The era of noninvasive blood pressure (NIBP) measurement started with the introduction of the modern sphygmomanometer by Riva-Rocci in 1896. The Korotkoff method for determining systolic and diastolic pressure in 1905 marked the beginning of the auscultatory method of blood pressure (BP) determination. This method has been used by health care professionals without substantive changes to the present time. The manual auscultatory method uses a sphygmomanometer (inflatable cuff and a manometer) and a stethoscope. The cuff is usually wrapped around an upper arm and inflated to about 30 mm Hg above the expected systolic blood pressure (SBP). With the stethoscope placed over the brachial artery, the cuff is deflated at a rate of 3 to 5 mm Hg per second. The SBP is determined as the point at which the phase 1 Korotkoff sound is first heard. The diastolic blood pressure (DBP) is the cuff pressure at which the phase 4 (muffling) or phase 5 (disappearance) of Korotkoff sounds occurs. Disagreements over the use of phase 4 and phase 5 Korotkoff sounds have existed, but the latest guidelines from the Joint National Committee on Prevention, Detection, Evaluation, and Treatment of High Blood Pressure recommend phase 5 (the point before sound disappearance) for detection of DBP.

Automatic, electronic NIBP devices started appearing shortly after the introduction of microprocessors. In automated auscultatory NIBP measurement, at least one microphone is used in place of the stethoscope to detect Korotkoff sounds. Another method used in automated NIBP devices is the ultrasound method, which uses ultrasonic detection of arterial wall motion during cuff deflation. The auscultatory or ultrasonic electronic NIBP devices need external sensors in addition to the cuff. The sensors must be placed correctly over the artery for proper function of the device. The need for external sensors is eliminated by the oscillometric method.

Most noninvasive blood pressure (NIBP) devices use the oscillometric method. Published studies of oscillometric methodology introduced varied algorithmic approaches for determination of systolic (SBP), diastolic (DBP), and mean arterial (MAP) blood pressures. While there is a general agreement about MAP determination, controversy exists about the determination of SBP and DBP. Accuracy of oscillometric devices has been questioned and validation studies have revealed problems. Several validation protocols have been developed but they are expensive and time consuming to conduct and they have their own limitations. Instruments for bench testing of NIBP devices are useful for some device functions, but they cannot perform dynamic accuracy tests. The issue of accuracy is becoming very important as health care professionals increasingly rely on electronic NIBP devices. The authors developed a compact system for acquisition of NIBP waveforms. Some representative oscillometric waveforms are introduced here to demonstrate the oscillometric method and its shortcomings. A finger photoplethysmograph (PPG) was used to demonstrate a potential improvement of SBP determination. The concept and significance of an oscillometric blood pressure waveform database is introduced and its applications are discussed.

method, which requires only a cuff and a pressure sensor for its operation.

Oscillometry

Oscillometry was introduced by Marey in 1876, who placed the forearm and the hand in a water-filled chamber to which a variable counterpressure was applied. The counterpressure for maximum amplitude of oscillations determined that the vessel walls were maximally relieved of tension during the cardiac cycle and BP was communicated to the water in the chamber. A similar spectrum of oscillations in cuff pressure was seen when an air-inflated cuff was used. For some time, it was thought that the lowest cuff pressure for maximal oscillations was equal to diastolic pressure. This assumption was proven to be incorrect by Posey and Geddes. They showed that the point of maximal oscillations corresponded to true mean-arterial pressure. When pressure in the cuff was increased above mean pressure and then decreased below mean pressure, the amplitude of oscillations decreased.

Electronic oscillometric instruments capable of determining SBP, DBP, and mean arterial pressure (MAP) started appearing on the market in the 1970s. Microprocessors facilitated algorithmic methods for the determination of SBP and DBP. One of the first descriptions of a microprocessor-based oscillometric device appeared in 1978. Unfortunately, disagreements about oscillometric methodology started appearing in the literature at that time and have continued to appear today.

For example, a publication on hypertension makes an assertion that the oscillations in the cuff appear at approximately systolic pressure. This assertion contradicts Geddes work. Geddes showed that the artery pulsates under the upper edge of the cuff at pressures well above SBP and the pulsations are communicated to the cuff via the intervening tissues.

Oscillometric waveforms in Figure 1 support the assertion of Geddes. The upper trace represents cuff pressure (CP) decreasing from supersystolic to supradiastolic pressure. The lower trace represents the oscillometric waveforms (OMWs) that were derived from the CP by low-pass filtering and amplification. The oscillometric waveforms appear well above the reference SBP and their amplitudes continue to rise until MAP is reached.

Published methods for oscillometric determination of SBP and DBP present differing approaches. Geddes makes certain assumptions about algorithmic determination of SBP and DBP. These algorithms are based on the ratio of oscillometric waveform amplitudes. According to Geddes, SBP corresponds to the point of 50% of maximal amplitude; for DBP, the ratio is 80%. Another author claims that SBP should be at 40% and DBP at 5% of maximal amplitude.

The amplitude ratio methods are not the only ones used in oscillometric determination of SBP and DBP. Methods based on the change in the slope of amplitude envelope have been described. The investigators of slope methods differ in their claims as well. An article describing the function of an oscillometric BP device claims that the device determines SBP as the point of the initial increase of the cuff pulsations. Another author puts SBP on the minimal ascending slope of the amplitude envelope and DBP on the maximum slope of the descending amplitude envelope.

The above algorithmic approaches result in differing SBP and DBP values. The published reports on algorithmic determination of SBP and DBP do not offer physiological explanation for their assertions. The only commonly recognized and physiologically verified oscillometric variable is MAP.
Advantages and Pitfalls of the Oscillographic Method

There are many oscillometric NIBP devices on the market today. They range from expensive, rugged instruments for clinical use to miniaturized units that fit on a wrist. Most of these devices use continuous linear or nonlinear deflation methods. Some devices use a step-deflation method, and some recent monitors use an inflation method. Ease of use has made oscillometric devices very popular. The elimination of external sensors contributed to their popularity at the price of increased uncertainty in the determination of SBP and DBP.

Examination of oscillometric waveforms in Figures 1 and 2 reveals the challenge that designers of oscillometric BP devices face in attempting to determine SBP and DBP algorithmically. There are no easily identifiable SBP and DBP points on the waveform envelope. Oscillometric BP determination is complicated by other factors, such as movement artifacts, deep breathing, tremors, and arrhythmias. Arrhythmias introduce especially difficult problems. Their nature and frequency of occurrence are not always apparent. The waveform envelope in Figure 2 contains irregular beats. The uneven sequence of waveform amplitudes results in unpredictable BP determination. Reference SBP and DBP could not be determined reliably by auscultation. An external sensor located distally from the cuff diminishes the uncertainty of oscillometric SBP determination. Figure 2 illustrates this point. The upper trace represents pressure waveforms obtained with a finger photoplethysmograph (PPG) and the lower trace shows OMWs. When the cuff is gradually deflated from suprasystolic pressure, the oscillometric waveforms are present but the PPG baseline is flat. When the CP decreases below SBP, turbulent blood flow passes past the cuff. Blood volume and pressure in the finger begin to rise due to blocked venous blood return. The PPG trace reflects the rising blood volume and arterial pulsations. The availability of a PPG signal makes the determination of SBP easier than reliance on just the oscillometric waveforms.

The waveforms shown in Figures 1 through 3 were acquired with an experimental data-acquisition system. The system consists of a BP cuff; a module containing pneumatic components, pressure circuits, and data acquisition electronics; and a notebook computer (Figure 4). Cuff pressure is converted to analog voltage by a pressure sensor.

The pressure-sensor output is amplified by an instrumentation amplifier and filtered by a low-pass antialiasing filter. A high-pass filter is used to eliminate the cuff deflation component of the signal and an amplifier is used to obtain waveforms of sufficient amplitude for digitization. A commercially available finger PPG was used to acquire the PPG waveforms. A PPG uses a light source to illuminate a circumscribed portion of the tissue. The intensity picked up by a photoelectric sensor is then related to the blood volume in the respective area.11 Cuff pressure voltage, amplified oscillometric waveforms, and finger PPG signals are digitized by a 4-channel, 12-bit analog-to-digital converter. The sampling rate is 11.8 milliseconds. The digitized data are transmitted to the notebook computer via a serial interface. The computer controls acquisition and processing of pressure data. The data used in this report were acquired from volunteers in informal settings. Reference BPs were measured using the standard auscultation method.

Oscillometric BP Device Performance Testing and Validations

All oscillometric devices use algorithms for BP determination, but one can only speculate what algorithms they use. Published algorithms show disagreements, and device manufacturers consider their algorithms proprietary and keep them secret.12 This makes verification of accuracy difficult. There are several NIBP test instruments on the market today. They can perform useful tests, such as static-pressure accuracy, cuff deflation rates, leak tests, and overpressure tests. They cannot, however, perform dynamic algorithmic NIBP accuracy tests. The operation manual of the popular NIBP ana-
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Figure 4. Oscillometric and photoplethysmograph (PPG) waveform acquisition system.

Oscillometric techniques are briefly described in this chapter and the following conclusions are drawn: “Various interpretations have emerged from the manufacturers with varying degrees of agreement. At present, no regulatory agency has put forth a standard as to how oscillometric pulse amplitudes should be interpreted to determine blood pressure. Therefore, the accuracy and repeatability of these monitors is difficult to determine. Should any public standards emerge, CuffLink may be programmed to implement them to test blood pressure monitor accuracy. Absolute dynamic accuracy cannot be assigned to MAP, diastolic, and systolic target values at this time because no standard exists.” The issue of accuracy is becoming increasingly important as many health care institutions rely heavily on automatic NIBP devices. Because there are no reliable instruments for testing of algorithmic accuracy, performance-testing protocols for device validations have been developed. The Association for the Advancement of Medical Instrumentation, the British Hypertension Society, and the European Society of Hypertension recommend validation of NIBP devices against auscultation or against intra-arterial methods. Many validation studies have been conducted and some reviews of validation results have been published. Their findings indicate that the accuracy of BP determination is problematic for many NIBP devices. Validation protocols are not without problems either. A recently published study exposed limitations of current validation protocols. The study concludes that the existing protocols are likely to pass devices that can be systematically inaccurate for some patients. Disappointing validation results, lack of information from device manufacturers, and errors observed in health care institutions have led to warnings issued by experts in the field of BP measurement. The American Heart Association issued an advisory statement from the Council for High Blood Pressure Research. The Council cautioned health care professionals not to abandon mercury sphygmomanometers until adequate replacement instruments are available. A recent report by a group of leading experts stressed the importance of accurate BP measurements. The report called for additional research to assess accuracy of NIBP devices and concluded that mercury sphygmomanometer remains the gold standard for noninvasive BP measurement.

The Case for a Public Database of Oscillometric BP Waveforms

Oscillometric BP waveforms are indispensable for noninvasive determination of BPs and they may contain other useful information. An investigator or a device developer who wants to study oscillometric waveforms needs a reasonably large database of waveforms and reference BP measurements. Manufacturers of oscillometric BP devices must have such databases in order to conduct their development efficiently. These databases are, however, proprietary. There are no publicly accessible databases of oscillometric waveforms at the present time. On the other hand, public databases for some physiologic waveforms do exist, mainly for interpretation of electrocardiograms. The National Center for Research Resources (NCRR) operates a website, PhysioNet. PhysioNet offers free access to a collection of recorded physiologic signals. Oscillometric BP waveforms are not included in the present PhysioNet collection. General principles of acquisition and use of physiological waveforms are described in the Association for the Advancement of Medical Instrumentation Technical Information Report. The report stresses the necessity to test algorithmic functions of digital devices with real physiologic data. Properly documented databases are needed for such testing. The waveforms can then be used to test devices repeatedly and reproducibly.

A wide-ranging, publicly available database of oscillometric BP waveforms could advance the field of oscillometric BP measurement in the following ways:

- New research into the largely unknown physiological basis of oscillometric BP measurement. The research could result in the development of a generic algorithmic method for the determination of SBP and DBP.
Device developers would enjoy the advantage of not having to develop their own proprietary databases, as the past and present manufacturers had to do. Costs of development and time to market could be decreased. A standardized, public database would serve as a common knowledge base and it should produce devices performing in a similar, predictable manner.

Repeatable, reproducible performance testing of oscillometric BP devices could become possible. The expensive, time-consuming testing as performed today could eventually be eliminated.

Determination of hemodynamic variables. It may be possible to derive cardiac output (CO), total peripheral resistance, and arterial compliance from oscillometric waveform contours and blood pressures. Several contour methods for CO determination already exist.22,23

A computerized, compact system similar to the system developed by the authors could be used to develop the database. The oscillometric and reference BP data would be acquired from a varied population and a wide range of blood pressures. The acquired, carefully annotated database could be made available to the public via PhysioNet or other media.

**Conclusion**

Oscillometric method for NIBP measurement as used in the state-of-the-art devices is attractive for the simplicity of cuff application and device operation. On the other hand, the empirical nature of existing algorithmic methods, the disagreements over methodology, the proprietary nature of commercial algorithms, and the resulting problems with accuracy have led to warnings and calls for more research.

The proposed oscillometric BP waveform database could facilitate such studies. The widespread use of oscillometric BP devices and the importance of accurate BP measurements justify increased efforts devoted to the improvement of oscillometric methodology.

**References**