthy subjects within 20–30 min of acute drinking (Payseur *et al* 2020). Further, the SBP was significantly higher after drinking cold alcohol than that of normal temperature alcohol within 0–20 min after drinking (Sarafian *et al* 2018). However, the effect of red wine on BP is different. Experiments showed that BP decreased in 4 h after drinking red wine (Mahmud and Feely 2002, Fantin *et al* 2016).

Six studies have found that coffee, including hot and cold instant coffee, cold espresso and hot filtered coffee, causes an increase in BP (Noordzij *et al* 2005, Sudano *et al* 2005, Giggey *et al* 2011, McMullen *et al* 2011, Papakonstantinou *et al* 2016, Shah *et al* 2016). Compared with no coffee intake, SBP and DBP increased significantly within 3 h of coffee intake (Kurtz *et al* 2013). Due to the wide variety of energy drinks, researchers have made different controlled experiments on the effect of different energy drinks on BP. Healthy men who consumed Red Bull, caffeinated energy drinks and drinks containing fructose had a significantly higher SBP and DBP after 30 min (Grasser *et al* 2014, Grasser *et al* 2015, Attaur-Rasool *et al* 2019). However, not all energy drinks caused an increase in BP. Acute drinking of Noni juice resulted in a significant decrease in SBP, DBP, and heart rate (HR), while drinking chokeberry juice only resulted in a slight decrease in DBP (Nowak *et al* 2019).

3.1.2. Drinking water

Seven studies have shown that the salt content in drinking water was positively correlated with BP (Pomeranz *et al* 2000, Pomeranz *et al* 2002, Scheelbeek *et al* 2016, Talukder *et al* 2016, Scheelbeek *et al* 2017, Schmidt 2017, Naser *et al* 2019). It has been reported that SBP decreased significantly within 30 min of drinking water (Monnard and Grasser 2017). But another study has shown that after taking 500 ml of water, the sitting SBP, DBP, pulse pressure, and mean arterial pressure of men increased significantly after 30 min, while only SBP and pulse pressure of women increased significantly (Olatunji *et al* 2011). One study has also shown that bladder dilatation can increase BP (Choi *et al* 2011).

3.1.3. Exercise before measurement

Many studies have shown that short-term aerobic exercise is negatively correlated with SBP, and vigorous exercise is positively correlated with SBP prior to formal BP measurement (Furtado *et al* 2009, Instebo *et al* 2012, Tibana *et al* 2013, Ko and Kwon, 2014, Oliveira Dantas *et al* 2016, Cunha *et al* 2017, Somani *et al* 2018, de

Oliveira *et al* 2020, Lopes *et al* 2020, Tomeleri *et al* 2020, Ferrari *et al* 2021, Huang *et al* 2021, Nakamura *et al* 2021, Wu *et al* 2021, Yan *et al* 2021). Compared with sitting for a long time, the BP drop was not obvious for normal people within 30 min of morning exercise (Jones *et al* 2008, Carpio-Rivera *et al* 2016, Wheeler *et al* 2019). However, the range of reducing BP also depends on the types of exercise (Oliveira *et al* 2018, Costa *et al* 2020, Perrier-Melo *et al* 2020). Endurance, dynamic resistance, and isometric resistance training reduce both SBP and DBP, while combined training can only reduce DBP (Cornelissen and Smart, 2013).

3.1.4. Smoking

Six studies have shown that both acute smoking and second-hand smoking can increase BP (Vaz *et al* 2005, Lee and Jung 2006, Yarlioglues *et al* 2010, Dimitriadis *et al* 2019, Keeley *et al* 2020, Zhang *et al* 2021). Regardless of gender, within five minutes of smoking or second-hand smoking, BP rises 3.1/2.2 mmHg for SBP/DBP and returns to normal after an hour (Azar *et al* 2016). Therefore, smoking or exposure to second-hand smoke should be avoided before BP measurement.

3.1.5. Rest period before measurement

The interval is defined as a rest period between the arrival at the clinic and the official BP measurement. Four studies have shown that the shorter the rest period, the higher the SBP and DBP (MacRae and Allen, 1998, Stanforth *et al* 2000, Sala *et al* 2006, Boivin *et al* 2014). However, considering the effect of specific time on BP measurement error, papers have shown that BP is measured every minute and gradually decreases with increasing rest time at rest periods of 10 min (Nikolic *et al* 2014) and 16 min (Sala *et al* 2006). BP was as likely to rise as to fall for pregnant women after 5 min break (Duggan, 1999).

3.1.6. Other potential sources of error before BP measurement

Some studies have shown that bathing before BP measurement significantly reduces BP (Kawabe and Saito 2006, Ishikawa *et al* 2016, Tai *et al* 2019), suggesting that the subject should be told not to take a bath one hour before the formal BP measurement. In addition, satiety may also affect BP. However, since satiety is not an exact standard for the study, the effect of BP measurement on satiety was not quantified.

3.2. Patient's factors

3.2.1. White-coat effect & masked hypertension

The white-coat effect and masked hypertension (MH) are among the main factors affecting the accuracy of AOBPM (Antonio Garcia-Donaire *et al* 2012). Many studies have shown that the white-coat effect increases BP (Figueiredo *et al* 2013, Mancia *et al* 2014, Filipovsky *et al* 2016, Leung *et al* 2016, Myers *et al* 2016, Wang *et al* 2017, Andreadis *et al* 2018, Carey *et al* 2018, Humbert *et al* 2018, Myers, 2018, Tomitani *et al* 2021), while masked hypertension decreases BP relative to home BP measurement (Hanninen *et al* 2010). In addition, through the comparison of BP monitoring in manned offices and unattended offices, the results have shown that the white-coat effect becomes more obvious with age, independent of the subject's weight and gender (Adiyaman *et al* 2015, Sakuma *et al* 2020). Similarly, by comparing BP measurement with AOBPM and ABPM and Home Blood Pressure Measurement (HBPM), it was found that ABPM and HBPM were more accurate in tracking the MH effect, especially for nocturnal BP measurement (Cohen *et al* 2020).

3.2.2. Atrial fibrillation

It is well known that patients with atrial fibrillation often suffer from hypertension, some of which may be pseudo hypertension. There was a large error between invasive or auscultatory BP measurement methods and the measured oscillometric BP in patients with atrial fibrillation who measure BP (Selmyte-Besusparе *et al* 2017, Feenstra *et al* 2018, Narkiewicz *et al* 2018, Xie *et al* 2020). Some studies have shown that the age of patients with atrial fibrillation is related to the error of DBP measurement (Xie *et al* 2021). In addition, the use of arm sphygmomanometers should be reduced because of the low reliability of the measurements when measuring BP in patients with atrial fibrillation. (Halfon *et al* 2018).

3.2.3. Other potential sources of error related to patients

Pregnant women have BP changes due to prenatal weight gain. External interference can also affect fetal BP (Royal-Thomas *et al* 2015, Garcia Gonzalez *et al* 2017). However, most studies were based on the ambulatory BP measurement (ABPM) and are not within the scope of this review. The degree of arterial sclerosis can likewise have an impact on AOBPM results, with BP being overestimated in stiffer arteries due to increased resistance of the arterial wall to cuff collapse (Raamat *et al* 2011, Ma *et al* 2021b). In addition to the above factors, emotions can also affect BPs. Negative emotions increase BP (Shapiro *et al* 2001, Davydov *et al* 2012, Dich *et al* 2020, Tsutsumi *et al* 2020). Therefore, relaxed emotion is key to reducing errors in BP measurement.

3.3. Environment

3.3.1. Measurement room temperature

BP measurement is often affected by the measurement room temperature. Many studies have shown a negative correlation between room temperature and BP. When the room temperature is higher than 5 ℃, SBP and DBP decrease with higher room temperature (Kimura *et al* 2010, Hozawa *et al* 2011, Kwan *et al* 2012, Martinez-Nicolas *et al* 2015, Saeki *et al* 2015, Yang *et al* 2015, Li *et al* 2016, Madaniyazi *et al* 2016, Radin *et al* 2018, Zarzycka *et al* 2018, Yu *et al* 2020, Zheng *et al* 2020, Ringrose *et al* 2021, Zheng *et al* 2021). However, there was a parabolic relationship between room temperature and BP (Xu *et al* 2019). Their BP values are more sensitive to room temperature for some specific populations. Drinkers, women, people with low BMI, young people and the elderly are more vulnerable to the cold environment (van den Hurk *et al* 2015, Hu *et al* 2019, Zhao *et al* 2019, Kang *et al* 2020).

3.3.2. Supported back

A back-supported chair has been investigated in clinical BP measurements, and two studies reported measurement errors in SBP and DBP for unsupported backs than supported backs (Ringrose *et al* 2017, Wan *et al* 2021). Although the errors in SBP and DBP were less than 3 mmHg, a chair with a supported back was necessary to improve the measurement accuracy.

3.3.3. Other potential sources of error from the environment

All hypertension guidelines require that the measurement room be quiet and undisturbed (O'Brien *et al* 2003, Williams *et al* 2004, Kurtz *et al* 2005). Many studies have also shown that prolonged exposure to noise can lead to a significantly higher prevalence of hypertension (Paunovic *et al* 2018, D'Souza *et al* 2021, Petri *et al* 2021). However, there is no quantitative study on the effect of noise on BP measurement results.

3.4. Measurement procedures

3.4.1. Clothing

In clinical measurement, the error of BP is also caused by the thickness of the clothes. According to ESH/AHA guidelines, BP measurements should be performed on a bare arm, and the sleeve of a cardigan should be rolled up to the elbow (Ozone *et al* 2016, Ozone *et al* 2018). However, measuring BP with the cuff on clothes is commonly observed in clinical measurements to save time and privacy. Thirteen studies reported the effect of clothing on BP measurement results. Nine studies were selected based on search and exclusion strategies. Six studies reported no significant differences in BP recorded on sleeves or bare arms (Kahan *et al* 2003, Liebl *et al* 2004, Eder *et al* 2008, Ma *et al* 2008, Pinar *et al* 2010, Ki *et al* 2013, Woloszyn *et al* 2019). However, in terms of the accuracy of the data, one study reported that the results of BP measurement were the same when the thickness of the clothes was less than 2 mm (Liebl *et al* 2004). In other studies, the sleeves and rolled-up sleeves caused an increase in SBP/DBP values of 3.9/5.2 mmHg and 4.5/7.0 mmHg, respectively, compared to the bare arm. There was a significant difference in BP between bare arms and cardigan sleeves ($P < 0.001$) and over a rolled-up cardigan sleeve ($P < 0.001$) (Ozone *et al* 2018). These studies suggested that BP should be measured on the bare arm or sleeve according to the health care professional's judgment.

3.4.2. Difference between left and right arms

The difference in BP between the left and right arms has been investigated in clinical measurements. Inter arm BP difference (IAD) has attracted more and more attention in recent years because it is related to CVD and has been identified as one of the risk factors (Weinberg *et al* 2014). The BP of the right arm is usually higher than that of the left. This is because the left subclavian artery originates from the aorta and therefore forms turbulence with the right artery, thereby reducing blood flow and BP (Park *et al* 2017). Ten studies have quantified IAD in different countries and age structures (Cassidy and Jones, 2001, Lane *et al* 2002, Kimura *et al* 2004, van der Hoeven *et al* 2013, Song *et al* 2016, Kranenburg *et al* 2017, Mayrovitz 2019, Jegatheswaran *et al* 2020, Yu *et al* 2021, Ma *et al* 2021a). This inter-arm BP difference was between 3–7 mmHg, but the difference was greater than 10 mmHg for some subjects (Park *et al* 2017). Mayrovitz's study showed that IAD was not significantly different between left and right-handers (Mayrovitz, 2019). Some guidelines recommend measuring BP in both arms at least once during the initial measurement and using the arm with the higher BP value as the reference arm (Williams *et al* 2004).

3.4.3. Respiration

Although the subject is asked to maintain shallow and continuous breathing when the BP is measured, some potential deep breathing or breath-holding is not easy to notice. 10 studies from 29 studies were included in this review through search strategies (Laude *et al* 1993, Mori *et al* 2005, Zheng *et al* 2012a, Telles *et al* 2013, Zheng *et al*

2014, Chen *et al* 2016, Gui *et al* 2018, Kow *et al* 2018, Pan *et al* 2019, Webb *et al* 2020). Different breathing patterns (Pattern 1: 4.5s versus 4.5s; Pattern 2: 6s versus 2s; Pattern 3: 2s versus 6s; Pattern 4: 1.5s versus 1.5s, respectively for the duration of inhalation and exhalation) had different effects on BPs (Herakova *et al* 2017). SBP significantly reduced 3.7 ± 5.7 mmHg, 3.9 ± 5.2 mmHg, 1.7 ± 5.9 mmHg and 3.3 ± 5.3 mmHg, respectively for the four patterns abovementioned. The results of these studies indicated that deep breathing could cause a decrease in both SBP and DBP (Mori *et al* 2005, Zheng *et al* 2012a, Chen *et al* 2016, Herakova *et al* 2017, Pan *et al* 2019). In addition to deep breathing, alternate nostril yoga breathing has also been shown to lower BP, especially for people suffering from hypertension (Telles *et al* 2013). In addition, breath-holding can cause errors during BP measurements (Webb *et al* 2020). The adoption of a normal breathing pattern by the subject is an important factor in improving the accuracy of the measurement.

3.4.4. Body movement

The subjects should be asked to remain still according to all BP guidelines. Unfortunately, these guidelines are not strictly followed, and BP errors are caused due to some unconscious body movements during the measurement. A total of four studies have discussed the effect of body movement on BP measurements (Zheng *et al* 2012a, Alpert *et al* 2019, Alpert, 2019, Pan *et al* 2019, Liu *et al* 2021). The errors of SBP and DBP caused by the involuntary movement were (Mean ± SD of error) −2.93 ± 6.64 mmHg and −2.45 ± 5.48 mmHg, respectively (Alpert, 2019). However, compared to standard conditions (remain still), arm movement caused an increase in SBP and DBP by 3.7 and 5.0 mmHg, respectively (Zheng *et al* 2012a). Another study also proved this result (Pan *et al* 2019).

3.4.5. Arm position

Seven studies addressed the effect of arm position on BP measurements (Terent and Breig-Asberg, 1994, Netea *et al* 1999, Netea *et al* 2003, Mourad and Carney 2004, Familoni and Olunuga 2005, Adiyaman *et al* 2006, Guss *et al* 2008). For the standard BP procedure, the subject's forearm should be at the heart level, which is the level of the middle sternum. However, in clinical practice, it is common for the arm to be placed on a table, on chair support, or even suspended. Four studies have shown that placing the arms below the heart level overestimated SBP and DBP (Terent and Breig-Asberg, 1994, Netea *et al* 1999, Netea *et al* 2003, Adiyaman *et al* 2006). Among these studies, Netea *et al.* showed that placing the patient's arm on the chair's armrest instead of at the reference right atrial level increased SBP and DBP by 7.3 and 8.3 mmHg, respectively (Netea *et al* 1999). The results of other studies also showed that this error was between 5–10 mmHg. Therefore, measuring BPs with the correct arm position is crucial in clinical measurements.

3.4.6. Body posture

The most common posture for measuring BP is in a sitting or supine position. BP can also be measured in a standing position for some special populations. Eighteen studies indicated that body posture (sitting, supine and standing) influenced BP values (Jamieson *et al* 1990, Imai *et al* 1998, Netea *et al* 1998, Hofsten *et al* 1999, Kario *et al* 2001, Eser *et al* 2007, Lui *et al* 2008, Cooke *et al* 2009, Cicolini *et al* 2011, Breeuwsma *et al* 2017, Goh *et al* 2017, Lacruz *et al* 2017, O'Riordan *et al* 2017, Mol *et al* 2018, Privsek *et al* 2018, Kuwabara *et al* 2019, Mol *et al* 2020, Bartling *et al* 2021). It is widely believed that BP measured in the supine position was lower than in the seated position (Lacruz *et al* 2017, Privsek *et al* 2018). But in other studies, the opposite conclusion was reported. They compared the readings of the two positions and found that the SBP and DBP in the supine position were significantly higher than those in the sitting position, and the error was about 5–10 mmHg (Hofsten *et al* 1999, Netea *et al* 2003, Eser *et al* 2007, Lui *et al* 2008). The results from (Cicolini *et al* 2011, Kuwabara *et al* 2019) showed a significant increase in SBP and a decrease in DBP in the sitting position compared to the supine position. The BP difference with body posture can be partially explained by the arm position difference in each posture. In the supine position, the arms are below the heart level, when the arm should be supported by a pillow. A tendency for BP to decrease in the standing position compared to the sitting and supine positions (Eser *et al* 2007). This rate of orthostatic BP drop was associated with weakness and falls and needs to be noted, especially in the elderly (Mol *et al* 2020). Gender and the order of the experiment were also factors for the difference in results (Hofsten *et al* 1999, Cicolini *et al* 2011, Bartling *et al* 2021).

3.4.7. Crossed legs

The results of eight studies showed that crossed legs had an impact on measured BP (Foster-Fitzpatrick *et al* 1999, Peters *et al* 1999, Avvampato 2001, Keele-Smith and Price-Daniel 2001, Pinar *et al* 2004, Adiyaman *et al* 2007, van Groningen *et al* 2008, van Velthoven *et al* 2014). In addition to one study (Avvampato 2001), the results of the other seven studies all showed that the readings of SBP and DBP with crossed legs have significantly increased BPs. However, no significant increase in BP values was found when the legs were crossed at the ankles (Adiyaman *et al* 2007). The increased cardiac output may be a factor in the higher BP when the legs are crossed (van Groningen *et al* 2008). Clinicians and nurses should ensure that patients' feet are flat on the floor when measuring BP.

3.4.8. Talking

Talking is often considered a common source of errors in clinical BP measurement. Talking may cause the patient to be nervous or breathe deeply, resulting in measurement errors. Eight studies that showed the influence of talking on BP measurement were included in this review, and they all indicated that talking caused a significant increase in BP (Hellmann and Grimm, 1984, LePailleur *et al* 1996, Le Pailleur *et al* 1998, Zheng *et al* 2011b, Zheng *et al* 2012a, Qi *et al* 2017, Pan *et al* 2019). The degree of change of BP depends on the type of talking (Le Pailleur *et al* 1998).

3.4.9. Number of repeated measurements

The number of repeated measurements has always been a concern in BP measurement. This review included 16 papers on the effect of the number of measurements on BP (Mallion *et al* 2004, Figueiredo *et al* 2009, Graves and Grossardt 2010, Handler *et al* 2012, Kawabe *et al* 2012, Niiranen *et al* 2015, Salazar *et al* 2015, Saito *et al* 2016, de Oliveira *et al* 2017, Bello *et al* 2018, Burkard *et al* 2018, Tran *et al* 2018, Castro *et al* 2019, Lim *et al* 2019, Bayo *et al* 2020, Vischer *et al* 2021). 10%–20% of subjects were given different diagnoses based on different measured BP values, leading to the misclassification of normal or hypertensive individuals based on a single reading (Kawabe *et al* 2012, Tran *et al* 2018). However, it is inappropriate to discard the first BP measurement and the measurement should be repeated regardless of the first value (Graves and Grossardt, 2010, Salazar *et al* 2015, Bayo *et al* 2020). Three or more measurements should be introduced into the clinic to reduce the variability of BP (Niiranen *et al* 2015, Lim *et al* 2019, Vischer *et al* 2021).

3.4.10. Short interval between repeated measurements

The guideline recommends that an interval of more than 1 min be given between repeated measurements (Kurtz *et al* 2005). Four studies showed the effect of shortening the interval between repeated measurements (Koehler *et al* 2004, Chiolero *et al* 2008, Kruger *et al* 2018, Juraschek *et al* 2021). The BP values obtained were as accurate and reliable for the 30-second interval between BP measurements as for the 60-second interval (Juraschek *et al* 2021).

3.5. Device settings

3.5.1. Fast deflation rate

The speed of cuff inflation and deflation is an important factor restricting accurate BP measurement. 2–3 mmHg per second is an appropriate cuff deflation rate according to the AHA and ESH recommendations. This review included three studies, and they all reported the effect of the cuff deflation rate on BP (Zheng *et al* 2011a, Lin *et al* 2012, Pan *et al* 2021). High cuff deflation rates lead to SBP underestimation and DBP overestimation (Zheng *et al* 2011a, Pan *et al* 2021).

3.5.2. Inflation versus deflation

The traditional AOBPM device measures BP when the cuff is deflated. However, some devices measure BP when the cuff is inflated to save measurement time (Golara *et al* 2002). Six studies demonstrated differences in BP during cuff deflation compared to inflation (Usuda *et al* 2010, Zheng *et al* 2012b, Zheng *et al* 2013, Liu *et al* 2014, Fabian *et al* 2016, Pan *et al* 2021). Compared with the deflation of the cuff, the measured SBP is smaller and the DBP is higher during inflation (Zheng *et al* 2012b, Zheng *et al* 2013). Although this error is within 5 mmHg, it is a source of error that needs to be noted.

3.5.3. Cuff size

The size of the cuff is one of the most critical factors affecting BP measurement comfort. This review included 12 studies that investigated the impact of the cuff on BP (Sprafka *et al* 1991, Gomezmarin *et al* 1992, Verdon, 1992, Bakx *et al* 1997, Berntsen *et al* 1998, Arafat and Mattoo, 1999, Bur *et al* 2000, Oliveira *et al* 2002, Fonseca-Reyes *et al* 2009, Veiga *et al* 2009, Muhamed *et al* 2016, Li *et al* 2020). Four studies explored the effect of the cuff on different subject populations, such as pregnant women (Oliveira *et al* 2002) and adolescents (Gomezmarin *et al* 1992). The standard-size cuff is not suitable for them. A specially designed cuff should be designed for these subjects to obtain more accurate BP measurements. Generally speaking, the small size of the cuff led to an increase in BP values and larger cuff sizes resulted in lower BP values. This BP error is usually between 5 and 10 mmHg (Verdon 1992, Veiga *et al* 2009). In summary, the right cuff size needs to be determined by the subject's arm circumference and type, which can be a challenge for doctors in hospitals or clinics.

Table 2. Explanation of sources of error in clinical measurements.

Classification of error sources	Sources of error	Analysis
The activities before measurement	*Stimulant drinks*	The sympathetic nervous system is activated
	Drinking water	
	Smoking	
	Exercise before measurement	The elasticity of blood vessels is improved and the hardness of arteries is reduced
	Rest period before measurement	Stabilize the patient's emotions
Patient's factors	*Atrial fibrillation*	The heart rhythm is affected
	White-coat effect & Masked Hypertension	The sympathetic nervous system is activated
Environment	*Measurement room temperature*	Peripheral resistance and cardiac output are increased
	Supported back	The sympathetic nervous system is activated
Measurement procedures	*Clothing*	The stability of the pulse wave is destroyed
	Talking	
	Respiration	
	Body movement	
	Arm position	The measured posture does not conform to the recommended procedure
	Crossed legs	
	Body posture	
	Difference between left and right arms	
	Number of repeated measurements	Accidental errors in measurements
	The short interval between repeated measurements	
Device settings	*Excessive deflation rate*	Inaccuracy of equipment or human error
	Inflation versus Deflation	
	Cuff size	

3.5.4. Other potential sources for device settings

American National Standards Institute/Association for the Advancement of Medical Instrumentation/International Organization for Standardization (ANSI/AAMI/ISO) requires the overall mean and SD between the BP measurement method and the reference equipment are less than 5 mmHg and 8 mmHg, respectively. During the use of the device, the depletion of the AOBPM device can lead to some potential errors in BP measurements. However, these errors are not observed by clinicians and nurses. Therefore, these aneroid sphygmomanometers need to be brought back to ISO/AAMI standards through a certain calibration process to reduce errors. This service is usually provided by the device manufacturer, although this implies a high cost. Some hospitals will also set up a department to calibrate regularly. A calibration interval of one year is generally considered to be appropriate (Muntner *et al* 2019).

For clinical BP measurement, the experience and professional knowledge of the doctor or nurse are crucial (Zhang *et al* 2017). Not all clinical practitioners are professionally trained in BP measurement (Rabbia *et al* 2013), such as standard BP measurement procedures, cuff selection, etc, which is often the main source of error (Roubsanthisuk *et al* 2007). Some studies have shown that professional training can improve the accuracy of BP measurements (Roubsanthisuk *et al* 2007, Rabbia *et al* 2013, Ulusoy *et al* 2018).

4. Discussion

4.1. Explanation of BP measurement errors

This review included 22 sources of BP error in clinical measurement from 224 studies. Table 2 gives the potential explanation of these measurement errors. For the first category, this error comes from the patient's activities before measurements, such as stimulating drinks and exercise. These studies have shown that alcohol, coffee, and some energy drinks contain ethanol, caffeine, fructose, and other substances that could activate the sympathetic nerve to increase BP (Grasser *et al* 2014, Brothers *et al* 2017, Basrai *et al* 2019). For red wine, there were flavonoids in the components of grapes, resulting in lower BP (Mahmud and Feely, 2002). Similarly, smoking also activates the sympathetic nerve through nicotine in tobacco to increase BP. Exercise reduces BP by increasing vascular elasticity and reducing arterial stiffness (Carpio-Rivera *et al* 2016). Sala *et al.* 's study has shown that systemic vascular resistance is the smallest and the impact on BP is the smallest after supine rest (Sala *et al* 2006). Therefore, it is required to avoid exercise before BP measurement, and measurements should be taken after a period of rest.

The second category considers the effect of the patient's factors on BP measurement. The measurement error for patients with atrial fibrillation is caused by irregular heart rhythms (Xie *et al* 2021). For the influence of the white-coat effect, some studies have shown that similar to the influence of emotion on BP, AOBPM causes negative emotion to some measurers, accelerate HR, activate sympathetic nerve, and cause pseudo hypertension (Antonio Garcia-Donaire *et al* 2012, Banu *et al* 2015, Dich *et al* 2020).

The environment of the measurement room is considered the third category. All hypertension guidelines suggest that measurements should be taken in a temperature-controlled room that is quiet and undisturbed. In addition, an office chair with a supported back is needed. And for the unsupported back, Wan *et al.* showed that this posture activated the sympathetic nervous system. This change is the main reason for the increase in BP. Low room temperature increases people's peripheral resistance and cardiac output to increase BP (Tu *et al* 2013). This phenomenon is also associated with subjects' fitness. The BP of people who often exercise is not very sensitive to temperature. On the contrary, the elderly, women, young people and people with a high BMI index are more sensitive to the cold effect (Kang *et al* 2020).

The standard measurement procedure is the most important aspect of clinical BP measurement, and it is also the category with the most sources of error (10 errors from measurement procedures were included in this review). For these sources, this review attributed the causes of the error to three. The first one includes clothing, cuffs, breathing, talking, body movement, etc The pulse wave recorded during oscillometric BP measurement is very weak with a small amplitude, which is easily disturbed. These behaviors destroy the stability of pulse waves, leading to measurement errors. The second error source includes inter-arm variation, sitting position, arm position, etc All hypertension guidelines provide detailed recommendations on the posture of BP measurements. The subjects are seated on a supported chair with their feet on the ground and their left arm supported at heart level. Accurate BP values should be recorded under this standard procedure. Unfortunately, the above incorrect measurement procedure results in that the reliability of BP cannot be guaranteed. The last one includes the measurement interval and the number of repeated measurements, which contributed to accidental errors in BP measurements.

This review considered the measurement device and the operator for the last category of error sources. For clinical practitioners, the accuracy of the device is critical. However, the error of the AOBPM device cannot be completely avoided during clinical use, so recalibration of the device is necessary. In addition to device errors, operator (usually by clinicians or nurses) errors or misinterpretations are also major sources of error. Of course, errors are inevitable, but operators need more patience and multiple measurements to obtain accurate clinical data.

4.2. Strengths and limitations

Although many studies have supported the recommendations for the standardization of BP measurement, no study has systematically described the sources of error in clinical practice for AOBPM. Table 3 illustrates the quantitative effect of each type of error on BP. Since the new century, there has been a gradual increase in the number of studies on BP errors. Studies from the last four decades (1980–2021) were summarized in this review to make the data more comprehensive and representative. Timely data can be convenient for other researchers, and this study shortened the literature search time for other researchers.

This study has some limitations due to the constraints of many factors. First, the literature was searched in the following six online databases: CSCD, WOSCC, KCI-Korean Journal Database, MEDLINE, RSCI, and SciELO Citation Index. Limited by the availability of online databases and time, other databases were not considered. Second, this review incorporates all studies since 1980 by comparing the availability of results in the literature. Many results are not available in papers prior to the 1980s. The mercury sphygmomanometer was the main method of measuring BP in the last century. Although AOBPM was used in some studies, it was not mainstream. Third, the choice of search terms is also a potential constraint. Two or more researchers deliberated each terminology decision. This review selects appropriate terms as much as possible, but there may be some loopholes (some terms were not used in a few studies), which is also the direction of efforts in the future. Fourth, the gold standard for BP measurement is still the Mercury sphygmomanometer which is still used in some clinics (Liu *et al* 2015), especially in low-income countries. This review only discusses the recording of BP in the upper arm by an oscillometric-based AOBPM device in a clinical setting and mercury sphygmomanometers were not discussed. Fifth, this review has focused on the effects on BP measurements before and during BP measurements and has not paid much attention to other physiological factors, including potential physiological changes due to season and time of day, or other types of disease (e.g., diabetes or other heart valve disease), that need to be considered as factors affecting BP measurements. Sixth, in the reviewed literature, there is enough research on the sources of error in BP measurement to provide a more comprehensive recommendation or requirement for BP measurement, as well as to give a reference for the error value caused by each source of error. However, most of the literature does not comprehensively consider the impact of patients' own potential physiological changes

Table 3. The effect of different error sources on SBP and DBP.

Classification of error sources	Sources of error	Effect on SBP (mmHg)	Effect on DBP (mmHg)	
The activities before measurement	*Stimulant drinks*	−3–13	−3–11	
	Drinking water	↑ 1–9[a]	↑ 1–8[a]	
	Exercise before measurement	−14–33	−6–7	
	Smoking	↑ 3–23	↑ 2–19	
	Rest period before measurement	−11–1	−4–2	
Patient's factors	*White-coat effect & Masked Hypertension*	−13–15[b]	−10–8[b]	
	Atrial Fibrillation	↑ 0–24	↑ 2–18	
Environment	*Measurement room temperature*	↑ 0–9	↑ 0–6	
	Supported back	↑ 1–2	↑ 1–2	
Measurement procedures	*Clothing*	NS[c]	NS[c]	
	Difference between left and right arms	↑ 3–7	↑ 2–5	
	Respiration	↓ 2–11	↓ 1–6	
	Body movement	↑ 1–7[a]	↑ 3–9[a]	
	Arm position	↑ 5–16	↑ 4–14	
	Crossed Legs	↑ 3–11	↑ 2–6	
	Body posture	−3–10[d]	−3–15[d]	
	Talking	↑ 4–22	↑ 4–17	
	Number of repeated measurements	↓ 1–14	↓ 0–4	
	The short interval between repeated measurements	↑ 3–7	↑ 1–4	
Device settings	*Excessive deflation rate*	↓ 1–4	↑ 1–7	
	Inflation versus Deflation	↓ 3–4	↑ 2–3	
	Cuff size	*larger*	↓ 3–9	↓ 2–8
		smaller	↑ 4–19	↑ 2–13

[a] : Only a few studies (usually only one) show that it causes a decrease in BP.
[b] : Effect error values > 0 are caused by the White-coat effect and < 0 are caused by Masked Hypertension.
[c] : Only two studies show an effect on BP.
[d] : There is no uniform conclusion on the increase or decrease of BP in a supine position.

on BP measurement results, but only focuses on one factor as a BP error analysis. Also, there are not too many papers emphasizing the influence of the number of BP measurements, the time point of measurement, and the age of the patient on the measurement results. Finally, non-English studies were not included in this review.

4.3. Recommendation

Accurate and reliable BP measurements depend not only on clinical practitioners but also on the combined efforts of patients and manufacturers. Table 4 shows the recommendations for all three.

4.3.1. Recommendations for patients

The influence of the patient on BP has been overlooked. Clinical practitioners usually default to patients not doing anything that would affect the accuracy of the measurement before the official measurement. The patient should avoid stimulating drinks (coffee, alcohol, etc), exercise and smoking for 30 min before the formal measurement. In addition to this, they need to ensure that the bladder has been emptied. Any history of cardiovascular disease (such as atrial fibrillation) needs to be disclosed to the doctor before the measurement begins. If the patient is pregnant or has a rapid HR, these are also things that need to be proactively told to the doctor. The most important thing for patients is to follow the clinician's arrangement and answer their questions honestly.

4.3.2. Recommendations for clinical practitioners

Standardization of measurement procedures is usually ensured by the clinician or nurse in clinical practice. For every clinical practitioner, the importance of understanding the standard BP measurement procedure is unquestionable. This review made recommendations for standard BP measurement procedures based on the summary of other studies. The patients should be seated on a supported chair with their feet on the ground and their left arm supported at heart level. They should take off their coat and put their left arm on the edge of the table. All patients are asked to rest for at least 5 min on a chair to stabilize their cardiovascular system. It is not allowed to move any part of the body or talk during BP measurement unless otherwise specified. The patients should breathe shallowly and continuously. If there is any distraction, measurements should be repeated. At the

Table 4. Recommendations for different objects in clinical measurements.

Recommended objects	Specific instructions for recommendations
Patients	① Avoid acute stimulating drinks (e.g., alcohol, tea, coffee, etc), acute smoking, bathing and acute exercise for 30 min before measurement. ② Avoid taking any drugs that affect BP. ③ The patient should ensure that the bladder is emptied. ④ Avoid acute eating. ⑤ Have at least 10 min of rest before formal measurement. ⑥ In advance, special patients (pregnant women, patients with cardiovascular disease and white coat effect) need to inform the clinician.
Clinical practitioners	① Ensure the measurement room is constant temperature and quiet. ② BP equipment used needs to be validated. ③ The chair has a supported back. ④ The time of BP recording (morning or evening) should be uniform for the same subject (Fasting measurement in the morning is recommended). ⑤ The size of the cuff is determined by the patient's arm circumference. ⑥ Remove the clothing covering the upper arms and the sleeves should not be rolled up. ⑦ BP is recorded in both arms at the first visit, using the arm with the higher reading as the reference arm. ⑧ The subject's forearm must be at the heart level, which is the level of the middle sternum. ⑨ Patients are not allowed to talk or move any part of their body. ⑩ Feet flat on the ground. ⑪ The patient should sit on an office chair with a supported back. ⑫ Three or more repeated measurements at intervals greater than 1 min ⑬ The interval between regular training should not exceed 6 months.
Manufacturers	① The validation process of the equipment must be standardized. ② The deflation rate of 2–3 mmHg is appropriate. ③Regardless of the type of the AOBPM device, its accuracy and reliability must be ensured. ④ A complete instruction manual is a must. ⑤ BP measurement devices suitable for special groups also need to be considered.
Researchers	① Improving the measurement accuracy of sensors in BP monitors. ② Combining multiple physiological signals to analyze BP trends. ③ The effect of the above factors on AOBPM is considered through other sensor measurements, such as the effect of room temperature on AOBPM through temperature sensors. ④ Oscillometric pulse wave signal quality assessment. ⑤ Three consecutive BP measurements are taken and the average is calculated as the final AOBPM result.

first visit, BPs in both arms should be recorded. If the BP of one arm is consistently higher than the other arm (such as 10 mmHg), use the arm with the higher reading as the reference arm. The cuff size depends on the patient's arm circumference, which is determined by the clinician's experience. A single measurement should not be taken as the final result. The mean of three or more measurements is an appropriate choice. Patience and attentiveness are necessary for clinical practice, although this is a challenge for most clinicians and nurses. In general, the standardization of BP measurements and proficiency in measurement are the main ways to reduce errors. Clinical practitioners should receive regular training on the importance of BP measurement and the correct measurement techniques.

4.3.3. Recommendations for manufacturers

For each device manufacturer, the development of new technology is based on the accuracy of the AOBPM device being ensured. The validation process for all devices needs to be strictly followed before they are launched. A regular recalibration service and detailed instructions for AOBPM devices are necessary. In addition, the suitability of AOBPM devices for special groups (such as pregnant women, older people) also needs to be considered. This review provides support for clinical practitioners in recording accurate BP values.

4.3.4. Recommendation for researchers

For researchers in this field, it is also a challenge to improve the accuracy of the oscillometric BPs. Among the currently available ways to improve accuracy, performing BP measurements three times and subsequently calculating the average of the three measurements is an effective method. It is also important to consider or improve the measurement accuracy of the sphygmomanometer's sensors, as well as to improve the BP measurement accuracy through more accurate algorithms. For example, combining multiple physiological signals to analyze the measurement error, or measuring the actual effect of the above factors on BP measurement through physiological signals collected by other sensors. For instance, a signal quality assessment is performed as one of the conditions to determine whether it can satisfy the BP measurement.

4.4. Impact on clinical measurement

The most confusing aspect for clinical practitioners is inaccurate BP and its contributing factors. And this study summarized these factors and provided quantitative evidence for them. The accuracy of BP measurements is influenced by many factors and it is not practical to control for all variables. The abnormal BP value needs to be treated with caution in clinical measurement. Clinical practitioners should increase the number of measurements and standardize the measurement procedure rather than as the final clinical measurement results.

4.5. Future direction

The AOBPM device based on the oscillometric method is still mainstream for clinical BP measurement. It does not require much expertise and is less costly. Standard BP measurement procedures have been published in the guidelines of many hypertension organizations. However, these guidelines are unfamiliar to some clinical practitioners as they are often cumbersome. A suitable guideline should be simple, short, multilingual, and widely accessible. The popularisation of these guidelines and the organization of regular training is essential. This is a challenge for international organizations and each country.

5. Conclusion

Hypertension is a global public health problem, and the increasing incidence of hypertension each year is placing an ever-increasing financial burden on countries. The importance of reliable and accurate BP measurement is without doubt. In summary, this review summarized 22 sources of error in clinical BP measurements and their influence on BP values and provided comprehensive evidence for the need for BP measurements. On this basis, this study made recommendations for standard BP measurement and provided guidance for clinical practitioners when measuring BP with AOBPM devices.

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