Chapter 2

Blood Pressure Measuring

Blood pressure is considered to be one of the most important vital signs during patient assessment because it can provide clinicians with a fast indication of cardiovascular performance. Now in this chapter will be introduced the BP as physiological parameter, and the different procedures for measuring it. Also in the last section will be described the new non-invasive method based in the relation between the PTT and the BP.

2.1 Blood Pressure

The pumping action of the heart must create enough force to push blood through the major arteries, into the smaller arteries, and finally into the capillaries, where the porous walls allow the fluid exchange between blood and body tissue. Here is where the Blood Pressure appears, it refers to the force exerted by circulating blood on the walls of blood vessels, and constitutes one of the principal vital signs [1]. The blood pressure decreases as blood moves forward through arteries, arterioles, capillaries, and veins, as it is shown in Figure 2.1.The term blood pressure generally refers to *arterial pressure* (AP), due to the fact, that they are the vessels where the pressure is measured. The AP values are reported in *millimetres of mercury* (mmHg).

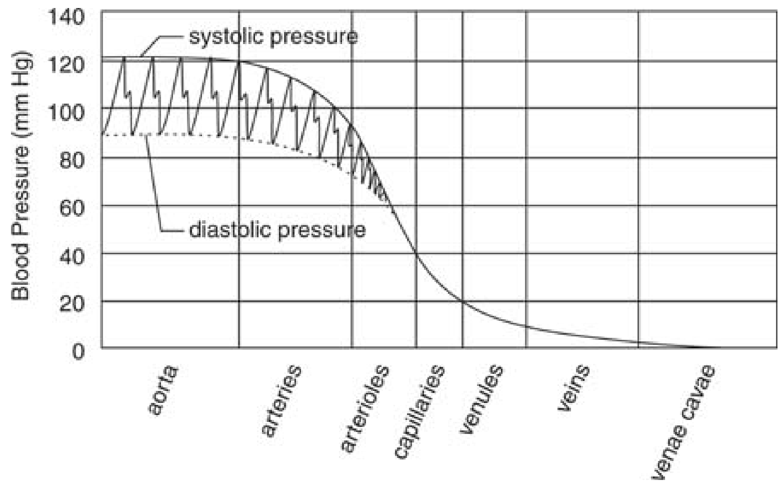


Figure 2.1: Blood Pressure decreasing.

For each heartbeat, arterial pressure varies between systolic and diastolic pressures, where systolic is the peak pressure, which occurs near the beginning of the cardiac cycle when the ventricles are contracting (systolic phase). The normal value for a 20-year-old man is $120mmHg$. On the other hand, diastolic pressure is the minimum pressure in arteries, which occurs near the end of the cardiac cycle when the ventricles are filled with blood (heart's relaxation or diastolic phase). The normal value for a 20-year-old man is $80mmHg$.

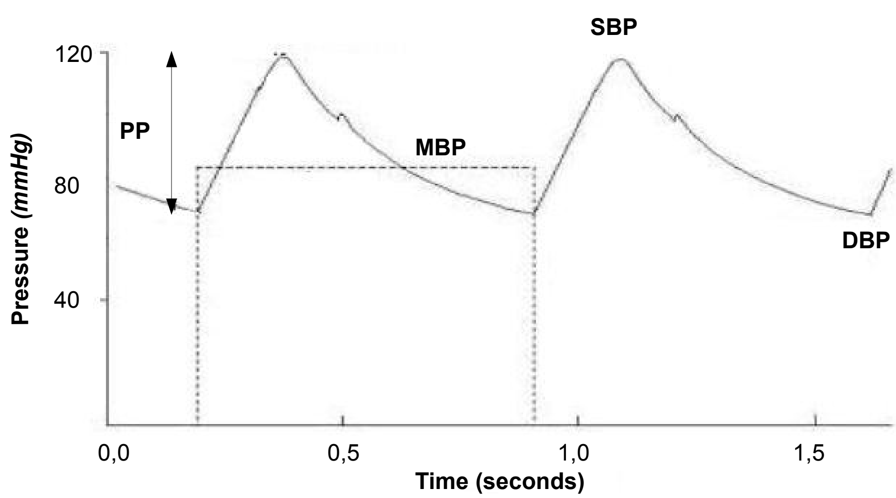


Figure 2.2: Blood Pressure Parameters

Operating with these two values, are obtained, *Pulse Pressure* (PP) as the difference between SAP and DAP (which normal value is $40mmHg$.), and

Mean arterial Pressure (MAP) as the result from the Equation 2.1. MAP is an estimate of the average effective pressure forcing blood through the circulatory system. The normal measured value varies from 96 to $100mmHg$ quite similar to the value that would be obtained from the equation, $93.3mmHg$.

$$P_{dia} + \frac{1}{3}(P_{sys} - P_{dia}) \tag{2.1}$$

SAP and DAP are not static but undergo natural variations from one heartbeat to another and throughout the day. They also change in response to stress, nutritional factors, drugs, disease and exercise. Sometimes the variations are large, like the known anormalities, hypertension and hypotensionrefers which refer to arterial pressure being abnormally high or abnormally low respectively. Along with body temperature, arterial pressure measurements are the most commonly measured physiological parameters.

2.2 Blood Pressure Measuring Methods

The schema in Figure 2.3, shows the organisation of the different existent Blood Pressure Measuring Methods. The first division separates invasive methods and non-invasively. After that the different methods are grouped attending to the characteristics of their procedures of work.

In the next subsections, a description will be made of the most used methods from both, invasive and non-invasive proceedment. From the non-invasive, they will be described in great details oscillometric and auscultatory methods, due to the fact that both are implemented in most of the actual medical monitoring equipment (when both are implemented, they are used in either measuring or validation/recalibration tasks). After this introduction to the actual available equipment a short overview from other not so popular methods will be presented. And finally in the last section from this chapter it will be described the essence from this research, *The Pulse Transit Time Method*.

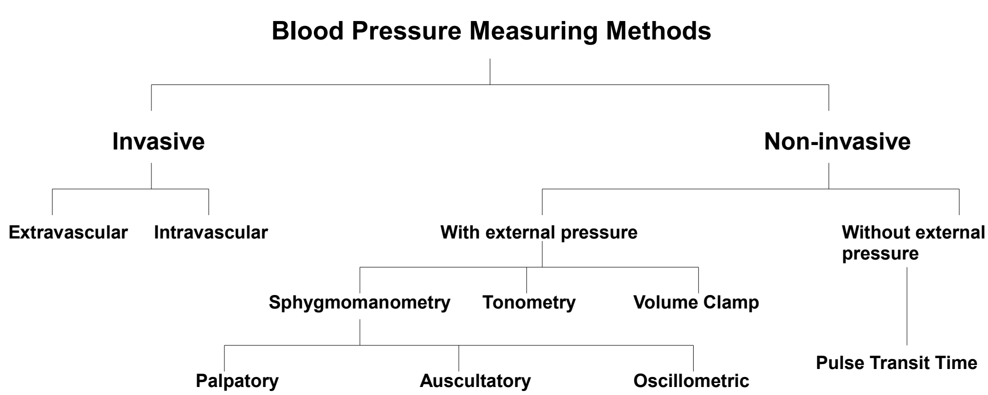


Figure 2.3: Classification of Blood Pressure Measuring Methods

2.2.1 Invasive Method

In the case of a hospitalized patient, it is frequently desired to be able to measure the AP on a continuous basis, e.g. in case of concomitant illness, cardiovascular diseases (hypotension or hypertension), severe lung problems, sudden or big hemodynamic changes during the surgery or pharmacology or mechanic manipulation from the cardiovascular system.

In one of the situations above, or simply if it is impossible to obtain non-invasive measurement of AP, clinicians will resort to the invasive method or arterial catheterization. It is a very reliable technique for continuously measuring arterial pressure, consists in inserting a saline filled catheter through the patient's vascular system to the point at which it is desired to perform the measurements. The catheter is connected to an electronic pressure transducer, which measures the pressure in the artery (usually radial, femoral, dorsalis pedis or brachial). This is usually done by an anaesthesiologist or surgeon in a hospital [1] [30] [12]. Since these techniques involve making an incision through the patient's skin and inserting the catheter into a blood vessel, as a consequence, they entail pain and also some problems, like possibility of infection, blood clots and other risks which are presented in Table 2.1. Patients with invasive arterial monitoring require very close supervision, as there is a danger of severe bleeding if the line becomes disconnected [4].

The advantage of this system is that pressure is constantly monitored beat-by-beat, and a waveform can be displayed. What is also remarkable from this method, is that they provide the most accurate arterial pressure reading from patients. Anyway it is generally reserved for patients where rapid variations in arterial pressure are anticipated, especially in ICU.

Risks in Table 2.1 could be avoided, however, if there was a non-invasive method offering a high degree of accuracy and real time operation in a continuous, beat-to-beat, mode. Further, the method should be insensitive to the patient's movement and respond rapidly to cardiovascular changes, such as a sudden drop in arterial pressure. As it is, invasive methods are currently prevalent.

Risk Factors	Cannulation prolonged. Previous Vasculopathy. Use of vasopressors. Women. Multiple attempts.
Risks if bad use or interpretation from equipment (<5%)	Infection Bleeding Thrombosis and distal Ischaemia. Necrosis of the skin. Embolization. Hematoma and neurological damage. Latter vascular complications.

Table 2.1: Invasive Methods Characteristics

2.2.2 Non Invasive Methods

In clinics and home care, non-invasive blood pressure measurement devices have become increasingly common during the last decade, as their prices have been reduced to an appropiate level for ordinary consumers. Non-invasive blood pressure measurement methods are indirect and based mainly on measuring counterpressure.

The most common methods until the present day, are the sphygmomanometric methods. In them arterial pressure is measured by a sphygmomanometer shown in Figure 2.4. Which consists of:

1. A rubber bag surrounded by a cuff.
2. A manometer (usually a mechanical gauge, electronic or a mercury column).
3. An inflating bulb to elevate the pressure.
4. A deflating valve.

There are some problems related to these methods due to:

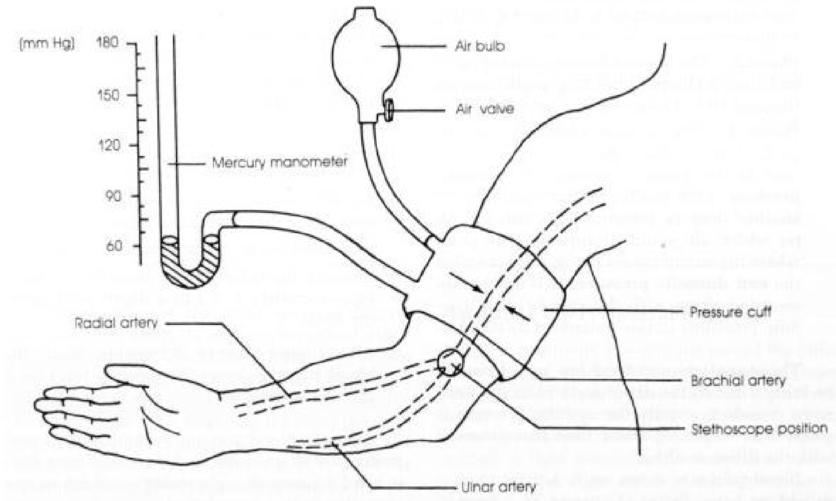


Figure 2.4: Standard of the Sphygmanometric Methods

- Improper positioning of the extremity: The position of the artery in which the blood pressure is measured must be at the level of the heart.
- Recording the first Blood Pressure: Spasm of the artery upon initial compression and the anxiety and apprehension of the subject can cause the first blood pressure reading to be erroneously high.
- Improper application of the cuff: If the rubber bladder bulges beyond its covering, the pressure will have to be excessively high to compress the arm effectively. If the cuff is applied too loosely, central ballooning of the rubber bladder will reduce the effective width, thus creating a narrow cuff. Both result in excessively high readings.

These sphygmanometric methods can be ausculatatory, oscillometric and palpatory, attending to how they determine the pressure values. Both are based in the same principle, it is to occlude an artery, normally the brachial artery, with the cuff, and then it is time to observe how this pressure affect to determinated characteristics in the mentioned artery.
From now on these methods will be desribed in details.

2.2.2.1 Palpatory Method

This method used when other methods failed or to detect vital constants. It is only used to measure SAP and underestimates $30mmHg$ in this measure. It requires tactile sensibility and experience.

After the cuff is placed snugly over the arm, the radial artery is palpated while the pressure is increased until the pulse can no longer be felt. Then inflate $30 - 40$ mmHg over, and after that while the pressure is released the artery is palpated until the pulse is felt again. That denotes systolic pressure.
Identification of SAP by palpatory method helps one to avoid a lower systolic reading by auscultatory method if there is an auscultatory gap. It also minimizes the discomfort of over inflating the bladder of the cuff.

2.2.2.2 Auscultatory Method

It is based in the auscultation of the Korotkoff noises. It can measure SAP and DAP. In the Figure 2.5 is shown how the blood flow again throw the artery, while the cuff pressure is releasing. It is also shown the instants in which the Korotkov sounds take place, and so where will be the instant in which SAP or DAP can be read. That it is made attending to five different phases. These are:

- Phase I. The two first audible noises after start deflating the cuff. Here is defined the SAP.
- Phase II. A kind of murmur can be listened.
- Phase III. The noises become more clear and they increase their intensity.
- Phase IV. An obvious decrease of the noises intensity. Here is determined the DAP for children and for some pregnant women.
- Phase V. The last sound that can be listened. After it every noise disappear. Here is determined the DAP for adults.

It will be interesting to mention the possible situations when errors can happen. It is important to avoid an improper deflation of the compression cuff. This pressure in the cuff should be lowered at about $2mmHg$ per heartbeat. At rates slower than this venous congestion will develop and the diastolic reading will be erroneously high. On the other hand if the cuff is deflated too quickly the manometer may fall 5 or $10mmHg$ between successive Korotkow sounds, resulting in erroneously low readings.
There could be also errors with the obtained pressure values due to an inadequate equipment, like an inappropriate size of the cuff, compared to the size of the arm; Aneroid pressure measure decalibrated; The cuff is not centred on the brachial artery; Variations due to arrhythmias.

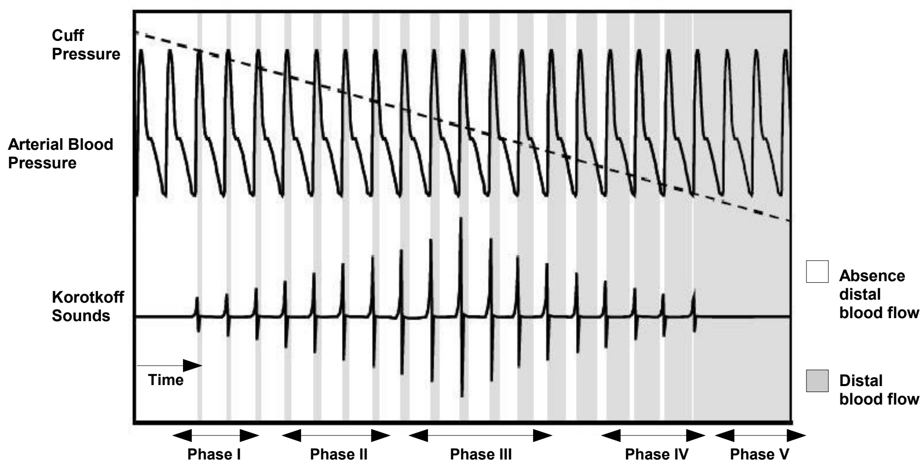


Figure 2.5: Fundamentals of Auscultatory Method

This auscultatory technique is based on the ability of the human ear to detect and distinguish sounds. This is a great advantage since it allows the clinician to determine the quality of each measurement. However, inherent in this, is the possibility for measurement error due to differences in hearing acuity from clinician to clinician. Unqualified or inexperienced personnel may be more susceptible to outside noise, other interference, or inconsistent assessment of Korotkov sounds. In an attempt to increase reproducibility, some automated devices have replaced the human ear with a microphone.

2.2.2.3 Oscillometric Method

The last type of noninvasive arterial pressure measurement strategy throw sphygmomanometric techniques is the oscillometric method. The equipment is functionally similar to that of the auscultatory method, but with an electronic pressure sensor fitted in to detect blood flow, instead of using the stethoscope and the expert's ear. In contrast to the auscultatory method, which relies on detection of Korotkov sounds, this oscillometric method operates by sensing the magnitude of oscillations caused by the blood as it begins to flow again into the limb.

In most cases the cuff is inflated and released by an electrically operated pump and valve, which may be fitted on the upper arm. First of all, like with auscultatory method, the cuff is inflated to a pressure initially in excess of the systolic arterial pressure, and then reduces to below diastolic pressure over a period of about 30 seconds. When blood flow is nil (cuff pressure exceeding systolic pressure) or unimpeded (cuff pressure below diastolic pressure), cuff pressure will be essentially constant. When blood flow is present, but restricted, the cuff pressure, which is monitored by the pressure sensor, will vary periodically in synchrony with the cyclic expansion and contraction of the brachial artery, that means that the cuff pressure will oscillate. This oscillations can be observed in Figure 2.6.

Typically, very faint blood flow oscillations begin to be detected as the air pressure in the cuff coincides with SAP. As air pressure is slowly released from the occluding cuff, the amplitude of these pulsatile oscillations increases to a point and then decreases as blood flow to the limb normalizes. Although the oscillation with the greatest amplitude has been shown to correspond reliably with mean arterial pressure (MAP), determinations of SAP, which are associated with a marked increase in amplitude of oscillations, and DAP, which are associated with the point at which oscillations level off, are often less accurate when compared with auscultatory measures. There are many empirical strategies to determine SAP and DAP.
The most popular criterion [12] consists in normalizing the peak to peak values from the oscillation wave. Then the SAP is related to the instant when the normalized graph reach for first time the 40-60% from the maximun oscillation amplitude. And the DAP for the second time it reachs approximately the 70-90%. The idea is presented in Figure 2.6.

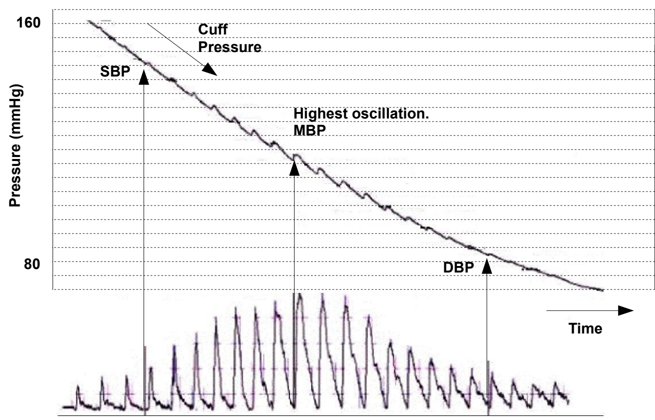


Figure 2.6: Oscillometric Method

These oscillometric methods vary widely in accuracy, but while they tend to overestimate SAP and underestimate DAP (due to the reduced accuracy of the empirical estimations), they can be useful for determining accurate estimates of MAP. This method allowed arterial pressure measurement of critical care and intensive care unit (ICU) patients with muted Korotkoff sounds [6].

In the estimations, is essential that the cuff size is correct, undersized cuffs may yield too high a pressure, whereas oversized cuffs yield too low a pressure.

Oscillometric monitors may produce inaccurate readings in patients with heart and circulation problems, that include arterial sclerosis, arrhythmia and preeclampsia. Also artificials movements that can have influence on lectures, like trembling or shaking. It is also possible the occurrence of some complications like: pain, petechiae and ecchimosis, edemas in the extremities, venous congestion, trombophlebitis, and peripheral neuropathy, but they are rare to happen.
These oscillometric methods are sometimes used in the long-term measurement and in general practice. And it requires less skill than the auscultatory technique, and may be suitable for use by untrained staff and for automated patient home monitoring.

2.2.2.4 Other Methods

There are some other methods not so popular, some of them based in auscultatory and oscillometric techniques, and the rest based in new ideas. But they still need to prove their efficiency. Some examples of these methods are here explained:

- **Infrasound**
  - **Description.** It is an improvement for the auscultatory technique. It attempts to improve on the auscultatory method by detecting low frequency Korotkoff vibrations below about 50 Hz.
  - **Advantages.** Same as auscultatory method, but more accurate.
  - **Disadvantages.** Same as auscultatory method, and not so sensitive to noises in the ambient.
- **Doppler Ultrasound**
  - **Description.** It is based on the Doppler phenomenon: The frequency of sound waves varies depending on the speed of the sound transmitter in relation to the sound receiver.
    Ware in 1965 suggested the motion of a pulsating artery partially compressed by a cuff could be detected by the Doppler ultrasonic technique for estimation of AP [14]. The Dopler apparatus consists basically in an ulstrasound oscillator and transducer which trasmits and receives the generated ultrasound. If the ultrasound strikes an immobile structure such as the compressed arterial wall, the ultrasound frequency is reflected back unchanged. If a moving structure (pulsating artery) is encountered, however, the frequency is altered up or down (Doppler effect) and this is detectable by an audible alteration of the reflected sound. It is commonly used in the intensive care unit for the measurement of AP in low-flow states.
  - **Advantages.** Continuous. Non-painfully. Non-invasively.
  - **Disadvantages.** Frequency shift can only be detected for blood flow greater than $0,5 cm/sec$.
- **Tonometry**

  - **Description.** The artery is flattened by applying pressure non-invasively to squeeze the artery against bone. The applied pressures required to maintain the flattened shape are recorded. This is accomplished by using an array of sensors, each of which measures pressure. The result of this method is a waveform similar to catheter measurements, and an algorithm must be used to calculate pressures from that waveform [30].
  - **Advantages.** Continuous. Non-painfully. Non-invasively.
  - **Disadvantages.** Tonometry has several limitations as well as it is very expensive. First, it is a measure of the peripheral circulation, which has different pressures from more centrally-located sites (such as the brachial artery), and it has limited capacity to respond in front of fast and transient variations of the blood pressure. Second, tonometry has a high sensitivity to sensor position and angle . Therefore, inter-operator reproducibility may be low. Lastly, tonometry requires calibration via an initial blood pressure measurement obtained by an independent technique.

- **Impedance Plethysmography**
  - **Description.** It measures the volumetric change associated with arterial distension. Volumetric changes cause changes in the electrical conductivity (impedance) of the measurement site. When graphed with time, an impedance waveform is produced, similar to the pressure-generated oscillometric waveform. Blood pressure is estimated in a manner similar to the oscillometric technique. By means of empirical algorithms [7].
  - **Advantages.** Continuous. Non-painfully. Non-invasively.
  - **Disadvantages.** Empirical involve less accuracy.

- **Volume Clamp**
  - **Description.** Invented by Penaz in 1973. It is a continuous non-invasive blood pressure measuring method based on a transparent finger cuff, photoelectric plethysmogram, i.e. transmitter and detector, and pressure controller unit. The main idea is to use the controller unit (servo mechanism), to keep constant the blood volume in finger. In such a way that the cuff pressure will represent the actual arterial pressure [12] [30].
  - **Advantages.** In many investigations it has been proved that it understimates 6 mmHG for both SAP and DAP. Continuous. Non painfully. Continuous. Non-painfully. Non-invasively.

- **Disadvantages.** Many problems with patients which have low peripheral blood flow, where the control system will become unstable. When vascular diseases or hypothermia, the blood flow in finger can be very weak. So it can be concluded that this method is not appropiated to use in many situations.

2.3 Pulse Transit Time

2.3.1 Introduction to PTT Method

As is already known, both auscultatory and oscillometric methods of arterial pressure assessment are intermitent in that a single arterial pressure determination can take almost an entire minute to obtain. Additionally, a brief rest period is recommended between measures of arterial pressure that require use of an occluding cuff to allow circulation in the limb to return to normal. Sphygmomanometric methods usually provide a measure each 3 minutes, which is not frequent enough for certain situations. Therefore, if takes interest to measure immediate and short-lived alterations in arterial pressure, intermittent arterial pressure measures would not be a good choice. Here is where appear this non-invasive approach, which is the main thema in this report, called *Pulse Transit Time Method* (or pulse wave velocity).

First of all, it would be interesting to give a definition of what is understood by Pulse Transit Time. It can be defined in two ways attending to the measuring points:

Definition 1 *Pulse transit time reflects the time it takes the pulse wave to travel from the heart to a site in the peripheral circulation, typically the finger or earlobe. It is commonly assesed by measuring the duration of time (in ms) between the initiation of the cardiac contraction from the electrocardiogram (EKG) and the arrival of the pulse wave at the peripheral site, typically measured using photoplethysmography.([22])*

Definition 2 *Pulse transit time is the difference in time between two pulse waves detected at different distances from the heart measured in ms.([19])*

For this research that PTT will be the time required for a blood pressure pulse wave from the heart beat to propagate between two points in the vascular system.

The origin from this approach, is the presumably assumption that, as an arterial pressure increases, the pulse wave travels more quickly to the peripheral site (lower PTT); converserly, as arterial pressure declines, PTT lengthens. It is commonly accepted that PTT is correlated with AP and by the time a number of commercial AP monitors use PTT to infer AP. Althought studies comparing changes in PTT with arterial pressure change have proved significant inverse correlations, these correlations have been more commonly observed between measures of PTT and SAP than between PTT and DAP [7]. An as it will be later proved, the results with SAP in this research where much more succesful than with the other three parameters, DAP included. So this SAP, will be the measure in which this report will be focused.

There are many limitations associated to this method, first of all the reference signals to measure PTT values, can include noise due to external factors, e.g. photoplethysmography measures are sensitive to movements of the patient. Also for PTT values that include as reference the EKG, another problem appears. As the R wave peak marks the electric excitation of the heart contraction, there is a small delay before mechanical contraction. This delay is the PEP (heart pre ejection period). Due to the dificulty of measuring in a non-invasive way the PEP, the PTT measured will include the PEP.
In addition changes in the compliance of the blood vessels also affects the pulse transit time. Chronic changes in arterial compliance occur due to aging, arteriosclerosis, and hypertension. Arterial compliance can also change acutely due to neural, humoral, myogenic or other influences. Previous monitoring systems have been unable to separate changes due to compliance from changes due to arterial pressure. As a consequence, some degree of inaccuracy exists in calculating arterial pressure from the variation of the PTT.

Researchers who employed measures of PTT have disagreed as to wether the continuous temporal parameter actually represented an index of arterial pressure, as there was considerable evidence suggesting it was more strongly linked to beta-adrenergic cardiac activity than to arterial pressure. Because of these equivocal findings linking changes in PTT to alterations in AP, this method has not been recommended as a surrogate measure of arterial pressure [21].

2.3.2 Pulse Transit Time Measure Points

As it was already mentioned in Definition 2, PTT is the difference in time between two pulse waves detected at different distances from the heart measured in ms.. So now the idea of this research, is to implement a learning machine algorithm using this PTT data, as well as other variables that will be later discussed. The learning machine algorithm in this case will be an Artificial Neuronal Network. And the idea, is to provide a dataset with the most possible variety of PTT parameters. In Figure 2.7, are described the

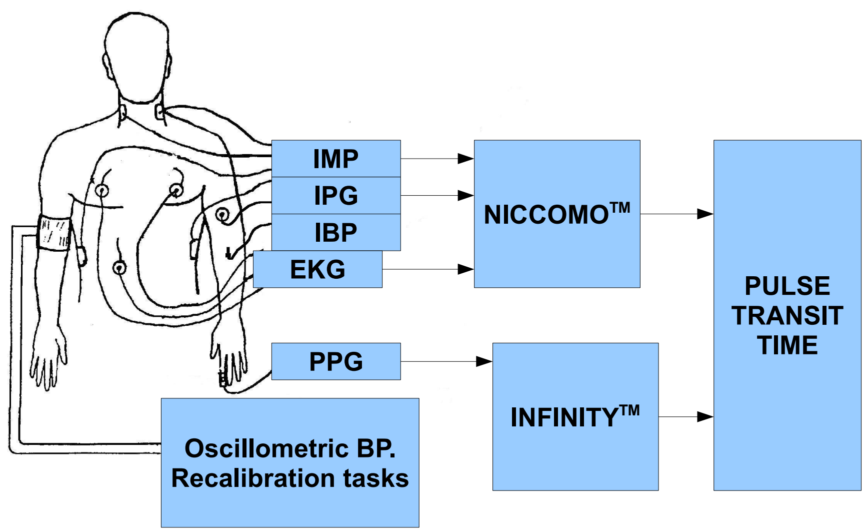


Figure 2.7: Pulse Transit Time Diagram

different measuring points that will be taken into account. These are:

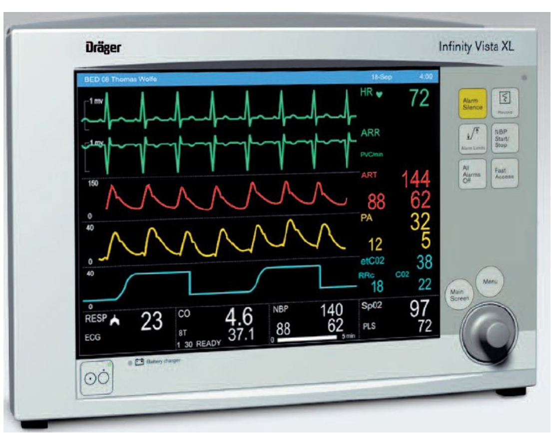
- EKG. Electrocardiogram. An electrocardiogram (EKG) is a recording of the electrical activity of the heart over time produced by an electrocardiograph, usually in a noninvasive recording via skin electrodes.
- IMP. Impedance Cardiogram. Impedance cardiogram (IMP) is a hemorheology technique of using sensors to detect the properties of the blood flow in the Thorax.

Four dual disposable sensors on the neck and chest are used to transmit and detect electrical and impedance changes in the thorax.

- IPG. Impedance Plethysmography. Impedance plethysmography (IPG), is a non-invasive medical test that measures small changes in electrical resistance of the chest, calf or other regions of the body. These measurements reflect blood volume changes. This procedure provides an alternative to venography, which is invasive and requires a great deal of skill to execute adequately and interpret accurately.
- PPG. Photoplethysmographie (SpO2). Designed by Penaz 1973. It is an optically obtained plethysmograph (a volumetric measurement of an organ). The change in volume caused by the pressure pulse is detected by illuminating the skin with the light from a Light Emitting Diode (LED) and then measuring the amount of light either transmitted or reflected to a photodiode [2].
- IBP. Invasive Blood Pressure. Catheterization. (See Section 2.2.1)

These cardiovascular measurement techniques, will represent the pulse wave in different instants of time, and the difference between these instants will represent the PTT values.

All these measures were carried out with $Niccomo^{TM}$ and $Infinity^{TM}$ equipment (Figure 2.8), in the way shown in Figure 2.7.



(a) $Infinity^{TM}$

(b) $Niccomo^{TM}$

Figure 2.8: Devices

The time reference from the Electrocardiogram was taken in the R-wave. In Figure 2.9 is shown how the PTT was computed.

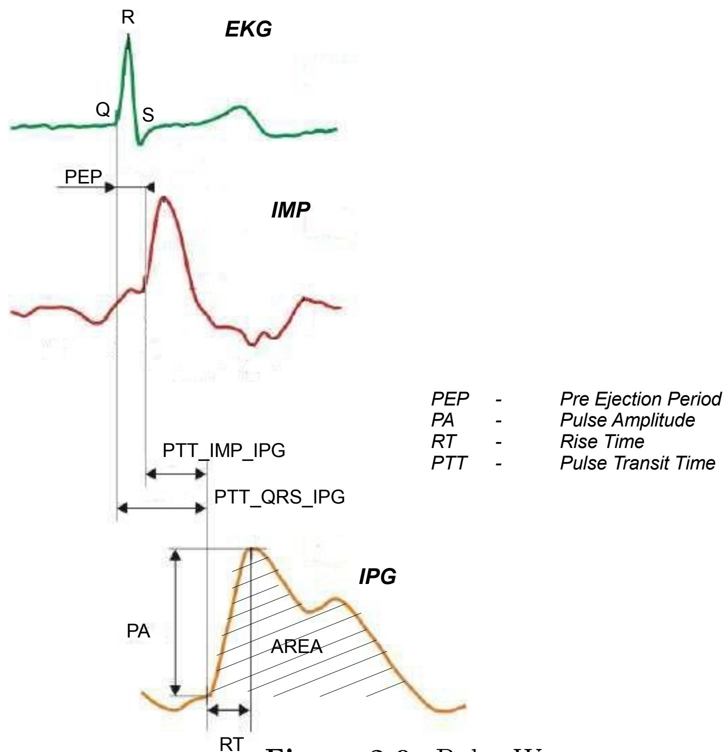


Figure 2.9: Pulse Wave

As well as the PTT variables, other parameters were added to the final data set. These were the **hearth rate** (HR), measured with $Niccomo^{TM}$ and $Infinity^{TM}$, the *pulse amplitude* (PA) and the area of the pulse waves measured from PPG, IMP, IPG (See Figure 2.7). With all these parameters will be tried to estimate the SAP, as it is the most important parameter of pressure.