BRAUN

Blood Pressure Measurement

The following is a detailed description of the main techniques used for measuring human blood pressure. Possible sources of error and influences on measurement are discussed, with an emphasis on the oscillometric method and how Braun has adapted it to improve measurement results.

Influence of the measurement site on blood pressure values

Many people think that the blood pressure in the aorta is equivalent to that in the brachial artery. However, there are differences between the central aortic blood pressure and the invasively obtained peripheral blood pressure. In general, the more peripheral the measurement site, the higher the systolic blood pressure and the greater the pulse pressure, i.e. the difference between the systolic and diastolic pressure [1].
The differences between invasively obtained aortic and brachial (upper arm) systolic pressure values in young, healthy adults are usually about 5 mm Hg [2]. In elderly people, these differences can rise to 20 mm Hg [2]. The pulse pressure in young people is up to 50% greater in the brachial artery than in the aorta [2]. The pulse pressure in the elderly is approximately 5–20 mm Hg greater in the brachial artery [2], while the diastolic blood pressure is about the same in both the aorta and brachial artery [3], [2], differing by only about 1 mm Hg.
There are possible pressure differences between the brachial artery and the radial artery. In general, these differences are small, in the range of 1–4 mm Hg [2]. However, in patients with arterial abnormalities (stenosis, atherosclerosis, etc.), these differences can vary greatly in both directions. With a stenosis proximal to the measurement site, the blood pressure is significantly lowered according to the degree of stenosis.

Invasive blood pressure measurement

In order to obtain blood pressure values invasively, a catheter (a sterile, flexible tube with a diameter of about 0.66–2 mm) must be inserted into an artery. This procedure is performed under local anesthetic using aseptic methods, as in an operation. This “gold standard” of blood pressure measurement is used almost exclusively in diagnostic procedures such as heart catheterization, or for monitoring patients during operations and in critical care. The pressure transducer is usually outside the patient's body and connected to the fluid-filled catheter. The pressure waves are transmitted to the transducer via the saline solution in the catheter. As a result, the measurement is sensitive to the elastic properties of, and friction in the catheter, which cause damping of the signal.

A small air bubble in the catheter can lead to very low pressure signals. Moreover, the entire system must have a resonance frequency of above 16 Hz in order to avoid a marked distortion of the intra-arterial pressure signal.
There is a difference of 2–3 mm Hg between systolic pressure recordings with the catheter opening perpendicular to the direction of the bloodstream (recording “lateral pressure” only) and recordings with the catheter opening directly against the direction of the bloodstream (adding “impact pressure” to the lateral pressure).
Minor blood clotting at the tip of the catheter is a further source of error, damping the signal. A visual inspection will usually reveal the problem, which can be solved by flushing the system, without danger to the patient.
If the catheter is positioned inside the artery in constant contact with the wall of the vessel, early and pronounced blood clotting will result, disturbing the signal. The longer a catheter is in the artery, the greater the likelihood of a disturbed signal. A severe atherosclerosis in the vessel may also obstruct the tip of the catheter if it is positioned too close to a plaque.

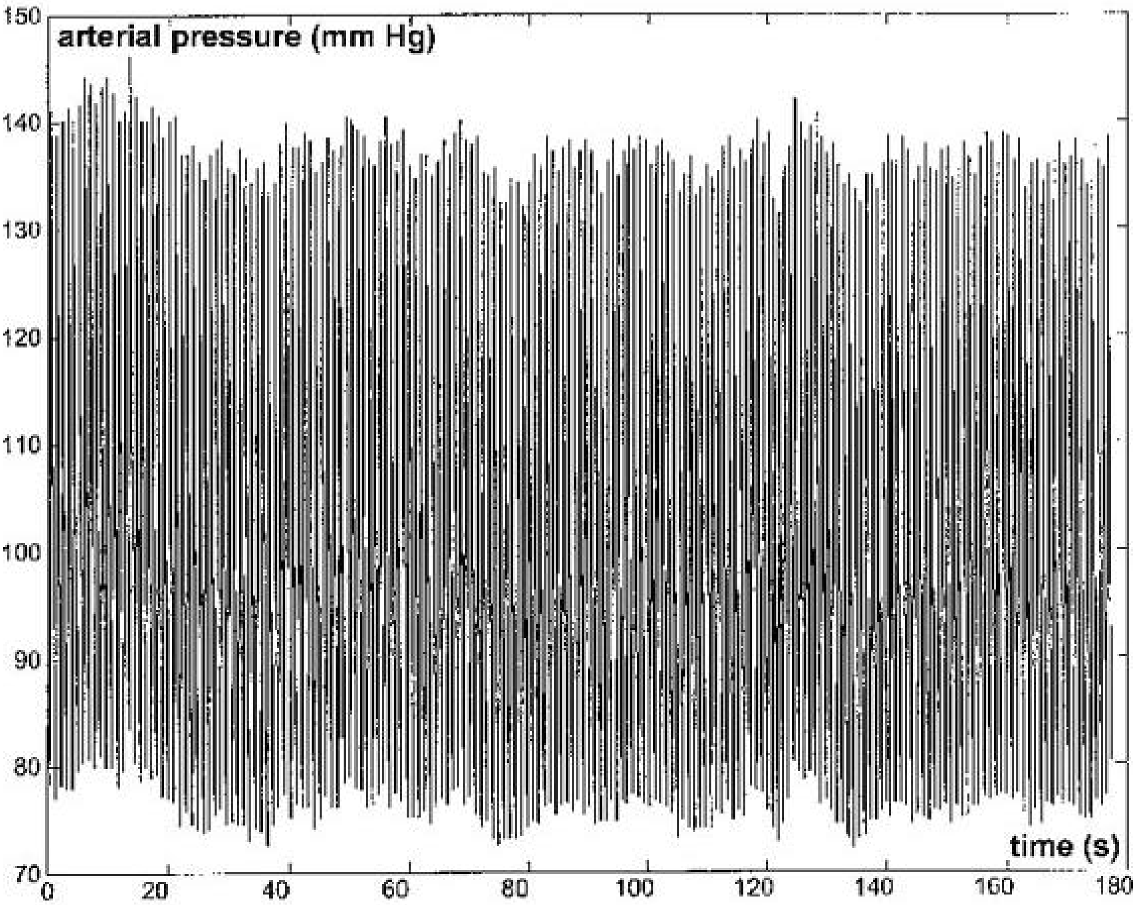

Figure 1: Invasively measured blood pressure.

The main causes of error in intra-arterial measurements, as they have been described above, are systematic. The statistical errors of the transducers and the electronics used are, by law, less than 1 mm Hg and negligible. In short, the intra-arterial signal is correct to within 1 mm Hg, or otherwise completely unreliable. Unfortunately, the determination of reliability is not always easy.

Auscultatory blood pressure measurement

The non-invasive, quantitative measurement of blood pressure was introduced by Riva-Rocci in 1896, and refined by the auscultatory method of Korotkoff in 1905.

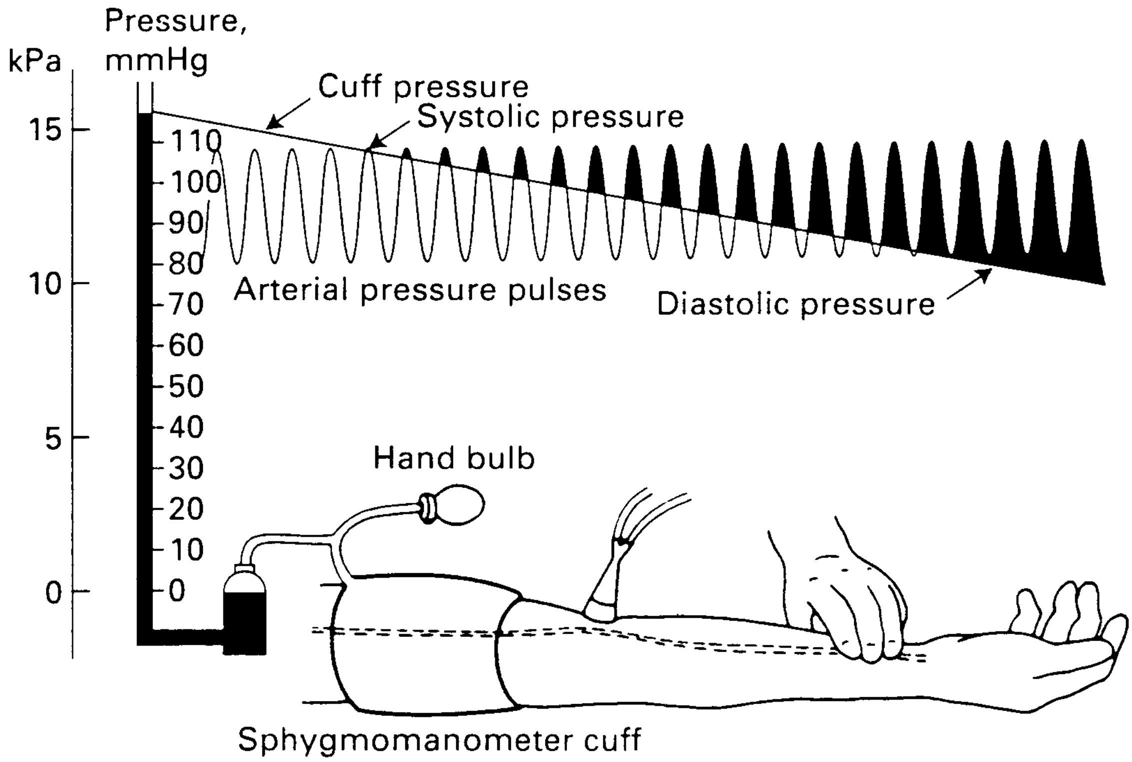

Figure 2: The principle of auscultatory blood pressure measurement.

The recommended procedure today is as follows:
The patient must have been at rest for at least five minutes. The upper arm must be positioned level with the heart, i.e. next to the chest.

1. Wrap the appropriately sized cuff snugly around the bare upper arm, with the lower edge about 1.5 cm above the inner skin fold at the elbow. The cuff must be centered level with the heart.
2. Quickly inflate the cuff to 100 mm Hg and more, while palpating the radial pulse. Inflate to about 20 mm Hg higher than the pressure at which the radial pulse is no longer palpable.
3. Place the stethoscope over the brachial/cubital artery below the cuff.
4. Deflate the cuff at a rate of 2–3 mm Hg/s. Auscultate for Korotkoff sounds in order to determine systolic pressure with the manometer upon the appearance of the first Korotkoff sound and diastolic pressure at the *end* of phase 4 Korotkoff sounds, i.e. the onset of silence. Then, quickly deflate the cuff's bladder.

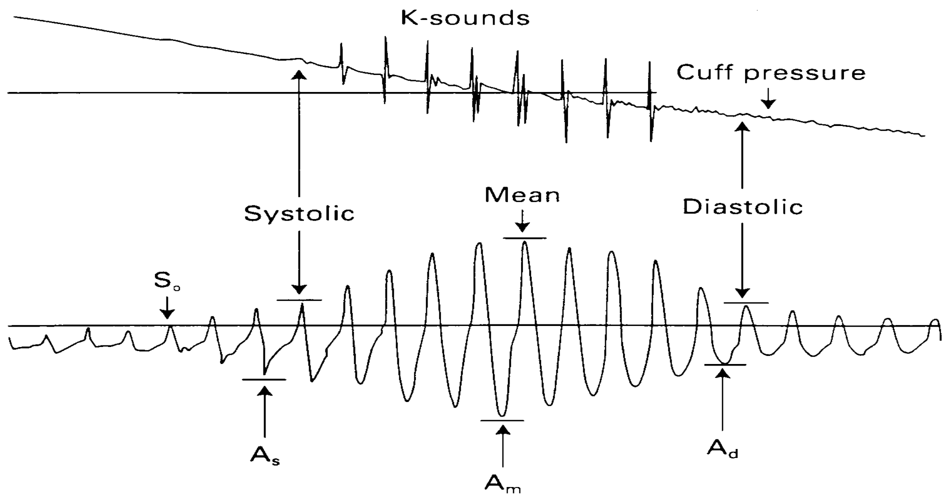

Figure 3: Korotkoff sounds and oscillations in the cuff.

It should be noted that the systolic and diastolic blood pressures do not correspond to the same heartbeat.
The diastole is measured 10–20 seconds after the systole. The physiological variation of blood pressure depicted in Figure 1 demonstrates the variation in auscultatory readings over a range of 10 mm Hg. Remember, the changing readings are not due to the person who is doing the measurement, but rather to principal variation in the subject and the limitations of the method.

The repeatability of this method is greater for systolic values than for diastolic pressure, since it is easier to detect the onset of quite marked sounds (about 40–600 Hz) than it is to judge the end of fading sounds at diastole. The error of trained auscultation observers corresponds to a standard deviation of about 1–3 mm Hg, as compared with a standard deviation of less than 1 mm Hg for invasive measurements.

Differences between auscultation and invasive blood pressure measurement

Numerous authors [1], [2], [4], [5], [6], [7] have reported differences between invasive and non-invasive blood pressure measurements. At the brachial artery (upper arm), overestimation of the diastolic pressure of up to 20 mm Hg has been reported in a large number of hypertensive patients, using both auscultation and oscillometry [4], [7]. The reported ranges are between 0.8 and 18 mm Hg, mostly around 4mm Hg. Case reports describe even larger overestimations [7]. Today, the American Heart Association recommends using the cessation of Korotkoff sounds (end of phase 4) for determining diastolic pressure. This pressure is somewhat lower than the invasively obtained diastolic pressure in healthy patients. The error in hypertensive patients remains a problem.
The systolic pressure is often underestimated by up to 5 mm Hg, in some cases even more. More important is the problem of “pseudohypertension” [7] in the elderly, with overestimation of systolic pressure of up to 30 mm Hg [8]. Hence, in some people,

the non-invasively obtained blood pressure values do not represent a direct equivalent of invasively obtained values. On the other hand, invasive blood pressure measurement is only available at special medical sites or during certain diagnostic procedures.
In clinical practice, it is assumed that blood pressure is approximately equal at all measurement sites and at the central arteries. Moreover, there is only little concern in clinical medicine about differences between invasive and non-invasive blood pressure values.

General description of the oscillometric blood pressure monitor

An introduction to the field of non-invasive blood pressure monitoring using oscillometric devices can be found in [9], [10], [11], and [12].

As in auscultatory measurement, an artery must be compressed over a sufficiently long segment, usually by means of an inflatable cuff. Once the artery wall's transmural pressure (pressure difference between the inside and outside of the artery) is zero, the cuff pressure corresponds to the intra-arterial blood pressure. Since this pressure varies with time, oscillations of the cuff pressure will occur. The amplitude of these oscillations is related to both the cuff pressure and blood pressure.

There are several factors that oppose the applied pressure of the cuff:

- Hydrostatic pressure difference between the cuff and heart levels
- Compressible tissues, including veins
- Non-compressible tissues, e.g. bone
- Stiffness of the arterial wall
- The intra-arterial blood pressure, which varies with time.

The aim here is to determine the intra-arterial blood pressure. It is known that the effect of compressible and non-compressible tissues influences the choice of cuff, which must be large enough to compress an arterial segment of sufficient length. Other aspects of the tissues' opposing forces are usually negligible, except in the blood pressure measurement of severely obese patients.
The hydrostatic pressure difference plays an important role in blood pressure measurement at the wrist, since not holding the cuff at heart level changes the blood pressure. You can notice for example a positive difference if the wrist is lower and a negative one if the wrist is higher than heartlevel. To ensure the proper position of the forearm and wrist, blood pressure monitors of the Braun BP 2000 range feature an inclination sensor that gives the user feedback on the correct position. The suggested user posture is seated upright with the arms crossed. The forearm with the device is then raised to the angle indicated by the inclination sensor of the BP2000, as shown in the display.

The arterial wall stiffness is dependent on its thickness, diameter, and composition, which change with age and as a result of disease. This is one reason for many of the differences between intra-arterial and non-invasive blood pressure measurements.

A typical measurement cycle of an oscillometric device is shown in Figure 4.

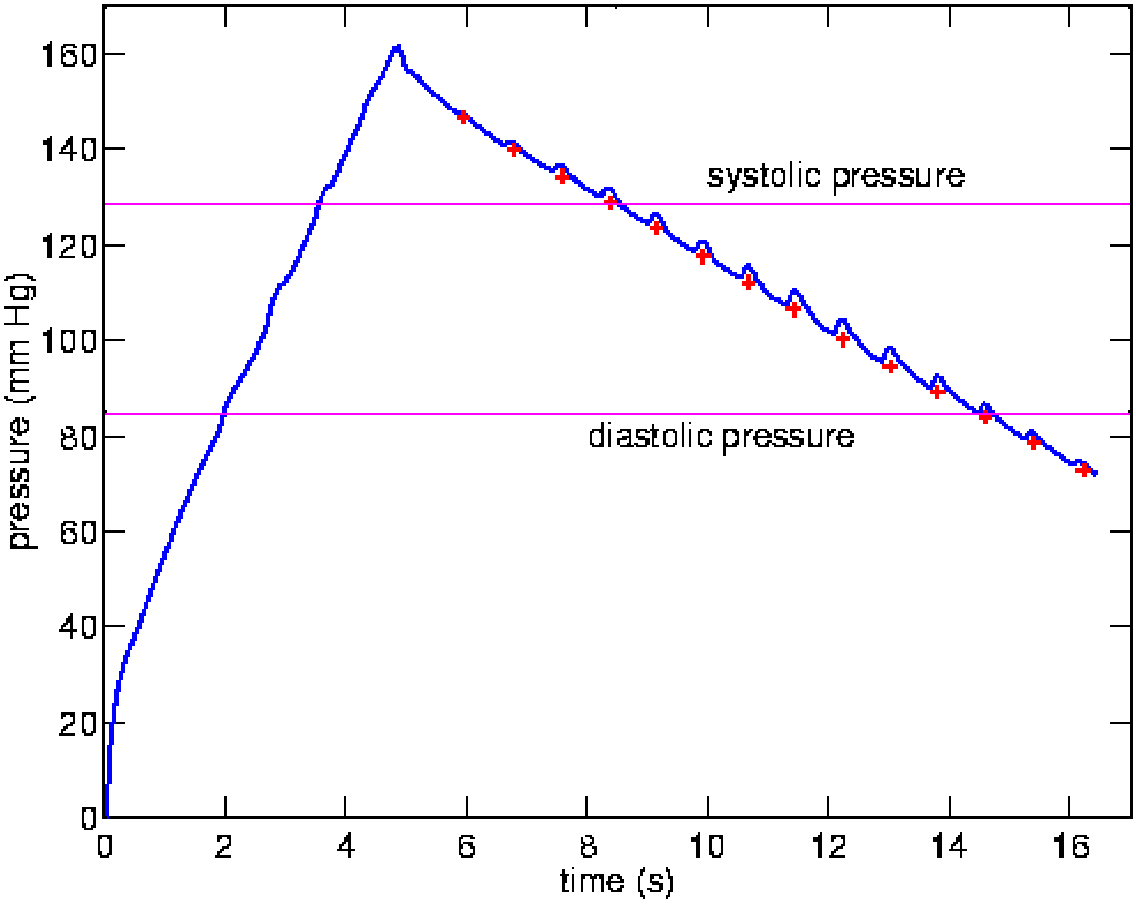

Figure 4: Typical measurement cycle of an oscillometric blood pressure monitor. The cuff is quickly inflated to a certain pressure, as shown by the pressure-time curve in the diagram. Then, the cuff is slowly deflated and arterial pulsations are detected (red crosses). For orientation, systolic and diastolic blood pressures are indicated by horizontal lines.

With inflation of the cuff, the external pressure on the artery rises, and hence the artery is increasingly compressed. At pressures exceeding the systolic blood pressure, the artery will be occluded. Only blood pulsations that are closely proximal to the occluded segment will be transmitted to the edge of the cuff, causing small oscillations in the cuff pressure. However, when the cuff is slowly deflated, the cuff pressure, and hence the external pressure on the artery will be lowered to that of the systolic blood pressure. Now, the artery is no longer continuously occluded. At systolic blood pressure, small amounts of blood pass through the compressed artery segment and cause changes in the artery volume, conducted to the cuff. This leads to pressure oscillations in the cuff. These oscillations increase with lower cuff pressure values, as more blood passes through the compressed artery. The maximum oscillation amplitude is reached around the mean intra-arterial blood pressure.

Here, the amplitude is about 1–10 mm Hg. As the falling cuff pressure approaches the diastolic blood pressure, the oscillation amplitude decreases and remains at a low level below diastolic pressure (see Figure 5)

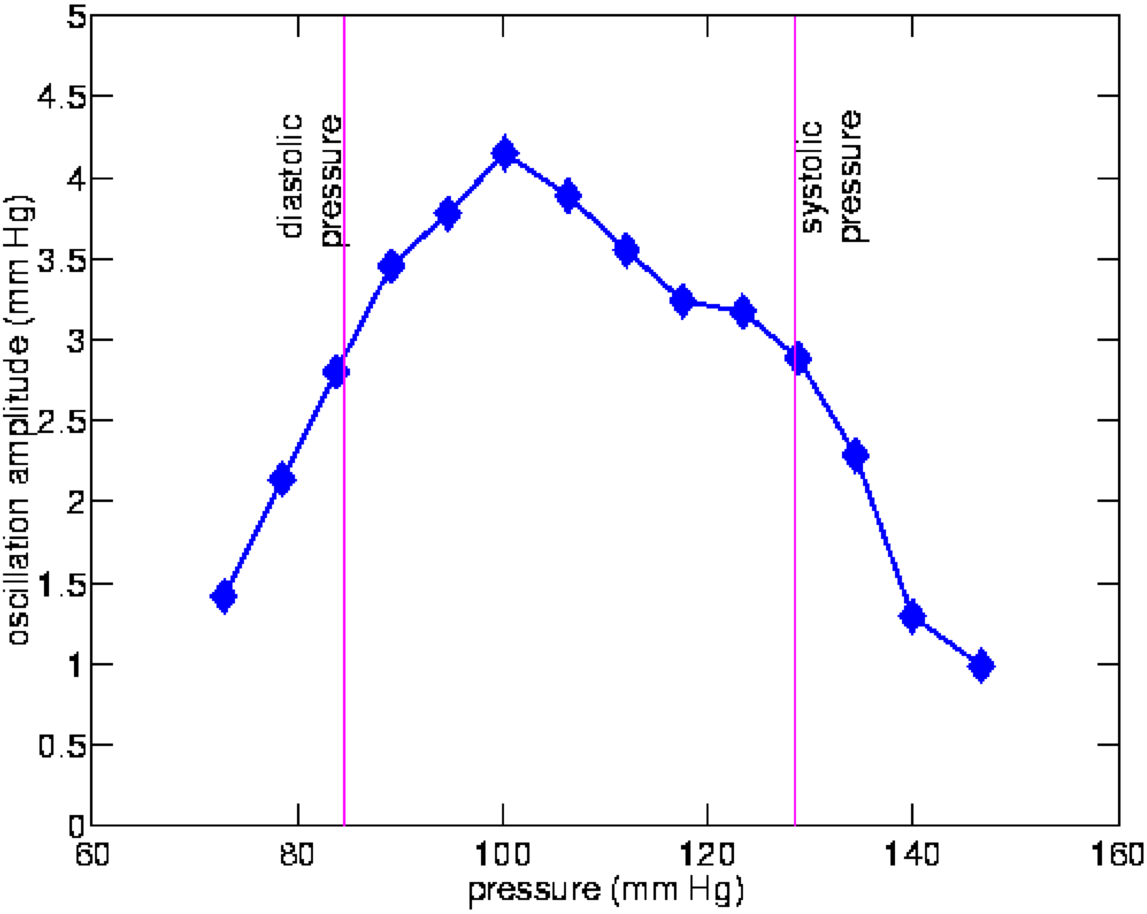

Figure 5: The amplitude of the cuff pressure oscillations is dependent on the cuff pressure itself. This relation is associated with the blood pressure, as shown by the vertical lines. The diamonds in the diagram correspond to the oscillations depicted in Figure 4.

The systolic, mean, and diastolic blood pressures can be characterized and measured by the cuff pressure at different oscillation amplitudes. This is usually done by means of a pressure transducer to measure the cuff pressure, a signal amplifier, the control unit with an algorithm to calculate blood pressure from the recorded oscillations, and a display for the result. The major components of an oscillometric blood pressure monitor are shown in Figure 6.

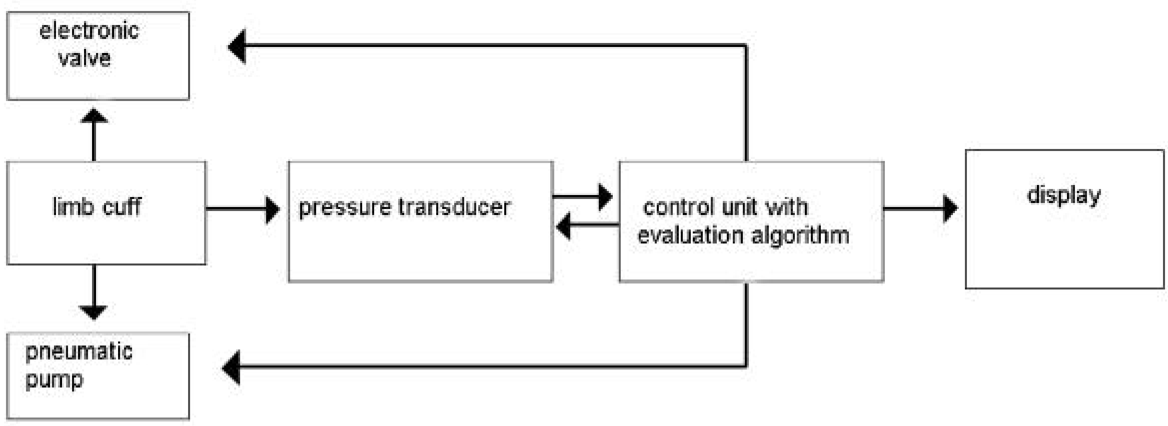

Figure 6: Major components of oscillometric blood pressure monitors.

There are several methods of calculating the blood pressure values from the measured oscillations. All these need to determine the so-called “envelope of amplitudes” from the measured oscillation amplitudes. On the basis of this curve, the blood pressure is calculated with an algorithm and experimentally obtained coefficients.

The Braun PrecisionSensor Device

The Braun PrecisionSensor uses the oscillometric method to determine blood pressure. The basic data for the blood pressure calculation are taken from the so-called “envelope curve” shown in Figure 5, giving the relation between cuff pressure and arterial pulsation.
First-generation oscillometric devices used fixed amplitude ratios to determine the systolic and diastolic pressure from the envelope curve. This was done, more or less, by determining the maximum amplitude of the envelope, calculating the systolic and diastolic amplitudes from fixed ratios, and reading off the systolic and diastolic pressure from the envelope curve as those pressures whereby the pulsating amplitude was the calculated systolic and diastolic one, respectively.
A great number of clinical studies during the course of the device’s development, and also the literature [9] showed that the fixed ratios described above are inadequate for a sufficiently accurate determination of blood pressure over all pressure ranges. Put more simply, the blood pressure to be determined is dependent on more than just two single points of the envelope curve. The Braun PrecisionSensor makes unique use of this finding for its blood pressure calculating algorithm.
Another point worth mentioning is the Braun PrecisionSensor’s adaptable inflation and deflation control. As mentioned above, the most important input for the blood pressure calculation is the envelope curve, shown in Figure 5. From this diagram, it is easy to conclude that only a certain number of pulses are necessary, i.e. heartbeats around the maximal pulsation. Excessive (with respect to the blood pressure) or inadequate inflation of the cuff yields an envelope curve that contains more or less data points than necessary. Excessive cuff inflation leads to patient discomfort and prolongs the measurement procedure unduly. Inadequate cuff inflation leads to a re-inflation of the device that often stresses the user, in turn influencing the blood

pressure. Hence, this re-inflation regularly occurs in hypertensive users. The Braun PrecisionSensor has a “smart” inflation control that estimates the blood pressure during the inflation phase and stops inflation at an appropriate pressure, so that re-inflation of the cuff is very rare.

Another lesson to be learned from the envelope curve is that only a certain number of heartbeats need to be detected by the device. This means that the measurement time should be heart-rate dependent. At a higher heart rate, the necessary number of pulsations occurs over a shorter time interval, and vice versa. Hence, the Braun PrecisionSensor estimates the heart rate during inflation and controls the deflation process according to this estimate. Normally, the measurement time must be adapted to the slowest specified heart rate measured by the device, meaning that the total measurement time is unnecessarily long.

The dependence of the measurement cycle on blood pressure and heart rate is illustrated in Figure 7.

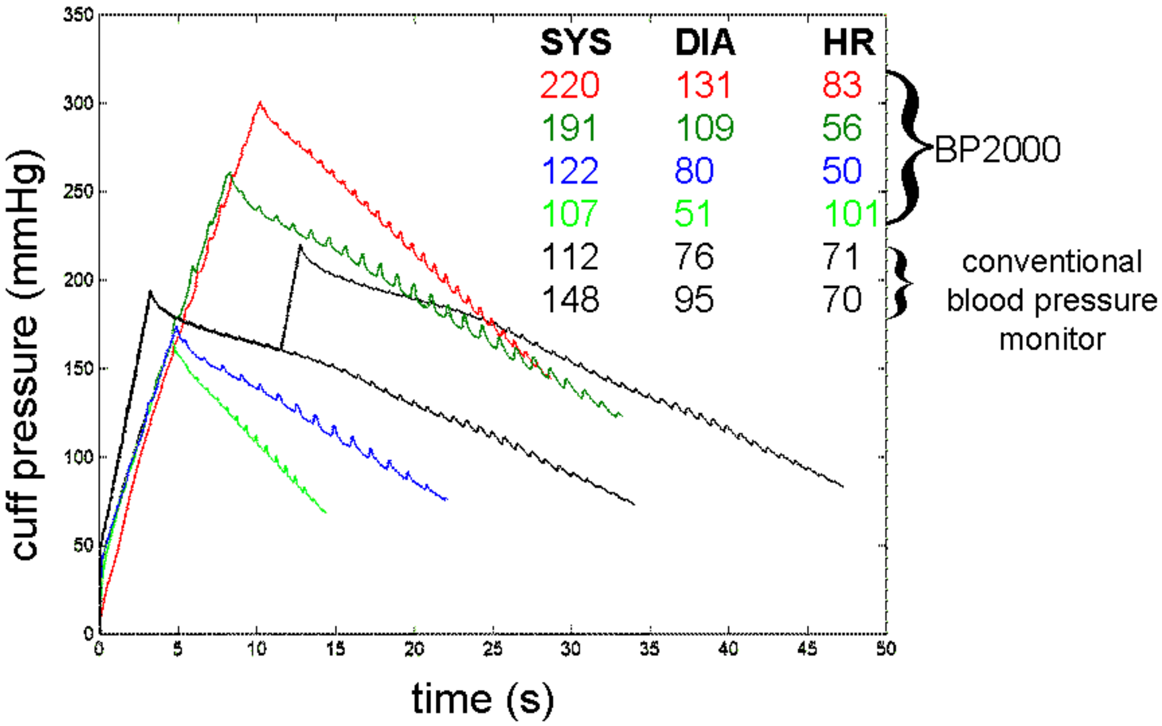

Figure 7: Comparison of measument cycles between monitors of the Braun BP2000 range (colored lines) and conventional blood pressure monitors (black lines).

Mechanical design

The oscillometric blood pressure measurement device consists of the components shown in Figure 6. The size of the cuff depends on where it is to be applied (upper arm, wrist, or finger). The recommended ratio of the cuff's air chamber width to limb circumference is 0.4, while the length to circumference ratio should be 0.8. However, it must be mentioned that the above ratios are based on experience with upper arm devices. At the wrist, for example, they may be inapplicable, since the position of the respective arteries (arteriae radialis and ulnaris) relative to the skin where the cuff is applied differs from that at the upper arm (arteria brachialis). At the upper arm, the artery is surrounded by far more damping tissue than at the wrist. The cuff consists of an inflatable PVC or polyurethane air chamber and surrounding fabric, with a Velcro securing strap.

The measurement site also determines the size of the pneumatic pump for inflating and deflating the cuff, and the housing for the electrical and mechanical components. In a wrist or finger device, the housing is directly attached to the cuff, while in an upper arm measurement device it is connected to the cuff by a long tube.

Differences between results from auscultation and the oscillometric method

As demonstrated in Figure 3, the determination of the systolic, and especially the diastolic values from the oscillations must be adapted to either the somewhat different auscultation or the intra-arterial measurement. The limits of agreement are defined by guidelines. Since the determination of blood pressure using the oscillometric method is dependent on calculations, and not just measurements, the calculations must be adapted to fit the values of the chosen reference method.

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