A CLINICAL GUIDE

PULSE WAVE ANALYSIS

SphygmoCor
AT THE HEART OF
CARDIOVASCULAR MANAGEMENT

Foreword

This educational guide outlines the development and clinical applications of Pulse Wave Analysis. It has resulted from written contributions by an honorary advisory group each involved in aspects of the management and prevention of cardiovascular disease.

The objective has been to produce an understandable and interesting document that can be updated at intervals with useful information from the world literature.

The adoption of innovative technology in the routine practice of medicine requires objective and protracted appraisal. In the development of new medical technology a compelling influence is the need to visually represent, quantify and to store what would otherwise be only observer subjective information.[1] This is true for PWA that has evolved from a mechanical recording of the peripheral pulse with a slow response time in the 19th century into a sophisticated computer-based non-invasive method for the accurate recording of both peripheral and central pulse profiles. Based on current world experience, this document introduces how the technology should be used in the management of a range of macrovascular, hypertensive and cardiac problems.

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Reference 1. Stanley J. Reiser. *Medicine and the reign of technology.* Cambridge University Press 1978.

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Non-Invasive Vascular Assessment (NIVA) using SphygmoCor

1.1

Introduction

A growing number of risk factors including diabetes, hypercholesterolaemia, smoking, hypertension, and age have been linked to the adverse cardiovascular endpoints of heart attack, stroke and heart failure.

Importantly, it is known that these risk factors lead to an increase in arterial stiffness. Increased arterial stiffness accelerates the speed at which the left ventricular ejection pressure wave travels through the arteries, and leads to an earlier return of the reflected pressure wave back to the left ventricle. The reflected pressure wave starts to arrive more and more during systole, where it augments the late systolic pressure (afterload) on the left ventricle. Because the wave is therefore arriving less during diastole, it reduces the coronary artery perfusion pressure during this critical period. Therefore, increased arterial stiffness leads to a greater risk of:

- angina and heart attack (by reducing coronary artery perfusion pressure during diastole)
- stroke (by increasing central pulse pressure)
- heart failure (by increasing left ventricular load).

Arterial stiffness can be increased by three key mechanisms:

1. A breakdown of the elastic structure (elastin fibres) in the arterial walls. This is a function of cumulative cycles and artery wall pulsatility, and is the prime cause of increasing stiffness in the aorta with ageing.

2. Damage to the endothelium/smooth muscle mechanism by which arterial stiffness is dynamically controlled. This is the prime cause of arterial stiffness in the muscular conduit arteries.

3. An increase in mean arterial pressure, which increases the stiffness of an artery. This mechanism influences the entire arterial tree as a passive effect.

The process by which the arterial system interacts with the left ventricle and coronary arteries can be clearly visualised when the patient's aortic root pressure waveform is available for analysis. SphygmoCor is a non-invasive device that enables this aortic root pressure waveform to be measured during a normal clinical consultation. The system elucidates the mechanisms that cause increased systemic arterial stiffness, and then provides a visual display of these parameters in relation to cardiovascular health.

1.2

History and Development

SphygmoCor is an integrated system of **pulse wave analysis**. It was developed from the concept that there is haemodynamic information contained in the shape of the **arterial pressure pulse**, which can be used to supplement the conventional measurement of blood pressure. The systolic and diastolic values of blood pressure are the maximum and minimum points of the pressure curve obtained in a peripheral location, usually the upper arm. However, similar values of systolic and diastolic pressures can be associated with many different pulse wave shapes, and these determine the type of interaction between the heart as a pump and the arterial system as the load.[1] The elastic and geometric properties of the arteries cause the arterial pressure pulse to change its shape as it travels along the arterial tree, such that mean pressure is approximately similar along the large arteries of the arterial tree, but pulse pressure can be markedly different (*see Section 2, Figure 2.1*).[2]

The graphical registration of the arterial pulse was the first physiological recording that was used for clinical diagnosis in the mid-to-late nineteenth century. Seminal work was done by a young and observant medical student in 1872, Fredrick Akbar Mahomed, at Guys Hospital in London. He first described the changes in the shape of the arterial pulse with age
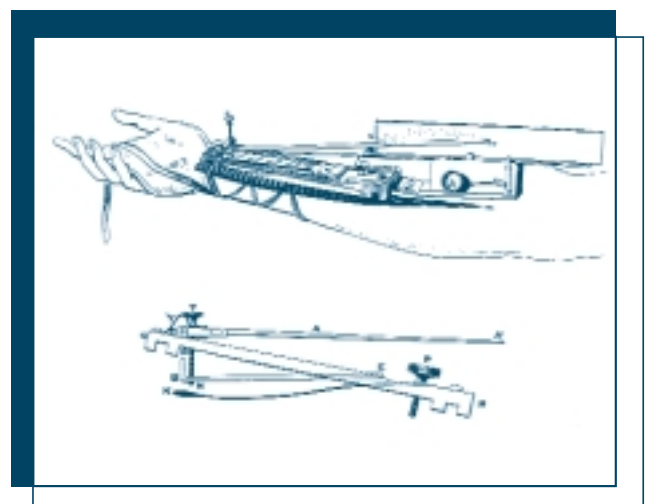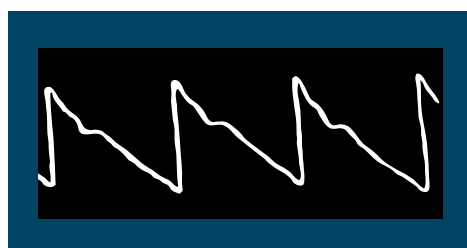
Figure 1.1

Illustration of the Sphygmograph developed by French physiologist Etienne-Jules Marey (as described by B. Sanderson in 1867 in "The handbook of the sphygmograph", Hardwiche, London). The lower part shows the lever mechanism in profile.

and hypertension.[3] The pulse was recorded by means of a sphygmograph (*Figure 1.1*), a device strapped to the wrist with a set of levers moving in response to the pulse and writing on a moving paper strip or smoked drum. In fact, this was the way to confirm cardiac arrhythmia before the advent of the electrocardiograph.[1,4] The vasodilator effects of nitroglycerin were actually first described in terms of changes in the pulse wave shape (*Figure 1.2*),[5] and not in terms of blood pressure changes. Similar changes in waveshape have been reported recently using more sophisticated pulse sensors.[6]
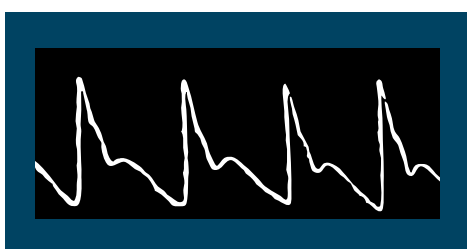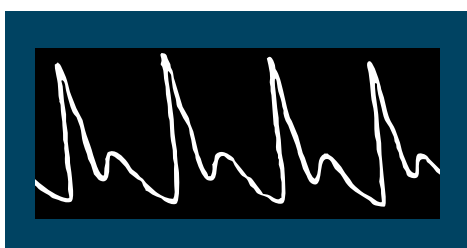
Figure 1.2

No.1 - Before dose.

No.2 - Two minutes after dose.

No.3 - Eight minutes after dose.

No.4 - Nine minutes after dose.

Radial artery waveforms recorded by Murrel in 1879[5] using a sphygmograph (*Figure 1.1*) following the ingestion of nitroglycerin. Note the marked change in waveform with time due to dilatation of pre-arteriolar vessels. For further explanation, refer to Section 4, Effects of Drugs on Central Pressure.

The work of Donald McDonald and colleagues, conducted in the three decades after the Second World War, is fundamental to the development of the concepts underlying SphygmoCor. The first edition of the monograph of *Blood Flow in Arteries* was published in 1960 by McDonald, and the 4th edition was published 25 years after his death by Nichols & O'Rourke in 1998 as *McDonald's Blood Flow in Arteries: Theoretical, experimental and clinical principles.*[1] This recent edition contains an entire chapter on **'sphygmocardiography'**, highlighting the connection between the early work on the arterial pulse, and the latest concepts of arterial haemodynamics.

Sphygmocardiography is defined as 'the study of the dynamic interaction of the left ventricle and the arterial system by analysis of the blood pressure waveform'. In relation to SphygmoCor, this involves the derivation of the **central aortic pulse waveform** from the recording of the pressure waveform in peripheral locations (eg the radial artery). 'Sphygmocardiography' is derived from the Greek term *sphygmos* for 'pulse'. Other derivative terms are 'sphygmograph' (a plot of the pulse waveform) and 'sphygmocardiograph' (a plot of the ventral pressure waveform, together with the derived indices from the waveform (eg pressure to first systolic shoulder, augmentation pressure, augmentation index, as illustrated in Section 2).[1]

The main attribute of SphygmoCor is its ability to derive the central aortic pressure waveform non-invasively from the pressure pulse recorded at a peripheral site. Two specific things made this possible and contributed to the practical use of the device in both research and clinical situations: (i) the accurate recording of the peripheral pulse by means of **applanation tonometry**; and (ii) the use of a **generalised transfer function** of the upper limb across the adult population.

1.2.1

Detection of peripheral blood pressure waveforms

The **peripheral pulse** can be detected by a suitable transducer that can respond to dynamic changes in force or volume due to the expansion of the segment of artery underlying the transducer. There are many such devices, but what initiated the development of SphygmoCor was the use of the extremely sensitive **pressure sensor** used at the tip of catheters (eg Millar catheters) to obtain an accurate measurement of intravascular pressure during catheterisation procedures. It was found in initial experimental trials

that if this element was pressed on the outside of the skin over an artery, and the artery was compressed slightly against a firm structure such as bone (*Figure 1.3*), the signal produced was similar to that of the intravascular pulse.

This, in fact, is the principle of applanation tonometry, which is used to measure intra-ocular pressure for the assessment of glaucoma and its response to treatment. The application of this principle to arteries[7,8] made it possible to obtain a high-fidelity signal without penetrating the skin or blood vessels. Following a liaison with Millar Instruments, a pencil-type hand-held probe was produced with the sensing element at the tip (*Figure 1.3*) so that a pulse could be obtained at peripheral locations (eg radial, carotid, femoral, dorsalis pedis arteries).[1,9]

Since the development of the hand-held tonometry probe there have been many adaptations of the technique, including non-operator dependent devices.[10]
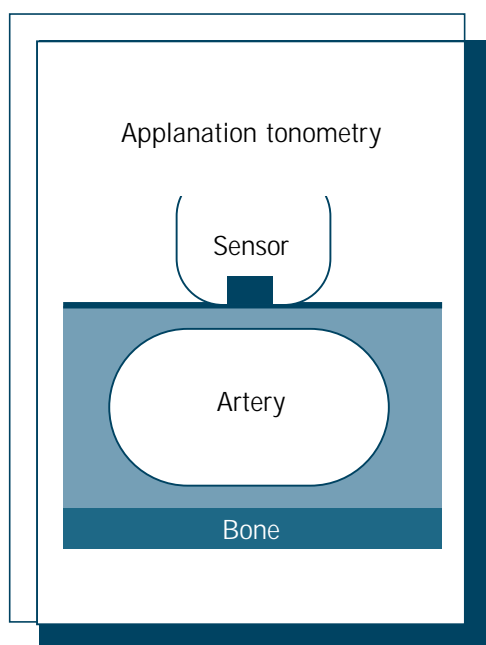
Generalised Transfer Function

A **transfer function** defines the relationship between two parameters, the input and the output of any system. If the input signal is the aortic pressure pulse, and the output is the radial artery pressure pulse, then the transfer function of the connecting brachial arterial system (ie, aorta to radial artery) can be obtained by relating the frequency components of the radial and aortic pulse wave (see further explanation in Section 2).[1] A mathematical model can be constructed which describes the transfer function such that if one signal is available, then the other can be derived. This is the principle employed by SphygmoCor, where the aortic pulse is reconstructed from the non-invasive **radial waveform.**

The characteristics of the transfer function are determined by the physical properties of the arterial system, such as arterial diameter, wall elasticity, wall thickness, amount of branching, and the condition of the peripheral vascular beds. Of course not all brachial vasculature is identical in all adults, and it is expected that there would be some difference in the overall transfer function among individual subjects. However, it was found that the main components of the transfer function do not change markedly between normal adults with age for example, such that it would give large errors in the derived waveforms. Studies of pulse wave velocity (a parameter which is related to arterial stiffness) in hundreds of people have shown that most of the ageing changes occur in the aortic trunk, and not in the arteries of the arm (*Figure 1.4*).[1,11,12]

Figure 1.3

The principle of applanation tonometry, where the artery is partially compressed against a hard structure. The small sensor (0.5 mm in diameter) detects the force on the artery wall.

Figure 1.4
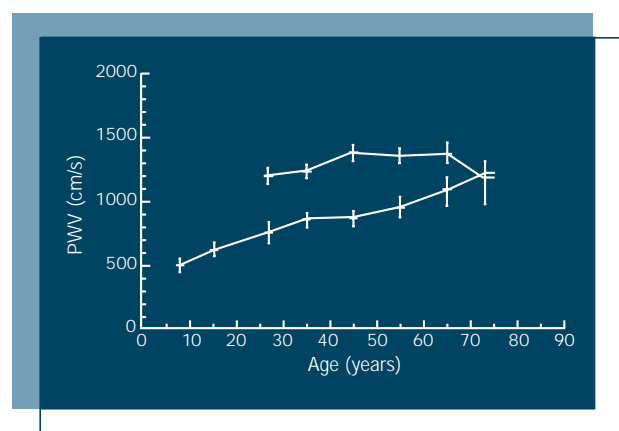
Pulse wave velocity in the arm (upper curve) and the aortic trunk (lower curve) in 450 subjects. Note the marked increase with age in the aorta for adult subjects compared to only slight changes in the brachial artery. This indicates that functional elastic properties of the arteries in the arm are reasonably constant with age.

Another piece of evidence in support of a generalised transfer function came with the observation that the transfer function did not differ markedly in normal conditions and in conditions of vasodilatation following administration of nitroglycerin.[1,13] This then made it possible to utilise the concept in a practical way to determine aortic pressure non-invasively in a range of situations.[1,9,13,14] While there has been some discussion on the use of a generalised transfer function,[15] recent evidence is emerging that the general transfer function concept can even apply to analysis of finger volume pulses.[16]
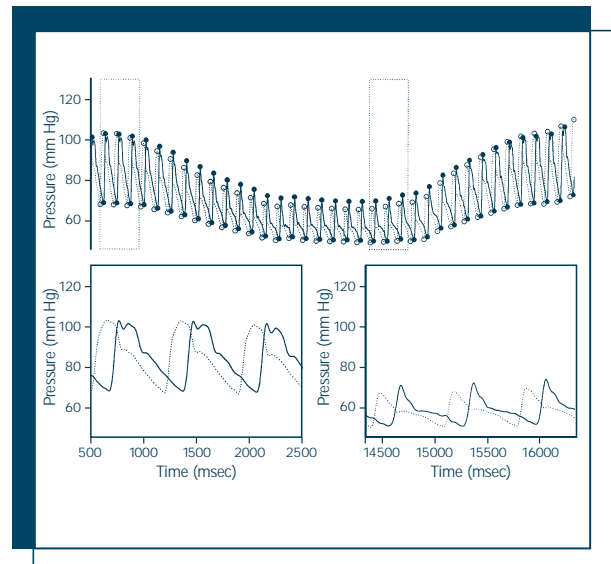
Validation

The study by Chen et al validated the use of the generalised transfer function under normal conditions, and when there are marked changes in blood pressure following a valsalva manoeuvre (*Figure 1.5*).[14]

The study reports results of invasive central aortic pressure measured by micromanometer and radial pressure by automated tonometry in 20 patients at steady state and during haemodynamic transients (Valsalva manoeuvre, abdominal compression, nitroglycerin, or vena caval obstruction) (*Figure 1.6*). A generalized transfer function was determined from the average of individual transfer functions. The generalized transfer function estimated central arterial pressures to 0.2 ± 3.8 mm Hg error and **augmentation index** (*see 2.3.3*) to within $\pm 7\%$. The study shows that individual transfer functions were only marginally superior to the generalized transfer function for reconstructing central pressures (*Figure 1.6*).[14]

Further evaluation of the technique has shown a very good correlation between the derived and measured central aortic systolic pressure.[1,13] Various studies[1,17] have reported a good correlation between the augmentation index determined from measured (y) and derived (x) aortic pressure waveform: $y = 0.92x + 0.24$; $r = 0.75$; $p < 0.001$.

Figure 1.5

Results from validation study by Chen et al[14] comparing derivation of aortic pressure using a generalised transfer function. Measured aortic pressure (dotted line) and aortic pressure derived from the radial pulse (solid line) using a GTF. Lower panels show individual pressure tracings at rest (left) and reduced preload (right).

Figure 1.6
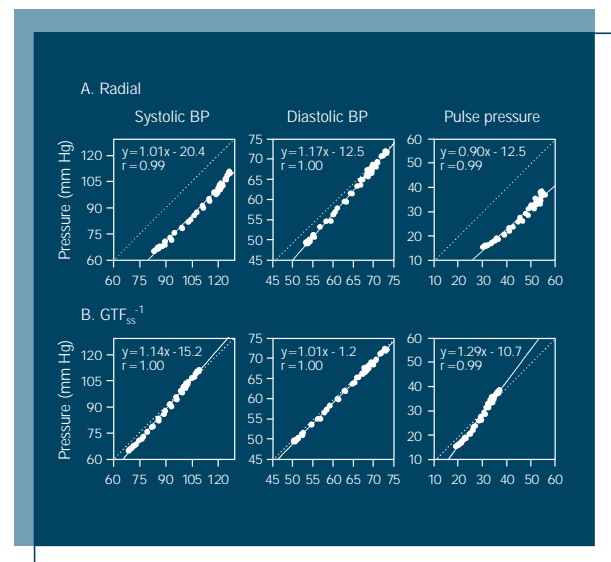
Results from validation study by Chen et al[14] showing regression analyses for systolic, diastolic, and pulse pressures during haemodynamic transients (eg valsalva manouvre). A=pressure measured in the radial artery (horizontal axis) compared with pressure measured in the central aorta (vertical axis). Note the markedly reduced systolic and pulse pressure in the central aorta compared with the radial artery while there is little difference in diastolic pressure. B=aortic pressure derived from the radial artery using the generalised transfer function (GTF) (horizontal axis) compared with pressure measured in the central aorta (vertical axis).

Reproducibility

Reproducibility of central aortic pressure and pulse wave velocity measurements with SphygmoCor depend on the quality of the data recorded. The essential element is to obtain an accurate radial pulse waveform, from which all parameters are derived. As with any technique, results of reproducibility will depend on both the stability of subject's physiological status and operator skill. Clinical studies have shown that the technique is highly reproducible. For further details, refer to Appendix 7.1.

Limitations

The use of the transfer function does not depend on the shape of the aortic pulse. For example, if there is incompetence of the aortic valve, the aortic pulse waveshape will be changed, and of course, so will the radial pulse. In these situations SphygmoCor can be used to analyse the radial pulse, since there is no real modification of the arterial properties. However, if the radial pulse is modified due to severe obstruction of any part of the brachial arterial system, SphygmoCor cannot be used in these situations to derive aortic pressure.

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2.1

The Pressure Pulse Waveform

One of the most basic physiological properties of the arterial pulse is that the shape becomes modified as it travels along the arterial tree. The amplitude generally increases, and the pulse waveform features are altered. For example, the peripheral pulse tends to have a narrower and sharper systolic peak than the central pulse.[1-3]

The normal **pulse pressure amplification** between central and peripheral locations, which can be quite marked, will depend on the heart rate. As the heart rate increases the peripheral pulse pressure can be approximately three times that at the aorta[4-6] as seen during exercise and with other causes of increased heart rate. At normal heart rates, the pulse pressure at the brachial artery (where it is normally measured) is 20-50% greater than that at the aorta, although this is dependent on age, with a greater difference in pulse pressure seen in the young compared to the elderly.[2] The increased **arterial stiffness** in the elderly leads to increased wave reflection, which increases central pulse pressure (*see Section 2.3*).

Conventional measurement of cuff blood pressure in the brachial artery does not take into account these two essential properties of the arterial pressure pulse. These are:

(i) the **pulse amplitude** increases at it moves away from the heart (*Figure 2.1*).

(ii) the **amplification** of the pressure pulse increases with heart rate in the normal population (*Figure 2.2*).

This means that:

- the conventional pressure measurement, which gives only the maximum (systolic) and minimum (diastolic) values of the peripheral pressure pulse, is not an accurate measure of the pressure load on the heart;

- any intervention that causes an increase in heart rate can cause a significant overestimation.

These features can be accounted for by analysing the information present in the pressure pulse waveform itself.

Figure 2.1
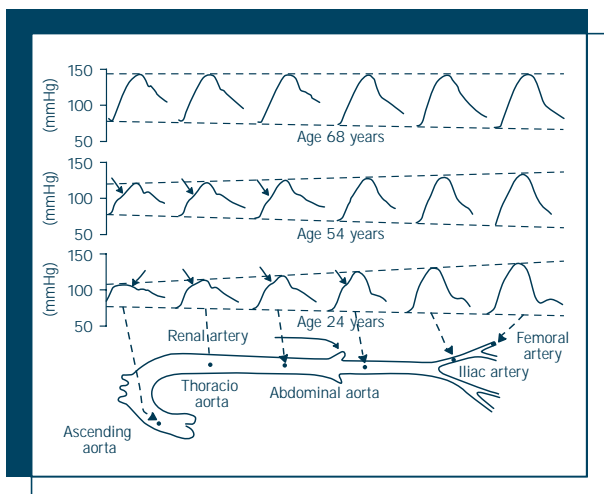
Change of pressure wave contour along the aortic trunk and peripheral arteries recorded in adult human subjects aged 24, 54 and 68 years. The amplification of the pulse towards the periphery decreases with age. The arrow on the waveforms indicates the first systolic inflection corresponding to the beginning of the reflected wave at different positions in the arterial tree. Note that this point tends to occur earlier in systole with advancing age.[1]

Figure 2.2

Amplification with Heart rate

$y = 0.006x + 1.0477$
$R^2 = 0.1939$
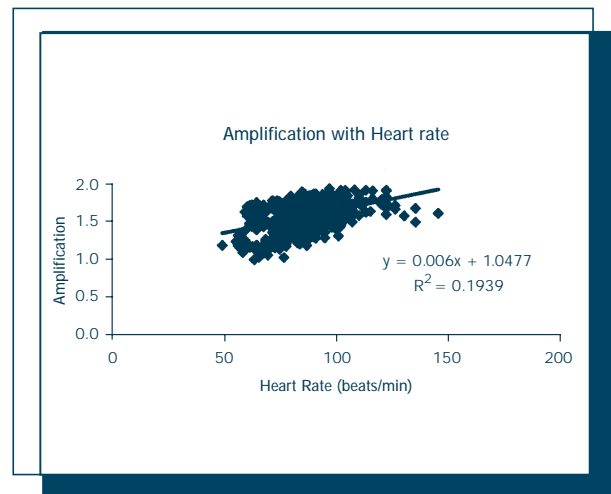
Amplification of the pressure pulse between the central aorta and radial artery with heart rate. The data were obtained with SphygmoCor in over 200 subjects and amplification calculated as the ratio of radial/central aortic pulse pressure. For a reference heart rate of 60 beats/min, the amplification increase is approximately 1% per beat/min.

Central Aortic Pressure from the Peripheral Pulse

The SphygmoCor system incorporates the actual pulse recorded at the radial artery and the properties of the transfer function between the aorta and the radial artery to estimate central aortic pressure non-invasively. When considering the transfer function, the input is considered to be the aortic pulse and the output the peripheral pulse. However, if the inverse of the transfer function is used as a mathematical model, then the input is the peripheral pulse and the output will be the aortic pressure.

The radial pulse is detected by a non-invasive high fidelity sensor using applanation tonometry (similar to the technique used for measurement of intra-ocular pressure - *see Section 1*). The waveform is calibrated using systolic and diastolic pressure values from conventional cuff measurement and SphygmoCor derives a complete waveform for the whole cardiac cycle for the aortic pulse (*Figure 2.3*). An average waveform is calculated from the ensemble average of a series of contiguous pulses.[1,6,7]

Once the aortic pulse is derived, a number of features can be extracted to enable calculations to be made, which cannot be made from the peripheral pulse or from the conventional measurement of brachial blood pressure.

Aortic Pressure Waveform

The shape of the aortic pressure pulse is a result of the ventricular ejection and the physical properties of the arterial system. The load on the ventricle during ejection is described by the pressure during systole. In the absence of wave reflection, the shape of the pressure wave during systole is determined by the ejection wave and the elastic and geometric properties of the ascending aorta. If there is no wave reflection, the shape of the pressure and flow look quite similar.[1]

The contracting ventricle of a normal heart is able to eject blood under a range of pressure loads, so even if the pressure is changed, the form of the ejection wave is quite similar. If wave reflection occurs during systole, it will increase the pressure against which the ventricle has to eject its contents. Thus, in addition to having the values of systolic and diastolic pressure in the aorta, knowledge of the pressure waveform will facilitate analysis of the coupling between the ejecting heart and the pressure load. These parameters can be extracted from the features of the aortic waveform such as the first systolic inflection (P1), the systolic peak (P2), the relative difference between the two in terms of pressure augmentation, the pressure at the end of systole, and the relative area during systole and diastole (*Figure 2.4*). The way these parameters are determined by SphygmoCor is addressed in the following sections.

Figure 2.3

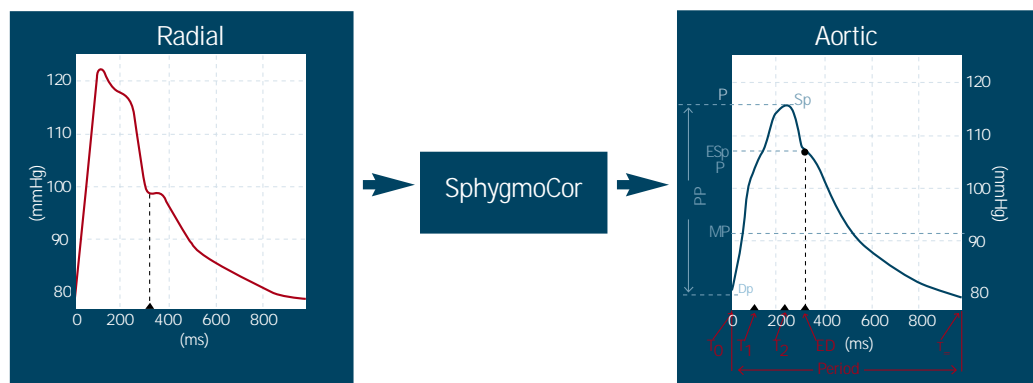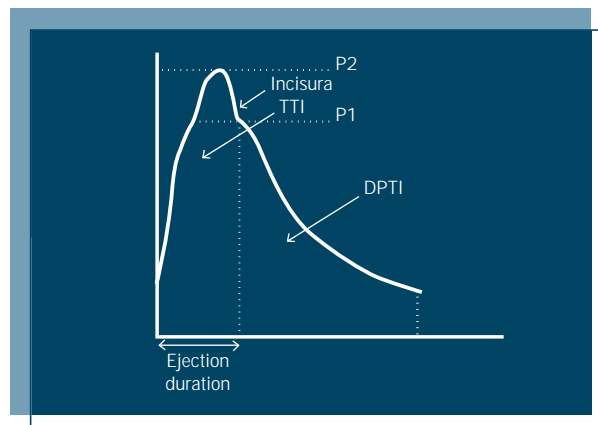Features of the Arterial Pulse

Figure 2.4

Aortic pressure waveform

Categories of pressure pulse waveforms (A, B, C)

Generally, the aortic pressure waveform can be divided into three broad categories, labelled as Type A, B and C.[8] These indicate different degrees of wave reflection primarily due to arterial stiffening. This may occur physiologically with age or pathologically in disorders such as hypertension, diabetes or hypercholesterolaemia (*Figures 2.5a and 2.5b*). They are described in terms of the feature of augmented pressure:

Type A   Early systolic shoulder; late systolic peak, positive augmentation pressure

Type B   Zero augmentation pressure

Type C   Peak pressure coincides with peak flow; late systolic shoulder; no augmentation pressure, negative augmentation index (AI) - *see Section 2.3.3*

Figure 2.5a
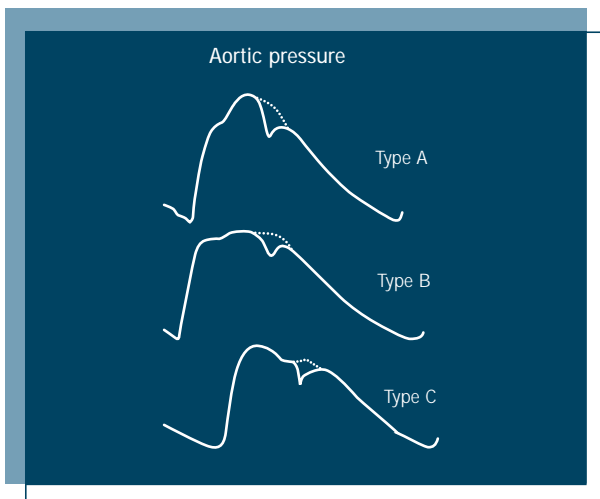
Figure 2.5b
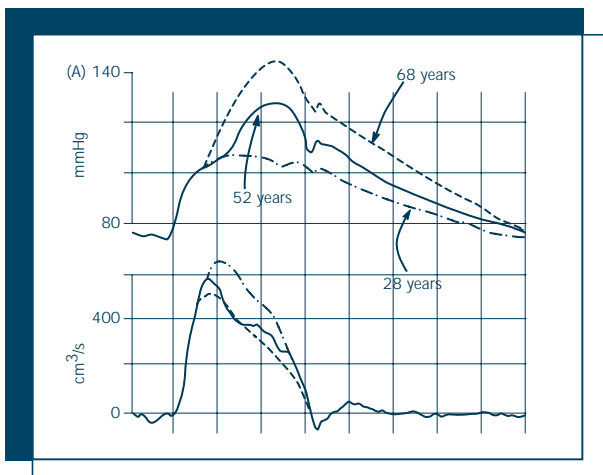
Typical pressure (above) and flow waves recorded in three normotensive subjects age 28,52,68 years. Note the slight decrease in aortic flow but an increase in late systolic augmented pressure with age as a consequence of increased arterial stiffness and wave reflection.[1]

Augmentation pressure

The ejection of blood from the ventricle into the aorta generates an aortic pressure pulse. In many cases the timing of peak pressure does not coincide with the timing of peak flow, such that peak pressure may occur later. In this event, there is usually a systolic shoulder on the ascending limb pressure curve which coincides with peak flow, then a rise in pressure to the systolic peak (*Figure 2.5b*). This increase in pressure is described as the 'augmentation pressure' (*Figure 2.6*) and is predominantly due to the reflected components of the original pressure pulse generated by ventricular ejection. The speed of the pulse in arteries is normally such that the reflection occurs in the diastolic phase but it can return during systole, while the aortic valve is still open, thus increasing the afterload pressure against which the heart has to eject blood.[3,8]

The amount of augmentation increases as the arteries stiffen. In the young (15-25 years) it is common to see no augmentation. That is, peak pressure coincides with peak flow, and the systolic shoulder occurs after the peak. This would seem to be an important characteristic in differentiating cases with similar central systolic and diastolic pressures but different pulse patterns during systole. Augmented pressure during systole produces a different loading pattern on the myocardial fibres, even if peak systolic values are identical.[9]

This situation can only be identified by analysis of the whole central wave form and not by the conventional means of blood pressure measurement.

Figure 2.6

Augmentation pressure (ΔP)

Figure 2.8

Ejection duration (ED)

2.3.3
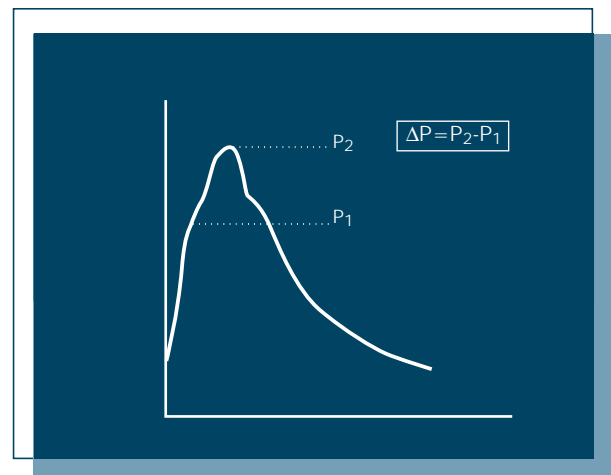
Augmentation index

The amount of augmentation pressure is quantified in terms of the relative change over the whole pulse. That is, once the early systolic shoulder (peak, P1) and the peak, or late systolic shoulder (P2) are identified, the absolute augmentation is calculated ($\Delta P =$ P2-P1) and an **augmentation index** (AI) is defined (*Figure 2.7*). SphygmoCor defines this in two ways: i) relative to P1 (ie AI 1 $= \Delta P/P1$) and ii) in relation to the pulse pressure (PP) (ie AI 2 $=$ (PP/P1). Both give similar information, but expressed in different forms.[1,3]

Figure 2.7

$$AI = \frac{\Delta P}{SBP\text{-}DBP}$$

Augmentation Index (AI)

2.3.4

Ejection duration

The usual method of measuring the **duration of ventricular ejection** (*Figure 2.8*) is by detecting the beginning of the pulse and the closure of the aortic valve, using the incisura as a marker or the second heart sound. However, these parameters are not readily available, and SphygmoCor makes use of the fe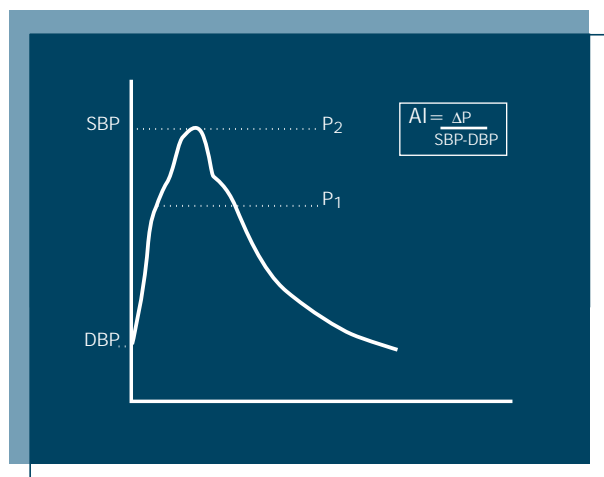atures in the peripheral pulse to determine the systolic time. It has been found that although the sharp incisura is not present in the radial pulse because of the attenuation of high frequencies, the analysis of higher derivatives is able to locate the corresponding point with reasonable accuracy. Thus, the systolic time is estimated from the peripheral pulse and then transferred to the derived aortic pulse.

2.3.5
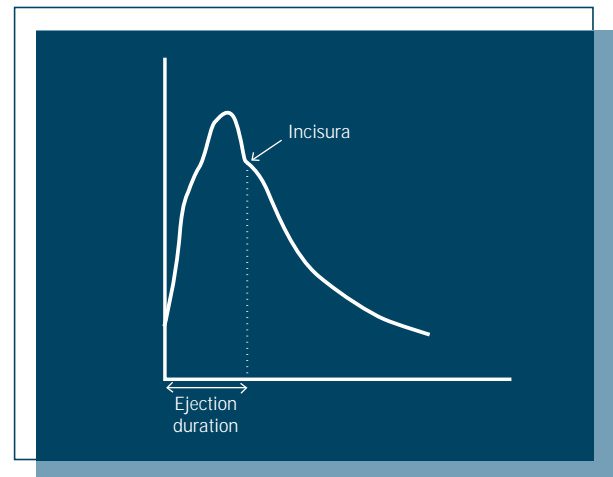
Subendocardial viability ratio (SEVR)

From the derived aortic pulse, calculations can be made which make use of the waveform features. By transferring the ejection duration determined from the peripheral pulse, the area under the systolic (AS) and diastolic (AD) part of the curve can be calculated. AS has been shown to be related to the work of the heart and to oxygen consumption (commonly known as the Tension Time Index). AD is associated with the pressure and time for coronary perfusion, thus is related to the energy supply of the heart. The ratio of supply and demand is termed the **Subendocardial Viability Ratio** or the **Buckberg Index**[10] (ie, SEVR = AD/AS). It has been shown that when SEVR is below unity (or 100%), the layers of the subendocardium are underperfused (*Figure 2.9*).

SEVR for normal conditions is usually high (~130-200%). However, it can decrease markedly with high heart rates or high systolic pressures. In measurements there is considerable variability in SEVR. However, if low values are consistently found in patients with known coronary artery disease, this may indicate the potential for aggravating subendocardial ischaemia[10,11] due mainly to reduction in diastolic perfusion time. Thus, this simple non-invasive measurement contributes to the decision-making process for specific therapeutic interventions and for further investigations in patients at risk of ischaemic events.

Figure 2.9

TTI= Tension time index
DPTI= Diastolic pressure time index

$$SEVR = \frac{DPTI}{TTI}$$

TTI

DPTI

Ejection duration
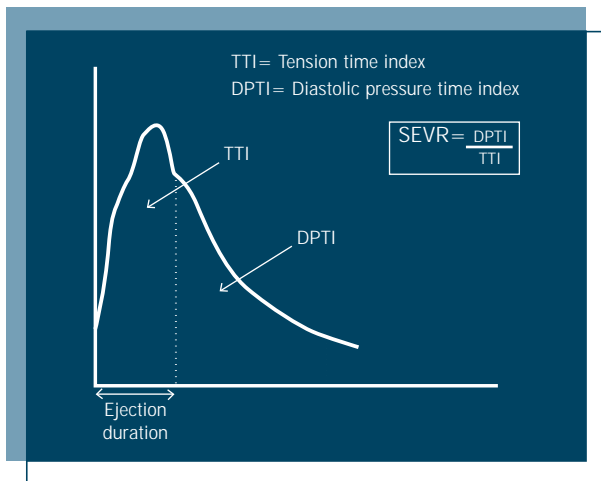
Subendocardial viability ratio (SEVR)

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3.1

Introduction

Cardiovascular damage is the final common pathway for a number of diseases. One of the most difficult challenges for the practitioner treating a patient with cardiovascular risk factors is to establish a diagnosis early, in order to allow pre-emptive action to be taken. In the patient with established disease, it would be of great assistance to have treatment directed appropriately at the physiological vascular abnormality.

Clinical examination of the cardiovascular system typically includes measurement of the pulse rate and character, measurement of blood pressure and cardiac auscultation. Further information can be gained by echocardiography, and by invasive haemodynamic monitoring. There is great potential value in a non-invasive tool to augment information gleaned from the clinical examination. Applanation tonometry, permitting accurate description of peripheral pulse wave characteristics and pulse wave velocity, and extrapolation of findings to central cardiac and aortic physiological events, is such a tool.

Medical disorders with clear potential cardiovascular complications provide the greatest opportunity for using applanation tonometry. These include:

- Hypertension (including essential and secondary causes, and hypertension complicating pregnancy)
- Left ventricular hypertrophy (LVH) and failure
- Systolic heart failure
- Diabetes mellitus
- Renal disease
- Hyperlipidaemia

In some of these disorders, there is already compelling evidence for the use of pulse wave velocity measurements. In this section of the guide, evidence is presented for pulse wave velocity in several disease states. Where available, the value of measurements in guiding diagnosis and/or therapy is presented. In some areas, studies are incomplete and therefore no specific recommendations can yet be made. As such information is acquired it will be reviewed for future editions of the guide.

Arterial Hypertension

Significance

Chronic elevation of arterial blood pressure is the most common medical problem in the developed world. It leads to unacceptable morbidity and mortality due to target organ damage, which is frequently accentuated by other cardiovascular (CV) risk factors. Systolic, and to a lesser extent, diastolic pressure rise with age such that 50% of the population aged 65 and over is at risk.[1] There is a continuous relationship between blood pressure and the risk of cardiovascular events, and based on an ideal maximum target pressure of 140/90 mmHg (high normal), 70% of patients currently receiving antihypertensive therapy are inadequately or poorly controlled.[1]

Detection

Despite extensive clinical and population studies, the specific physical properties of the arterial pulse that are most closely associated with the risk of target organ damage continue to be debated. In ageing societies, elevated systolic pressure has been identified as more important than elevated diastolic pressure. However, recent CV risk studies suggest that pulse pressure could be the most important variable.[2] This implies that at a particular level of elevated systolic pressure, risk could increase as diastolic pressure decreases. This has been confirmed in several risk analysis trials,[3-5] but does not deny that diastolic pressure above 90 mmHg is a strong separate risk predictor and requires therapeutic intervention irrespective of the systolic pressure.

The association between pulse pressure and cardiovascular risk has implications for the choice of antihypertensive therapy (see Treatment Objectives, Section 3.2.5). Studies leading to these conclusions have been based on conventional sphygmomanometry arm pressures, usually in the clinic setting and taken in the sitting position. Sphygmomanometry is convenient and when clinic pressures are confirmed with occasional ambulatory and home values, most physicians would conclude that effective monitoring and management of hypertension are achievable.

But what is missing from this current practice is a clear understanding of why, in particular patients, systolic, diastolic or pulse pressures are elevated and the consequences this can have for drug selection and prognosis. This insight requires quantitative information relating to stroke volume, large artery stiffness and peripheral vascular resistance. Thus, systolic pressure is influenced directly by stroke volume and vascular stiffness. But while diastolic pressure rises with increasing peripheral resistance to blood flow and also when neurohormonal factors increase the heart rate, it actually falls as large artery stiffness increases. This results from the faster 'run-off' of the stroke volume from the main arteries due to their reduced visco-elastic properties and inability to retain the ejected volume.[3] Information relevant to these variables, and to the cause of increased pulse pressure and consequently CV risk, can be derived non-invasively and conveniently from pulse wave analysis (PWA).

Pulse wave analysis

Using the SphygmoCor system of pulse wave analysis, the hallmark of increasing arterial stiffness is an augmentation of central aortic systolic peak pressure due to an increased pulse wave velocity and rate of wave reflection (*see Section 2*). This has secondary effects on cardiac work and coronary perfusion that can become decisive factors for left ventricular function. In the routine management of hypertension, PWA at intervals together with sphygmomanometry permits the physician to identify more accurately the physical cause and progressive consequences of the hypertension. With this information the selection of therapy appropriate to the specific causation, whether systolic, diastolic or pulse pressure is more informed.[5]

Typical waveforms in hypertension

Young normotensive

Radial Waveform	Average Aortic Pulse
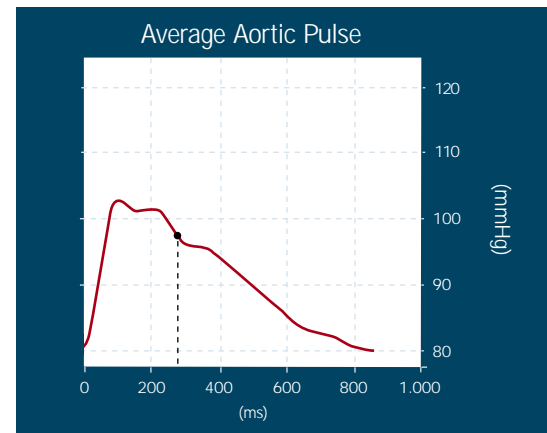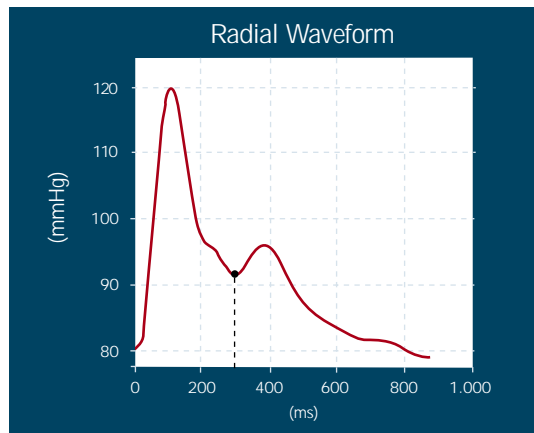
Note: Narrow radial peak. Late systolic shoulder in aortic pulse is lower than the early systolic peak (negative augmentation).

Middle aged normotensive

Radial Waveform	Average Aortic Pulse
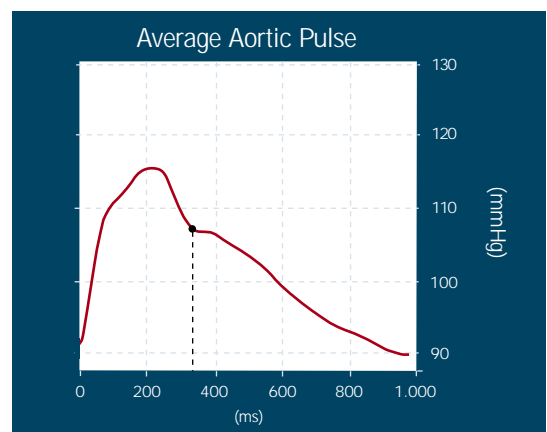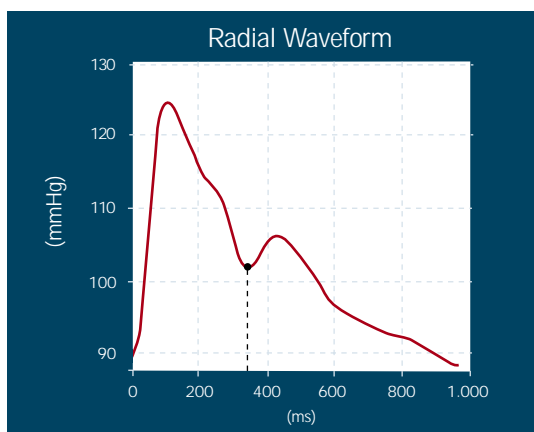
Note: Wide radial systolic peak. Late systolic peak in aortic pulse is higher than early systolic shoulder (positive augmentation).

Elderly normotensive

Radial Waveform	Average Aortic Pulse
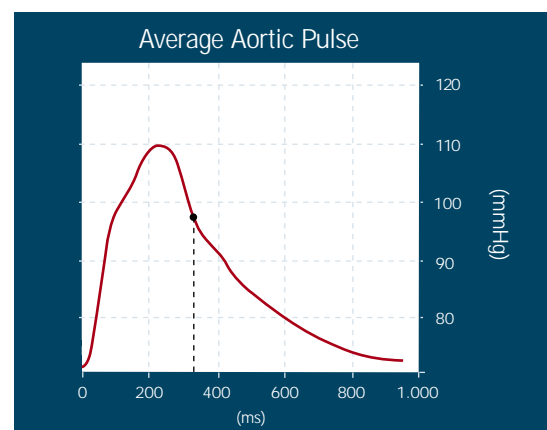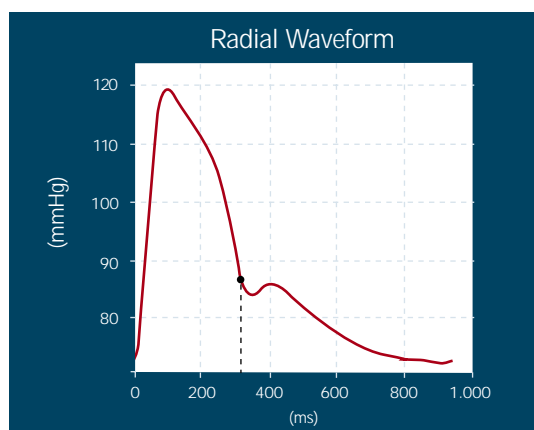
Note: Increased late systolic shoulder in radial pulse. Increased late systolic augmentation in the aortic pulse.

Young hypertensive

Radial Waveform — (mmHg) vs (ms)

Average Aortic Pulse — (mmHg) vs (ms)
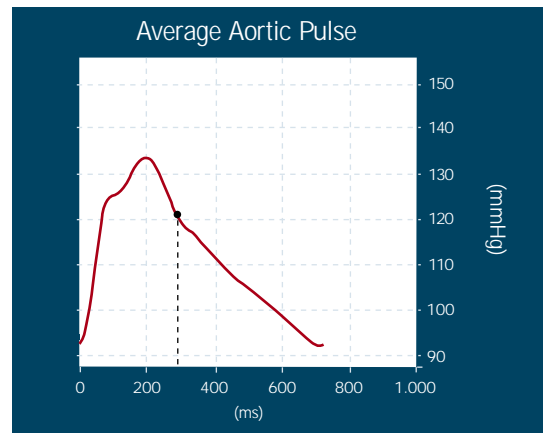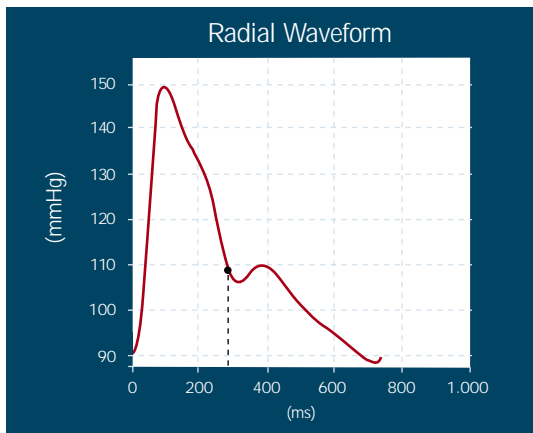
Note: Prominent late systolic shoulder in the radial waveform. Presence of late systolic augmentation in the aortic pulse.

Middle aged hypertensive

Radial Waveform — (mmHg) vs (ms)

Average Aortic Pulse — (mmHg) vs (ms)
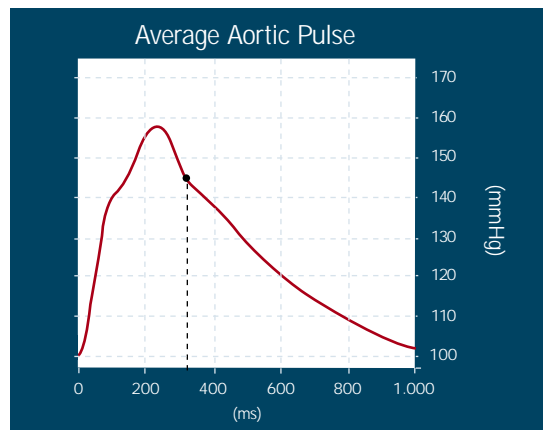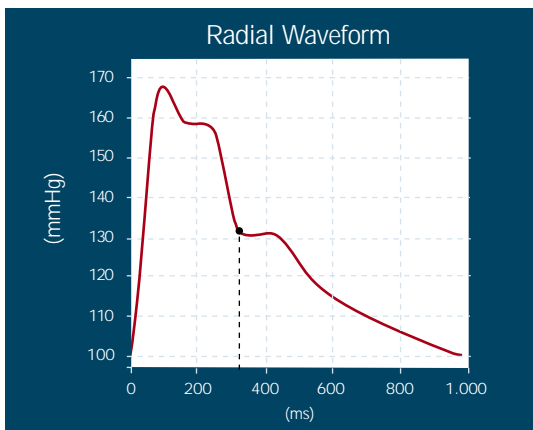
Note: Increased late systolic shoulder in the radial waveform. Increased late systolic augmentation in the aortic pulse.

Elderly hypertensive

Radial Waveform — (mmHg) vs (ms)

Average Aortic Pulse — (mmHg) vs (ms)
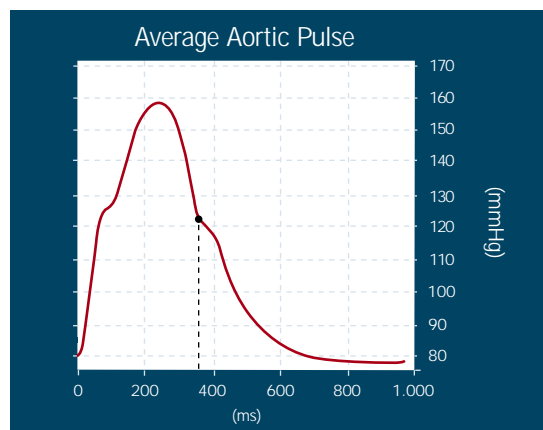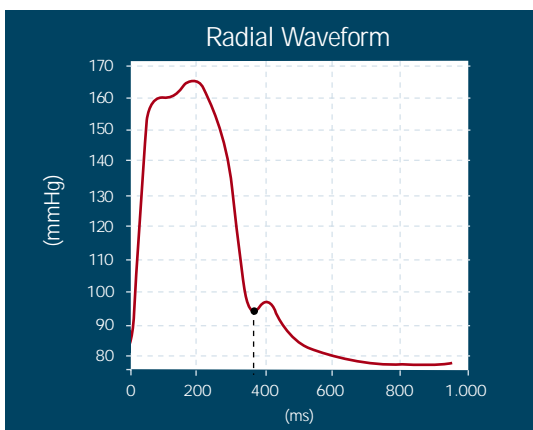
Note: Exaggerated increase in late systolic peak in radial waveform is higher than earlier systolic shoulder, in contrast to young and middle aged hypertensive pulse. This is associated with prominent augmentation of late systolic aortic pulse. Note also the relative reduction in pressure during the diastolic phase indicating reduced coronary artery perfusion pressure.

Treatment objectives

Assuming there are no associated conditions accentuating CV risk, such as diabetes, the general objective in all hypertension management is to reduce systolic/diastolic pressures to below 140/90 mmHg. However, the increasingly common problem of isolated systolic hypertension with increased pulse pressure requires further consideration. In these patients, the target should be achieved without reducing diastolic pressure further, thus avoiding the risk associated with high pulse pressure. The ideal drug in this situation would be one that reduces large artery stiffness, pulse wave velocity and augmentation pressure (as monitored by PWA) but without decreasing peripheral vascular resistance. Of the commonly used agents, calcium channel blockers (CCBs) and inhibitors of the renin-angiotensin system (ACE inhibitors, angiotensin II receptor antagonists) are recommended, but are not specific and do not act selectively to increase large artery compliance. Low dose nitrates, not currently recognised for the routine management of hypertension, do increase large artery compliance and have been shown to reduce pulse wave velocity.[4] Further aspects and future prospects relating to the rational selection of drugs to correct the pulse profile are outlined in Section 4.

Summary

- 70% of patients receiving antihypertensive therapy are inadequately controlled

- Pulse pressure is an important determinant of cardiovascular risk

- PWA enables the physical cause of hypertension to be accurately identified

- Specific treatment programs can be developed and monitored based on PWA results

- Central aortic pressure derived from SphygmoCor is expected to relate more closely to hypertension, morbidity and mortality than conventional brachial artery pressure measurements alone

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3.3

Left Ventricular Hypertrophy and Failure

3.3.1

Significance of left ventricular hypertrophy (LVH) and failure (LVF)

LVH is a powerful risk indicator in hypertension[1] and constitutes a major independent risk factor for sudden death, myocardial infarction, stroke and ischaemic heart disease.[2] LVH also predicts the eventuality of ventricular failure.

The major cause of LVH is essential hypertension which is initiated by increased peripheral vascular resistance and with time is compounded by increasing stiffness of the main conduit arteries due to secondary structural changes. Aortic stiffness, by increasing pulse wave velocity, has two potentially serious consequences for LV function:

1) Central systolic pressure is augmented by the earlier return of the reflected wave which increases the ventricular after-load and systolic work and decreases late systolic flow (*Figure 3.3.1*).

2) Diastolic coronary perfusion time is reduced due to the augmented and protracted systole while coronary perfusion pressure is also lowered due to the shift in the timing of the returning reflected wave from diastole into systole (*see Section 2*).

These are important compromising factors for ventricular function and contribute to a slowly developing vicious cycle that will ultimately result in left ventricular failure.

3.3.2

Detection

LVH is routinely confirmed by non-invasive imaging and electrocardiography but it is surprising that these methods cannot provide insight into the progression of events described above. To reveal the impact of increased pulse wave velocity on cardiac function requires the recording of the central arterial pressure profile at intervals during the management of the complaint.

Figure 3.3.1
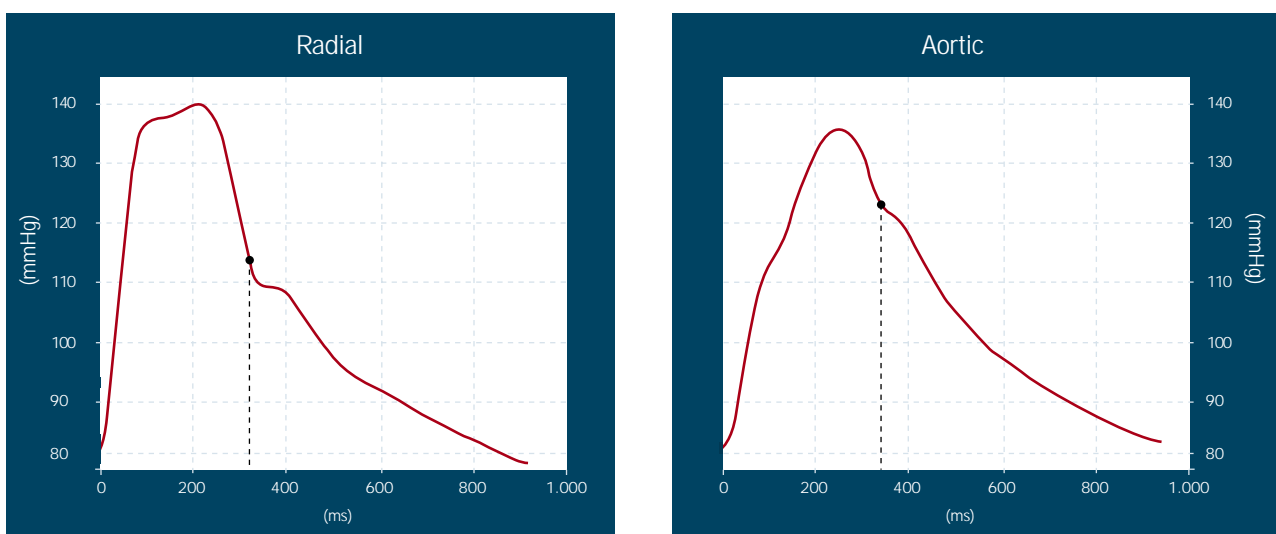
Increased effects of wave reflection associated with arterial stiffness are seen in the augmented late systolic peak in the radial waveform (left) and derived aortic waveform (right).

3.3.3

Pulse wave analysis

PWA using SyphgmoCor enables an accurate determination of central aortic pressures non-invasively via the transfer function. The sequential measurements of central pulse pressure profile, augmentation index and subendocardial perfusion ratio (*see Section 2*) quantifies the factors listed above that can be the main contributors to the development of LVH and ultimately ventricular failure.

A main characteristic of early left ventricular failure is the loss of contractile power to cope with increased impedance to ejection. The impedance resides both at the arteriolar level and in the central arteries.[3-5] In heart failure the arterioles are constricted due to increased neurohormonal influences and central pressures may be augmented due to slower systolic ejection and aortic stiffness each causing the reflected wave to lie within the systolic period. (*Figure 3.3.1*)

3.3.4

Treatment objectives for LVH and failure using SyphgmoCor

Treatment is directed to reverting the progression of events described above and again this can only be monitored by a technique that allows assessment of central arterial pressure profiles. For LVH, the objective is to determine the presence and then to reduce the degree of systolic augmentation. This is true also for ventricular failure but with failure there is additional concern to obtain evidence of increased contractility, increased late systolic flow and improved subendocardial perfusion. Reducing mean arterial pressure by any means will improve aortic compliance and potentially reduce pulse wave velocity but without altering the degenerative structural wall changes that have occurred to that time. There are currently no drugs available to reverse these changes but their progression should be decreased by pressure control. On the other hand vasodilator drugs reduce impedance to ventricular ejection and improve late systolic flow.

Renin-angiotensin blockers have proved particularly effective in LVH and failure. They appear to break the cycle of events that otherwise lead to increasing LVH and failure. It is becoming clear that their beneficial long-term effects are due to interference with myocardial paracrine growth systems and improved large artery endothelial function. The effects of drugs on the central pulse profile are discussed further in Section 4.

3.3.5

Summary

- LVH is a major risk factor for cardiovascular disease and predicts the development of LV failure

- Traditional methods to detect LVH do not provide information about the arterial dynamics that determine LVH

- PWA enables direct assessment of the severity of central aortic pressure elevation, and thus the development of LVH

- PWA can accurately assess the effects of drug treatment for LVH

- PWA can reveal the haemodynamic basis for ventricular failure and follow its therapeutic correction

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3.4

Systolic Heart Failure

3.4.1

Significance

Coronary artery disease is the most common cause of myocardial systolic dysfunction in Western society. This dysfunction can include ischaemia in the absence of infarction, and sometimes in the absence of symptoms of inadequate coronary perfusion.[1] Transient loss of nutritional support for myocardial relaxation and contraction can result in prolonged functional impairment without loss of cellular integrity.[2]

Systolic heart failure may result from a variety of conditions including myocyte loss, impaired myocyte function, interstitial or pericardial structural alterations that affect ventricular function, and electrical disturbances that impair pump function.

3.4.2

Detection

Systolic heart failure is characterised by reduced exercise capacity resulting from dyspnoea or fatigue. The signs and symptoms of heart failure relate not only to the abnormality of cardiac function but also to a wide variety of systemic responses that alter the vascular tone and neurohormonal milieu. It is these complex physiological responses that make heart failure such a multifaceted syndrome.

3.4.3

Pulse wave analysis

The use of sphygmonometry to identify patients with low subendocardial perfusion ratio (SEVR)[3] can be helpful in preventing ischaemic induced systolic dysfunction.[4-6]

In systolic heart failure, increased arterial stiffness and early wave reflection result in a reduction of late systolic blood flow, and vasodilator drugs targeted at large arteries will be of benefit by increasing late systolic flow rather than late systolic pressure.[7-9]

Systolic heart failure manifests as a reduction in cardiac output due to systolic dysfunction which is extremely sensitive to arterial loading conditions.[10-13] Pulse contour analysis studies have also demonstrated abnormalities of oscillatory arterial compliance.[14]

A characteristic of the dysfunctional left ventricle is that it loses its ability to cope with an increase in impedance to ejection.[15] This force is composed of resistance predominantly at the arteriolar level, due to the activity of the neurohormonal system, and increased vascular stiffness in the central arteries resulting in increased cardiac afterload.[14-16]

Ventricular systolic function is the result of shortening of sarcomeres and as a consequence, the myocyte contracts. The extent of sarcomere shortening is dependent on loading conditions before and during contraction. Reduced systolic shortening may result from global or regional reduction of contractility or a high impedance to left ventricular ejection which can be accurately quantified using central haemodynamic parameters as measured using SphygmoCor.

3.4.4

Treatment

Acute drug administration has been demonstrated to alter pulsatile loading conditions in patients with heart failure. Both nitroprusside[16] and dobutamine[17] can decrease aortic afterload in patients with heart failure.

Management of the systolic dysfunction therefore includes efforts to treat the reversible causes of heart failure and to use drugs to improve left ventricular function through the optimisation of central haemodynamics and neurohormonal function.

Summary

- HF is a multifaceted syndrome – it not only impairs cardiac function but also alters vascular tone and neurohormonal milieu

- PWA can identify patients with low SEVR and thus help to prevent ischaemic-induced systolic dysfunction

- Measurement of central haemodynamic parameters with SphygmoCor can help to define the cause of reduced systolic shortening

- Pharmacotherapy can alter pulsatile loading conditions in patients with HF

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Use of SphygmoCor in Diabetes Mellitus

Diabetes mellitus (type II diabetes) is parallel with obesity and is increasing in incidence and prevalence throughout the developed world.[1]

Not only is diabetes associated with microvascular disease, but also with an increase in macrovascular disease. The American Heart Association has gone so far as to say "diabetes is a cardiovascular disease".[2]

Atherosclerosis is more common, more generalised and occurs at an earlier age in diabetic subjects than in the population at large.[3] The resultant high risk of major cardiovascular complications is exacerbated further by its common associations with hypertension and hyperlipidaemia. Aggressive lowering of blood pressure in this situation undoubtedly results in prevention of vascular disease.[4]

Even after correction for blood pressure, those with type II diabetes have increased left ventricular mass,[5] and a high incidence of heart failure.[6] This suggests a role for increased vascular stiffness, augmenting central systolic pressure.[7]

The significance of the atherogenic dyslipidaemia of diabetes is shown clearly by results from the FINMONICA Study,[8] describing an almost 50% death rate within 12 months of myocardial infarction in both male and female diabetics under the age of 65 years, almost double the rates of non-diabetic subjects. Effective treatment of hyperlipidaemia in diabetic patients was of great value in both primary and secondary prevention of cardiovascular disease, both in the CARE study[9] and in the Scandanavian Simvastatin survival study (4S).[10]

A small study by Goodfellow and colleagues,[11] utilising a combination of techniques, showed increased vascular stiffness early in the course of type II diabetes. Using SphygmoCor, these findings were later confirmed in a larger study.[12] It is likely that this stiffness is related to endothelial dysfunction rather than structural vascular alterations - this in turn raises the possibility that it is reversible. Since direct measurement of endothelial function *in vivo* is invasive and expensive, reliable and reproducible surrogate measures are of great clinical value. They have the potential for use in population screening for risk detection, as well as for use in monitoring responses to therapeutic manipulation in individual patients.

Candidates for causation of endothelial dysfunction and vascular disease are many, including hyperglycaemia, insulin resistance, abnormal lipid metabolism and the presence of advanced glycation end products. Each of these is susceptible to a variety of potential therapeutic or preventive manipulations.

The value of techniques to analyse the peripheral arterial pulse wave in detection and assessment of the severity of these abnormalities is dealt with in detail elsewhere in this manual, and a broader perspective is described in 'Diabetes: Current Perspectives'.[13] Insulin administration has been shown to cause endothelial dependent vasodilatation,[14] associated with a reduction in central aortic pressure augmentation.[15] It is likely therefore that SphygmoCor will have a role in patients with newly diagnosed diabetes, in the detection of early cardiovascular disease (*Figure 3.5.1*). Further, it is likely to be of assistance in evaluation of responses to control of hyperglycaemia, hyperlipidaemia and hypertension, and in tailoring of individual therapeutic regimens.

Figure 3.5.1
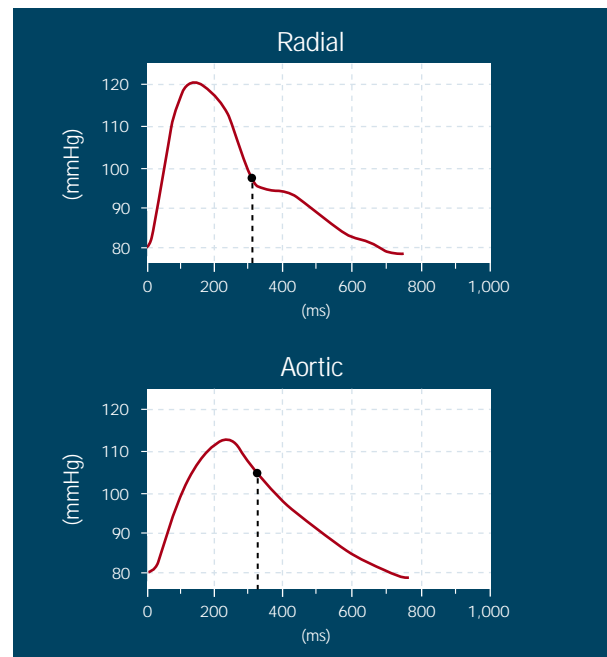
Note: Normal values of peripheral blood pressure. Elevated late systolic shoulder in radial pulse associated with a high calculated aortic augmentation index of 39%. This value lies outside the confidence intervals for the patients' age. This together with relatively long ejection duration (41% of cardiac cycle) results in elevated systolic load on the heart, resulting in a relatively low SEVR of 127%. These indices calculated by SphygmoCor indicate that left ventricular load could be increased even at normal blood pressure.

Summary

- Diabetes is a cardiovascular disease

- Diabetic patients have increased vascular stiffness that contributes to increased LV mass and heart failure.

- SphygmoCor can monitor and quantify the onset of these changes.

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Renal Disease - Assessment of the Cardiovascular System in Patients with Chronic Renal Failure and on Dialysis

Pulse wave analysis and renal failure

Cardiovascular complications are a major cause of morbidity and mortality in patients with renal failure. Deaths due to myocardial infarction and stroke are more frequent in haemodialysis patients than in the total population. Methods which permit simple but accurate assessment of cardiovascular status are therefore important. Arterial stiffness, determined by a variety of methods, is undoubtedly increased in renal failure.[1] Aortic stiffness, determined by measurement of aortic pulse wave velocity (PWV) (via Doppler ultrasonography)[2] is a strong independent predictor of all-cause and cardiovascular mortality in patients on chronic haemodialysis. The same group has recently reported that aortic PWV index (calculated as measured PWV - theoretical PWV) has greater predictive power than blood pressure or pulse pressure measurements.[3]

Techniques to allow non-invasive and simple measurement of these haemodynamic variables are necessary before they can be included in routine clinical assessment of cardiovascular risk. There is now good evidence that central aortic pulse wave information can be acquired from examination of the pulse wave characteristics of medium sized peripheral arteries by applanation tonometry. Carotid artery tonometry measurements in non-diabetic haemodialysis patients have shown markedly increased PWV and augmentation index (AI).[4]

Acquisition of similar information from the radial artery would further simplify assessment of pulse wave characteristics. Radial artery tonometry has the potential problem of previous and current vascular access, which will alter the measurements made in the arm. Interpretation of measurements also demands understanding of the acute effects of dialysis, in particular of rapid fluid balance shifts.

The first report on radial artery tonometry findings in patients on regular maintenance haemodialysis appeared recently.[5] The authors describe pre- and post-dialysis values in 51 subjects with a wide range of pre-dialysis pulse waveforms (*Figures 3.6.1 and 3.6.2)*, and several different patterns of response to the blood pressure and volume effects of dialysis therapy.

The clinical significance of these acute changes has yet to be determined, as has the most appropriate timing of measurements to determine the longer term prognosis of cardiovascular disease in this complicated patient population.

Figure 3.6.1
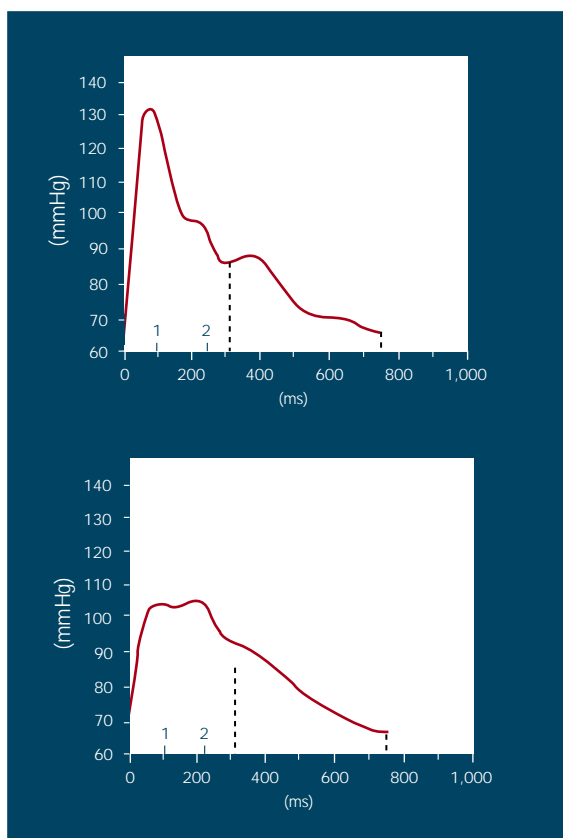
Figure 3.6.2

Representative pulse wave form from a subject with normal brachial artery blood pressure levels (top) and virtually normal aortic function (bottom) (AGI of +2%). Adapted from reference 5.
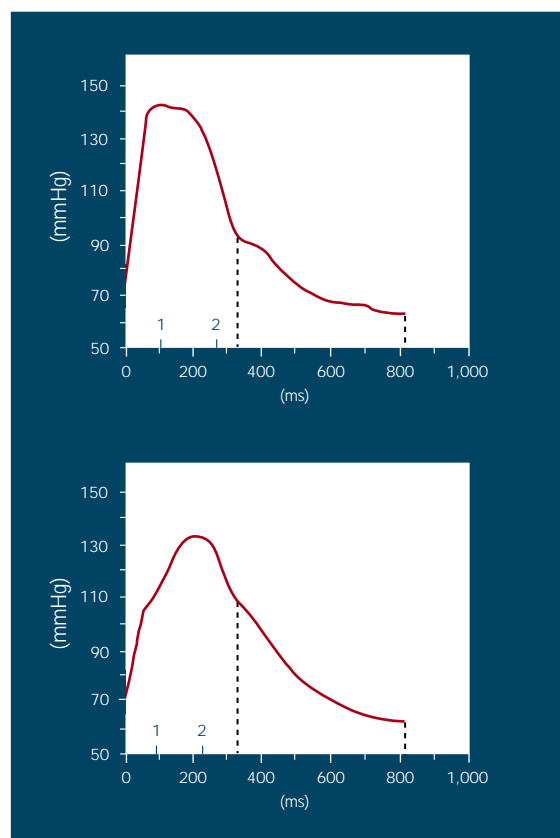
Representative pulse wave form from a subject showing raised brachial artery blood pressure levels (top) and abnormal aortic function (bottom) (AGI of +31%). Adapted from reference 5.

3.6.2

Summary

- Arterial stiffness is increased in patients with renal failure
- Aortic stiffness is a strong independent predictor of mortality in patients on chronic haemodialysis
- PWV and AI are increased in non-diabetic haemodialysis patients
- Haemodialysis may have a positive impact on arterial haemodynamics

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Pregnancy and the Arterial Pulse

Cardiovascular function in normal human pregnancy

Extensive information from invasive and non-invasive studies regarding the haemodynamic alterations of the normal human pregnancy has been available for many years. These studies demonstrate an increase in plasma volume,[1] stroke volume,[2] heart rate[3] and cardiac output,[4] plus a fall in total peripheral resistance[5] and systolic and diastolic blood pressures.[6]

Cardiovascular function in human pregnancy complicated by pre-eclampsia

Maternal vascular function is abnormal in pre-eclampsia. In addition to hypertension, there is:

i) volume contraction[1]

ii) increased total peripheral vascular resistance[5]

iii) increased uterine artery resistance[7,8]

iv) increased maternal vascular reactivity to external pressor substances.[9]

Non-invasive *in vivo* assessment of arterial compliance and cardiovascular load in pregnancy

A variety of non-invasive methods have been developed to allow better description of cardiovascular physiology *in vivo*. These involve measurement of the arterial pulse waveform from a medium-sized or small peripheral artery, and calculation of central arterial pressure characteristics. Some of these techniques have been examined in normal and/or hypertensive pregnancy. Reproducible assessment of wave propagation and reflection, which are major components of pulsatile arterial load, would give information about vascular stiffness, pulse wave velocity, central aortic pressure augmentation, and hence cardiac afterload.

Early work in pregnant women by Hon *et al*[10] described the development of a non-invasive pressure transducer for application to the finger, permitting the recording of peripheral pulse wave patterns. From these recordings and simultaneous ECG tracings, information was gained about pulse wave velocity (PWV) and about the associations of different pulse wave contour patterns with pregnancy outcomes. There are a number of publications from this group describing the patterns observed both in normal pregnancy and in hypertensive pregnancy of different causes.[11,12] However, the measurements made are potentially affected by local circulatory changes in the hand. The device is not yet commercially available in Australia, and is being evaluated in ongoing studies in various international centres.

A recent report utilising finger photoplethysmography has also described calculation of indices related to pressure wave reflection and large artery stiffness.[13] The calculated values were increased in women with pre-eclampsia, in keeping with the concept of increased vascular stiffness in pre-eclampsia. Again, the parameters measured, while undoubtedly related to PWV, arterial stiffness and pressure wave reflection, suffer from the potential effects of extraneous stimuli on the local digital circulation.

Using a combination of procedures (two-dimensional M-mode echocardiography, oscillometric brachial artery blood pressure measurement, ECG, Doppler estimation of ascending aortic blood flow velocity, and subclavian artery pulse wave tracings), a group from the University of Chicago described an increase in arterial compliance in normal human pregnancy, and both a delay and a reduction in the magnitude of peripheral arterial wave reflection.[14] These changes were felt to represent adaptations in both conduit and peripheral arteries, and help to accommodate the increased plasma volume and the efficiency of ventricular-arterial coupling and diastolic perfusion pressure. Unfortunately, women with pre-eclampsia or chronic hypertension were excluded from this study. A specialised in-house apparatus was used to acquire the subclavian artery pulse wave information, and the methodology is therefore not applicable to routine clinical practice.

Potential applications of SphygmoCor to normal and hypertensive pregnancy

We hypothesise that in pre-eclampsia, because of the combination of vasoconstriction and small vessel disease secondary to coagulation activation, there will be a detectable increase in both PWV and augmentation index (AI), the latter increasing sharply in proportion to clinical severity. It is likely that some pregnant women with chronic hypertension also have increased PWV.

We hypothesise that this will be the subgroup which develops superimposed pre-eclasmpsia, which is characteristically very rapidly progressive when it occurs on a background of chronic hypertension. We therefore suggest that measurements of either AI or PWV will be of value in assessing the clinical severity and the likelihood of complications such as pulmonary oedema, and may help to guide therapy for these patients.

Increased vascular reactivity, increased uterine artery resistance, increased BP measured by ambulatory BP monitoring, and a reduction in plasma volume all precede the development of pre-eclampsia. Therefore, it is possible that the PWV and AI values may be detectably abnormal prior to the clinical appearance of the disorder. It is not known yet whether this is so, or whether the measurements will be a reliable predictor of pre-eclampsia. It is also not known whether this will be a useful prognostic indicator in women with early disease.

Current research is underway to assess PWV in normal women at different stages of pregnancy to establish baseline ranges. Future investigations will examine women with hypertension.

A recent study[15] illustrates the potential use of pulse wave analysis in pregnant patients, highlighting the effect of normal pregnancy on pulse pressure (*Figure 3.7.1*), and augmentation pressure and augmentation index (*Figure 3.7.2*).

Figure 3.7.1
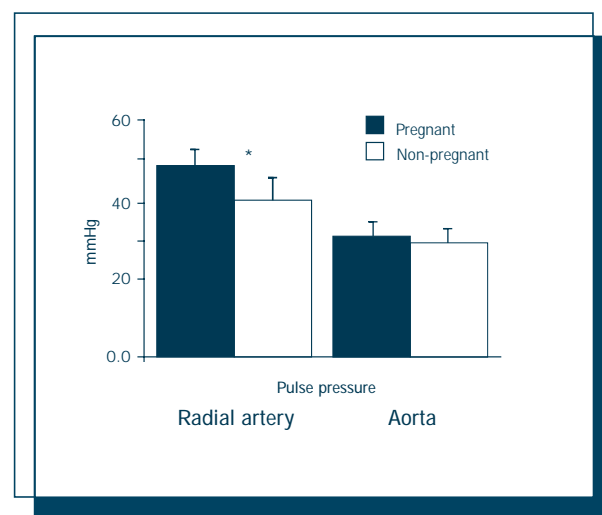
The effect of normal pregnancy on pulse wave pressure measured at radial artery and derived by SphygmoCor at the aorta.

Values are shown (mean, 95% CI) for women at 25-28 weeks amenorrhoea, and for non-pregnant women. The wider pulse pressure at the radial artery, well described in normal pregnancy (p<0.05), is not seen centrally.

Figure 3.7.2
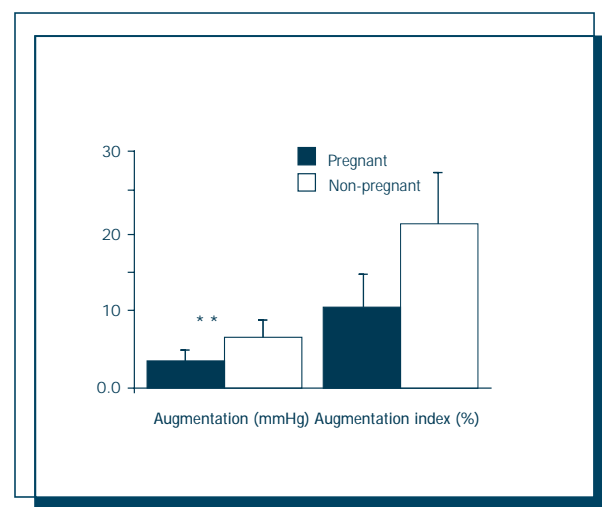
The effect of normal pregnancy on augmentation (mmHg) and augmentation index (%). Values are shown (mean, 95% CI) for women at 25-28 weeks amenorrhoea, and for non-pregnant women. Augmentation and augmentation index are significantly lowered in normal pregnancy (p<0.01), reflecting peripheral vasodilatation.

Summary

- Maternal vascular function is abnormal in pre-eclampsia

- There is likely to be increased PWV and AI in patients with pre-eclampsia

- Measurements of PWV may be valuable for assessing the clinical severity or pre-eclampsia

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4.1

Introduction

In routine clinical practice, the selection of drugs for the treatment of hypertension and/or cardiac contractile failure requires knowledge of their established effects on systolic and diastolic brachial artery pressure, cardiac ejection and excitability, autonomic function and heart rate. In particular, awareness of cardiovascular, cerebrovascular and renal outcome statistics from long term treatment studies is required.

There is little opportunity to improve on such evidence-based criteria unless a patient's individual cardiovascular characteristics are more fully explored and then progressively monitored. This is particularly true when systolic hypertension and cardiac contractile impairment are specifically aggravated by decreased vascular compliance (i.e. increased arterial stiffness). Central arterial systolic pressure increases not only as a direct function of the ventricular ejection properties and vascular conduit stiffness, but also indirectly through vascular stiffness, which causes increased velocity of the pulse wave propagation and reflection. This can lead to potentially dangerous augmentation of central systolic peak pressure, limiting cardiac ejection and exposing central and cerebral vessels to higher than anticipated pressures. The augmentation can account for as much as 40% of the central pulse pressure in older patients with isolated systolic hypertension. However it is specifically reducible in individual patients with drugs that modify the velocity and size of the pulse wave and its reflection.

In order to apply these haemodynamic principles responsibly in practice, published evidence regarding the different classes of drugs should be carefully considered, particularly:

- The acute effects of the drug on peripheral (i.e. brachial) and central arterial wave forms. This information allows functional information about both aortic and systemic arterial stiffness to be assessed, as well as the degree of augmentation of the central pulse due to reflection, and the timing of the reflected wave.[1]

- Evidence that these initial changes are maintained with long-term administration.

- Multicentre outcome studies in which drugs that decrease central arterial pulse augmentation, or at least retard the progression of vascular stiffness, provide better statistical associations with reduced morbidity and mortality than brachial artery pressure alone.

4.1.1

Nitric oxide donors

Acute studies using various nitric oxide (NO) donor preparations (e.g. nitroprusside in hypertensive patients) have shown that augmentation of the central systolic pressure is consistently abolished. This is evident with both invasive and non-invasive assessment, and is seen with or without a fall in brachial artery pressure. The acute beneficial effect of nitrates may be due not only to a reduction in total vascular stiffness or pulse wave velocity, but to a reduction in the size of the component of the wave complex reflected from peripheral arteries larger than arterioles.[2-4]

Long-term non-invasive observations (e.g. 34 weeks on isosorbide mononitrate) in elderly hypertensives have confirmed that the reduction in central systolic pressure is sustained,[5,6] but to date, morbidity and mortality outcome comparisons of pulse wave analysis with brachial pressures are not available.

4.1.2

Dihydropyridine calcium channel blockers, alpha adrenergic blockers and hydralazine

This heterogenous group of antihypertensive drugs are classified by their main site of action, and act primarily by decreasing peripheral arteriolar resistance. They have been shown to reduce brachial artery pressure and augmentation of the central pulse both acutely and long-term in middle-aged essential hypertensives.[4]

Studies have shown that the calcium blocker nifedipine completely abolished augmentation by apparently reducing pulse wave velocity, vascular stiffness, and wave reflection. Any drug that decreases mean arterial pressure will also reduce pulse wave velocity acutely as wall tension decreases in central vessels.[7] In addition, drugs that tend to increase heart rate, such as hydralazine, will reduce augmentation irrespective of their other actions due to a faster systolic ejection, allowing the main component of the reflected wave to fall in the post-systolic peak period. Conversely, drugs that increase systolic ejection time, which can occur with calcium blockers, may negate the beneficial effects of the reduced pulse wave reflection. To date, no outcome data using this insight from pulse wave analysis are available for this group of agents.

ACE inhibitors and AT1 receptor blockers

ACE inhibitors and AT1 receptor blockers act on the tone in muscular arteries and arterioles. Interfering with the actions of angiotensin decreases blood pressure without changing heart rate. Pulse wave changes with these agents are similar to those seen with calcium blockers, i.e. reduced pulse wave velocity, vascular stiffness, wave reflection and central augmentation.[4,7] These drugs appear to be the most beneficial for reducing the morbidity and mortality associated with hypertension, and the application of pulse wave analysis to long-term outcome studies is presently being assessed.[8] The possibility that these drugs retard or improve vascular pathology and therefore the compliance properties of the main conduit vessels in the long-term seems likely.[9]

Beta-receptor blockers

Beta-receptor blockers adversely affect pulse wave reflection characteristics in the short term and are manifestly less active than other antihypertensives in the long term.[4] This may be due to:

- bradycardia with increased systolic ejection time
- vasoconstriction in some vascular beds increasing pulse wave reflection
- lack of direct effect on vascular compliance.

Despite these features, beta blockers have been repeatedly shown to improve outcome statistics, especially in combination with diuretics. However, they are not as beneficial as ACE inhibitors in hypertension which may be partly accounted for by their failure to reduce augmentation of the central pulse.

Diuretics and combination therapy

The effect of diuretics alone on pulse wave analysis has not been seriously studied. These agents are not expected to produce significant changes on pulse wave, since they act acutely through fluid reduction and cardiac output and long-term by moderate reductions in peripheral resistance. In combination with calcium blockers or ACE inhibitors, the salutary effects of the primary antihypertensive drug on the central pulse wave are not obviously improved,[4] but long term studies with diuretics alone are required.

Summary

- Drugs that modify the velocity and size of the pulse wave and its reflection can effectively reduce augmentation of central systolic pressure

- Evidence regarding the effects of different drug classes on peripheral and central arterial waveforms should be carefully considered when applying haemodynamic principles in clinical practice

- Nitric oxide preparations, calcium channel blockers, ACE inhibitors and angiotensin II receptor blockers have been shown to abolish augmentation by reducing pulse wave velocity, vascular stiffness and wave reflection

- The application of PWA to long-term outcome studies with various agents is currently being assessed

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SphygmoCor in Clinical Practice: Nitroglycerin for Angina

Patient: GTN

Presents with acute angina and is given a sublingual capsule of nitroglycerin.

SphygmoCor studies are done as a control, and then every 30 seconds for 3 minutes, to derive calibrated aortic pressure waveforms.

Waveform Analysis
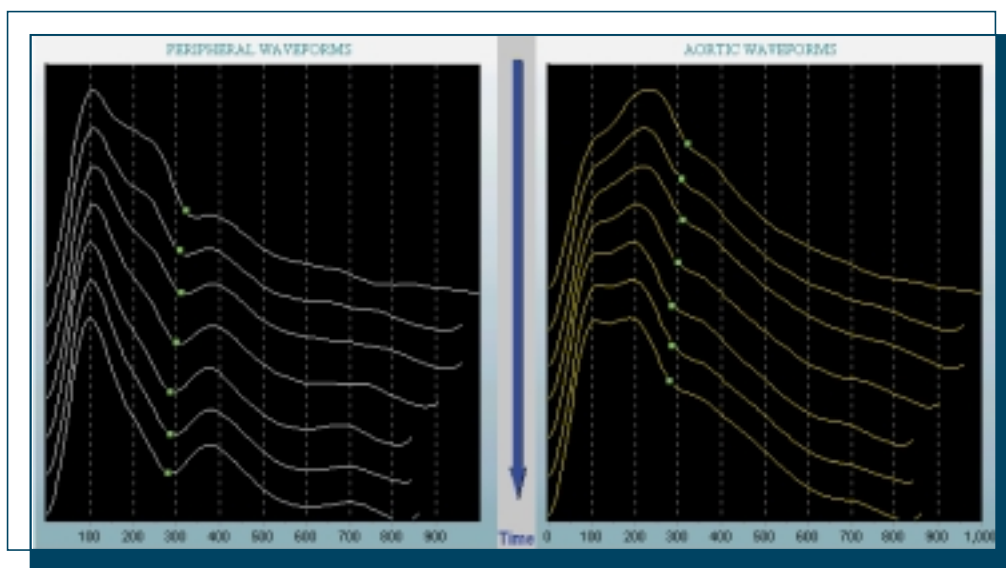
This SphygmoCor display shows the dramatic reduction in aortic systolic peak pressure due to arterial vasodilation (reduction in aortic pressure augmentation, or "afterload").

Parameter Trend Analysis
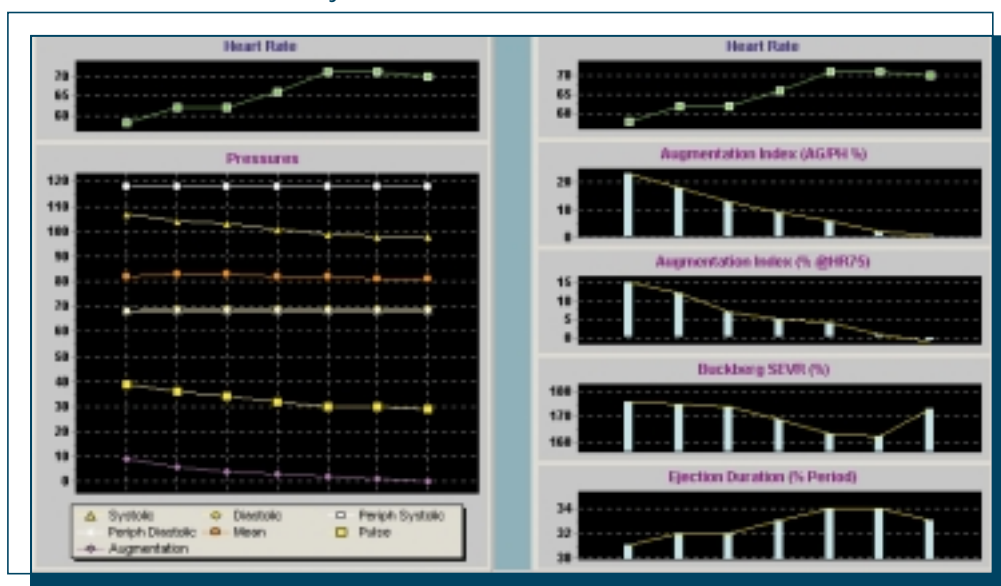
This SphygmoCor display plots the changing aortic parameters over time for the seven nitroglycerin studies above.

Summary

The use of PWA provided additional valuable information to guide treatment in this patient. It demonstrates clearly the effects of nitroglycerin, where as little change could be seen in peripheral blood pressures.

This case demonstrates the importance of central pressures in optimising drug choice, drug dose and drug combinations to achieve best results.

Notes

Patient: DH

Female aged 89, with 10-year history
of mild hypertension.

First visit: October 1997

Presents with chest pain and
dyspnoea on exertion; dizziness
at times

Non-smoker

Examination

Examination NAD

Rapid pulse, HR 93

Height: 148 cm; weight: 53 kg;
BMI: 24

Medication: diltiazem hydrochloride
180 mg

Sitting BP: 150/95 mmHg; Lying
BP: 166/87 mmHg

PWA (*see Figure 5.1*): AG 21 mm; SVR
120%; ED 42%

ECG: L ant hemiblock

Echo: EA reversal, mild LVH, diastolic
dysfunction, normal systolic function

Ex ECG: NAD

VO_2 max: 15 ml/kg/min

Chol: 5.0 mmol/L

Glu: 4.8

Plan: stop diltiazem; start atenolol

Figure 5.1

	Radial Pulse Waveform		Aortic Pulse Waveform

Blood Pressure	166/87 (121) mmHg	Blood Pressure	155/92 (121) mmHg
1st, 2nd Peak	36%ED, 53%ED	1st Peak	36%ED, 102 ms
Aug. Index	102% (P2/P1)	2nd Peak	72%ED, 203 ms
Maximum dP/dt	1178 mmHg/s	Augmentation	+25 mmHg

CENTRAL HAEMODYNAMIC PARAMETERS

TIMING DATA		PRESSURE DATA	
Heart Rate, Period	89 bmp, 674 ms	Pulse Height (PH)	63 mmHg
Eject. Duration (ED)	42%, 280 ms	P1 Height (P1-DP)	42 mmHG
Diast. Duration	58%, 394 ms	Augmentation (AG)	+21 mmHg
Buckberg. SUR (Ad/As)	120% (3986/3308)	Aug. Index (P2/P1, AG/PH)	152%, +33%
– Systolic Area/min	3308 mmHg. s/m	Mean Press. (Syst/Diast)	135/112 mmHg
– Diastolic Area/min	3986 mmHg. s/m	End Systolic Pressure	140 mmHG

Review: March 1998

Dyspnoea improved, occasional chest pain

Examination NAD

Siting BP: 165/80 mmHg; Lying BP: 158/70 mmHg

HR: 75

Meds: atenolol 25 mg; aspirin

HRV: normal

PWA (*see Figure 5.2*): AG 37 mm; ED 38%; SVR 126%

Plan: start diuretic (indapamide)

	Radial Pulse Waveform		Aortic Pulse Waveform

Radial Pulse Waveform

Blood Pressure   158/70 (105) mmHg
1st, 2nd Peak   30%ED, 59%ED
Aug. Index   124% (P2/P1)
Maximum dP/dt   927 mmHg/s

Aortic Pulse Waveform

Blood Pressure   151/73 (105) mmHg
1st Peak   28%ED, 102 ms
2nd Peak   72%ED, 258 ms
Augmentation   +37 mmHg

CENTRAL HAEMODYNAMIC PARAMETERS

TIMING DATA		PRESSURE DATA	
Heart Rate, Period	63 bmp, 952 ms	Pulse Height (PH)	78 mmHg
Eject. Duration (ED)	38%, 358 ms	P1 Height (P1-DP)	42 mmHG
Diast. Duration	62%, 594 ms	Augmentation (AG)	+37 mmHG
Buckberg. SUR (Ad/As)	126% (3533/2795)	Aug. Index (P2/P1, AG/PH)	198%, +47%
– Systolic Area/min	2795 mmHg. s/m	Mean Press. (Syst/Diast)	126/93 mmHg
– Diastolic Area/min	3533 mmHg. s/m	End Systolic Pressure	131 mmHG

Review: October 1998

Dyspnoea stable, no further chest pain

Examination NAD

Sitting BP: 145/75 mmHg; Lying BP: 150/76 mmHg

HR: 64

HRV: normal

Meds: atenolol 25 mg; indapamide 2.5 mg; aspirin

PWA (*see Figure 5.3*): AG 29 mm; ED 36%; SVR 140%

Plan: start ACE inhibitor (for high augmentation pressure)

Figure 5.3

Radial Pulse Waveform

Blood Pressure	150/76 (105) mmHg
1st, 2nd Peak	30%ED, 57%ED
Aug. Index	117% (P2/P1)
Maximum dP/dt	905 mmHg/s

Aortic Pulse Waveform

Blood Pressure	143/78 (105) mmHg
1st Peak	30%ED, 102 ms
2nd Peak	72%ED, 250 ms
Augmentation	+29 mmHg

CENTRAL HAEMODYNAMIC PARAMETERS

TIMING DATA		PRESSURE DATA	
Heart Rate, Period	62 bmp, 967 ms	Pulse Height (PH)	65 mmHg
Eject. Duration (ED)	36%, 345 ms	P1 Height (P1-DP)	37 mmHG
Diast. Duration	64%, 622 ms	Augmentation (AG)	+29mmHG
Buckberg. SUR (Ad/As)	140% (3680/2631)	Aug. Index (P2/P1, AG/PH)	185%, +44%
– Systolic Area/min	2631 mmHg. s/m	Mean Press. (Syst/Diast)	124/95 mmHg
– Diastolic Area/min	3680 mmHg. s/m	End Systolic Pressure	125 mmHG

5

Review: April 1999

Dyspnoea stable

Examination NAD

Sitting BP: 126/76 mmHg; Lying BP: 130/76 mmHg
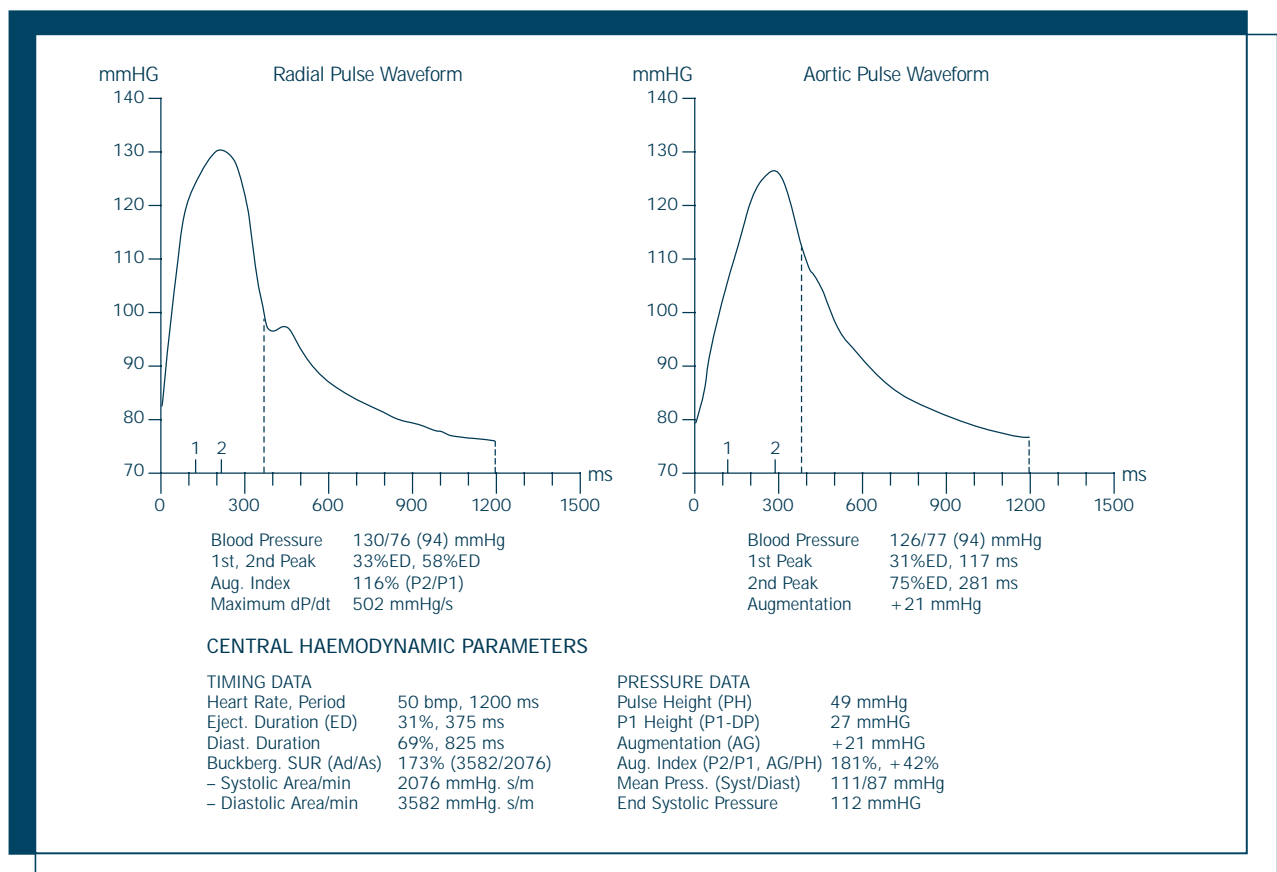
HR: 54

VO_2 max 20 ml/kg/min

HRV: normal

Meds: atenolol 25 mg; trandolapril 1 mg; indapamide 2.5 mg; aspirin

PWA (*see Figure 5.4*): AG 21mm; ED 31%; SVR 173%

Figure 5.4

Radial Pulse Waveform

Blood Pressure   130/76 (94) mmHg
1st, 2nd Peak   33%ED, 58%ED
Aug. Index   116% (P2/P1)
Maximum dP/dt   502 mmHg/s

Aortic Pulse Waveform

Blood Pressure   126/77 (94) mmHg
1st Peak   31%ED, 117 ms
2nd Peak   75%ED, 281 ms
Augmentation   +21 mmHg

CENTRAL HAEMODYNAMIC PARAMETERS

TIMING DATA		PRESSURE DATA	
Heart Rate, Period	50 bmp, 1200 ms	Pulse Height (PH)	49 mmHg
Eject. Duration (ED)	31%, 375 ms	P1 Height (P1-DP)	27 mmHG
Diast. Duration	69%, 825 ms	Augmentation (AG)	+21 mmHG
Buckberg. SUR (Ad/As)	173% (3582/2076)	Aug. Index (P2/P1, AG/PH)	181%, +42%
– Systolic Area/min	2076 mmHg. s/m	Mean Press. (Syst/Diast)	111/87 mmHg
– Diastolic Area/min	3582 mmHg. s/m	End Systolic Pressure	112 mmHG

Review: May 2000

Dyspnoea on exertion worse

Examination NAD

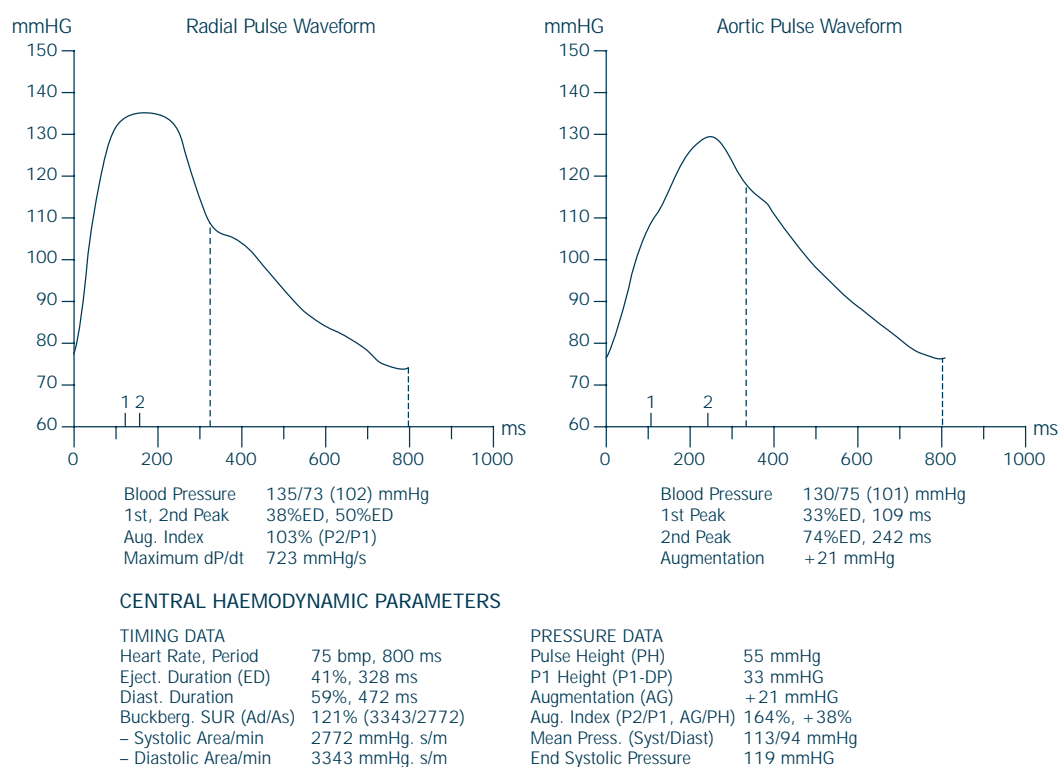Sitting BP: 135/68 mmHg; Lying BP: 135/73 mmHg

HR: 78

HRV: normal

Meds: trandolapril 1 mg; indapamide 2.5 mg; aspirin
(stopped atenolol due to symptomatic bradycardia)

PWA (*see Figure 5.5*): AG 21mm; ED 41%; SVR 121%

Plan: re-start low-dose atenolol

Figure 5.5

Blood Pressure	135/73 (102) mmHg
1st, 2nd Peak	38%ED, 50%ED
Aug. Index	103% (P2/P1)
Maximum dP/dt	723 mmHg/s

Blood Pressure	130/75 (101) mmHg
1st Peak	33%ED, 109 ms
2nd Peak	74%ED, 242 ms
Augmentation	+21 mmHg

CENTRAL HAEMODYNAMIC PARAMETERS

TIMING DATA		PRESSURE DATA	
Heart Rate, Period	75 bmp, 800 ms	Pulse Height (PH)	55 mmHg
Eject. Duration (ED)	41%, 328 ms	P1 Height (P1-DP)	33 mmHG
Diast. Duration	59%, 472 ms	Augmentation (AG)	+21 mmHG
Buckberg. SUR (Ad/As)	121% (3343/2772)	Aug. Index (P2/P1, AG/PH)	164%, +38%
– Systolic Area/min	2772 mmHg. s/m	Mean Press. (Syst/Diast)	113/94 mmHg
– Diastolic Area/min	3343 mmHg. s/m	End Systolic Pressure	119 mmHG

Summary

The use of PWA provided additional valuable information to guide treatment in this older patient. In particular, the low SVR at the first visit identified the need to reduce HR to optimise the coronary perfusion in this symptomatic patient who has evidence of diastolic dysfunction on echocardiography. The rate reduction achieved with atenolol resulted in a reduction in symptoms and an improvement in SVR. However, there was a dramatic increase in augmentation pressure which was not reflected by an increase in peripheral pressures. If left untreated, this may have worsened the diastolic dysfunction and caused increasing dyspnoea over time. Judicious use of a diuretic and an ACE inhibitor resulted in a reduction in augmentation pressure and maintenance of a normal SVR.

This case demonstrates the importance of central pressures in optimising drug choice, drug dose and drug combinations to achieve best results.

Notes

Reproducibility

Reproducibility of central aortic pressure and pulse wave velocity measurements with SphygmoCor depend on the quality of the data recorded. The essential element is to obtain an accurate radial pulse waveform, from which all parameters are derived. As with any technique, results of reproducibility will depend on the both stability of subject's physiological status and operator skill.

Reproducibility studies should be conducted by each operator, or groups of operators to determine the extent of variability inherent in the specific measurements. Clinical studies have shown that the technique is highly reproducible.

Three recent studies address the issue of reproducibility of parameters derived by SphygmoCor.[1-3]

1. Filiposky et al[2] studied 88 healthy subjects aged 19-53 years and determined the reproducibility of parameters estimated by pulse wave analysis (PWA), mainly of central systolic blood pressure in the aorta (CSP), central systolic pressure-time index (CSPTI), and central augmentation index (CAI). Variability within and among subjects was significantly different for peripheral systolic pressure (PSP) and for all the above-mentioned parameters (p <0.0001 by ANOVA for all). Variability within and between observers did not show any trend for the variability to be dependent on the underlying mean value. PSP, CSP and CSPTI decreased significantly during one visit (by 4.6, 4.7 and 4.2%, respectively), PSP and CSP were higher at the first than at the second visit (by 2.2, 2.2%, respectively, and not significant for CSPTI), and there were also significant inter-observer differences in all the three parameters as one observer measured higher values (by 2.4, 3.2 and 6.0%, respectively). CAI did not change within and between visits; the same applied to the difference between PSP and CSP since these pressures always changed in parallel. The study concludes that PWA gives estimates of several parameters characterizing the pressure load of central circulation and the wave reflection. The reproducibility of CSP and CSPTI is similar to that of PSP. CAI and the difference between PSP and CSP is not influenced by order of measurement, of visit or by investigator.

2. Siebenhofer et al[1] studied 33 healthy subjects of mean age 33 years (SD 10.3) and determined the inter-operator variability from 75 paired measurements. The table below summarises their results:

SphygmoCor Parameter	Inter-operator variability
Derived Systolic pressure	0.1 ± 1.7 mmHg
Derived Diastolic pressure	0.1 ± 0.7 mmHg
Augmentation index	0.4 ± 6.4 %
Subendocardial Viability Ratio	2.7 ± 15.4 %

3. O'Rourke[3] and colleagues examined the typical coefficients of variability obtained in a representative reproducibility study, and these are outlined below.

Definitions

Coefficient of Variation CV (%) = 100 x standard deviation/mean.

Repeatability Repeatability was assessed in 18 subjects (age 22-57 yrs; 7 m, 11 f) with ten consecutive measurements at both the radial and carotid arteries.

Reproducibility Reproducibility was measured in 8 subjects (age 22-36 yrs; 2 m, 6 f) on four separate occasions over a 2-week period.

Interobserver variability This was assessed in 9 subjects (age 22-57 yrs; 5m, 4f) with measurements taken by three independent operators on the same occasion.

Right vs left radial waveforms Studies were also conducted in 45 subjects (24 on antihypertensive treatment; age 22-80 yrs) to assess the difference in derived parameters when recordings were taken from the left or right wrist.

Coefficient of Variation (%)

RADIAL	Repeatability	Reproducibility	Interobserver
Heart rate	4.5 ± 1.7	9.1 ± 4.0	2.9 ± 1.7
Ejection duration	1.6 ± 0.6	3.0 ± 2.0	1.6 ± 0.6
Aortic AI	4.5 ± 2.7	10.3 ± 5.5	5.1 ± 3.1
dp/dt	3.8 ± 2.0	16.7 ± 8.3	15.1 ± 2.3
Mean SP	0.8 ± 0.4	6.2 ± 3.3	3.1 ± 1.9
Mean DP	1.1 ± 0.5	6.6 ± 2.8	3.9 ± 3.2

CAROTID	Repeatability	Reproducibility	Interobserver
Heart rate	4.5 ± 1.7	8.8 ± 5.0	2.4 ± 1.3
Ejection duration	2.4 ± 3.7	3.1 ± 0.8	1.0 ± 0.5
Aortic AI	6.5 ± 3.6	11.0 ± 4.0	8.4 ± 7.7
dp/dt	7.3 ± 4.2	12.5 ± 5.1	17.8 ± 13.3
Mean SP	1.0 ± 1.7	5.8 ± 2.4	2.8 ± 1.7
Mean DP	1.8 ± 1.7	6.1 ± 2.5	3.7 ± 2.5

Right/ Left Radial

	Left	Right	P
Heart rate	67 ± 12	66 ± 12.	NS
Ejection duration	327 ± 29	325 ± 30	NS
Radial AI	59 ± 20	62 ± 21	0.04
Aortic AI	127 ± 25	129 ± 27	NS
dp/dt	805 ± 267	781 ± 263	NS
Mean SP	101 ± 16	106 ± 15	NS
Mean DP	86 ± 11	86 ± 12	NS

Pulse wave velocity

SphygmoCor also performs measurements of pulse wave velocity as an index of arterial stiffness (see Section 2). This is associated with wave reflection phenomena and with the augmentation index (AI) of the central aortic waveform obtained by means of a transfer function from peripheral recordings of the arterial pulse. Reproducibility assessed through the Bland-Altman method with calculation of the repeatability coefficient was, following intra-observer comparison, for Brachial PWV: 1.64m/sec (for a mean value of 8.65±1.58 m/sec); and for aortic PWV: 2.34m/sec (for mean value of 8.15±3.01 m/sec). Corresponding data for between-observer values were 2.18m/sec and 2.50 m/sec, respectively.[4]

The augmentation index was analysed in terms of the relationship to pulse wave reflection and global arterial stiffness. Comparison between AI and aortic pulse wave velocity has shown a significant association,[5] with a significant but relatively weak positive correlation found between AI and aortic PWV (r=0.29, p<0.005). However, the correlation increased when gender was considered. The role of height, heart rate and blood pressure, and the heritable component, as seen in twins,[6] could partly explain this weak relationship.

References

1. Seibenhofer A, Kemp CRW, Sutton AJ, William B. The reproducibility of central aortic blood pressure measurements in healthy subjects using applanation tonometry and sphygmocardiography. *J Human Hypertension*, 1999; 13: 625-629.
2. Filipovsky J, Svobodova V, Pecen L. Reproducibility of radial pulse wave analysis in healthy subjects. *J Hypertens* 2000, 18: 1033-1040.
3. O'Rourke MF, et al. Unpublished data.
4. Wilkinson IB, Fuchs SA, Jansen IM, *et al*. Reproducibility of pulse wave velocity and augmentation index measured by pulse wave analysis. *J Hypertens* 1998; 16: 2079-2084.
5. Yasmin, Brown MJ. Similarities and differences between augmentation index and pulse wave velocity in the assessment of arterial stiffness. *Q J Med* 1999; 92: 595-600.
6. Snieder H, Hayward CS, Perks U, *et al*. Heritability of central systolic pressure augmentation: a twin study. *Hypertension* 2000; 35(2): 574-579.

8.1

Starting the software

You can start the **SphygmoCor** software from the Windows Start menu, by clicking and holding down the Start button, then navigating your mouse to the **SphygmoCor** 2000 program. Lastly, release the mouse button:
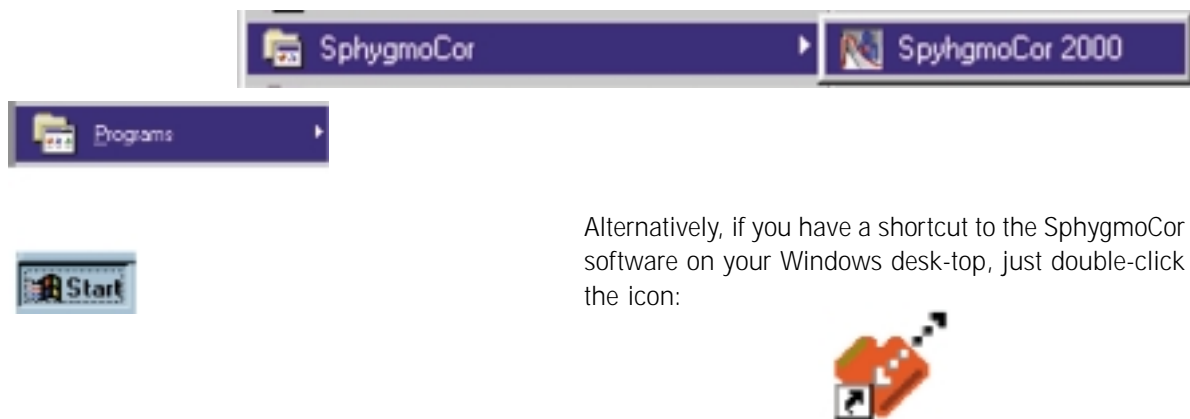
Alternatively, if you have a shortcut to the SphygmoCor software on your Windows desk-top, just double-click the icon:

The SphygmoCor software displays a splash screen while it is loading and preparing itself for use. The Patient screen then appears.

Note on Communications Error

If, at this stage, a communications error message appears, this is usually because either,

(a) the electronics module is not connected to the computer

(b) the electronics module is not switched on

Click YES if you wish to attempt detecting the module again.

> (note that if the module is not detected on it's second attempt a message window will appear prompting you if you wish to change the configuration settings. If you click YES the SphygmoCor Configuration Window will appear, allowing you to change the computer communications port to which the electronics module is connected.)

Click NO or CANCEL or press the Esc key to ignore the communications error message and continue working with the SphygmoCor system.

THE MENU AND THE TOOL-BAR BUTTONS

When SphygmoCor has started, the Patient screen appears. At the top of the screen is the System menu and the tool-bar buttons, and these are displayed whenever the program is running.

Menu Bar   **Tool-Bar Buttons**
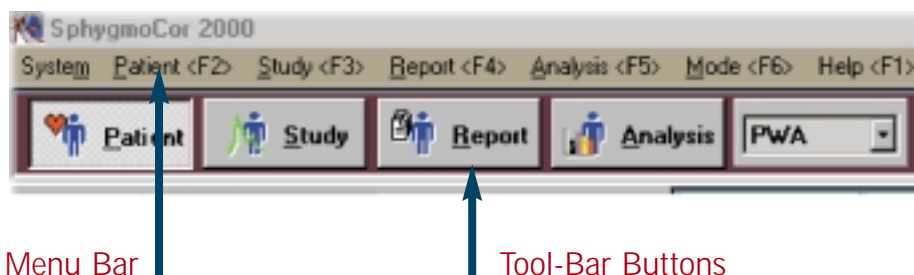
Menu Bar	The menu bar gives you access to all the major areas of the program. When you click and hold down the mouse on the System and the Help menu options, further sub-menu options appear below them. For all the other menu options, when you click the option the relevant screen appears immediately.
	Note that you can also use the function keys F1 to F5 to perform common functions, as shown on the menu bar.
Tool-Bar Buttons	The tool-bar buttons allow quick access to all the major screens of the program.

THE STATUS BAR

When SphygmoCor has started, the Patient screen appears. At the top of the screen is the System menu and the tool-bar buttons, and these are displayed whenever the program is running.

Function   **Active Database**   **Mode, when in the patient screen**

Active Database	This shows the name of the Patient database you are currently using.
Mode	When using the Patient screen, this shows whether you are currently in Edit mode or in Browse mode. See Section 3.1 for more on modes in the Patient screen.
Function	When using the Patient screen, this shows what function you are currently performing. See Section 3 for more on this.

TAKING A MEASUREMENT

This section takes you step-by-step through the procedures necessary to take a measurement from a patient. See Sections 3, 4, 5, and 6 for further details on each of the major screens in the program.
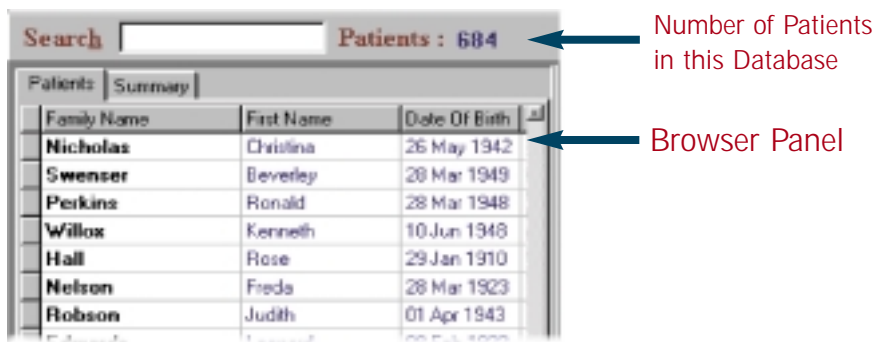
SELECT THE PATIENT

To take a measurement (also called making a Study) you must first choose a patient on the Patient screen. Either select an existing patient, or add new patient details to the system.

ⓐ BROWSE FOR AN EXISTING PATIENT

The Patient screen has a browser panel on the left hand side. Use the browser panel to choose a patient. Choose a patient by one of the following means:

- Place the cursor in the Patient Search field and enter the patient's family name. As you do so the system selects the patient in the browser whose name best matches the characters you are typing.

Number of Patients in this Database

Browser Panel

- Click on any row in the browser to select that patient. When a patient is selected, the arrow-head symbol appears to the left of that patient in the panel, and the patient name is highlighted.

Patient is selected

- Use the VCR buttons at the bottom of the browser panel to select the patient. For more details on using this method, see Section 4.

VCR buttons
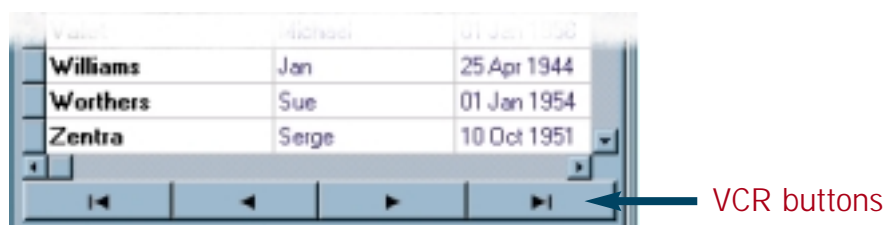
ⓑ CREATE A NEW PATIENT RECORD

Use this option if the patient is not already in the database, and you want to add details about the new patient.

Step 1   Click the Create New button on the Patient tool-bar:

Click to create a new Patient record

Step 2   Enter the patient details into the Patient Edit panel. Only the fields Last Name, First Name, Date of Birth and Sex are mandatory. For more on editing patient details, and the Patient Edit panel, see Section 3.

Step 3   Click the Update button to add the details of the new patient to the database, or the Reject button to discard the details you have entered.

Click to add details to database   Click to discard details

8.2.2

PERFORM THE STUDY

Next, to perform the Study (take the measurement) for the selected patient, open the Study screen. You can do this by clicking the Study tool-bar button or pressing F3 (refer to the Menu Bar).

Alternatively, you can double-click any patient in the browser panel of the Patient screen to move directly to the Study screen, with that patient selected.

Step 4   Pick the artery, by clicking either the Carotid or the Radial check box.

Step 5   Enter the Diastolic pressure reading, taken using your sphygmomanometer or blood pressure meter.

Step 6   Enter either the Systolic pressure reading or the Mean pressure reading, taken using your sphygmomanometer or blood pressure meter.

Step 7   If required, enter the Medication, Notes and Operator details, and values for patient Height and Weight. All of these items are optional.

Step 8   To proceed to capture data click the Capture Data button at the top right of the Study screen. The data capture now commences. Alternatively, you can also press the Enter key or Alt-U to start the data capture.
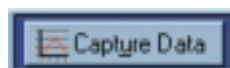
Step 9   On the Data Capture screen, you will see a horizontal trace in the Signal Detail area. When you obtain a waveform reading using the Tonometer probe, the waveform is shown in the Signal Detail area. The entire 10-second waveform that will be processed by SphygmoCor is shown in the Signal for Processing area.

Signal Detail Area

This area is refreshed and automatically re-scaled every five seconds. When a signal is detected the software will auto scale to zoom and fit the captured waveform within the window limits.

Signal for Processing Area

This area of the Capture Screen shows the last 10 seconds of the actual waveform that will be captured by SphygmoCor for processing.

Step 10   When you are satisfied that you have a good reading, press the Space bar on the computer keyboard, or click the OK button at the top of the screen. You have up to 2 seconds between removing the Tonometer and pressing the space bar – the system removes the last 2 seconds of data recorded.

For more information on the data capture procedures see Section 4.2.

8.2.3

EXAMINE THE REPORT

After you have completed the data capture, a "calculation" icon appears while the measurements are being calculated. Then the Report screen opens. The report you see relates to the measurement you have just taken. You should check data as explained in the following sections on the Report screen.

CHECK THE PATIENT AND STUDY DATA

Check that the Patient data and the Study data are correct.

```
PATIENT DATA
Patient ID
Patient Code

STUDY DATA
Medication
Notes
Operator
```
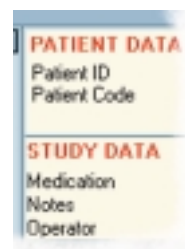
If the Patient Data is Incorrect

Click the Patient tool-bar button to return to the Patient screen and update Patient details.

```
Print   Delete   Recalculate   Export
```
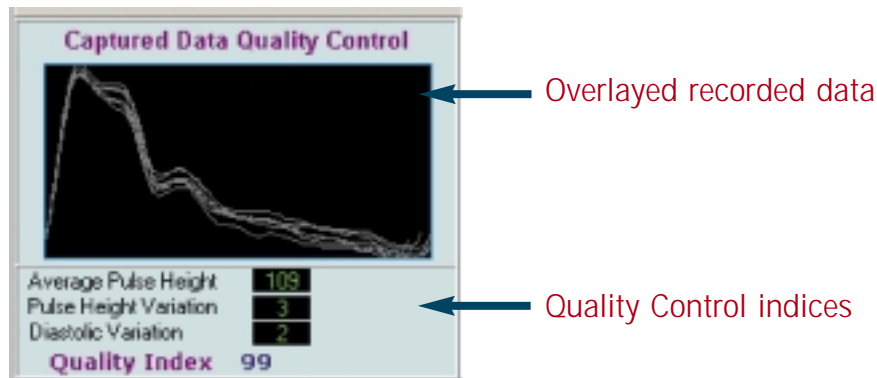
Delete the current Study   Recalculate the Study with changed parameters

If the Study Data is Incorrect

Click the Recalculate tool-bar button to open the SphygmoCor Recalculate Report window. This window allows you to change any of the details you entered in the Study screen, before you performed the data capture.

Check the Quality Control area of the screen to ensure that the measurement is within the limits of the current quality control settings.

Captured Data Quality Control

Overlayed recorded data

Average Pulse Height — 109
Pulse Height Variation — 3
Diastolic Variation — 2
Quality Index   99

Quality Control indices

The Quality Control area of the Clinical Report Screen shows the captured peripheral waveforms over-layed on one graph, the Quality Control Indices and the Quality Index.

Step 11   Check that the indices are displayed in GREEN, to indicate that they are within the quality limits. If they displayed in RED, then the values are outside the limits. Check also that the Quality Index is above 90%.

Step 12   Check that the over-layed recorded data are visually coherent. In other words, the waveform pulses should overlay without much spread.

If you decide that the report does not meet the Quality Control settings, you should do one of the following:

● Perform the Study again. First delete the Study by clicking the Delete tool-bar button on the right hand side of the Report screen. Then click the Study tool-bar button (or press F3) to return to the Study screen.

● Check that you entered information correctly on the Study screen. You can click the Recalculate tool-bar button on the Report screen to display the SphygmoCor Recalculate Report screen, and change any of the details you entered for the Study.

● Check that the Quality Control limits are in fact acceptable.

WORKING WITH THE PATIENT SCREEN

In this section the features of the Patient screen are described in detail. The section explains how to search for existing patients, and how to add and edit patient details.

Patient Search area   Patient tool-bar

Browser Panel   Patient Edit panel
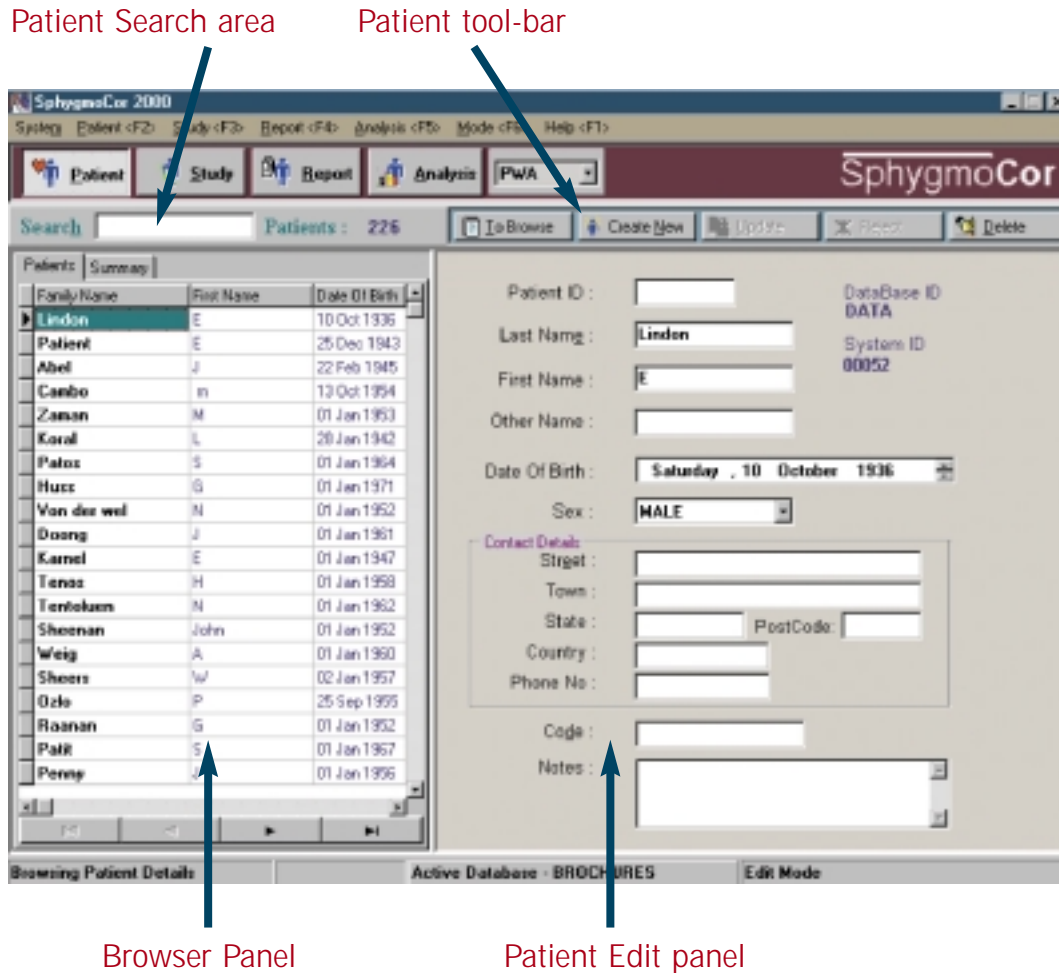
MODES

When working in the Patient Screen, there are two different modes you can work with:

- Browse mode is used when you want to find an existing patient in the database.
- Edit mode is used when you want to create a new patient record, or update the details held for an existing patient.

To switch between the two modes, use the first button on the patient tool-bar as follows:

- When in browse mode (which is the default mode), click the To Edit tool-bar button to enter the Edit mode:
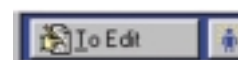
- When in Edit mode, click the To Browse tool-bar button to return to the Browse mode:
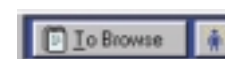
BROWSING FOR PATIENTS

The Browser panel on the left-hand side of the Patient Screen allows you to browse through the database and find an existing patient. There are several ways you can use the Browser panel.

USING PATIENT SEARCH

Enter characters into the Patient Search field at the top of the Browser panel. As you do so the system selects the patient in the browser whose name best matches the characters you are typing. The system shows which patient is selected by placing an arrow-head to the left of the selected patient:

Patient is selected ➡️

| ▶ Citizen | William | 01 Jan 1951 |

When a patient is selected, the full details of the patient appear in the Patient edit panel.

SELECTING A PATIENT IN THE BROWSER

You can select a patient by clicking on the row in the browser where you see the patient details you are interested in. The arrow-head symbol appears to the left of the patient you clicked on.

If you cannot see all the browser columns, use the horizontal scroll bar at the bottom of the browser panel to move the hidden columns into view.

⬅️ Horizontal scroll bar

USING THE VCR CONTROLS

You can use the VCR-style controls at the bottom of the Browser panel to find a patient.

⬅️ VCR controls

To top of list

To previous patient in list

To next patient in list

To bottom of list

Use the buttons as shown in the above picture. Note that by default, patients are sorted by Family Name in the browser. You can change the sort order of patients in the browser if you want to - see Section 3.2.4 for how to do this.

When you click the right hand mouse button when the cursor is on a selected patient, a small menu of options appears:
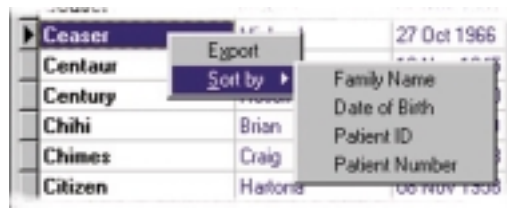
- Click the Export option to export the patient and study details to a file.
- Move the mouse over the Sort By option to see a list of columns by which you can choose to sort the browser panel contents.
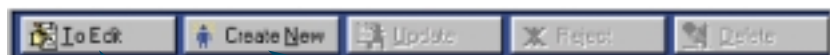
Click on any one of the options to sort the browser panel by the column of that name.

8.3.3

CREATING AND EDITING PATIENTS

When you are in the Browse mode and you want to create a new patient, or edit the details for an existing patient, do the following:

Step 1   Click either the To Edit or the Create New button on the Patient tool-bar:

Click to create new Patient record

Click to edit Patient record

Symbols displayed in the Browser

While you are editing a record, the arrow-head symbol in the first column of the browser changes to the I-beam symbol to show that you are editing. The function displayed on the left of the status bar also reminds you that you are Editing Patient Details.

While you are creating a new record, the arrow-head symbol in the first column of the browser changes to the asterisk symbol to show that you are inserting information into a new row of the browser. The function displayed on the left of the status bar also reminds you that you are Inserting New Patient Details.

Step 2   In the Edit panel, fill in the individual fields for the patient. The fields are as follows:

Field		Description
Patient ID	(Optional)	An identification number for the patient
Last Name	(Mandatory)	The last name of the patient
First Name	(Mandatory)	The first name of the patient
Other Name	(Optional)	Any other name, such as a middle name, for the patient
Date of Birth	(Mandatory)	The patient's date of birth

Entering the Date of Birth

The Date of Birth field has four components to it: the Day of the Week, the Day Number of the Month, the Month Name and the Year. Click on any one of these four components to select it, in order to change that component. Then use the spin control to increase or decrease the displayed value for that component.

For the numeric components (Day, Number and Year) you can also enter the required numbers directly, using the keyboard, when these components are selected.

Field		Description
Sex	(Mandatory)	The sex of the patient, selected by clicking the down-pointing arrow head and selecting either MALE or FEMALE
Street	(Optional)	The street number and name in which the patient lives
Town	(Optional)	The town or suburb in which the patient lives
State	(Optional)	The state or province in which the patient lives
Post Code	(Optional)	The post code or zip code for the patient
Country	(Optional)	The country of residence of the patient
Phone No	(Optional)	The telephone number of the patient
Code	(Optional)	A code, to a maximum of 15 characters, which can be used to help in categorising patients
Notes	(Optional)	Any notes about the patient

Step 3   When you have entered all the details for the patient, click the Update button to save the details in the patient database, or click the Reject button to discard the details you have entered.
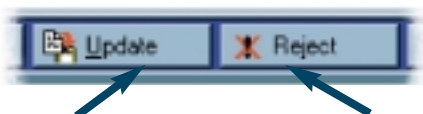
Click to update the Patient record   **Click to discard the Patient record**

Step 4   You can now click the To Browse button on the patient tool-bar to return to the browse mode; or you can remain in Edit mode and make further changes to the current patient record, or to another patient record.

8.3.4

DELETING PATIENTS

To delete an existing patient:

Step 1	Select the patient using the browser.
Step 2	Click the Delete button on the patient tool-bar. A message appears asking if you are sure you want to delete the patient and all the associated patient study data.
Step 3	Click Yes if you are sure about proceeding with the deletion or No or Cancel if you are not sure about proceeding.

CAUTION: Deleted data cannot be retrieved later.

8.3.5

PATIENT SUMMARY

The browser also has a Summary tab, which shows information about the currently selected patient. Click the Summary tab to see this information.

Summary tab

The Summary tab shows the number of studies performed on the selected patient, the dates of the first and the latest study, and the total number of days since the last study was performed, for the selected patient.

Click the Patients tab to return to the patient browser information.

8.3.6

MOVING TO THE STUDY SCREEN

When in the Patient Screen, you can select a patient and then move to the Study Screen by one of the following methods:

- Click the Study tool-bar button.
- Press F3.
- Double-click a patient in the patient browser.

The study that you perform in the Study Screen is recorded against the patient that you selected in the Patient Screen.

WORKING WITH THE STUDY SCREEN

Patient name

Study Browser   Study Definition Area
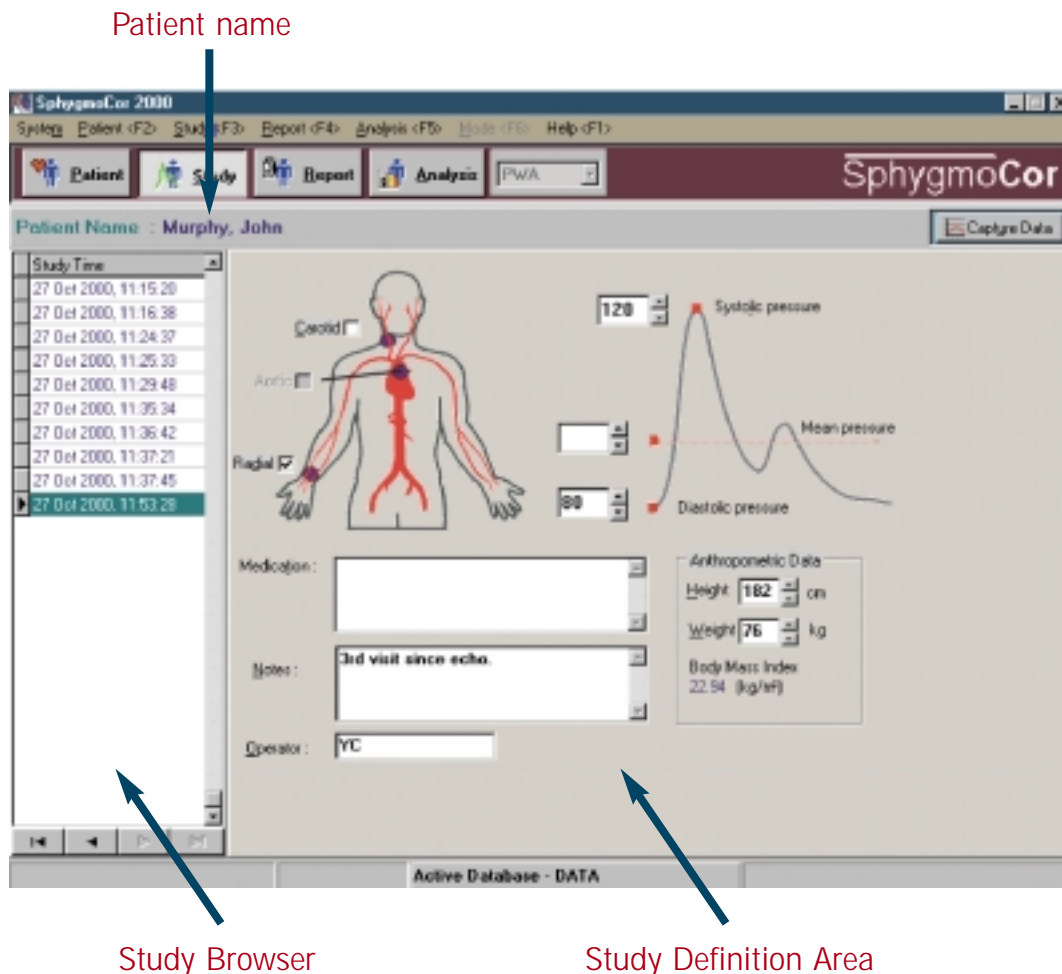
Measurements are taken in the Study Screen.

The Study Screen has the following key areas:

Patient Name	Check the name to ensure that you are performing the study for the correct person.
Study Browser	Use the browser to examine previous studies made for this patient. The arrow-head symbol identifies which study is currently selected. Details of this selected study are shown in the Study definition area.
Study Definition Area	This area of the screen shows the fields that you fill in prior to performing a study. You can display and edit these fields, for existing study records.

ENTERING THE STUDY FIELDS

The fields in the Study Definition Area are as follows. When you enter data into these fields, you are specifying the data for the study you are about to perform.

Carotid	Pick the carotid artery as the site for the study, by clicking this check box.
Radial	Pick the radial artery as the site for the study, by clicking this check box.
Aortic	Pick the aortic site for the study, by clicking this check box. (When this check box is selected, no processing is done to the captured waveform, this feature is not enabled in this version of software)
Diastolic pressure	Enter the diastolic pressure you have just measured using your sphygmomanometer or blood pressure meter. You can use the up/down keys to enter the value, or enter the numbers directly from the keyboard.
Systolic pressure	Enter either the systolic pressure reading or the mean pressure reading, taken using your sphygmomanometer or blood pressure meter.
Mean pressure	In the case of a carotid study enter the mean pressure you have just measured using your sphygmomanometer or blood pressure meter, instead of the systolic pressure.
Medication (Optional)	Enter details of any medication, if applicable.
Notes (Optional)	Enter any notes relating to the study.
Operator (Optional)	Enter the name or reference of the operator performing the study.
Height (Optional)	Enter the height of the patient.
Weight (Optional)	Enter the weight of the patient.

PERFORMING THE DATA CAPTURE

Signal Detail

Signal for Processing   Signal Statistics
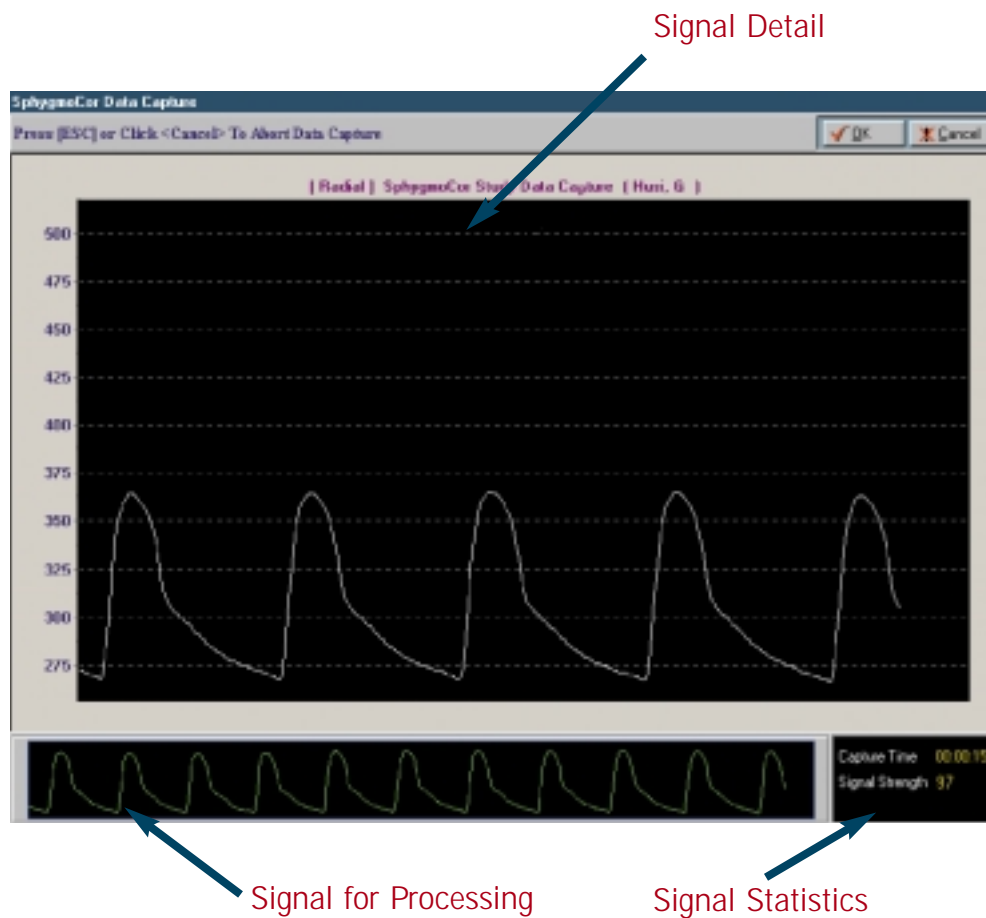
Step 1   Click the Capture Data button at the top right of the Study Screen or press Enter or Alt-U. The Data Capture Screen then opens:

Note on Communications Error

If, at this stage, a communications error message appears, this is usually because either:

(a) the electronics module is not connected to the computer, or

(b) the electronics module is not switched on.

Check that the eletronics module is connected to the computer, and is switched on.

Click OK to close the message box.

Step 2   On the Data Capture Screen, you will see a horizontal trace in the Signal Detail area. When you obtain a waveform reading using the tonometer, the waveform is shown in the Signal Detail area. The entire waveform that will be processed by SphygmoCor is shown in the Signal for Processing area.

Step 3 Using the Tonometer, obtain a waveform from the chosen artery. The waveform is displayed in the Signal Detail area of the screen. You can use the display in this area to check that the signal is of sufficient strength, and that the individual pulses look similar.

Step 4 If you press too hard or too soft with the Tonometer, the signal level will either pass the maximum height of the Signal Detail Area or a low-level signal will be seen. The next time the screen is refreshed the auto-scale function will place the signal in the centre of the screen to full scale of the pulse height. Ensure that the signal being captured is steady on a consistent scale.

Note on Tonometer Sensitivity

If the Tonometer is too sensitive and your signal is continuously passing the maximum height on the Signal Detail Area even though you are applying slight pressure, you will need to increase the Pressure Sensitivity Upper Limit in the Settings Configuration window.

Signal Detail Area

This area is refreshed and automatically re-scaled every five seconds. When the horizontal grid lines appear farther apart, the signal strength is better. Use this area to enable you be obtain the strongest possible waveform measurement from the patient. Adjust the way you position the Tonometer while you examine the strength of the waveform on the screen.

Note that the spaces between the horizontal grid lines are always 25 units. These units (that is, the vertical axis units) are raw signal units, and are not calibrated pressure units.

Signal for Processing Area

This area of the Capture Screen shows the actual waveform that will be captured by SphygmoCor. Make sure that you can see the bottom and the top of each wave pulse in this area, and that the wave pulses consistently fill the window. In other words, there should be a consistent pulse height on a horizontal base line.

Step 5 When you are satisfied that you have a good reading, press the Space bar on the computer keyboard, or click the OK button at the top of the screen.
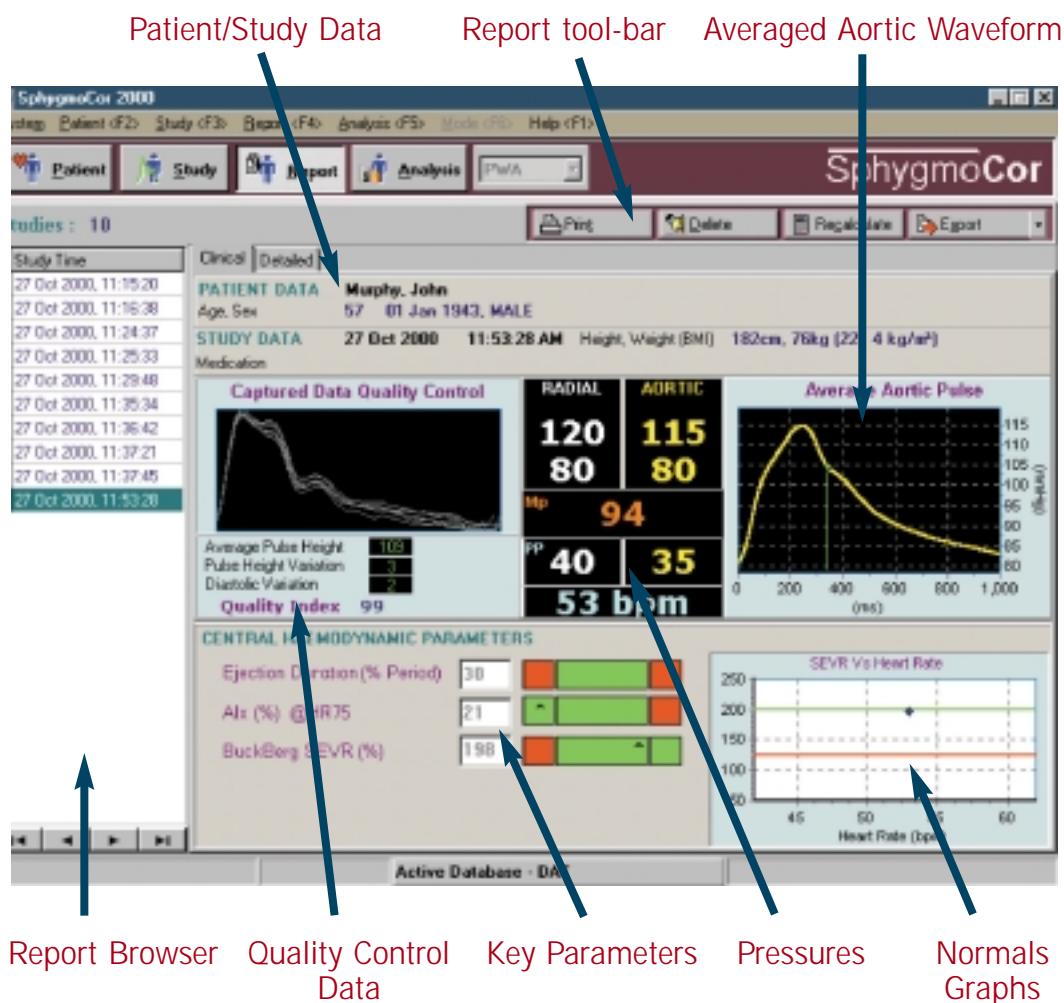
Checking the Signal Statistics

The Signal Statistics area shows you the following:

Capture Time   The length of time over which you have been capturing a signal.

Signal Strength The strength of the signal you are capturing. This is the difference between the signal maximum and the signal minimum. The value you see here is automatically updated every 5 seconds. Although you should set your own standards for minimum signal strength, a value of no less than 100 is recommended by PWV Medical.

WORKING WITH THE CLINICAL REPORT SCREEN

Patient/Study Data   Report tool-bar   Averaged Aortic Waveform

Report Browser   Quality Control   Key Parameters   Pressures   Normals
                        Data   Graphs

This section describes the on-screen clinical reporting that is available in the system, and how to print and export results.

The Clinical Report Screen has the following key areas:

Report Tool-bar	Use this tool-bar to perform functions relating to the report which is currently being displayed. See Section 8.5.2.
Patient/Study Data	This section summarises information about the patient and the study you have just performed. Check this section to ensure that the details you have entered for the patient and the study are correct. If the study data are not correct, click the Recalculate button on the Report Tool-bar to open the SphygmoCor Recalculate Report window. This window lets you change any of the study fields you originally entered in the Study Screen.
Quality Control Data	Check this area to ensure that the measurement conforms to the quality control settings. See Section 8.5.1.

|	
Report Browser	Use the Report Browser to examine other studies for the same patient. Notice that the current study (the one you have just performed) is the bottom study in the browser panel.
Averaged Aortic Waveform (Derived)	This section shows the derived averaged aortic waveform. This reading is obtained by applying mathematical transforms to the Peripheral Pulse Waveform.
Key Parameters	This section shows three key parameters which can be used for clinical cardiovascular evaluation • Ejection Duration (% of period) • Augmentation Index (AIx %) Heart Rate Normalised • Buckberg Sub-Endocardial Viability Ratio (SEVR %) The red and green bars to the right of the parameters indicate the position of that parameter within the normal ranges for that measurement. If the arrow (^) is in the green area this indicates that the parameter is within the normal range. See the relevant sections in the Clinical Guide for more information.
Pressures	This area displays the peripheral and central pressures. (SP/DP, MP, PP) and heart rate (HR).
Normals Graphs	This area displays the normals graphs associated with each parameter indicating the position of that value in the normal ranges.

To display a particular parameter graph, simply move and click the mouse cursor on the parameter text label.

QUALITY CONTROL

The Quality Control area of the Clinical Report Screen shows the captured peripheral waveforms over-layed on one graph, the Quality Control Indices and the Quality Index.

Check the Quality Control values to ensure that the measurement is within the limits of the current quality control settings.
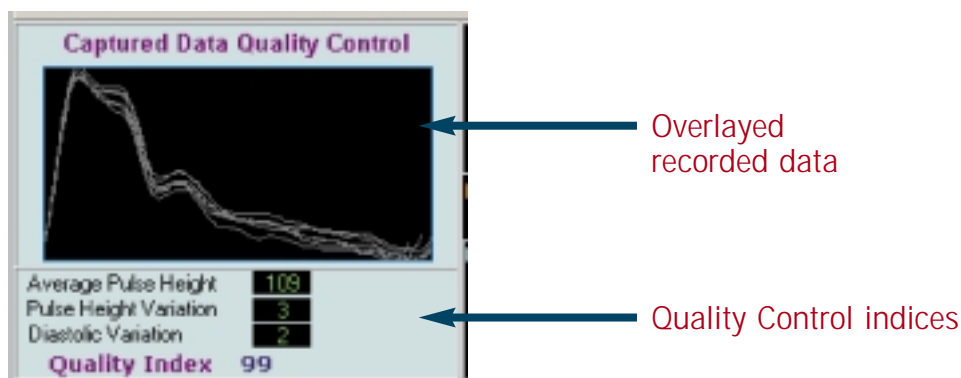
Check that the indices are displayed in GREEN, to indicate that they are within the quality limits. If they displayed in RED, then the values are outside the limits. Check also that the Quality Index is above 90%. The Quality Control values of the Report Screens shows information to help you ensure that the measurement you have recorded is of sufficient quality.

Quality Control Indices

> Where the figures appear in GREEN, they are within the limits set using the Configuration Settings. Where the figures are in RED, they are outside these limits.
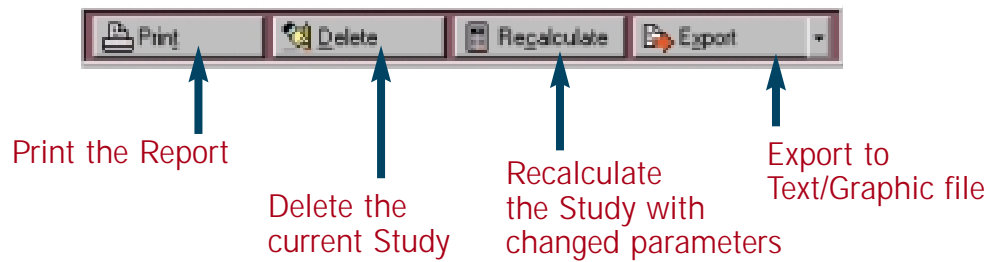
> - The Average Pulse Height is the average of the heights of all the pulses.
>
> - The Pulse Height Variation is the amount of variation present in the pulse heights.
>
> - The Diastolic Variation is the amount of variation present in the diastolic reading.
>
> - Quality Index is a number calculated from the three indices above. A weighting is given to each of the indices and then combined to produce this index. It is recommended that reports that have a Quality Index of less than 90% be rejected, and if possible, repeated.

Overlayed recorded data

> This area displays a visual guide to how well the individual pulses can be overlayed to form an averaged pulse. There should be as little variability in the pulses as possible.

REPORT TOOL-BAR BUTTONS

The tool-bar buttons are used as follows:

Print the Report

Delete the
current Study

Recalculate
the Study with
changed parameters

Export to
Text/Graphic file

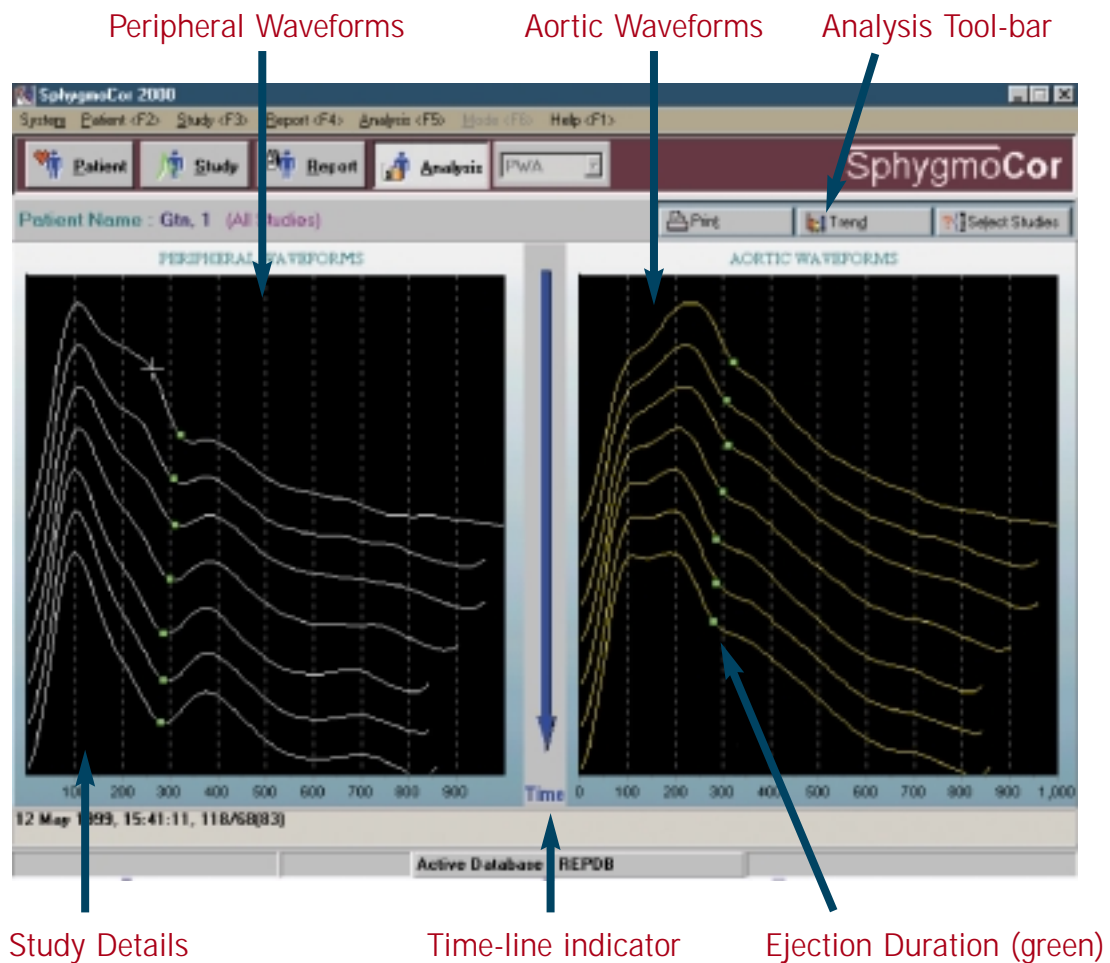|	
Print the Report	Use this option to print the SphygmoCor Pulse Wave Analysis Report. This is a summary report providing information concerning the Study, on a single A4 page.
Delete the current Study	Use this option to delete the Study. Note that the study that is deleted is the one currently highlighted in the Report Browser. Take care that you are deleting the Study you intended to delete.
Export to Text/Graphic file	Use this option to export the Study values to a text or graphics file.
	The **text file** can be used to import the data into a spreadsheet program.
	The **graphics file** can be used in documents or presentations. The exported file is in JPG format.
	Use the drop down menu to access the export type.
Recalculate the Study	Use this option to open the SphygmoCor Recalculate Report window. This window lets you change any of the Study fields you originally entered in the Study screen.

WORKING WITH THE ANALYSIS SCREEN

Peripheral Waveforms — Aortic Waveforms — Analysis Tool-bar — Study Details — Time-line indicator — Ejection Duration (green)

The Analysis Screen is designed to allow you to view multiple Studies, over time, for a patient. This enables you to perform both long-term and short-term analyses for a patient.

For example, you may want to examine drug effects over time. You could do this by making a control Study, followed by periodic Studies at regular intervals, after administering the drug. The Analysis screen could then be used to examine qualitative changes both in the shape of the aortic waveforms, and in the ejection duration, over the course of the Studies.

The Analysis screen has the following key areas:

|	
Peripheral Waveforms	This area shows the peripheral waveforms for the patient, in time sequence. The first waveform (oldest) is at the top of the screen, the last waveform (most recent) is at the bottom of the screen.
Aortic Waveforms	This area shows the aortic waveforms for the patient, in time sequence. The first waveform (oldest) is at the top of the screen, the last waveform (most recent) is at the bottom of the screen.
Analysis Tool-bar	This tool-bar enables you to perform functions related to the Analysis screen.
Study Details	This summary line shows you: ● When the cursor is placed over the green ejection duration symbol, the ejection duration for the study is displayed: ED = 257 ms ● When the cursor is placed over any other part of the waveform, information about the Study (date and time of the Study, systolic and diastolic pressure, and mean pressure) is displayed: 25 Jun 1998, 14:20:32, 120/80[93]
Time-line indicator	This area is a visual reminder of the time sequence of the Analysis information - with the earliest Study at the top and the latest Study at the bottom.
Ejection Duration	The value of the ejection duration is usually shown in green on the waveforms. Ejection duration is measured in milliseconds.

Analysis Tool-bar Buttons

Print the Analysis   Display the Trend screen   Select Studies for Analysis
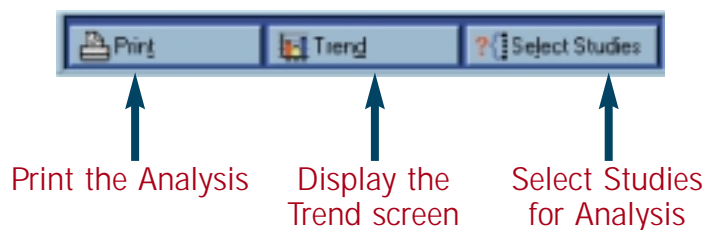
Print   Use this option to print the SphygmoCor Aortic Blood Pressure Report. This is a summary report providing information about all the Studies in the Analysis, on a single A4 page.

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Trend	Use this option to switch to the Trend Screen. The Trend Screen shows the trends for all the major measures in a study, over the course of the Analysis. The horizontal axes of the trend graphs show the separate studies in the Analysis. An example of a Trend Screen is shown below.
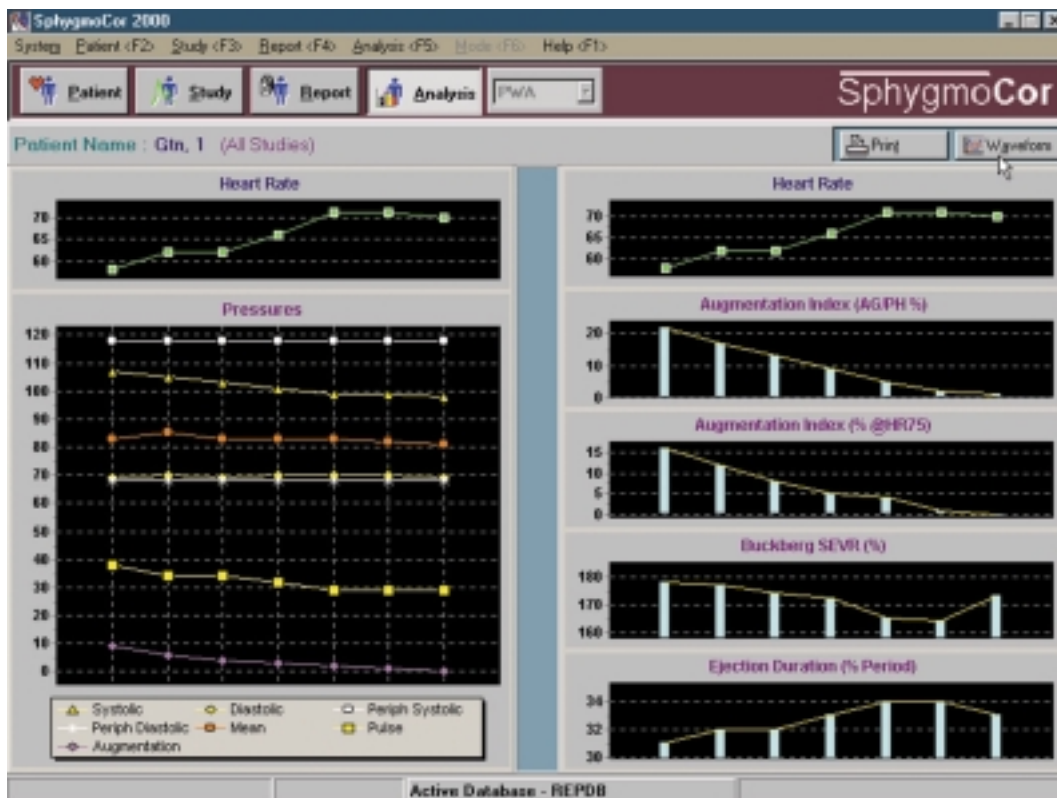
When you are in the Trend Screen:

- Click the Print tool-bar button to print the SphygmoCor Patient Trend Analysis Report. This is a summary report showing the trends in all the studies in the Analysis, on a single A4 page.

- Click the Waveform tool-bar button to return to the main (waveform) Analysis Screen.

Print the
Trend graphs

Switch to the
Analysis Screen
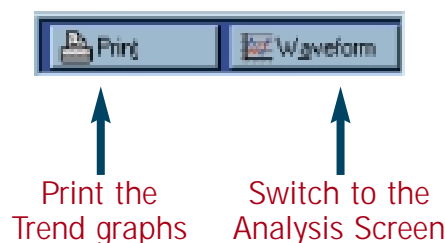
When you are in the Analysis Screen:

Select Studies	Use this option to determine which Studies are to be included in the Analysis. For more on how to do this, see Section 6.1.

SELECTING STUDIES FOR ANALYSIS

You can decide which Studies are to be included in any Analysis. You do this by clicking the Select Studies tool-bar button on the Analysis Screen. The SphygmoCor Analysis Select window then opens. This window is shown below.
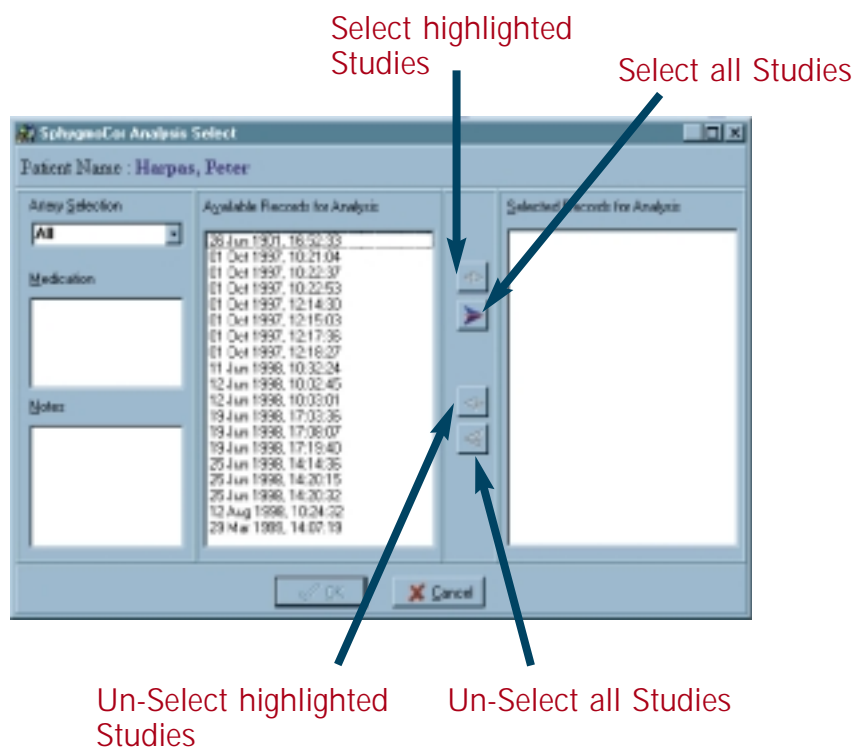
Using this window, you can select the Studies to be included. The following points relate to using this window:

● In the Available Records for Analysis panel, select the Studies you want to include by clicking on them to highlight them. If you want to highlight more than one Study, use the normal Windows conventions for highlighting multiple items in a list.

Highlighting Multiple Items

Hold down the Ctrl key while you click items, to highlight any number of items in the list.

After clicking a first item, hold down the Shift key while you click a second item, to highlight all items between the first item you clicked and this second item.

You can also use the mouse to drag across multiple items, to select that group of items.

● When you have highlighted multiple items, click the Select highlighted Studies button to copy the highlighted items to the Selected Records for Analysis panel.

● Alternatively, click the Select all Studies button to copy all the Studies to the Selected Records for Analysis panel.

- You can also highlight multiple items in the Selected Records for Analysis panel, then un-select them all (remove them from this panel) by clicking the Un-Select highlighted Studies button.

- You can remove all items from the Selected Records for Analysis panel by clicking the Un-Select all Studies button

- Whenever you click on an item in the Available Records for Analysis panel, any Medication or Notes about that item are displayed in the Medication and Notes fields.

- You can select Studies for just one of the two peripheral artery sites, by using the Artery selection pull-down. Alternatively, you can leave this pull-down set to All. Changing this setting causes the Available Records for Analysis panel to change to match the selection you made in the Artery selection pull-down.

- When you have completed your selection of Studies, click the OK button to return to the Analysis Screen. The Analysis Screen now changes to show only those Studies that you selected in the SphygmoCor Analysis Select window.

EXPLANATION OF PARAMETERS/INDICES

The SphygmoCor report screens and printed reports contain the derived central haemodynamic parameters. Each averaged waveform has the following parameters associated with it:

AORTIC HAEMODYNAMIC PARAMETERS

Heart Rate, Period	71 bpm, 844 ms	P1 Height (P1 - Dp)	29 mmHg	Buckberg SEVR (Ad/As)	162% (3015/1859)
Ejection Duration	286 ms, 34%	Augmentation	1 mmHg	MP (Systole, Diastole)	91, 76 mmHg
Aortic T1, T2, Tr	116, 192, 150 ms	AGIdx (AG/PP, P2/P1)	2%, 103%	End Systolic Pressure	89 mmHg

Displayed Parameter Summary:

CALCULATED PARAMETERS	ABBREVIATION	UNITS
Heart Rate	HR	beats/min
Period	T_F	msec
Ejection Duration	ED	msec
Peripheral Systolic and Diastolic Pressure	SP, DP	mmHg
Aortic Systolic and Diastolic Pressure	SP, DP	mmHg
Mean Pressure - Peripheral and Aortic	MP	mmHg
Pulse Pressure - Peripheral and Aortic	PP	mmHg
Time to 1st peak - Aortic	T_1	msec
Time to 2nd peak - Aortic	T_2	msec
Time to Reflection	Tr	msec
Central Aortic Indices:		
Augmented Pressure	AG	mmHg
Pressure at T_1	P_1	mmHg
Pressure at T_2	P_2	mmHg
Augmentation Index – (AG/PP, P2/P1)	AI	%
Primary Wave Pressure at T_1	P_1 H	mmHg
Buckberg Sub-Endocardial Viability Ratio (Ad/As)	SEVR	%
Mean Pressure in (Systole, Diastole)	MP (S,P)	mmHg
End Systolic Pressure	ESP	mmHg

In its analysis of the derived aortic pressure waveform, the SphygmoCor System extracts from the averaged waveform five time-relative points (described below) and from these further parameters relating to the heart and arterial system are determined (see graph below).

The basic features of an arterial pulse are shown below. After the foot of the pulse (T_0), indicating the onset of ejection, the pressure wave rises to an initial peak where it forms a shoulder (T_1). This is the peak of the primary LV ejection pressure. It then proceeds to a second shoulder (T_2) which is the peak of the arterial reflection wave. Usually this constitutes the peak pressure in the elderly. The end of ejection (ED) is point of closure of the aortic valve and time of End of Systole. T_F indicates the end of the waveform.

These timing points are the basis of the waveform analysis.

Features of the Arterial Pulse
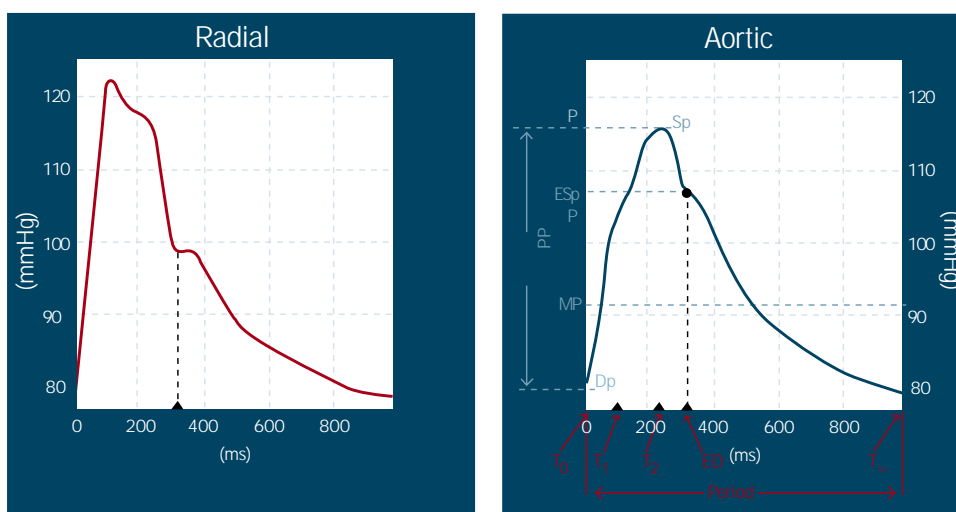
The following is a detailed explanation of displayed parameters and those used for calculations:

Refer to the previous waveform graph for feature identification.

PARAMETER	DESCRIPTION	FORMULA	SYMB.	UNITS
Timing parameters:				
Start of waveform	This is the start of the waveform where the time at the foot is used as T_0.		T_0	msec
Time to 1st peak - Aortic	The duration from the start of waveform to the 1st peak/ shoulder. This is indicated by the first triangle from the left at the horizontal millisecond axis on each graph.		T_1	msec
Time to 2nd peak - Aortic	The duration from the start of waveform to the 2nd peak/ shoulder. This is indicated by the second triangle from the left at the horizontal millisecond axis on each graph.		T_2	msec
End of waveform	This is the end time of an averaged peripheral or a derived aortic waveform.		T_F	msec
Time to Reflection	Time to return of the reflection wave of the aortic waveform.	Tr is usually greater than T_1 and always less than T_2	Tr	msec
Ejection Duration	The ED is derived from the recorded peripheral waveform. This point is indicated by a dotted line on the graph. The ED is the period of time from the start of the pulse for which the aortic valve is open (T_0) to the closure of the aortic valve (incisura), End of Systole.	$ED = T(incisura) - T_0$	ED	msec
Period	This is the length of an averaged peripheral or a derived aortic waveform.	$PD = T_F - T_0$	PD	msec
Heart Rate	This is the patient's average heart rate over the captured 10-sec data capture period.	$HR = \dfrac{1000}{PD} \, x60$	HR	beats/ min
Pressure parameters:				
Peripheral Systolic and Diastolic Pressure	These are the maximum (Sp) and minimum (Dp) pressures of the peripheral waveform.		Sp, Dp	mmHg
Aortic Systolic and Diastolic Pressure	These are the maximum (Sp) and minimum (Dp) pressures of the central waveform.		Sp, Dp	mmHg
Mean Pressure - Peripheral and Aortic	This is the average or mean pressure for the peripheral and aortic waveform. NOTE: This is a "true" mean, not the 1/3 method as commonly used in many other monitoring systems.	$MP = \dfrac{\sum\limits_{i=T_0}^{T_F} P_i}{n}$ $Pi = Pressure\ points;$ $n = number\ of\ pressure\ points$	MP	mmHg
Pulse Pressure - Peripheral and Aortic	The Pulse Pressure is the height of the peripheral and aortic pulse. This is determined by subtracting the minimum (Dp) pressure from the maximum (Sp) pressure.	$PP = Sp - Dp$	PP	mmHg

PARAMETER	DESCRIPTION	FORMULA	SYMB.	UNITS
Central Aortic Indices:				
Pressure at T_1	Pressure at 1st peak/shoulder		P_1	mmHg
Pressure at T_2	Pressure at 2nd peak/shoulder		P_1	mmHg
Augmentation	Augmentation is a pressure calculated for the Aortic Waveform only. The augmented pressure is the pressure difference between the 1st peak/shoulder (T_1) and 2nd peak/shoulder (T_2).	$AG = P_2 - P_1$	AG	mmHg
Augmentation Index - (AG/PP, P_2/P_1)	Aortic- Augmentation Index There are 2 ratios used to calculate AI. **(AG/PP)** - This value indicates the size of the increase or decrease in the pulse height as a result of the reflected wave. - If the reflected peak is greater than the primary peak, AI (AG/PP) is positive. - If the reflected peak is less than the primary peak, AI (AG/PP) is negative. **(P2/P1)** - This value indicates the size of the reflected peak (indicated by the second peak/shoulder T_2), with respect to the primary peak (indicated by the first peak/shoulder T_1).	$AI(AG/PP) = \dfrac{P_2 - P_1}{Sp - P(T_0)} \, x10$ $AI(P_2/P_1) = \dfrac{P_2 - P(T_0)}{P_1 - P(T_0)} \, x10$	AI	%
Primary Wave Pressure at T_1	The difference between the minimum pressure and the pressure at the 1st peak/shoulder (T_1).	$P_1 H = P_1 - Dp$	P_1 H	mmHg
Mean Pressure in (Systole, Diastole)	MP (Sp) This is the mean pressure between T_1 to ED during systole. MP(Dp) This is the mean pressure between ED and the end of the averaged pulse (TF) during diastole.	$MP(Sp) = \dfrac{\sum\limits_{i=T_0}^{ED} P_i}{n}$ $MP(Dp) = \dfrac{\sum\limits_{i=ED}^{T_F} P_i}{n}$	MP	mmHg
End Systolic Pressure	This is the pressure at the end of systole, the pressure at ED.	$ESp = P(ED)$	ESp	mmHg
Buckberg Sub-Endocardial Viability Ratio (Ad/As)	Ratio of Diastolic Area/min and Systolic Area/min. Systolic Area/min = Tension Time Index (TTI) Diastolic Area/min = Diastolic Time Index (DTI)	$SEVR = \dfrac{DTI}{TTI} \, x100$ where: $TTI = HRxMP(Sp)x(ED-T_0)$ $DTI = HRxMP(Dp)x(T_F-ED)$	SEVR	mmHg

Webpage: www.atcormedical.com

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