Automatic Noninvasive Measurement of Arterial Blood Pressure

Meir Nitzan

The non-invasive blood pressure measurement is probably the most common medical measurement, due to its clinical significance and simplicity. The manual version of the technique was introduced in 1905 by Korotkoff and relies on a pressure-cuff, mercury manometer, and hearing of Korotkoff sounds. It is still preferred by most physicians over the available automatic devices for blood pressure measurement. In this paper, I review the physical and physiological basis of the manual and the automatic techniques for the non-invasive measurement of blood pressure. The scientific background of the different techniques helps us to assess their ability to provide accurate evaluation of arterial blood pressure and reliable detection of hypertension.

Physiological Background

Circulation of blood by the cardiovascular system is essential for supplying metabolites and oxygen to the tissues and removing waste products from them. Blood is ejected from the left ventricle and flows through the arteries to the capillaries where material exchange with the tissue occurs and flows back to the right atrium through the veins. In the pulmonary circle, blood flows from the right ventricle through the pulmonary arteries to the lung capillaries in the alveoli where oxygen and CO_2 exchange occurs and returns to the left atrium through the pulmonary veins. During heart contraction (systole) the high pressure developed in the ventricles propels the blood through the arteries and the capillaries into the venous system where the blood pressure is relatively low. The force that causes the blood to move in a vessel segment is directly related to the pressure gradient along the vessel segment. During heart relaxation (diastole) venous blood returns to the atria, the collecting chambers of the heart. The pulsatile character of the heart activity causes the blood pressure in the arteries to increase during systole and decrease during diastole, as Fig. 1 shows. The highest value of the arterial blood pressure in a cardiac cycle is called the systolic blood pressure (SBP). The lowest value is called the diastolic blood pressure (DBP).

Arterial Blood Pressure

The blood flow, Q, through a blood vessel is equal to the ratio of the pressure gradient, ΔP, to the resistance-to-flow, R, of the blood vessel:

$$Q=\Delta P/R$$

where R is directly related to the viscosity of the blood and the length of the vessel segment and inversely related to the fourth power of the blood vessel diameter. The main drop in the arterial blood pressure occurs in the small arteries, primarily in the arterioles, the resistance arteries, but not in the broad conduit arteries, which have relatively large diameters and consequently relatively low resistance-to-flow. The expected constancy of the blood pressure along the conduit arteries actually happens for the diastolic blood pressure, but the systolic blood pressure may change along the conduit arteries and between them due to reflected pressure waves from the peripheral vasculature, mainly from bifurcations (branching) of the arteries. These reflected waves are superimposed on the incident wave and the resultant pressure pulse depends on the relative arrival time of the two waves at the site of measurement. The arrival time of the reflected wave is related

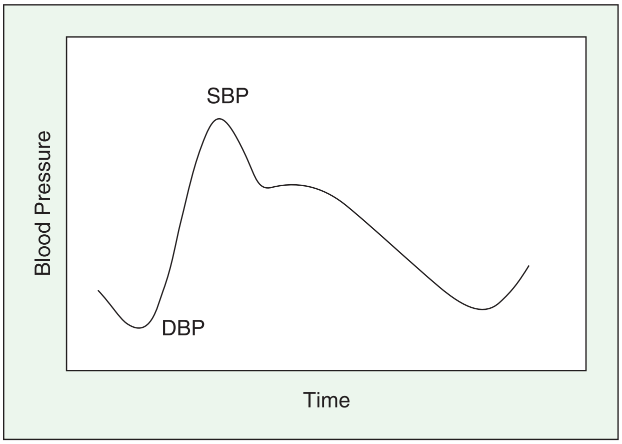

Fig. 1. The blood pressure pulses in the arteries.

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to the pulse wave velocity (which depends on the arterial stiffness) and the distance between the measurement site and the reflection site.

The arterial blood pressure is generally measured in the brachial artery – the artery along the arm, as will be described later. The mean values of the systolic and diastolic blood pressure for a healthy young adult male are 120 mmHg and 80 mmHg, respectively. In general, blood pressure is lower for females. Systolic blood pressure increases with age for both sexes, while diastolic blood pressure increases up to the age of 50-60 years and then tends to decrease. Deviations from normal blood pressure include hypotension (low blood pressure) and hypertension (high blood pressure). Both have adverse effects and should be diagnosed and treated. Hypotension can cause the blood supply to the brain, heart and other tissues to be too low, and hypertension is strongly correlated with higher risk for cerebral stroke and heart infarct.

Blood Pressure Regulation

To maintain a sufficient supply of oxygen and nutrients to the different tissues even in variable physiological conditions, the arterial blood pressure is regulated by means of several mechanisms, mostly by changing the stiffness of the conduit arteries and the diameter of the arterioles (the smallest arteries). These changes are modulated by the autonomic nervous system and the hormonal system which affect the tonus of the muscles of the blood vessels' walls. The autonomic nervous system is responsible for short-term regulation (with reaction times on the order of seconds) and the hormonal system is responsible for long-term regulation.

An important demonstration of the blood pressure regulation system is the increase of blood pressure that occurs after changing from the supine position (lying down), to the standing position. When rising to standing, blood tends to accumulate in the lower part of the body at the expense of the upper part of the body, reducing the blood pressure in the upper part of the body and consequently reducing blood supply to the brain. This decrease in blood pressure is detected by pressure sensors, baroreceptors, located in two arteries above the heart level: the aortic arch and the carotid artery. The baroreceptors' signals are transmitted to the autonomic center in the brain, activating the autonomic nerves, which cause constriction of the peripheral blood vessels, mainly those of the lower part of the body. In some diseases, including diabetes, dysfunction of the autonomic nervous system can be developed, preventing the required restoration of the blood pressure in the upper part of the body. This situation is named orthostatic hypotension and can lead to fainting and even death. Orthostatic hypotension can be diagnosed by measuring the blood pressure in the 3-4 min after changing to standing position [1].

The autonomic nervous system is also responsible for the short-term and diurnal (daily) spontaneous fluctuations in blood pressure which should be considered when arterial blood pressure measurement is performed. In particular, the arterial blood pressure decreases during sleep (dipping) and increases moderately during the morning (the morning surge) besides the rapid increase after awakening. Non-dipping is associated with greater cardiovascular risk, independently of the blood pressure level.

Blood Pressure Measurement

The measurement of the arterial blood pressure is of great clinical significance mainly for the detection and follow-up of hypertension which affects about one third of the adult population in the western world. An accurate and simple technique for the measurement of arterial blood pressure is essential for efficient diagnosis of hypertension and for its proper management. Because of the clinical significance of blood pressure measurements, a large market for blood pressure meters has been developed.

Arterial Blood Pressure Curve

The arterial blood pressure curve can be obtained by an arterial catheter which is connected to a suitable pressure transducer. Catheterization is, however, an invasive procedure. The arterial blood pressure curve can also be recorded by a non-invasive tonometer attached to the skin over a superficial artery, but this technique cannot provide absolute values of arterial blood pressure. To avoid arterial catheterization, sphygmomanometry was developed at the beginning of the twentieth century. This technique allows non-invasive measurement of systolic and diastolic blood pressure.

Sphygmomanometry

Manual sphygmomanometry requires that an external cuff be wrapped around the arm and that a stethoscope be placed on the arm over the brachial artery and beneath the end of the pressure cuff that is farther from the heart. The cuff consists of an inflatable rubber bladder which is encased in a non-expandable but flexible cover. When the cuff is inflated so its air pressure increases to above systolic blood pressure, the external pressure on the artery under the cuff is higher than the internal blood pressure, and the artery is occluded. When the cuff is slowly deflated, the air pressure in the cuff is continuously measured. When the cuff pressure is between systolic and diastolic blood pressure, sounds known as Korotkoff sounds can be heard in the stethoscope. These sounds are created when the lumen of the artery opens and closes during the cardiac cycle: the artery is occluded when the blood pressure decreases to below the cuff pressure and opened for blood pressure above the cuff pressure. The systolic blood pressure is the air pressure at the point for which Korotkoff sounds start to appear (Korotkoff phase I) during cuff deflation, and the diastolic blood pressure is the air pressure at which Korotkoff sounds disappear (Korotkoff phase V).

An inherent assumption required for the validity of the technique is that the arterial wall is flexible and no counter-pressure is exerted by it on the cuff, so that the cuff pressure at the moment of arterial closure is equal to the blood pressure. The assumption is not valid when the artery is rigid due to atherosclerosis (vessel calcification). In some patients, the air pressure required for arterial closure can be significantly higher than the systolic arterial blood pressure, and in some elderly patients the artery is not occluded even for a cuff air-pressure of 300 mmHg. This effect is named pseudo-hypertension, and if not properly diagnosed can lead to treatment that lowers the blood pressure below the required value, which can cause harmful effects to the patient [1].

The Manometer

The cuff air pressure is usually measured by a mercury manometer or by a mechanical manometer (an aneroid manometer). The mercury manometer is simple and because it is not subject to deterioration it is considered the most accurate manometer. However, mercury-based devices are being banned in many countries because of environmental concerns. The aneroid manometer is based on a metal bellows which expands and contracts with the variation of pressure within the manometer. The bellows movement is transmitted to a mechanical pointer, rotating on a circular calibrated scale. The mechanics of the aneroid manometer can change with use, in particular improper use, and the device must be calibrated every six months.

The cuff air-pressure can also be measured by an electronic pressure transducer which is generally accurate. The output of the electronic transducer can easily be recorded, so that the value of the air-pressure when Korotkoff sounds start can be determined by pressing a button, and the result can be read offline, avoiding the need to examine the scale during measurement.

Accuracy of Sphygmomanometry

Manual sphygmomanometry with a mercury manometer is considered to be the most accurate noninvasive method to which other methods should be compared. For simplicity, the units of the arterial blood pressure are defined by considering the height of the mercury column in the mercury manometer measured in millimeters of mercury (mmHg). This unit is related to the metric unit of pressure, kPa ($=10^3$ N/m^2), by the equation 1 mmHg = 0.133 kPa. However, manual sphygmomanometry requires a well-trained examiner. Generally speaking, such measurements are only made in a doctor's office and consist of a single measurement per visit.

As mentioned above, blood pressure varies spontaneously, and single measurements are not necessarily representative of the mean blood pressure. Furthermore, the technique depends on the hearing acuity of the examiner. The presence of the physician can psychologically affect the patient and influence blood pressure level, which is known as white coat hypertension. A technique for the automatic measurements of systolic and diastolic blood pressure enables multiple measurements to be taken at home, making it possible to obtain blood pressure measurements of higher statistical significance than those obtained by manual sphygmomanometry. An automatic measurement can also be performed during different activities and situations including sleep.

Automatic Measurement of Arterial Blood Pressure

Automatic sphygmomanometry (automatic detection of Korotkoff sounds by microphone during the pressure cuff deflation) has been suggested for the measurement of systolic and diastolic blood pressure. The main problem with automatic sphygmomanometry is ambient noise and motion artifacts which are created by movements of the extremities or the whole body.

Most of the commercial noninvasive automatic blood pressure monitors use either oscillometry (discussed below) or automatic detection of Korotkoff sounds or both [2].

Oscillometry is based on the measurement of the cardiac induced pressure oscillations in the cuff pressure during cuff deflation after inflating the cuff air pressure to above the systolic blood pressure. These oscillations are due to the impact of the blood pressure pulse on the cuff and they appear even for cuff pressure above the systolic blood pressure value where the arteries under the cuff are closed, due to the impact of the pulsating arteries on the side of the cuff nearer to the heart. The oscillations increase when the cuff pressure decreases, reach a maximum, and then decrease, as Fig. 2 shows. It was found experimentally that the maximal oscillations occur for cuff pressure which is equal to the mean blood pressure.

Systolic blood pressure is derived from the oscillometric pulse amplitudes versus the cuff pressure curve using empirical criteria [2], [3] such as a maximal derivative or some percentage of the maximal amplitude for cuff pressures above the one that corresponds to the maximal oscillations. Diastolic blood pressure is derived from the same curve for cuff pressures below the one that corresponds to maximal oscillations using similar empirical criteria. The algorithm for the determination of the systolic and the diastolic blood pressure from the oscillometric curve differ from manufacturer to manufacturer and might also differ between different types of devices of the same manufacturer. In Fig. 2, the criterion for systolic and diastolic blood pressure was an oscillometric wave with amplitudes of 0.6 and 0.8 of the maximal amplitude, respectively. These empirical criteria are probably the main source for the inaccuracy in blood pressure measurement by oscillometry. The amplitude ratio for systolic or diastolic blood pressure is probably not constant for different people and in different situations for the same person.

Ambulatory 24-Hour Blood Pressure Monitoring

Automatic techniques allow 24-hour monitoring of blood pressure. Several companies have developed ambulatory blood pressure monitors based on oscillometry or automatic detection of Korotkoff sounds or both. The measurement is taken every 15-30 min during a person's waking hours and at lower frequency while the person is asleep.

Ambulatory blood pressure monitoring provides information about the mean systolic and diastolic blood pressure and the blood pressure variability over the measurement

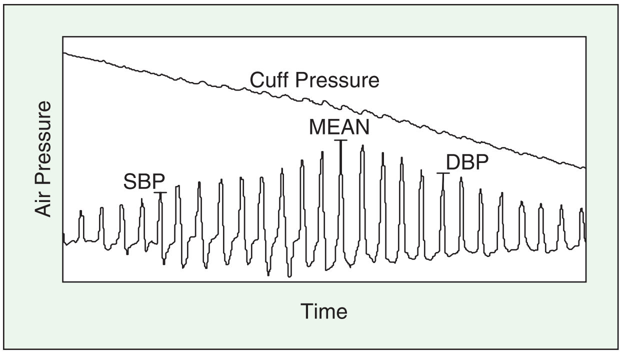

Fig. 2. Oscillometry: The upper curve shows the decrease of cuff pressure from above systolic blood pressure to below diastolic blood pressure. The oscillometric pulses are evident on the decreasing curve. The lower curve is the upper curve after subtracting the trend of the upper curve and amplifying the oscillations.

period. It can also yield the blood pressure's diurnal variations. The latter includes the dipping phenomenon generally defined as a 10% fall in blood pressure during sleep relative to values measured while the subject is awake. Non-dipping is associated with greater risk for cardiovascular events. The reproducibility of the technique is not high, but is significantly superior to that of office blood pressure measurement. In a recent study, two consecutive 24-hour examinations were performed, and the result for one out of five patients changed from dipper to non-dipper or vice-versa. Other studies claim that the absolute value of nighttime systolic blood pressure was the most useful parameter derived from ambulatory blood pressure data in terms of cardiovascular risk prediction.

Accuracy of Automatic Blood Pressure Meters

Available automatic blood pressure meters generally make use of the oscillometric method and despite great efforts, the oscillometric blood pressure meters have not been found accurate enough for clinical use. The low accuracy of the available automatic blood pressure meters can be deduced from the standards imposed by the Association for the Advancement of Medical Instrumentation (AAMI) and the protocols derived by the British Hypertension Society (BHS) and the European Society of Hypertension (ESH) [4]. The standards are based on comparing measurements made using an automated blood pressure meter with those made by manual sphygmomanometry (the gold standard) for three examinations performed on each of 85 subjects (AAMI and BHS) or 33 subjects (ESH) [5]. The 2010 version of the International Protocol [6] has more stringent validation criteria.

The AAMI standard requires that the mean difference between the systolic (or diastolic) blood pressure values measured by the manual sphygmomanometer and by the device under examination should not exceed 5 mmHg, and the standard deviation of that difference should not exceed 8 mmHg. The AAMI standard allows deviations of 16 mmHg or higher (two standard deviations) from the gold standard for 5% of the examinations. Similar standards were demanded by BHS. The reason for not demanding higher accuracy seems to be the low accuracy of the available oscillometric devices. It should be noted that several oscillometric devices have passed the validation criteria required by AAMI, BHS and ESH [4].

Other Direct Techniques for the Measurement of Systolic Blood Pressure

The collapse of the artery under the cuff when the cuff pressure is above the systolic blood pressure value results in stoppage of the blood flow and disappearance of the pressure pulses distal to the cuff. These effects can be utilized for measuring systolic blood pressure by making use of a pressure cuff wrapped around the arm. The reopening of the artery when the cuff pressure decreases below the systolic blood pressure value can be detected by a distal flow or pulse detector (placed on the limb's far side relative to the heart). The detector can be the doctor's finger palpating the pressure pulse in the wrist artery, a laser Doppler flow meter, a Doppler ultrasound flow meter, a tonometer (pressure detector), or a photoplethysmographic (PPG) sensor.

Photoplethysmography is the measurement of the oscillations in light transmission through tissue which are induced by the heart's repetitive ejection of blood to the peripheral tissue during systole. When the pressure in the cuff closes the artery, no pulses or flow are detected. The cuff pressure at which the pulses or the flow reappear during deflation equals the systolic blood pressure. Fig. 3 shows the disappearance and reappearance of the photoplethysmographic signal when the cuff pressure increases above the systolic blood pressure and decreases below it, respectively. It should be noted that these techniques are not applicable to the measurement of diastolic blood pressure, since no significant change in blood flow or photoplethysmographic pulse can be found when the cuff

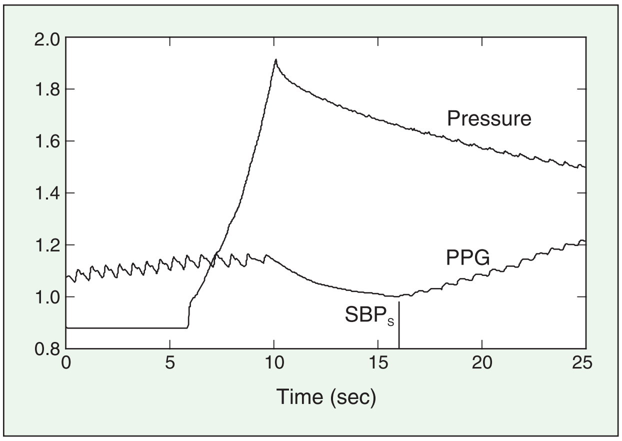

Fig. 3. Plots of the air pressure in the cuff (above) and the PPG signals in the finger distal to the cuff (below) as a function of time. The PPG signal disappears for air pressure above the systolic blood pressure. Note the oscillometric air-pressure fluctuations in the air-pressure plot. (© 2009 Bio Med Central, *BioMedical Engineering OnLine*, used with permission, [7].)

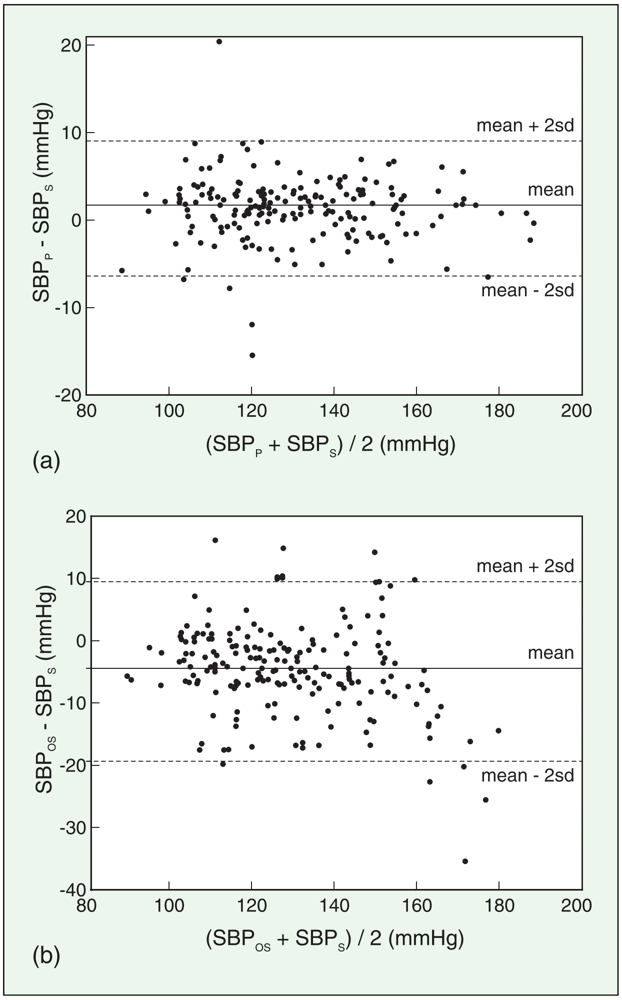

Fig. 4. (a) The difference between systolic blood pressure obtained by photoplethysmography, SBPp, and that of manual sphygmomanometry, SBPs, as a function of the systolic blood pressure, as measured by the mean of SBPp and SBps (Bland-Altman curve). This presentation provides information on the deviations between the two techniques, as well as on their mean and their dependence on systolic blood pressure. The two dotted lines are at a distance of 2 standard-deviations from the mean value. (b) The difference between systolic blood pressure obtained by oscillometry, SBPos, and that of manual sphygmomanometry as a function of the mean of SBPos and SBPs. (© 2009 Bio Med Central, *BioMedical Engineering OnLine*, used with permission, [5].)

pressure decreases from above the diastolic blood pressure to below the diastolic blood pressure.

This direct measurement of systolic blood pressure by means of the detection of the blood flow reappearance during cuff deflation has been applied in several studies, using the modalities above with varying degrees of success. More investigation and validation are necessary for this novel technology before it can be proposed for clinical use. Some of these modalities may be used automatically to detect the reappearance of the respective signal having direct relationship with arterial occlusion that is better than oscillometry, which is based on an empirical algorithm.

In a recent study [7], my colleagues and I found that systolic blood pressure values obtained by an automatic photoplethysmography-based technique were more accurate than those obtained by oscillometry. Both techniques were compared to manual sphygmomanometry, the gold standard. Figs. 4a and 4b present the difference between the value of systolic blood pressure obtained by each automatic technique and that of manual sphygmomanometry as a function of the mean of the two techniques. This kind of presentation, which is called a Bland-Altman plot, is regularly used for comparison of two methods. This curve provides information on the deviations between the two techniques, as well as on their mean and their dependence on systolic blood pressure. The two dotted lines are at a distance of 2 standard-deviations from the mean value. The standard deviation for the PPG technique was 3.7 mmHg, as compared to a standard deviation of 7.3 mmHg, obtained for oscillometry.

As Fig. 4a shows, the deviations between systolic blood pressure obtained by photoplethysmography and that of sphygmomanometry are even smaller for persons with systolic blood pressure values above 130 mmHg which constitute the population which actually requires the blood pressure measurement. Although the available evidence about photoplethysmography-based technique is encouraging, further investigation and validation are required before implementing it for clinical use. An automatic technique for accurate measurement of systolic blood pressure would be of significant clinical merit since isolated systolic hypertension is very common in the elderly population, and patients with isolated systolic hypertension are at increased risk of developing cardiovascular diseases.

Conclusion

Because of the high rate of hypertension in the adult population and its harmful effects, the measurement of arterial blood pressure is of great clinical significance. Manual sphygmomanometry, developed more than a hundred years ago, is currently the most accurate non-invasive technique for arterial blood pressure measurement. Since manual sphygmomanometry requires a well-trained examiner, only single measurements of blood pressure will generally be performed by a physician during a given visit. This single measurement only provides partial information since blood pressure changes spontaneously. The available automatic blood pressure meters, mainly based on oscillometry, can be used at home but some of them are of low accuracy. A direct technique for the measurement of systolic blood pressure by means of the detection of the blood pressure pulses' reappearance during cuff deflation has the potential to provide accurate automatic measurement of systolic blood pressure.

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Prof. Meir Nitzan (nitzan@jct.ac.il) received his PhD in physics in 1977 from the Hebrew University, Jerusalem, and is currently a staff member in the Department of Physics/Medical Engineering in the Jerusalem College of Technology. His research activities include the measurement of blood pressure and oxygen saturation in blood.