Inconsistency of intra-arterial pressure estimation

The practice of quality clinical medicine is predicated by evaluating accurate historical, physical, laboratory and imaging data, and making decisions based thereon. Intra-arterial pressure estimation has evolved over millennia from detailed analysis of the pulse to sophisticated instruments that determine pressure indirectly and display it as numerical data. Such data are only as accurate as the device permits. No matter how accurate the device, if the subject is not properly prepared and positioned, the data may be inaccurate. Those who take blood pressure in the clinic should be well trained in the correct technique and be aware of the factors that cause variation in the readings. Accurate estimation of intra-arterial pressure is even more challenging in pediatric patients. The correct cuff size must be used and motion artifacts minimized. Oscillometric readings are good for screening, but auscultation remains the gold standard.

KEYWORDS: blood pressure ▪ central arterial pressure ▪ history of blood pressure determination ▪ intra-arterial pressure ▪ oscillometric devices ▪ pediatrics ▪ sphygmomanometers

Barry J Materson†1 & Seema Chandra1

1Division of Hospital Medicine, Department of Medicine & Department of Pediatrics, University of Miami Miller School of Medicine, Miami, FL, USA
†Author for correspondence:
Tel.: +1 305 243 7221
Fax: +1 305 243 9902
bmaterson@med.miami.edu

Competent clinicians expect that the laboratory and imaging data on which they base their decisions are accurate. Indeed, there are organizations that monitor clinical laboratories and demand proof of proper technique, use of standards, calibration of machines and certification of technicians, technologists and supervising clinical pathologists. By contrast, the indirect estimation of intra-arterial pressure has no mandatory oversight of devices, personnel or the circumstances under which the data are derived. Yet clinicians make decisions on testing and treatment based on data reported to them by people who may not be using validated equipment or may not be appropriately trained to use it. The implications for patient care are far from subtle.

We have been deliberate in our choice of words for the title of this article. Indirect measurement of intra-arterial pressure, what we do in clinical practice, yields inconsistent results. We have avoided the term variability to avert confusion with the analysis of beat-to-beat variation in intra-arterial pressure. We have also rejected the term, heterogeneity, since its formal definition is not consistent with our intended topic.

In this article, we discuss the various sources of error in intra-arterial pressure estimation in the ambulatory or outpatient setting and make suggestions as to how to minimize those errors. For convenience, we shall use the widely accepted, although inaccurate, term blood pressure (BP).

History of intra-arterial pressure estimation

Devices and techniques to estimate BP are of relatively recent origin. It is instructive to review the work of many often brilliant individuals, whose efforts culminated in modern clinical techniques and instruments. Changes in this field are happening at such a rate that one might wish to define ‘modern’ in terms of what is available this morning.

The history of the evolution of the ability to measure and indirectly estimate intra-arterial pressure covers many millennia [1,2]. It is said that the scholars who served the Yellow Emperor of China some 4500 years ago knew that a hardened, bounding pulse was associated with a high risk of death. They were also aware that people who lived near the sea and had unlimited access to salt were more likely to have such characteristics of the pulse compared with those who lived far inland and had little access to salt.

The characteristics of the pulse were a topic of intense study and classification for millennia. Although Hippocrates was said to have ignored the pulse in his writings, a contemporary, Praxagoras (400 BCE) did describe various pulses. Erasistratus (294 BCE) used the examination of the pulse in clinical diagnosis. Galen (150 AD) wrote at least 18 books on the characteristics of the pulse. Unfortunately, he totally misunderstood the functions of the heart and arteries. His concepts on the pulse persisted into the 20th century [1]. It took nearly another

2000 years for William Harvey of England to prove in 1628 that the pulse was a function of the contraction of the heart [3]. Nearly 200 years passed before John Blackall (1814) described '*pulsus magnus et tardus*' as being associated with albuminuria and increased intra-arterial pressure [1]. Decades later (1827–1836), Richard Bright made clinical observations on the association of increased BP (estimated from palpation of the pulse) with kidney disease, cardiac hypertrophy, sclerotic arteries and stroke by careful review of autopsy material [1].

Stephen Hales was imbued with the laws of physics established by Sir Isaac Newton. He was a Doctor of Divinity and had his own church outside of London. Like Newton, he was impressed with the order of natural things and attributed that order to the workings of a divine being. He was a dedicated and careful scientist who made his mark as a plant physiologist. He measured the force of rising sap in a vine and compared that to the intra-arterial pressure that he measured in horses, dogs and a fallow doe. He cannulated arteries using the trachea of a goose attached to two brass pipes that were, in turn attached to a glass tube about 10 feet long and one-eighth of an inch in bore. The classic painting of the Rev. Hales measuring the arterial pressure of a restrained mare shows that the carotid artery was cannulated. In fact, he used the great crural (femoral) artery. He observed differences in pressure between the animals tested and observed the pulsations of blood in the column, thus noting systolic and diastolic pressures [2,101]. Unfortunately, he used the term 'blood pressure', a misnomer that has been carried on in the English language. Other languages generally refer correctly to intra-arterial pressure. A detailed and fascinating review of Hales' life is presented in the *Hales Newsletter* [101].

There were many other steps along the way. Jean Leonard Marie Poisseuille (1828) was perhaps the first physician-scientist [2]. His work is better known to physicists and engineers. He used mercury instead of water, thus enabling the measuring tube to be less than one foot instead of 10. He also used potassium carbonate as an anticoagulant. Jean Faivre, a French surgeon, recorded human BP directly by cannulating arteries in amputated limbs. Etienne Jules Marey (1860) used a mercury manometer and catheters to measure left (129 mmHg) and right (27 mmHg) ventricular pressure in a conscious horse. This turned out to be a clinically practical device. Frederick Akbar Mahomed (1860) published a paper describing a practical modification of Marey's device 1 year after his graduation from Guy's Medical School (London, UK). He measured BP in patients with scarlet fever and related increased BP to renal inflammation. He may have described the condition now known as 'essential' hypertension, although he is not responsible for that misnomer [1].

There were many who improved the observational and recording techniques for pulse and BP, but it was Scipione Riva-Rocci who was credited with the invention of the forerunner of the modern sphygmomanometer in 1895 [4]. He used a compression cuff that was only 1.75 inches wide and, therefore, inherently inaccurate. The cuff was later increased to approximately 5 inches and the device was soon marketed commercially. Riva-Rocci's invention alone would not have brought the technique into large-scale clinical practice. Invention of the stethoscope and interpretation of the Korotkoff sounds were required. Rene Theophile Hyacinthe Laënnec, a brilliant French clinician, invented a tube through which he could listen to sounds in the chest without having to place his ear directly on the chest wall (1816). He was an expert on pulmonary tuberculosis, which ironically was his own cause of death [102]. Almost a century elapsed before a Russian army physician, Nicolai Sergeivich Korotkoff (1905), described the classic sounds that bear his name [5]. He had graduated medical school with distinction but was drafted into the army during the Russian war with Japan. He was actually listening for evidence of arteriovenous fistulae in wounded soldiers when he observed the changes in sounds after compression of the limb was released. When he presented his findings, they were rejected by the cognoscenti of the time. Howard Sprague in the USA combined the stethoscope bell and diaphragm into one device making auscultation even more practical [6].

Of interest, van der Hoeven *et al.* have proposed that the Riva-Rocci techniques of determining systolic BP by determining the pressure required to occlude the radial artery might be at least as accurate as the auscultory technique in older people [7]. O'Brien and Parati wrote an editorial based on this paper and concluded that the palpatory technique should not be abandoned [8].

History is replete with examples of repudiation of ideas and inventors who were later recognized and even honored for their work. The Riva-Rocci device was not easily introduced into the USA. Crenner provided an illustrative report of the resistance to the routine determination of BP by methods other than pulse palpation and noted that ease of auscultation made the technique clinically feasible [9]. Harvey Cushing was the leading proponent of the use of the Riva-Rocci device, having obtained one in Italy. His efforts to introduce the method at Johns Hopkins (MD, USA) were largely rebuffed, although he achieved greater success in Boston (MA, USA). By 1910, BP measurement was recorded on most of the patient records at Massachusetts General Hospital (MA, USA) [9].

Devices for intra-arterial pressure estimation

By 1916, William Baum had introduced the portable and accurate instrument that he named the Baumanometer [1]. Tycos manufactured aneroid manometers that were also widely used. The 'modern' changes have been the withdrawal of mercury-based devices from the clinic owing to concerns over potential health hazards due to spilled mercury and the introduction of oscillometric devices.

Good quality, validated semi-automated devices to estimate intra-arterial pressure have become available both for home and office use. For home use, most of these sell for less than $100, but not all meet the standards set by the protocols of the Association for the Advancement of Medical Instrumentation (AAMI), the British Hypertension Society (BHS) and the International Protocol of the European Society of Hypertension [10,11]. These standards are available online from the dabl®Educational Trust [103]. This organization clearly warns against the use of finger-based devices and discourages the use of wrist devices. The former are inaccurate both owing to position and potential spastic changes in the digital arteries. Wrist devices depend on the patient supporting the arm at heart level.

Oscillometric methodology drives most of these devices. The advantage is that no stethoscope is required, observer bias is removed and the numerical results are clearly displayed. Disadvantages are that the oscillometric protocols are proprietary and, therefore, not generally subject to critique; that use of any of these devices does not guarantee that the patient has been properly rested and positioned or that the device is validated and currently in calibration. The danger is that numbers tend to be held as true and correct when that may be far from actual fact. If therapeutic decisions are based on false readings, there may be a great risk of either under- or over-treatment to the patient. An illustrative case follows.

Case 1

A 56-year-old man was self-referred to a hypertension specialist because his BP was not controlled and he was experiencing intolerable adverse effects from the six medications that he was taking for BP control. He was a certified public accountant who owned his own firm. He reported that he was unable to concentrate on his work as the peak tax season was approaching in March. His medications included a diuretic and clonidine 0.3 mg twice daily. All of the medications were at maximum doses, thus meeting the criteria for resistant hypertension.

The patient had been taking his own BP at home using an oscillometric device. He recorded his BP data on an Excel spreadsheet and sent them by e-mail to his physician. The physician adjusted the medications according to theses reports. When seen in the hypertension specialist's office, BP recorded using a hand-held calibrated aneroid sphygmomanometer was 102 mmHg systolic. The specialist had his fingers on the patient's radial pulse as he inflated the device and was startled when the pulse was obliterated at only approximately 100 mmHg. The patient did have orthostatic dizziness at the time. The specialist rechecked his aneroid device against a mercury sphygmomanometer and found the readings to match exactly. The patient was advised to reduce his dose of clonidine over the next week and to return to the office with his personal device.

The patient returned as scheduled and reported that his mind was clearer and that his mouth was not nearly as dry. He demonstrated the use of his device; this provided an elevated reading. When he was checked using the calibrated aneroid device, the difference was approximately 40 mmHg lower. That is, the patient's device was substantially over-reading his BP and driving unnecessary increases in medication. The patient had previously undergone an extensive and well-documented evaluation for secondary hypertension that was negative. He did have a strong family history of hypertension and was clearly hypertensive himself. When his medications were adjusted using BP determined by validated devices, he was brought under control, although three medications were required. He was able to return to his practice.

Ambulatory BP monitoring

Ambulatory BP monitoring was described by Sir George Pickering in his classic book, *High Blood Pressure*, in 1968 [12]. An intra-arterial catheter was connected to a recording device that could be worn for 24 h. He noted the early morning rise in BP, response to painful stimuli, increase in BP during coitus and nocturnal dipping. Direct intra-arterial monitoring is now limited to intensive care units and operating rooms. Even then, the transducer must be carefully calibrated and the arterial line maintained free from clot and damping.

Case 2

A 78-year-old man came to visit his brother, a patient in a Veterans Affairs Medical Center. It was May, a time when awareness of heart disease and hypertension was being promoted. Nurses set up BP measuring devices in the lobby of the hospital and offered readings to all visitors. The man had his BP measured and the device recorded a systolic BP of over 260 mmHg. This was rechecked multiple times with both the automated device and a standard sphygmomanometer. The patient was asymptomatic. Although not a veteran, he was admitted to the intensive care unit where an arterial line was placed and he was started on a sodium nitroprusside drip. The direct arterial readings were in the 150–160 systolic BP range, despite repeated indirect readings of approximately 260 mmHg. The transducer was thought to be defective and was changed. The differential persisted. The arterial line was flushed, manipulated and eventually changed without changing the indirect readings. In the meantime, the intra-arterial pressure continued to fall, eventually to less than 60 mmHg. The patient stopped urinating and lost consciousness. Ultimately, the physicians appreciated that the arterial line was accurate and stopped the infusion of nitroprusside. The patient regained consciousness, began urinating and eventually demanded to be discharged. Radiographs read later showed dense calcification of medium arteries in the arms and neck. In retrospect, he had pseudohypertension from Mönckeberg's medial calcification [13].

Modern devices measure and record BP indirectly over the 24-h period. They are set and read by computer programs. These use oscillometric methodology, the same as in the home units described.

Central aortic pressure measurement

Pressure estimated by indirect measurement in the brachial artery may be quite different from that to which the majority of the vascular bed is exposed. Central aortic pressure and augmentation index are purported to give more accurate results [14]. While this may be true, there are problems associated with this methodology. There are several devices on the market that use different technology. The person who makes the determinations must be carefully trained in the use of the device and recognition of valid wave forms. Results may be inconsistent both internally and externally. Finally, most of the epidemiological data referable to target organ damage by elevated BP has been gathered using brachial artery estimated pressure. We will not address these issues in further detail in this article.

Sources of error in BP estimation

There are numerous sources of error in estimating BP that need to be considered in order to prevent or to minimize such errors (Box 1).

Observer error

Observers in quality research studies are highly trained and certified as competent to acquire BP data. This may not be true of observers in community or clinical practice. Observers using nonautomated devices frequently have an unconscious preference for certain digits. Since the mechanical devices use scales calibrated in 2 mmHg intervals, there are only five choices for the terminal digit: 0, 2, 4, 6 and 8. There is a 20% chance of each of these being recorded at any one time. If review of multiple BP determinations by a given observer reveals a disproportionate number of recordings of the same terminal digit, digital preference is likely to be operating and is a source of error [15]. The Hawksley Random Zero sphygmomanometer was invented to circumvent this problem [16]. The device used a wheel that was spun to determine true zero on a random basis. The number on the wheel was to be subtracted from the actual reading. While this was conceptually sound and the instrument was used in many large-scale clinical trials, observer error could still occur from such simple things as errors in subtraction. Electronic devices that display the results as numbers on a screen eliminated digit preference.

The sphygmomanometer cuff must be of a size appropriate to the circumference of the subject's upper arm. It does not matter whether the device is mechanical or electronic. A cuff that is too small will create a measurement error. It may be necessary to use a large adult cuff or, in some cases, a thigh cuff. These larger cuffs may not always be present in all clinic locations.

Case 3

A 56-year-old woman had huge upper arms (not actually measured) for which a thigh cuff was too small. Her personal physician rejected her, telling her not to come back until she lost weight. Nevertheless, he treated her seemingly elevated pressures determined as well as could be done by the clinic nurses. She suffered a minor stroke. The academic clinic did not have a cuff large enough for her arm, so BP was estimated by placing a standard cuff on her forearm and using the radial artery to auscultate Korotkoff sounds. Her BP determined by this means was normotensive. Her medications were adjusted using forearm measurements. Whether her stroke was caused by hypotension related to overtreatment based on erroneously high BP reading is unknown. She subsequently changed to a more sympathetic primary care physician.

Box 1. Major sources of error in blood pressure measurement and evaluation.

- Patient not properly prepared and positioned:
  - Rest in a chair for at least 5 min
  - No smoking, coffee, stimulant medications for at least 30 min
  - Back supported, feet on floor, legs not crossed, arm at heart level
- Cuff size not appropriate to dimensions of upper arm
- Arm with highest systolic blood pressure not used and recorded
- Standing blood pressure not determined
- Device not validated or calibrated
- Operator not adequately trained (observer error)
- Situation error:
  - Patient in pain, anxious, panic attacks
  - Office (white coat) hypertension
- Environmental and physiological sources of inconsistency:
  - Time of day, season, ambient temperature
  - Some ‘nutriceuticals’ such as bitter orange, ephedra
  - Nonsteroidal anti-inflammatory drugs, diet pills, pressor agents

Patient positioning

Despite the attention paid to improving devices used for BP estimation, very little attention has been paid to appropriate preparation of the subject. Schwartz has detailed the requirements for accurate BP determination [17]. The American Heart Association was very deliberate in spelling out standards for BP determination that include the position of the patient [18]. The subject should be seated comfortably with their back supported, feet on the floor, legs not crossed and arm supported at heart level. The patient should be at rest in this position for at least 5 min. The Joint Commission on Prevention, Detection, Evaluation and Treatment of High Blood Pressure (JNC 7) has incorporated these directions in its guidelines [19]. The reality in many offices and clinics is that this is not practical. Patients are often seated on an examining table with back unsupported and feet dangling; the arm is not supported. These are all sources of measurement error.

Situation error

Situation error is generated by the venue or circumstances in which the BP is determined. When a patient arrives in an emergency department (ED), they are often in pain, anxious or both. If the emergency is of low priority to the triage personnel who may be dealing with far more emergent cases, the triage and registration process may be extremely frustrating to the patient whose personal emergency is the only one that counts. BP determination is rarely performed according to American Heart Association standards in that there may be no place to sit quietly and the surrounding noise and commotion may be anything but restful. In urban EDs that may deal with gunshot wounds, stabbings, automobile accidents and other trauma, determination that there is any detectable BP elevation is important to the triage staff. The exact degree of elevated BP may be unimportant at the time. Unless the BP elevation is associated with emergent comorbidities, such as acute heart failure, myocardial infarction or aortic dissection, emergent treatment is not required and probably should not be performed in the acute ED setting. The evaluating and treating physician must document the ‘true’ BP under more ideal circumstances before initiating therapy.

Anxiety reactions, including panic attacks, may not be obvious on first encounter with the patient. Elderly patients who have noncompliant major conduit arteries tend to have exaggerated elevations of systolic BP driven by anxiety. The exact inciting incident may be difficult to determine. The following case, previously published in greater detail [20], illustrates this point.

Case 4

A woman in her late 80s was known to have hypertension that could be aggravated by anxiety-generating situations. Her baseline office BP was well controlled with several medications. She came to the office on two separate occasions with her BP substantially elevated above her baseline. Patient and sympathetic inquiry revealed on one occasion that the exterminator had failed to come to her apartment as scheduled and her kitchen was overrun with bugs. Her BP was returned to baseline by hiring a new exterminator. Medications were not titrated upward. On a second similar occasion, the basis of her anxiety proved to be that she had been given a new state of the art television set by her family, but that the installer failed to teach her how to use the remote control. Her BP returned to baseline once she was taught how to use the new device.

Panic attacks

Hypertension specialists are likely to see patients whose episodic BP elevations are based on panic attacks. The general characteristics of such patients are listed in Box 2. The BP elevations experienced by these patients are real. Typically (note that these patients tend not to be typical and that there are many variations on the general theme), the patient is awakened at night with palpitations, sometimes flushing of the face, a lump in the throat (globus hystericus), pressure on the chest and may or may not have a feeling of panic or fear of imminent death. BP determined by a home device is invariably elevated and tends to become more elevated on repeat determinations. Frequently, emergency personnel are summoned and confirm the elevated BP. Patients are often transported to an ED. This type of BP elevation is usually reduced by reassurance, placement in a quiet area and use of an anxiolytic drug such as alprazolam. It is critical to be certain that they do not have secondary hypertension due to pheochromocytoma before attributing the BP elevation to a panic attack. These people can be helped by psychiatrists who are trained in treating anxiety disorders. A very useful summary was presented by Pickering and Clemow [21].

Office or white coat hypertension is a common confounder of accurate BP determination [22]. These patients have elevated BP readings in the office or clinic, but normal determinations at home. It is imperative to evaluate the device that the patient is using by having them bring it to the office and demonstrate that they know how to use it. This includes knowledge of the correct position. The device should be one that has been validated by the Dabl® Educational Trust [103]. The standard for home BP readings is 5/5 mmHg lower than those determined in the office. Unfortunately, office hypertension is not benign. It frequently increases to fixed hypertension. Over the long term (6 years in one study), the patients become at higher risk for stroke [23].

Pseudohypertension (calcified medium arteries)

An example of pseudohypertension was presented in case 2. Patients with calcified medium arteries do not generally have occlusive arterial disease and may be totally unaware of their condition. Calcified arteries are sometimes identified for the first time by radiographs taken for unrelated reasons. Indirect cuff determinations are inaccurate owing to the excess pressure required to compress the calcified artery. These patients may have some degree of intra-arterial pressure elevation and direct measurement may be necessary in some cases [15].

Environmental & physiological sources of error

Accurately determined intra-arterial pressure can still vary with a number of physiologic and environmental factors [24]. This includes time of day, season, ambient temperature and influence of consumed substances. In general, BP tends to be higher in the morning, especially with pre-awakening acceleration, and lower during sleep. Hypertensive patients who display the typical nocturnal decrease in BP are termed ‘dippers’, whereas patients in whom the nocturnal decrease in BP is absent or blunted are termed ‘nondippers’. BP tends to be lower in the summer months as a result of higher ambient temperatures. An uncomfortably cold examining room can elevate BP. The changes induced by consumption of caffeine or smoking a cigarette tend to be small and there is a great deal of individual variation. Nonsteroidal anti-inflammatory agents can elevate the BP in some patients. It is important to ask what the patient is taking for pain. So-called health foods and related substances may elevate BP. Such things as bitter orange, ephedra and other ‘natural’ ingredients may elevate BP. Patients rarely volunteer information about taking these substances. Obviously, substances such as cocaine

Box 2. Characteristics of panic attacks.

- History of having consulted multiple physicians without a satisfactory outcome
- Mysterious drug ‘allergies’: the patient is rarely able to articulate the exact nature of the allergy; the patient simply does not feel well. We suspect that this may be hypotension-related at a time when the patient is not anxious
- Totally negative workup for organic causes of hypertension; this is mandatory
- Improbable pharmacology: the patients often describe side or adverse effects highly unlikely to be due to the drug (e.g., edema from a diuretic)
- History of related anxiety-related symptoms, diagnoses or hospitalizations. Some patients have already been told that they have panic attacks
- Beneficial response to alprazolam: the physician should ask if they ever took Xanax®
- These patients can be helped. They need to be told that they are experiencing panic attacks, that this is not their fault, that they are not crazy and that psychiatrists who specialize in anxiety disorders can help with both medication and methods of coping

can cause acute BP elevations, but the other related effects of that drug are usually evident. Less evident may be the use of erythropoietin or weight-loss drugs. Talking during determination of BP and ambient noise may also elevate BP [19].

There may be differences in BP between the two arms. Systolic BP may be higher in one arm and diastolic BP in the other. Most (91%) individuals have less than 10 mmHg difference. Even those with a greater differential need not be subjected to vascular investigation unless they are known to suffer from known vaso-occlusive disorders or have relevant physical findings [25]. It is important to use the arm with the higher systolic BP and to note both the arm and position in the medical record.

A recent study of 98 patients who were undergoing cardiac angiography raises an interesting question about the influence of gender on oscillometric BP measurement. Patients had simultaneous oscillometric brachial cuff BP and intra-aortic catheter BP measurements. Overall, the results were similar. However, oscillometric mean BP was overestimated in men by 4.7 mmHg and mean BP in woman was underestimated by 4.4 mmHg. The oscillometric device overestimated aortic diastolic BP in men but not in women and underestimated aortic systolic BP more in women than in men [26]. The authors have computed equations to correct for these differences. The data need to be confirmed and the corrections validated, but these results are intriguing.

Minimizing variation in BP determination

Having trained personnel use validated, calibrated devices on subjects who are properly rested and positioned may not be good enough. Research studies usually require that at least three readings be taken at least 1 min apart and then averaged. Often, the first reading is discarded. Taking multiple readings in a clinical setting may be impractical, yet therapeutic decisions based on a single reading may be in error.

Readings should be taken at the same time of day by the same person, preferably when the patient is fasting or has had only a light meal. Diagnostic and therapeutic decisions should be based on three or more readings taken at least 1 week apart, unless the BP elevation is so high that immediate treatment is necessitated [19].

Patients should be queried by office staff regarding all medication, including those taken for pain and also health foods. Many patients do not consider 'nutriceuticals' to be medications or drugs. Patients should be asked about changes since the previous visit, especially in regard to diet, lifestyle and events that could cause anxiety or emotional upset. All of this can be performed by trained office personnel, especially if they are provided with either a written or electronic check list. Home BP measurements can be very useful providing that the patients are trained to take them correctly and that their devices are validated and calibrated. Ambulatory BP measurement provides the advantage of multiple readings over the 24-h period. 'Dipping' may also be assessed. The devices are expensive and the procedure is poorly reimbursed. It is also uncomfortable or inconvenient for some patients.

The net result should be to provide the practitioner the most accurate data possible on which to base clinical decisions. It is important to note that focusing on BP numbers alone may be misleading. Clinicians should be well aware of concomitant diseases and risks as well as the level of BP in making clinical decisions on treatment [27].

BP measurement in obese patients

Occasionally, a patient will have an arm that is so large in circumference that not even a thigh cuff is of sufficient length to fit. A further complication is that many arms, and especially obese arms, have a conical configuration thus making it difficult or impossible to fit even a cuff of appropriate length. Finally, some arms are not only obese, but short such that a thigh cuff is long enough but too large to fit on a short arm [28].

There are potential solutions. One is to use a regular cuff on the forearm and auscultate the radial artery for Korotkoff sounds. A second method is to use a wrist monitor that has been validated. The modern wrist devices are calibrated such that they work when the arm is at heart level. These methods make clinically accurate and useful estimation of intra-arterial pressure in very obese patients relatively simple and practical [28,29].

BP measurement in pediatric patients

Hypertension and prehypertension in children under the age of 18 years continues to be defined by percentile values based on gender, age and height [30]. By definition, hypertension affects 5% of all pediatric patients, although it is well known that some patients with underlying medical problems, such as renal disease, are far more likely to have hypertension. As the obesity epidemic worsens throughout the developed world, the reported incidence of hypertension is increasing in the pediatric population [31]. The current recommendation is that children over the age of 3 years should have their BP measured annually, preferably with the use of a conventional sphygmomanometer and auscultation [31]. However, there are still many issues surrounding the appropriate use of nonauscultatory methods and other potential sources of error that are not always apparent to the general clinician.

Due to the relatively small size and amplitude of the brachial pulse in the infant and toddler, the auscultatory method of determining the BP is difficult. It is largely for this reason that routine screening of infant BP is not recommended. Two alternate noninvasive methods have been investigated: ultrasonic measurements of BP based on Doppler methods and oscillometric measurements.

Multiple studies in the early 1980s performed on neonates and infants under anesthesia and in the intensive care setting found that noninvasive monitoring of BP with oscillometric devices correlated well with invasive measures. A study based in a pediatric intensive care unit found that oscillometric devices had a better correlation and lower degree of variation from direct measurements than attempted auscultatory measurements [32]. It was felt by the authors that this was due to observer bias (there were three study personnel involved in obtaining the auscultated readings) and also due to difficulty with the measurements in young children.

These data on noninvasive measurements were not readily generalizable to the outpatient setting where the influence of motion artifact and positioning could potentially play a much larger role. Thus, the same investigators attempted to establish normative oscillometric data for a clinic population of children under 5 years of age. They found that in 87% of children under 3 years old and all children older than 3 years, three consecutive BP readings of acceptable quality could be obtained [33]. In addition, the values obtained by oscillometric measurement were very similar to prior published normative values obtained by auscultatory or ultrasonic methods. Finally, they found that when three consecutive measurements were obtained, there was little difference in the measurements in infants under 1 year of age, but the first measurement in children over the age of 1 year is often elevated compared with subsequent measurements. Therefore, when an elevated BP is recorded, regardless of the type of device being used, a repeat measurement should be made.

Although the official recommendation is still for measurement of BP via auscultation in children, there appears to be a role for the oscillometric device in both the younger child as well as for routine clinic use as a screening tool, with confirmatory measurements obtained conventionally. The usual caveats about adequate calibration, knowledge of the particular device being used and the fact that the currently standard normative data were obtained by auscultation still apply [34].

The issue of appropriate cuff size is of significant importance in the general pediatric office. This is especially relevant for the premature infant (for whom even the smallest commercially available cuff may be large and difficult to adequately wrap around the upper arm) and for the overweight or obese teenager. Most general pediatric offices stock cuffs up to either the small adult or adult size, but as is well known for adults, the teenager with a large upper arm circumference may require a large adult or thigh cuff for accurate measurements.

This issue of body habitus is becoming more prominent even in younger children. An illustrative case was noted in the pediatric service.

Case 5

A 9-year-old girl presented to the emergency room with likely orbital cellulitis. Her past medical history included hypertension (not on medication) diagnosed by her primary care physician, obesity and 'prediabetes' based on glycohemoglobin measurements. She initially presented to the emergency room with a recorded oscillometric BP of 128/89 mmHg (which is >95th percentile for her age and height, but consistent with her reported history of hypertension). Shortly thereafter, she was evaluated by the emergency room physician. There was evidence of delayed capillary refill and weak peripheral pulses; therefore, an auscultated BP with an appropriate sized cuff was obtained by the physician and was noted to be 86/38 mmHg. It was never determined what size cuff was used for the initial oscillometric measurement as this was not recorded.

While this wide variability in the recorded BP cannot be fully attributed to the selection of an improper cuff size (other factors would include worsening infection/sepsis, severe pain and anxiety), it appears likely that the elevated BP recording by the triage nurse was partly due to the inappropriate selection of a pediatric cuff for this adult-sized child. Interestingly enough, after the child was treated for her acute infection, it was noticed that her recorded BP in the days prior to discharge ranged from 90–111/45–60 mmHg, all of which is below the 90th percentile for her height and age. Was the diagnosis of hypertension accurate or had her pediatrician been using an inappropriately sized cuff?

The effect of pain and anxiety on a child's BP measurements has not been well studied, but there is anecdotal evidence that these variables play a significant role in the pediatric patient. This is somewhat difficult to assess as the young child is unable to report on their feelings of pain or anxiety. In addition, the increased motion artifact frequently associated with pain or distress in the child confounds accurate measurement of BP.

An argument can be made that as a population of children becomes taller and heavier, perhaps due to improved nutrition, the standards for 'normal' BP should also be changed [35]. We fear that such increases in what is accepted as 'normal' on a statistical basis may not be devoid of target organ consequences owing to the increased pressure load [36].

The discussion of the adult population highlighted some of the potential pitfalls with home or ambulatory BP monitoring. However, another interesting phenomenon of masked hypertension has been recently reported in the pediatric literature. This is a phenomenon of elevated ambulatory BP measurements with normal readings in the clinic or hospital setting. A recent study of children with chronic kidney disease has found that the incidence of masked hypertension in this high-risk cohort may be as high as 38%. Alarmingly, this study also found that left ventricular hypertrophy correlated with the presence of masked hypertension, which would seem to indicate that untreated masked hypertension may lead to increased cardiovascular risk as these children mature [37].

In conclusion, the pediatric patient poses unique challenges in the routine screening for hypertension in the ambulatory setting. The main risk factors for hypertension in children remain low birth weight and obesity and the prevalence of both these conditions is currently increasing in the USA. The general pediatrician will need to be familiar not only with the recommendations for screening but also the potential errors involved in BP measurements.

Future perspective

Estimation of intra-arterial pressure will remain only an estimation so long as it is necessarily indirect. Nevertheless, innovation will continue to occur in oscillometric devices that are portable, relatively inexpensive and easy for people to use at home. Directly marketed cheap devices that are not validated may be a significant source of error. Pulse waveform analysis will likely return to the fore as increasingly sophisticated devices and algorithms are invented to acquire, transform, analyze and interpret the pulse wave. Such pressure determinations will always be subject to inconsistencies if subjects are not properly positioned and prepared or if observers are not trained on correct technique. Those who design future clinical studies or epidemiological surveys using new technology will need to be certain that the techniques are valid in order to avoid later questions as has happened with the random-zero device. Pediatricians need to be certain that they have a wide variety of cuff sizes available to span the range from premature infants to adult-sized adolescents. Hopefully, the calls for international validation of BP measuring devices will be heeded [38,39].

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Executive summary

- Intra-arterial pressure is estimated clinically by indirect methods.
- Instruments for blood pressure determination must be validated and frequently calibrated to ensure their accuracy.
- Training of personnel (or the subject) is vital to obtaining accurate data.
- Correct positioning and preparation of the patient and minimization of the sources of inconsistency are necessary to obtain accurate readings.
- Home readings tend to be 5/5 mmHg lower than office readings; this needs to be considered when interpreting home-derived data.
- Correct cuff size is especially important for the wide range of arm sizes; with a particular problem in pediatrics.

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