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Review

A Comprehensive Review and Comparison of Non-invasive Blood Pressure Measurement Strategies

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Abstract:

Currently, the most commonly used non-invasive blood pressure measurement method is office blood pressure monitoring. However, the blood pressure based on a single measurement may be inaccurate, and the diagnosis of hypertension requires multiple outpatient monitoring. Ambulatory and home blood pressure monitoring can be used to confirm the diagnosis of hypertension, identify patients with white-coat hypertension/white-coat uncontrolled hypertension or masked hypertension/masked uncontrolled hypertension, and predict the risks of cardiovascular diseases. The high accessibility of home blood pressure measurement allows people to perform multiple continuous monitoring at home by themselves. Ambulatory blood pressure monitoring can provide more information than home blood pressure monitoring, such as average 24-hour blood pressure, daytime blood pressure, night-time blood pressure, and nocturnal blood pressure dipping pattern. The integration of office blood pressure monitoring, home blood pressure monitoring, and ambulatory blood pressure monitoring could help physicians to improve the diagnosis and management of hypertension.

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1. Introduction

Hypertension is highly associated with various cardiovascular diseases, including myocardial infarction, stroke, and heart failure. It is a significant risk factor for tens of millions of deaths worldwide each year [1]. Since hypertension is a modifiable risk factor, accurate blood pressure (BP) measurement is essential in diagnosing and treating hypertension correctly.

By far, the most common method of noninvasive BP measurement is office BP monitoring (OBPM). From traditional mercury sphygmomanometers with a stethoscope to modern electronic oscillometers, human bias in BP measurement may be reduced. However, there are still other external factors that may affect this "snapshot" single measurement, including the presence of smoking, eating, exercise, and caffeine intake within 30 minutes before measurement [2]. Although most clinical

trials define hypertension from OBPM, its accuracy and standardized procedures are still criticized by many scholars. As a result, the development and research of out-of-office BP monitoring have been growing. Since 2011, a growing number of societies and guidelines have recommended out-of-office BP measurement, including ambulatory BP monitoring (ABPM) or home BP monitoring (HBPM), as more accurate BP measurement tools [3–5].

2. Ambulatory blood pressure monitoring (ABPM)

This non-invasive BP measurement method is performed at appropriate time intervals (15 to 30 minutes during the day and 30 to 60 minutes at night while sleeping) for 24 to 48 consecutive hours using a wearable device [6]. It has been shown in some studies that if long-term measurements are not achieved, measurements of 8 consecutive hours can be fairly representative [7]. Continuous records are calculated to obtain average 24-hour BP, daytime BP, and night-time BP. Night-time BP is usually 10% to 20% lower than daytime BP (nocturnal dipping). Patients with a nocturnal BP drop of less than 10% are defined as non-dippers, and those with a nocturnal rise rather than a fall in BP are reverse-dippers. Although ABPM is more impervious to interference from external factors and provides multiple sets of BP parameters, this type of BP monitoring is not available in most clinics due to a lack of expertise, high costs, and the fact that most medical insurance does not cover it. In addition, the results obtained by ABPM only reflect the BP status during the time the device is worn. Serial tracking is still necessary, but it has a negative impact on medical compliance.

3. Home blood pressure monitoring (HBPM)

Single-visit OBPM is susceptible to error due to external factors, and dynamic BP monitoring is not yet widespread. HBPM, also known as self-measured BP, is a semi-automatic measurement method with low cost and high accessibility, allowing not only for multiple measurements at different times and dates but also for timely recording when patients feel unwell. The use of HBPM can be used as a reference to identify white-coat hypertension/white-coat uncontrolled hypertension or masked hypertension/masked uncontrolled hypertension at the time of the return visit. However, this type of monitoring is still susceptible to pre-measurement factors, so patients should be reminded to avoid caffeine or smoking and to empty their bladders prior to measurement.

4. The definitions of hypertension

The definition of hypertension is constantly updated. In the hypertension guidelines published by the Taiwan Society of Cardiology in 2015, the diagnosis of hypertension is based on OBPM with a cut-off value of 140/90 mmHg, while the recommended cut-off values for HBPM and ABPM are provided for reference (Table 1) [8,9]. Nevertheless, the American Heart Association updated the recommended OBPM cut-off values to 130/80 mmHg in the 2017 hypertension guidelines [10], and the OBPM cut-off values recommended by the European Society of Cardiology in 2018 were 140/90 mmHg [11]. Studies in China, Hong Kong, and Korea found that patients with systolic BP between 130 and 139 mmHg were at significant risk for cardiovascular disease [12–14]. A large clinical trial of 8,511 Chinese (Strategy of Blood Pressure Intervention in the Elderly Hypertensive Patients, STEP) also found that intensive treatment with a systolic BP target of 110 to less than 130 mm Hg had a lower incidence of cardiovascular events than standard treatment with a target of 130 to less than 150 mmHg (hazard ratio, 0.74; 95% confidence interval [CI], 0.60 to 0.92; P=0.007) [15]. Therefore, the Taiwan Society of Cardiology updated the cut-off values in the hypertension guidelines in 2022 [16], which are the same as the American Heart Association's 2017 guideline target of 130/80 mmHg (see Table 1 for details) [10].

A consensus document recommends HBPM as a diagnostic tool for hypertension in Asian patients [17]. In addition, relevant Asian studies have shown that daytime BPs of HBPM and ABPM are good predictors of cardiovascular diseases [18,19]. BP measured in daytime by HBPM is a better predictor of

Table 1. Definitions of hypertension according to the Taiwan Society of Cardiology, the American Heart Association, and European Heart Association.

Guidelines	OBPM (mmHg)	HBPM (mmHg)	Daytime BP (mmHg)	Night-time BP (mmHg)	24-hour BP (mmHg)
2015 Guidelines of the Taiwan Society of Cardiology [9]	≥140/90	≥135/85	≥135/85	≥120/70	≥130/80
2022 Guidelines of the Taiwan Society of Cardiology [16]	≥130/80	≥130/80			
2017 Guidelines of the American Heart Association [10]	≥130/80	≥130/80	≥130/80	≥110/65	≥125/75
2018 Guidelines of the European Society of Cardiology [11]	≥140/90	≥135/85	≥135/85	≥120/70	≥130/80

stroke than that in evening [20]; HBPM measurements performed in the morning for seven consecutive days showed better correlation with left ventricular mass index than a single ABPM measurement. In some clinical trials and meta-analyses, HBPM has shown to be as good as ABPM in predicting cardiovascular diseases and hypertension-mediated organ damage [21–23]. Since ABPM is not yet common in Taiwan, the hypertension guidelines published by the Taiwan Society of Cardiology in 2022 suggest that the definition of hypertension should be based on HBPM [16]. Considering that patients may not be able to perform HBPM, OBPM uses the same hypertension cut-off values as HBPM [16], based on worldwide hypertension cut-off values and the results of studies that focus on disease prediction [11,24,25].

In most cases, the ABPM and HBPM values are slightly lower than the OBPM values by 5-10 mmHg. The American Heart Association and European Society of Cardiology also provides recommended values for ABPM (see Table 1 for details). Considering that ABPM is not common in Taiwan's current medical system, and the fee is not yet covered by the National Health Insurance, the Taiwan Society of Cardiology did not include cut-off values for target daytime BP, night-time BP, and average 24-hour BP in the hypertension guidelines issued in 2022 [16]. However, the cut-off values for ABPM listed in the 2015 guidelines can still be used as a reference [9]. It is important to note that patients do not always exhibit hypertension in the clinic, at home, or during ABPM. Medical societies have recommended that, in addition to BP monitoring in at least two separate clinic visits, HBPM or ABPM should also be recorded to improve diagnostic accuracy and to further classify different BP presentations by comparing the results of different BP monitoring [10,11].

5. Different hypertension phenotypes

Patients are classified as normotension or sustained hypertension when the results of OBPM and HBPM/ABPM are the same. However, if two monitoring results are different, the patient may have white-coat hypertension or masked hypertension for those patients without antihypertensive drugs. The former showed hypertension at OBPM and normotension at HBPM/ABPM, while the latter showed the opposite. Patients taking antihypertensive drugs in these two groups are classified as white-coat uncontrolled hypertension and masked uncontrolled hypertension, respectively [10,11,26] (Table 2).

Patients with white-coat hypertension or white-coat uncontrolled hypertension do not require additional antihypertensive drugs because their out-of-hospital BP usually remains normal despite the elevated office BP readings [27,28]. Conversely, BP readings in patients with masked hypertension or masked uncontrolled hypertension will reveal that their out-of-hospital BP is usually high. Although a related large randomized controlled trial is still ongoing [29], past studies have shown that these

Table 2. Definitions of hypertension phenotypes.

Classification	Antihypertensive drugs	OBPM	HBPM or ABPM
White-coat hypertension	No	At or above threshold for hypertension	Below threshold for hypertension
White-coat uncontrolled hypertension	Yes	Above goal BP	At or below goal BP
Masked hypertension	No	Below threshold for hypertension	At or above threshold for hypertension
Masked uncontrolled hypertension	Yes	At or below goal BP	Above goal BP

patients are at high risk for hypertension-related complications, and antihypertensive drugs should be given or intensified [10].

6. Prediction of hypertension complications by different BP monitoring methods

Measurements of average 24-h, daytime, and night-time ABPM values show better associations between hypertension and all-cause mortality than those obtained using OBPM [30–33]. ABPM measurements have been shown to be a better predictor of cardiovascular diseases in patients with resistant hypertension taking three different classes of antihypertensive drugs at maximally tolerated doses [34,35]. In addition, night-time BP from ABPM is a better predictor of end-stage renal disease than OBPM readings [36,37].

HBPM has not been studied as much as ABPM [38], but its ability to predict cardiovascular disease is also superior to OBPM [39,40]. A 2016 systematic review of nine studies comparing ABPM and HBPM found that the ABPM values in some studies, corrected by HBPM results, were significantly predictive of cardiovascular disease incidence but not vice versa [41]. Although there is no conclusive evidence that ABPM is superior to HBPM, ABPM has better predictive power than OBPM, and its nocturnal dipping pattern has independent predictive power [42,43].

7. Nocturnal BP dipping patterns

A 10% to 20% drop in nocturnal BP is a normal physiological condition (nocturnal dipping) [44], and it is currently thought that the underlying mechanism may be related to the decrease in the concentrations of epinephrine and norepinephrine [45] and the resetting of the vagal reflex at night [46]. The pathophysiology of nocturnal non-dipping (<10% decrease) or reverse dipping has not been determined. It is likely associated with abnormal nocturnal sympathetic nerve activity [47] and sleep apnea [48]. Impaired sodium excretion by the kidneys may also play a role [49]. As sodium excretion decreases during the day, the body needs to raise BP at night to speed up sodium excretion [50].

Several studies analyzing the correlation between the nocturnal BP dipping patterns and diseases have found that non-dipping and reverse dipping patterns are predictive of all-cause mortality, cardiovascular disease, stroke [31,51–54], atrial fibrillation [55,56], and the decline of renal function [57,58].

Extreme dipping, in which nocturnal BP is 20% lower than daytime BP, may lead to silent myocardial ischemia [59] and may also be associated with cerebrovascular disease [53,60,61] and cognitive decline [62]. The cause of the extreme dipping in nocturnal BP is unknown, but the brain lesions and cognitive decline may be associated with insufficient cerebral perfusion [**?**].

8. Conclusion

The combined uses of OBPM, HBMP, and ABPM can assist in establishing the diagnosis of hypertension and identifying white-coat hypertension/white-coat uncontrolled hypertension and masked hypertension/masked uncontrolled hypertension. HBMP and ABPM can better predict the development of cardiovascular diseases, and ABPM provides additional indicators such as average 24-hour BP, daytime BP, night-time BP, and nocturnal BP dipping patterns. Nocturnal BP patterns detected by ABPM, such as non-dipping, reverse dipping, and extreme dipping, can further predict disease progression in terms of death, cardiovascular disease, stroke, atrial fibrillation, and cognitive decline. However, ABPM is more likely to cause patient discomfort, has low penetration, and is expensive, while HBPM is more accessible to the public, offers a wide range of measurements, and has data reliability and validity comparable to OBPM. In this modern era, where personalized medicine is on the rise, and wearable monitors are leading the way, HBPM and ABPM may soon become more accessible, allowing for more accurate prediction of disease processes and earlier prevention and control.

Conflicts of Interest:
The authors declare no conflict of interest.

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