Accurate assessment of blood pressure is fundamental to the provision of safe obstetrical care. It is simple, cost effective, and life-saving. Treatments for preeclampsia, including antihypertensive drugs, magnesium sulfate, and delivery, are available in many settings. However, the instigation of appropriate treatment relies on prompt and accurate recognition of hypertension. There are a number of different techniques for blood pressure assessment, including the auscultatory method, automated oscillometric devices, home blood pressure monitoring, ambulatory monitoring, and invasive monitoring. The auscultatory method with a mercury sphygmomanometer and the use of Korotkoff sounds was previously recommended as the gold standard technique. Mercury sphygmomanometers have been withdrawn owing to safety concerns and replaced with aneroid devices, but these are particularly prone to calibration errors and regular calibration is imperative to ensure accuracy. Automated oscillometric devices are straightforward to use, but the physiological changes in healthy pregnancy and pathologic changes in preeclampsia may affect the accuracy of a device and monitors must be validated. Validation protocols classify pregnant women as a “special population,” and protocols must include 15 women in each category of normotensive pregnancy, hypertensive pregnancy, and preeclampsia. In addition to a scarcity of devices validated for pregnancy and preeclampsia, other pitfalls that cause inaccuracy include the lack of training and poor technique. Blood pressure assessment can be affected by maternal position, inappropriate cuff size, conversation, caffeine, smoking, and irregular heart rate. For home blood pressure monitoring, appropriate instruction should be given on how to use the device.

The classification of hypertension and hypertensive disorders of pregnancy has recently been revised. These are classified as preeclampsia, transient gestational hypertension, gestational hypertension, white-coat hypertension, masked hypertension, chronic hypertension, and chronic hypertension with superimposed preeclampsia. Blood pressure varies across gestation and by ethnicity, but gestation-specific thresholds have not been adopted. Hypertension is defined as a sustained systolic blood pressure of $\geq 140$ mm Hg or a sustained diastolic blood pressure of $\geq 90$ mm Hg. In some guidelines, the threshold of diagnosis depends on the setting in which blood pressure measurement is taken, with a threshold of $140/90$ mm Hg in a healthcare setting, $135/85$ mm Hg at home, or a 24-hour average blood pressure on ambulatory monitoring of $>126/76$ mm Hg. Some differences exist among organizations with respect to the criteria for the diagnosis of preeclampsia and the correct threshold for intervention and target blood pressure once treatment has been instigated. Home blood pressure monitoring is currently a focus for research. Novel technologies, including early warning devices (such as the CRADLE Vital Signs Alert device) and telemedicine, may provide strategies that prompt earlier recognition of abnormal blood pressure and therefore improve management.

The purpose of this review is to provide an update on methods to assess blood pressure in pregnancy and appropriate technique to optimize accuracy. The importance of accurate blood pressure assessment is emphasized with a discussion of preeclampsia prediction and treatment of severe hypertension. Classification of hypertensive disorders and thresholds for treatment will be discussed, including novel developments in the field.

Key words: ambulatory blood pressure, aneroid devices, aspirin, cardiovascular, chronic hypertension, CRADLE VSA, gestational hypertension, home blood pressure, hypotension, masked hypertension, mean arterial pressure, preeclampsia, shock, shock index, telemedicine, validation, vital sign alert device, white-coat hypertension

**Introduction**

The assessment of blood pressure (BP) is the cornerstone of antenatal, intrapartum, and postnatal care. Accurate measurement of BP enables the diagnosis and management of hypertensive disorders of pregnancy, including chronic hypertension, gestational hypertension, and preeclampsia (PE). Furthermore, measuring BP will identify hypotension, secondary to hemorrhage or septic shock, prompting the instigation of life-saving treatments. Globally, PE, hemorrhage, septic shock, and unregulated termination of pregnancy...
account for >50% of global maternal deaths each year.\(^1\) Treatments for PE, including antihypertensive drugs, magnesium sulfate, and delivery, are available in many settings.\(^2\) If hypertension is promptly and accurately identified and appropriate action taken, maternal deaths can be avoided; in the United Kingdom, there is now <1 maternal death from hypertensive disorders of pregnancy per 1 million births.\(^3,4\)

This review will outline the classification of hypertensive disorders of pregnancy, recommended BP devices in pregnancy, and potential pitfalls and sources of inaccurate measurements. Severe hypertension, thresholds for treatment, and novel developments in the field will be discussed, including early warning alert devices such as the CRADLE Vital Signs Alert (VSA) device and telemedicine.

**Classification of Hypertensive Disorders in Pregnancy**

Hypertension in pregnancy is defined as a sustained (≥2 readings at least 4 hours apart) systolic BP of ≥140 mm Hg or a sustained diastolic BP of ≥90 mm Hg.\(^5\) The International Society for the Study of Hypertension in Pregnancy recommends that the threshold of diagnosis depends on the setting in which the BP measurement is taken, with a threshold of 140 or 90 mm Hg for BP measured in a healthcare setting, 135/85 mm Hg at home, or a 24-hour average BP on ambulatory monitoring of >126/76 mm Hg, in recognition of the “white-coat” phenomenon.\(^6\) Although BP can vary across gestation (Figure 1), gestation-specific thresholds have not been adopted, and a single threshold for healthcare settings is recommended to facilitate the ease of interpretation for healthcare professionals.\(^7,8\) Furthermore, there are differences in BP in different populations. One study of 4023 pregnancies in Asian women found that mean arterial pressure was approximately 4% lower than that in a white population (median multiple of median value of mean arterial pressure, 0.961; 95% confidence interval [CI], 0.956—0.965).\(^9,10\)

Hypertensive disorders of pregnancy are classified as PE, PE with severe features, transient gestational hypertension, gestational hypertension, white-coat hypertension, masked hypertension, chronic hypertension, and chronic hypertension with superimposed PE.\(^6\) Chronic hypertension is defined as hypertension predating the pregnancy or diagnosed before 20 weeks’ gestation (Table).\(^11\) Outside of pregnancy, the American College of Cardiology (ACC) and the American Heart Association (AHA) have recently changed their criteria for diagnosing hypertension in adults. BP is classified into 4 categories: normal (systolic BP of <120 mm Hg), elevated (systolic BP of 120—129 mm Hg), stage 1 hypertension (systolic BP of 130—139 mm Hg and diastolic BP of 80—89 mm Hg), and stage 2 hypertension (systolic BP of ≥140 mm Hg and diastolic BP of ≥90 mm Hg).\(^13\) This may lead to an increase in women classified as hypertensive and may result in uncertainties on how to manage women with newly diagnosed stage 1 hypertension when they become pregnant. The American College of Obstetricians and Gynecologists (ACOG) recommends that a conservative approach with a higher level of surveillance is warranted for pregnant women with stage 1 hypertension.\(^11\)

Gestational hypertension is defined as new-onset hypertension in the absence of proteinuria or other features of PE. Very recent evidence suggests that women with stage 1 hypertension according to the ACC and AHA are at an increased risk of adverse pregnancy outcomes.\(^14\) A retrospective single-center cohort study of 2090 women found that women with an elevated BP of 130 to 139/80 to 89 mm Hg after 20 weeks’ gestation were at an increased risk
<table>
<thead>
<tr>
<th></th>
<th>American College of Obstetricians and Gynecologists&lt;sup&gt;5&lt;/sup&gt;&lt;sup&gt;,11&lt;/sup&gt;</th>
<th>International Society for the Study of Hypertension in Pregnancy&lt;sup&gt;6&lt;/sup&gt;</th>
<th>National Institute for Health and Care Excellence&lt;sup&gt;12&lt;/sup&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Chronic Hypertension</strong></td>
<td>BP of $\geq 140/\geq 90$ mm Hg, predating the pregnancy or before 20 wk gestation</td>
<td>BP of $\geq 140/\geq 90$ mm Hg, predating the pregnancy or before 20 wk gestation</td>
<td>BP of $\geq 140/\geq 90$ mm Hg present at the booking visit or before 20 wk gestation or if the woman is already taking antihypertensive medication when referred to maternity services</td>
</tr>
<tr>
<td><strong>Gestational Hypertension</strong></td>
<td>New-onset hypertension</td>
<td>New-onset hypertension</td>
<td>New-onset hypertension</td>
</tr>
<tr>
<td>$\geq 140/\geq 90$ mm Hg, after 20 wk gestation, in the absence of features of PE</td>
<td>$\geq 140/\geq 90$ mm Hg, after 20 wk gestation, in the absence of features of PE</td>
<td>$\geq 140/\geq 90$ mm Hg, after 20 wk gestation, without significant proteinuria</td>
<td></td>
</tr>
<tr>
<td><strong>PE</strong></td>
<td>New-onset hypertension</td>
<td>New-onset hypertension</td>
<td>New-onset hypertension</td>
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<tr>
<td>$\geq 140/\geq 90$ mm Hg, after 20 wk gestation, with at least one of the following:</td>
<td>$\geq 140/\geq 90$ mm Hg, after 20 wk gestation, with at least one of the following:</td>
<td>$\geq 140/\geq 90$ mm Hg, after 20 wk gestation, with at least one of the following:</td>
<td></td>
</tr>
<tr>
<td>- Proteinuria (≥ 300 mg per 24-h urine collection or protein-to-creatinine ratio of ≥ 0.3 or a dipstick reading of 2+)</td>
<td>- Proteinuria (protein-to-creatinine ratio of ≥ 30 mg/mmol)</td>
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<tr>
<td>- Renal insufficiency (serum creatinine of &gt; 1.1 mg/dL or doubling of serum creatinine concentration)</td>
<td>- Acute kidney injury (creatinine ≥ 90 μmol/L; ≥ 1 mg/dL)</td>
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<tr>
<td>- Thrombocytopenia (platelet count of &lt; 100 × 10&lt;sup&gt;9&lt;/sup&gt;/L)</td>
<td>- Hematological complications (platelet count of &lt; 150,000/μL, disseminated intravascular coagulopathy, hemolysis)</td>
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<tr>
<td>- Impaired liver function (elevated liver enzymes to twice the upper limit of normal)</td>
<td>- Liver involvement (elevated transaminase level at &gt; 40 IU/L)</td>
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<tr>
<td>- Pulmonary edema</td>
<td>- Neurologic complications</td>
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<td></td>
</tr>
<tr>
<td>- New-onset headache or visual symptoms</td>
<td>- Uteroplacental complications (fetal growth restriction, stillbirth)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*BP*, blood pressure; *PE*, preeclampsia.

of developing hypertensive disorders of pregnancy, with an adjusted risk ratio (RR) of 2.41 (95% CI, 2.02–2.85). The implications of these findings for clinical management require further research to evaluate whether initiation of treatment at stage 1 hypertension thresholds has maternal and fetal benefit (or harm).

PE is defined as new-onset hypertension after 20 weeks’ gestation with proteinuria or other evidence of maternal disease, including thrombocytopenia, renal insufficiency, impaired liver function, pulmonary edema, or new-onset headache. New-onset hypertension with fetal growth restriction is classified as PE by the International Society for the Study of Hypertension in Pregnancy, but not by the ACOG. Superimposed PE is diagnosed when a woman with chronic hypertension develops evidence of maternal organ dysfunction consistent with PE. Sudden worsening of hypertension or increase in proteinuria should prompt the evaluation for possible superimposed PE, but this may be difficult to diagnose and can be a diagnosis of exclusion. New-onset thrombocytopenia, increase in liver enzymes, elevated uric acid, or sudden development of symptoms should point to the diagnosis of superimposed PE. PE with severe features is defined as severe hypertension (≥160/≥110 mm Hg on 2 occasions at least 4 hours apart), thrombocytopenia, impaired liver function, renal insufficiency, pulmonary edema, new-onset headache unresponsive to medication and not accounted for by alternative diagnoses, or visual disturbances (hematological and biochemical abnormalities defined by the ACOG provided in the Table). Superimposed PE is defined as hypertension in a healthcare setting with normalization of BP of <135/85 mm Hg outside this setting. Masked hypertension describes normotension in a hospital or clinic, with hypertension manifesting in other settings (eg, on home BP readings). The likelihood of progression among classes has been well described, with 15% to 25% of women with gestational hypertension and 25% of women with chronic hypertension progressing to PE. Furthermore, white-coat hypertension is not a benign condition, because 40% of women develop gestational hypertension and 8% develop PE. A recent meta-analysis including 12 studies identified that women with white-coat hypertension have an increased risk of delivering a small-for-gestational-age newborn (RR, 2.47; 95% CI, 1.21–5.05) and preterm birth (RR, 2.86; 95% CI, 1.44–5.68) compared with normotensive women. Therefore, enhanced surveillance may be appropriate for women with white-coat hypertension, and ambulatory or home monitoring may help confirm the diagnosis and guide decisions regarding the initiation of antihypertensive agents.

**Blood Pressure Assessment**

**Auscultatory method**

There are numerous methods for assessing BP in pregnant women, including invasive and noninvasive monitoring, with the latter comprising auscultatory and oscillatory methods (Figures 2 and 3). In 1896, Riva-Rocci first described the use of a mercury sphygmomanometer to identify systolic pressure. In 1905, Korotkoff introduced the method of auscultation to determine systolic and diastolic BP. A stethoscope is used to auscultate the sound produced when the blood flows through a partially occluded artery. The origin of the Korotkoff sounds is not fully understood but may originate from the turbulence to blood flow and stretching of the arterial wall (see Figure 4). For typical BP measurement by the auscultatory method, a cuff is placed around the upper arm and inflated to 20 to 30 mm Hg above the point where the radial pulse is no longer palpable. The cuff is slowly deflated at approximately 2 mm Hg per second to avoid the underestimation of systolic BP and overestimation of diastolic BP. A stethoscope is placed over the brachial artery in the antecubital fossa (distal to...
the cuff), and the Korotkoff phase 1 (K1) sound, representing the systolic BP, is heard when the pressure in the cuff has deflated sufficiently to allow blood flow through the artery. Korotkoff phases 2 (K2) and 3 (K3) represent a change in the sound quality and can be mistaken for K1 if there is an auscultatory gap, underestimating the systolic BP. This can be identified by palpating the radial pulse, which will be palpable for K2 and K3 and not for K1. The Korotkoff phase 5 (K5) sound is denoted by the disappearance of this sound and represents the diastolic BP. It was previously thought that K5 was a rare occurrence in pregnant women and that Korotkoff phase 4 (K4) (muffling) should be used instead. A randomized trial of the use of K4 or K5 to monitor the BP of 220 pregnant women with hypertension found that K4 was significantly associated with a greater likelihood of recording severe diastolic hypertension ($P=0.006$), but all other episodes of severe hypertension were recorded with similar frequency. In a prospective study of 1460 paired measurements of BP in pregnant and nonpregnant women, Shennan et al demonstrated that K4 showed poor reproducibility, with agreement in only 19% of readings. In contrast, K5 was identified in all measurements, which is significantly more often than K4 ($P<0.05$) and is therefore recommended for use.

The auscultatory method is recognized as the original gold standard for BP measurement. Because most epidemiologic data have been based on this, this remains a reasonable assumption. This was originally performed using a mercury sphygmomanometer but this is no longer recommended owing to the risk of mercury toxicity. Now, mercury sphygmomanometers are only recommended for comparison in monitor validation protocols. Aneroid devices have been developed as the replacement for mercury sphygmomanometers. These devices have an aneroid gauge consisting of a bellows, with a watch-like motion and connected to a compression cuff. Changes in pressure within the system make the bellows expand and contract. This movement rotates a gear, which then turns a pointer across a calibrated dial. However, these are prone to calibration errors, particularly owing to mechanical wear and tear or trauma. Calibration should be performed according to the manufacturer’s guidelines; this is usually at least every 2 years. However, recalibration is rarely performed as specified, and 1 study of 279 sphygmomanometers in primary
care found that 53% of aneroid devices read an error of >3 mm Hg compared with 7.8% of combined mercury and automated devices (P=.002).28 Another study of 1462 sphygmomanometers found that 9.2% gave readings that were >5 mm Hg inaccurate.29 A study of systematic errors in measurements of BP found that an overestimation of systolic BP by 3 and 5 mm Hg would misclassify 24% and 43% as hypertensive, respectively. An equivalent underestimation would falsely reassure 19% and 30% of patients with systolic hypertension, respectively.30

Automated devices

Automated devices use the oscillometric method to measure BP, based on the principle that blood flow through a partially constricted vessel causes the arterial walls to vibrate.20 The air in the cuff conducts and transfers the vibration to a pressure transducer in the monitor. The pressure at maximum oscillation equates to the mean arterial pressure. Systolic BP is calculated or derived according to changes in the oscillation characteristics in the cuff as it deflates, whereas diastolic BP is often calculated according to an algorithm that incorporates the mean arterial pressure and systolic BP.19,20 One of the first automated BP monitors, the device for indirect noninvasive automatic mean arterial pressure (Dinamap; Ramsey Medical, Inc., Tampa, FL) was developed in 1976 and is still in frequent use in clinical practice today.

Home blood pressure monitoring

Home BP monitoring, or BP self-monitoring, is when an individual measures their own BP outside of a clinical setting, and this is likely to play an increasingly important role in pregnancy. An advantage of home monitoring is the detection of white-coat and masked hypertension, particularly if ambulatory BP monitoring over 24 hours is not acceptable or available.20,31 Other potential benefits include reduced face-to-face attendances, enhanced patient convenience, and additional readings providing a better basis for diagnostic and management decisions. The severe acute respiratory syndrome coronavirus 2 pandemic has stimulated numerous maternity units to implement home BP monitoring to reduce face-to-face consultations while maintaining essential monitoring for the mother.32,33 Trials are underway to evaluate whether home BP monitoring improves the detection of raised BP and reduces systolic BP during high-risk and hypertensive pregnancies.34 A cohort study of 294 BP measurements from 147 women demonstrated that median systolic BP measurements from home monitoring were lower than clinic measurements (132.0 mm Hg vs 138 mm Hg; P<.001).35 A feasibility randomized controlled trial of 154 women demonstrated that median systolic BP measurements from home monitoring were lower than clinic measurements (132.0 mm Hg vs 138 mm Hg; P<.001).35 A feasibility randomized controlled trial of self-monitoring in the postnatal period similarly indicated that a larger trial would be feasible and also found that self-management resulted in better diastolic BP control to 6 months.36 A trial of telemonitoring (incorporating BP monitoring and cardiotocography) is also being conducted to assess the impact on patient safety, satisfaction, and cost effectiveness.39 The ACOG recommends that ambulatory management at home is an option for women with gestational hypertension or PE without severe features.5 It is necessary that the BP monitor used is validated in pregnancy and that the woman has been adequately trained on how to self-monitor and escalate, if required. Frequent maternal and fetal surveillance is still necessary, with assessment of proteinuria, hematological and biochemical abnormalities, and ultrasound scans to assess fetal growth.

Ambulatory blood pressure monitoring

Ambulatory BP monitoring involves an individual wearing an ambulatory BP
monitor, and BP is automatically measured at repeated intervals through day and night. It is recommended as the definitive test for diagnosing chronic hypertension (outside of pregnancy) in the United States, Canada, and the United Kingdom, because there is evidence of clinical and cost effectiveness. However, home BP monitoring may be favored over ambulatory BP monitoring owing to the ease of use with increased availability and lower cost. However, this is a pragmatic decision and there is a balance between a marginal improvement in diagnostic accuracy and clinical utility. Ambulatory BP monitoring has the advantage of identifying nocturnal hypertension, because home BP monitoring is not usually performed at night. This has been particularly associated with deaths and cardiovascular events in the nonpregnant population. The diurnal variation in BP is sometimes reversed in pregnant women with PE, with the highest mean arterial pressure seen during the night. A study of 24-hour ambulatory BP monitoring in 109 nulliparous women with hypertension after 20 weeks’ gestation demonstrated that automated diastolic BP was significantly related to adverse outcomes, including proteinuria (P=.034), preterm delivery (P<.001), birthweight at <10th percentile (P<.001), and admission to the neonatal unit (P=.001), compared with conventional sphygmomanometry in antenatal clinic and an obstetrical day unit. Therefore, ambulatory BP monitoring may have some clinical advantages, but the added difficulty in terms of lower availability and increased cost and inconvenience may not justify its use. The ACOG advises that ambulatory monitoring may be beneficial to guide the diagnosis and treatment decisions in women with white-coat hypertension.

Invasive monitoring
Invasive BP monitoring involves the placement of a cannula into an artery (usually the radial artery) with the external distal end connected to a pressure transducer. Numeric measurements and graphical recordings are presented on a monitor in real time, enabling dynamic management of critically unwell patients in an intensive care setting, including women with severe PE, massive hemorrhage, septic shock, and high-risk cardiac lesions during labor. It is useful for assessing rapid changes in cardiovascular status, rather than identifying diagnostic or treatment thresholds. Validation of oscillometric BP monitors may be against an invasive rather than an auscultatory standard. The risks of invasive monitoring include bleeding, infection, hematoma, embolism of air or thrombotic material, vessel injury, pseudoaneurysm formation, and local nerve injury.

Comparative diagnostic accuracy of devices
Outside of pregnancy, ambulatory BP monitoring is accepted as the best test to diagnose hypertension, because it has been shown to predict cardiovascular events more accurately than other devices. A review of 13 studies comparing 3 diagnostic tests in nonpregnant adults (home BP monitoring with telemonitoring, home BP monitoring without telemonitoring, and clinic BP assessment) with a reference standard of 24-hour ambulatory monitoring found that home BP monitoring without telemonitoring demonstrated the best sensitivity and specificity for identifying hypertension. To the best of our knowledge, there have been few randomized trials comparing the diagnostic accuracy of different modalities of assessing BP in pregnancy. A Cochrane review of settings and technique for monitoring BP during pregnancy has been conducted. This included 3 studies; one was a feasibility study of self-measurement vs clinic measurement, one compared K4 with K5 to represent diastolic BP, and the final trial compared the CRADLE intervention with usual care. Other studies have identified intrindividual variation among types of monitors, and BP is influenced by the environment and the person who is assessing the BP. Therefore, further evidence of the diagnostic accuracy of different devices and settings for BP measurement in pregnancy is needed. The most accurate device for assessing severe hypertension in pregnancy has similarly not been established. Many cases of severe hypertension can be appropriately managed without an arterial line.

Calibration
All devices must be calibrated, which relates to whether the pressure transducer equates accurately to a true pressure measured in millimeters of Mercury. A technical calibration check can be performed by an authorized laboratory, which will measure and calibrate the device against a reference manometer, such as an electronic sensor with a high accuracy of ±0.1 mm Hg and standardized to the world pressure standard, or a column of mercury. Devices must be put into a calibration mode to achieve this and checked across the pressure range.

Validated devices in pregnancy
It is paramount that BP monitors are validated in pregnancy. Pregnant women are classified as a “special population” according to BP monitor validation protocols, and validation procedures require at least 15 normotensive pregnant women and at least 15 women with both PE and hypertension. Monitors are required to be validated in the general population first in 85 subjects, according to power calculations and consensus agreed by the Association for the Advancement of Medical Instrumentation, the European Society of Hypertension, and the International Organization for Standardization (ISO). In addition to the 85 nonpregnant subjects, 45 pregnant women are further required. The number of additional pregnant women is limited for pragmatic reasons to ensure compliance with validation protocols, including the 15 women in each group. Validation not only ensures correct calibration but also tests that all aspects of the devices are functioning adequately to achieve a correct BP measurement, including the hardware and the algorithm. The physiological changes in pregnancy include an increase in heart rate and stroke volume, thus increasing cardiac output. Total peripheral resistance is reduced, leading to high capacitance vasculature and a hyperdynamic circulation. Generally, these changes do not interfere with the accuracy of
Oscillometric devices, evidenced by devices passing validation studies in normotensive pregnancies, but not pregnancies affected by PE. By contrast, in PE, there is altered vascular reactivity, reduced intravascular volume, and reduced vessel compliance, along with interstitial edema. These changes may affect the amplitude and detection of the oscillometric waveform or alter the validity of the algorithm used to calculate systolic and diastolic BPs. One study compared oscillometric monitoring with invasive monitoring in 6 women with severe PE and demonstrated that the oscillometric monitor significantly underestimated the systolic BP by 19 mm Hg ($P<.01$). Validation protocols have been agreed by the British Hypertension Society, the European Society of Hypertension, and the Association for the Advancement of Medical Instrumentation, and strict adherence to an individual protocol is fundamental for accuracy and validity. These protocols have now been harmonized into an ISO standard. Of >4000 BP monitors available on the market, few have been evaluated in pregnant women and fewer have passed a validation protocol. In a systematic review of 28 devices examined, 2 ambulatory devices, 2 home devices, 4 clinic BP devices, and 1 home/clinic device passed a validation protocol without any violations. Devices that have been proven valid and accurate should be used, given the consequences of inaccurate BP measurement during pregnancy. The devices that can be recommended for pregnancy are presented in Box 1.

**Technique**

BP measurement technique is important and training of healthcare professionals measuring BP is essential but often overlooked. Ideally, for all methods of BP assessment, pregnant women should sit quietly for 5 minutes before assessment. Smoking or ingestion of caffeine or other pressor substances should be avoided for 30 minutes before the assessment. BP measurement should be done sitting or, if this is not possible, in the left lateral position to avoid aortocaval compression. Care should be taken to ensure this latter position does not falsely lower BP by allowing the cuff to rise above the level of the heart. The appropriate cuff size should be selected based on the midarm circumference, which is the midpoint of the line between the olecranon process and the acromion process. An appropriately sized cuff should have a bladder length that is 80% of the arm circumference and width that is 40% of the arm circumference (Figure 5). An inappropriately small cuff will overestimate the BP, enough to misdiagnose hypertension status in 5% to 7% of obese pregnant women. Obesity is increasing and accurate BP assessment in such women is crucial because of the association between obesity and adverse outcomes, as highlighted in reports from Mothers and Babies: Reducing Risk through Audits and Confidential Enquiries across the UK. Legs should not be crossed, because in 15% of cases, this elevated BP by 2 to 8 mm Hg and conversation ceased, because this may increase systolic and diastolic BP by as much as 20%. The radial pulse should be palpated, because an irregular heart rate will influence oscillometric accuracy, in which case Korotkoff sounds should then be relied upon.

The FIGO Textbook of Pregnancy Hypertension recommends that if an auscultatory device is used, the first reading should be discarded and an average of the second 2 readings taken, ideally 15 minutes apart. For an automatic device, an average of 2 readings should be reliable. Validated devices that automatically measure the BP 3 times and report an average will provide a standardized and unbiased evaluation of BP. Additional technology is available that uses a “weighted” average of at least

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**BOX 1**

**Automated devices validated for use in pregnancy and preeclampsia**

<table>
<thead>
<tr>
<th>Ambulatory devices</th>
<th>Welch Allyn QuietTrak (Hillrom, Chicago, IL)</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>BP Lab (Nizhny Novgorod, Russia)</td>
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<tr>
<td></td>
<td>PAR Medizintechnik GmbH &amp; Co. Physio-Port (Berlin, Germany)</td>
</tr>
<tr>
<td>Clinic devices</td>
<td>Dinamap ProCare 400 (Ramsey Medical, Inc., Tampa, FL)</td>
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<tr>
<td></td>
<td>A&amp;D UM-101 (A&amp;D Company, Limited, Tokyo, Japan)</td>
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<tr>
<td></td>
<td>Nissei DS-400 (Nissei, Tokyo, Japan)</td>
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<td></td>
<td>Omron HEM907 (Omron, Kyoto, Japan)</td>
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<tr>
<td>Portable devices</td>
<td>Omron M7 (HEM 780E) (Omron)</td>
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<tr>
<td></td>
<td>Omron MIT (Omron)</td>
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<tr>
<td></td>
<td>Omron MIT Elite (Omron)</td>
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<td>Omron HEM-9210T (Omron)</td>
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<td></td>
<td>Omron BP760N (HEM-7320-Z) (Omron)</td>
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<td></td>
<td>Microlife WatchBP Home A (Microlife, Taipei, Taiwan)</td>
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<td></td>
<td>Microlife BP 3BTO-A (Microlife)</td>
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<td></td>
<td>Microlife BP 3A1-2 (Microlife)</td>
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<tr>
<td></td>
<td>Microlife WatchBP Home A BT (Microlife)</td>
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<tr>
<td></td>
<td>Microlife WatchBP Home S (Microlife)</td>
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<tr>
<td></td>
<td>Microlife CRADLE VSA (Microlife)</td>
</tr>
<tr>
<td></td>
<td>Andon iHealth Track (Andon Health Co. Ltd, Tianjin, China)</td>
</tr>
</tbody>
</table>

*BP*, blood pressure.

*Additional devices may be sanctioned through equivalence criteria. The STRIDE BP website provides an updated list of validated BP monitors.*

8.3% of women.69 The change in systolic BP was thought to be a result of an obstetrical day unit.64 It is important to monitor BP in pregnant women at booking visit and thereafter take BP on the arm with the highest reading. Failure to do so may result in the underestimation of BP in up to a third of cases, and in a study of 5435 pregnant women at 11 to 14 weeks’ gestation, the interarm difference in systolic BP was ≥10 mm Hg in 8.3% of women.69

There are numerous potential pitfalls and sources of error during this process (Boxes 2 and 3). These can broadly be broken down into manufacturer related, patient related, health system related, and health worker related. Manufacturers must provide appropriately and independently validated devices, with clear limitations and instructions for use. Arm shape may impair BP measurement in morbid obesity, but this can be overcome by specialized cuffs for conical arms.19 Healthcare settings may have a dearth of validated approved devices or trained professionals to use them. BP monitors must be maintained and calibrated. Finally, healthcare professionals may ask the woman to sit in the wrong position, use poor technique, or perform an insufficient number of measurements (Figure 6). Professionals may exhibit “terminal digit preference,” evidenced by 1 study that found 23% of midwives round BP to the nearest 10 mm Hg,70 and other studies demonstrating that 78% to 85% of BP readings were recorded as ending in a 0.71,72 Finally, there may be an “observer bias” toward a preferred BP, or “threshold avoidance,” to avoid thresholds that require additional work or intervention.73 Healthcare professionals and providers must strive to overcome these challenges.

Severe Hypertension
BP needs to be measured accurately and frequently in pregnant women to mitigate adverse maternal and perinatal outcomes. Uncontrolled severe hypertension of ≥160/≥110 mm Hg is a risk factor for stroke and as such should be treated as a medical emergency.74 Prolonged severe hypertension may lead to the loss of autoregulation of the cerebral vasculature, resulting in cerebral hypoperfusion, edema, and disruption of the blood-brain barrier.20,75,76 However, some evidence suggests that it may be PE that induces a state of abnormal cerebral regulation and that this does not directly correlate with BP.77 It is recommended that once severe hypertension of ≥160/≥110 mm Hg is detected, first-line treatments are instigated within 30 to 60 minutes to reduce BP.75 However, there may often be delays in treatment, and delays for >60 minutes have been associated with initial lower BP, absence of PE symptoms, presentation overnight, white ethnicity, symptoms of labor, and increasing gestational age.78

In a case series of 28 women who had a stroke owing to severe hypertension, systolic hypertension of >155 mm Hg was seen in all cases immediately before the stroke, whereas only 13% had a diastolic BP of >110 mm Hg.74 However, there is conflicting evidence, because another study of 30 cases of antenatal stroke demonstrated that the risk of stroke increases by 3% (adjusted odds ratio [OR], 1.03; 95% CI, 1.00–1.05) with a 1 mm Hg rise in systolic BP compared with an 8% increase (adjusted OR, 1.08; 95% CI, 1.03–1.13) with a 1 mm Hg rise in diastolic BP.79 Posterior reversible encephalopathy syndrome seems to occur at lower systolic BPs in pregnant women compared with the nonpregnant population, necessitating expeditious, controlled reduction of BP. A small study of posterior reversible encephalopathy syndrome found a mean peak systolic BP of 173±17 mm Hg in 13 cases in pregnant women compared with a mean peak systolic BP of 199±54 mm Hg in a study of 113 cases in nonpregnant patients.80,81 Other short-term complications of severe hypertension include eclampsia, preterm birth, placental abruption, and fetal growth restriction.82 More recently increased relative risks of future heart failure (RR, 4.19; 95% CI, 2.09–8.38) and cardiovascular disease.

### BOX 2
**Sources of sampling errors**

<table>
<thead>
<tr>
<th>Source of error</th>
<th>Precautions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rapid deflation</td>
<td>Deflate 2–3 mm Hg/s (deflation duration of &gt;30 s on average)</td>
</tr>
<tr>
<td>Auscultatory gap</td>
<td>Obtain systolic pressure by palpation</td>
</tr>
<tr>
<td>Threshold avoidance</td>
<td>Check again if in doubt</td>
</tr>
<tr>
<td>Digit preference</td>
<td>Record measurement to the nearest 2 mm Hg</td>
</tr>
</tbody>
</table>

death (RR, 2.21; 95% CI, 1.83–2.66) have been identified.\textsuperscript{82}

Risks are not confined to the woman, and hypertensive disorders of pregnancy are associated with 2.6 million stillbirths each year worldwide.\textsuperscript{83} PE is a leading cause of iatrogenic preterm birth, with resulting increased perinatal morbidity and mortality, including broncho-pulmonary dysplasia, necrotizing enterocolitis, and neurodevelopmental sequelae.\textsuperscript{84} The Control of Hypertension in Pregnancy Study (CHIPS) in 987 women found that severe hypertension (\(\geq 160/\geq 110\) mm Hg) was significantly associated with the primary study outcome of perinatal loss or high-level neonatal care for >48 hours (\(P<.001\)).\textsuperscript{85} Finally, exposure to a hypertensive pregnancy increases the lifetime risk of hypertension in the infant.\textsuperscript{86,87}

### Thresholds for Treatment

The thresholds for treatment of hypertension in pregnancy have evolved over time, as new evidence has emerged. Hypertension is classified as BP of 140 to 159/90 to 109 mm Hg and \(\geq 160/\geq 110\) mm Hg as severe hypertension.\textsuperscript{11}

Until recently, treatment for mild hypertension was not recommended and concern prevailed about the risk of fetal growth restriction if diastolic BP was consistently <85 mm Hg.\textsuperscript{88} However, recent evidence from the CHIPS, which compared less tight (target diastolic BP 100 mm Hg) vs tight (target diastolic BP 85 mm Hg) control of hypertension in 987 women with chronic hypertension and gestational hypertension, found that tight BP control reduced the risk of maternal severe hypertension, without increasing perinatal adverse outcomes.\textsuperscript{89} This has been incorporated into national guidance in the United Kingdom and Canada, recommending treatment if mild hypertension is sustained.\textsuperscript{11,90} The American guidelines have not incorporated this, concluding “tight control of hypertension conferred no benefit to the fetus and had only marginal effects for the woman, namely reduced frequency of progression to severe hypertension.”\textsuperscript{11}

The Chronic Hypertension and Pregnancy trial is ongoing, in which women are randomized to antihypertensive therapy if the BP is >140/90 mm Hg compared with no antihypertensive therapy unless severe hypertension is >160/110 mm Hg thresholds (ClinicalTrials.gov NCT02299414). The results of this trial will further inform guidelines regarding treatment thresholds. The use of mean arterial pressure in the assessment of BP is not recommended, and there is no role for an incremental rise of BP in the absence of persistent hypertension.\textsuperscript{11,91}

### Intrapartum and Postnatal Blood Pressure Assessment

In addition to antenatal BP management, monitoring BP is also critical during labor. Contractions force blood flow from the uterine vessels into the systemic circulation, resulting in increased stroke volume, cardiac output, and BP. Therefore, regular assessment of BP is necessary to safeguard against stroke, eclampsia, and cardiac failure. Measuring BP also facilitates the management of hemorrhage, by assessing the extent of hypovolemia, guiding fluid management, uterotonics, blood transfusion, and appropriate level of care, including transfer to a specialist unit.\textsuperscript{92,93}

Postnatal assessment of BP is also crucial. The majority of postnatal eclampsia occurs in the first 48 to 72 hours after birth, and cautious management is necessary during this period.\textsuperscript{94,95} Guidance from the National Institute for Health and Care Excellence does not dictate the duration of postnatal admission, but rather the requirement for additional monitoring. BP should be measured at least 4 times a day while the...
woman is an inpatient and then every 1 to 2 days for up to 2 weeks after discharge, until normotension has been achieved without antihypertensive treatment.11

**Prediction and Prevention of Preeclampsia**

Early identification of women at high risk of developing hypertensive disorders of pregnancy enables prophylaxis with aspirin, as recommended by national guidelines.3,11 A Cochrane review of 77 studies (including 40,249 women) investigating antiplatelet agents for the prevention of PE found that aspirin reduced proteinuric PE by 18% (RR, 0.82; 95% CI, 0.77–0.88), with a number needed to treat of 61 (95% CI, 45–92).96 However, a secondary analysis of the Aspirin for Evidence-Based Preeclampsia Prevention trial found that aspirin may be less effective in preventing preterm PE in women with chronic hypertension.97 A recent randomized, double-blind, placebo-controlled trial of low-dose (81 mg) aspirin for the prevention of preterm birth in 11,976 women in low- and middle-income countries demonstrated a significant reduction in preterm birth in women with hypertensive disorders (RR, 0.38; 95% CI, 0.17–0.85).98 Therefore, aspirin is a safe and simple strategy that is likely to have far-reaching benefit.

BP can be used as a risk factor to calculate which women will likely benefit from aspirin use. The United States Preventive Services Task Force recommends screening for PE with BP measurements throughout pregnancy, and both the ACOG and the National Institute for Health and Care Excellence recommend obtaining BP measurements at every antenatal visit.5,11,66

BP has been incorporated into algorithms used to predict PE.99,100 The Fetal Medicine Foundation has developed an algorithm to combine maternal risk factors with mean arterial pressure, uterine artery pulsatility index, and serum placental-derived growth factor. A prospective multicenter study of screening for PE in 8775 singleton pregnancies found that this algorithm detected 100% of PE before 32 weeks’ gestation, 75% before 37 weeks’ gestation, and 43% beyond 37 weeks’ gestation, at a false-positive rate of 10%.101 This was superior to detection according to National Institute for Health and Care Excellence guidelines, which detected 41%, 39%, and 34%, respectively, at a false-positive rate of 10.2%, or the American College of Obstetrician and Gynecologist guidelines, which detected 95%, 90%, and 89%, at a false-positive rate of 64.2%. The use of prediction algorithms such as these emphasizes the importance of accurate BP assessment. In the future, more sophisticated algorithms may need to incorporating a multiple of median formulas of mean arterial pressure, to take account of contributing variables such as gestational age, maternal age, weight, height, ethnicity, history of PE, and presence of chronic hypertension or diabetes mellitus.102

**Shock Index and Early Warning Scores**

Hypovolemic shock can initially be difficult to detect, because the physiological increase in blood volume during pregnancy means that women may compensate in the early stages, before rapidly decompensating. More than 60 years ago, shock index was first suggested as an early indicator of excessive blood loss during gastrointestinal hemorrhage.103 Shock index is the ratio of heart rate to systolic BP and is the most consistent predictor of adverse maternal outcomes, including death.104 In a retrospective cohort study of 233 women with postpartum hemorrhage, shock index of >0.9 had 100% sensitivity (95% CI, 73.5–1.00) and 43% specificity (95% CI, 36.8–50.3) for predicting intensive care admission, and a shock index of >1.7 had 25% sensitivity (95% CI, 5.5–57.2) but 97.7% specificity (95% CI, 94.8–99.3) for predicting intensive care admission.105 A study of 958 women from low- and middle-income settings demonstrated that a shock index of >0.9 prompts referral, >1.4 necessitates urgent intervention, and >1.7 indicates a high chance of adverse outcome.106

Modified early warning scores have been widely introduced in obstetrics. Color coding of early warning scores according to a traffic light system facilitates prompt identification of abnormal vital signs and thereby early intervention. This was introduced in the United Kingdom after the Confidential Enquiries report in 2003 to 2005.106 Although evidence of clinical effectiveness is lacking, the use of early warning scores overcomes some of the human factors involved in delayed escalation of care.107 The effectiveness of early warning scores is clearly dependent on accurate measurement and documentation and appropriate action.

**Early Warning Alert Devices**

Novel technologies prompting action may circumvent failure to escalate abnormal BP readings. The Microlife CRADLE Vital Sign Alert (VSA) device (Microlife, Taipei, Taiwan) is a semi-automated device that measures heart rate and BP and calculates shock index (Figure 3). It has been specifically designed for low- and middle-income countries, which bear the burden of global maternal mortality and morbidity. Notably, 99% of maternal deaths occur in low- and middle-income settings, and there is an urgent need for simple, cost-effective, robust, and accurate monitoring.7 The lifetime risk of maternal death is 1 in 36 pregnancies in Sub-Saharan Africa compared with 1 in 6000 pregnancies in high-income countries.108 In 2015, an estimated 303,000 women died in pregnancy and childbirth, and more than 50% of maternal deaths were caused by hypertensive disorders of pregnancy, hemorrhage, or sepsis.1

The CRADLE VSA device has been validated as accurate outside of pregnancy109 and in normotensive,110 hypertensive,110 and hypotensive111 women, making it widely applicable. The device meets the World Health Organization requirements for suitability for low- and middle-income countries, in that it is affordable (US $20), robust, easy to use, and portable. It has a dual auscultatory/oscillometric function, does not require calibration, and has low
power requirements (it can be charged from a micro-Universal Serial Bus charger, the same as most international phone chargers). The results are shown on a digital display (avoiding digit preference), and it provides an early warning score traffic light, which is triggered by abnormalities in BP or shock index. Qualitative data from healthcare professionals were unanimously positive for the traffic lights early warning system, and pregnant women unanimously liked the device. In 2019, Vousden et al published a pragmatic, stepped-wedge, cluster-randomized trial of the CRADLE VSA device, in 10 clusters in 8 low- and middle-income countries. The device was introduced in primary (first point of access), secondary (first referral point), and tertiary facilities (specialty referral facilities), and all existing devices for measuring vital signs were removed, unless specific functions were needed (such as repeated automated measures in a high-dependency setting). The introduction of the device in conjunction with an educational package led to an absolute reduction in a composite of maternal mortality and morbidity (comprising maternal death, eclampsia, and hysterectomy) of 8%, from 79.4 per 100,000 deliveries before intervention to 72.8 per 100,000. However, after planned adjustments for variation in event rates within and among clusters, the unexpected degree of variability meant the effect could not be attributed to the device.

**Novel Technologies and Future Developments**

The future of BP measurement will be linked to other novel technologies. Digital innovation and the development of telemonitoring for BP readings to be reviewed remotely by healthcare professionals will likely play more of a role. A number of application-based systems are already available in the United Kingdom, including Bpm-Health, Florence, and Hampton. Bpm-Health and Hampton have been specifically designed for pregnant women, but Florence is intended for use in the general population. Women can record their BP on the application, and the telemonitoring system incorporates an algorithm that reminds women to submit readings and alerts them to contact their healthcare professional if their BP is abnormal. Healthcare professionals can review BP measurements on the application but are not usually alerted with abnormal BP readings in real time. This is similar to telemonitoring used in the nonpregnant population. The ACOG recommends frequent BP monitoring in the clinic and at home in the case of poorly controlled BP or elevated risk of PE, and digital monitoring will facilitate this. Small studies have demonstrated the advantages of telemonitoring include fewer hospital visits, better BP control, and cost savings. Large randomized controlled trials will guide the widespread introduction of home BP monitoring and telemonitoring, if clinical and cost effectiveness is established. The integration of telemonitoring is still a work in progress within obstetrics, but this has been achieved in other fields of medicine. A recent randomized controlled trial of 1182 participants found that self-monitoring with telemonitoring was associated with a reduction in BP at 12 months, with an adjusted mean difference of −4.7 mm Hg (95% CI, −7.0 to −2.4). A study of pooled individual patient data from 4 studies showed self-monitoring with telemonitoring increases the likelihood of antihypertensive intensification (OR, 1.8; 95% CI, 1.2–2.6) and could improve BP control rates at 5 years.

Despite promising advances with biomarkers, Doppler velocimetry, and prediction models, there are currently no screening tests for PE with sufficient clinical and cost effectiveness to have been adopted into widespread clinical practice. Therefore, BP monitoring remains the single most important and frequent screening test worldwide. Furthermore, prompt identification of PE relies fundamentally on the frequency of antenatal care. Therefore, work must continue to overcome the complex challenge of instigating basic antenatal care worldwide to reduce inequality and bring down the persistently unacceptable high level of maternal mortality.

**Conclusion**

BP assessment in pregnant women is a simple procedure of vital importance. It is fundamental to the safety of pregnant women that BP is measured accurately, with a monitor validated in pregnancy and hypertensive disorders of pregnancy. Abnormal results must be acted upon with appropriate measures. In some countries, such as the United Kingdom, universal screening of BP and risk assessment have driven down deaths related to PE to <1 per 1,000,000 births, and this may be attributed to the implementation of evidence-based guidelines and confidential enquiries of adverse outcomes. However, inequality across the globe is stark and work must continue tirelessly to strive for safe childbirth. Universal provision of accurate BP assessment remains a desirable goal.

**REFERENCES**


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