

Why use Finapres or Portapres rather than intra-arterial or intermittent non-invasive techniques of blood pressure measurement?

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In the clinic, blood pressure is measured almost exclusively using non-invasive intermittent techniques, of which the auscultatory (Riva-Rocci/Korotkoff, RRK) and the computerized oscillometric method are most often used. However, both methods only provide a momentary value. In addition, the accuracy is hampered by phenomena such as cuff response and white coat hypertension, thus providing artefactually increased values. The vascular unloading technique of Peñáz together with the Physioal criteria of Wesseling provide reliable, non-invasive and continuous estimates of blood pressure. This technique is thus an alternative to the invasive intra-arterial measurements in many cases, without the risks and ethical questions inherent to invasive measurements. Since the pressure waveform is available continuously, computations such as pulse contour and Modelflow cardiac output, spectral analysis and baroreflex sensitivity provide further information on the dynamics of the cardiovascular system on a beat-to-beat basis, similar to intra-arterial measurements.

Introduction

Blood pressure is one of the most frequently measured parameters in medical practice. It has long been known that blood pressure is a very unstable parameter; arterial blood pressure is nowhere the same in different sites throughout the cardiovascular system. The blood pressure waveform will change shape depending on the properties of the blood vessels and the tone of the smooth muscle cells in the vessel wall [1,2]. Blood pressure is also modulated by respiration and spontaneous fluctuations appear throughout the day (figure 1). Therefore, blood pressure is a variable parameter, the uncritical use of which may have limited our understanding of the nuances of blood pressure measurement and the physiology of arterial circulation. Blood pressure variability, on the one hand, poses a problem for the clinician attempting to classify a patient as normo- or hypertensive. On the other hand, it challenges researchers who aim at explaining and understanding the underlying mechanisms, and hope

to identify clinical applications of this phenomenon to the benefit of the individual patient. Recent research has shown that blood pressure variability is an important predictor for the development of heart disease [3–5]. The presence of high blood pressure imposes a higher risk of cerebrovascular accidents, coronary artery disease, myocardial infarction and kidney abnormalities, especially in older patients. Mortality increases progressively with an increase of blood pressure and there is now a consensus that treatment of severe hypertension is beneficial for the individual patient. In this paper we wish to discuss different methods of blood pressure measurements, and the factors affecting their accuracy. Emphasis will be placed upon recently developed methods for measuring continuous blood pressure non-invasively, such as FinapresTM† and PortapresTM‡.

Methods of measuring blood pressure

Methods used to measure blood pressure can be subdivided into two categories:

- (1) direct invasive methods; and
- (2) indirect non-invasive methods.

Direct invasive measurements

Invasive methods provide insight into the actual blood pressure pattern, including its variability. Therefore, these methods are well-suited for the assessment of both short-term variability (10 s rhythm) and long-term variations in blood pressure, among others the diurnal (day–night) rhythm. From spontaneous fluctuations in blood pressure occurring in unison with pulse interval changes it is possible to derive baroreflex sensitivity (BRS). In addition, it is possible to derive stroke volume (SV) or aortic flow waveform from the continuous blood pressure waveform using the pulse contour method or the recently developed Modelflow method [6]. Additional calculations provide further information on cardiac output (CO) and systemic vascular resistance (SVR).

Invasive measurements require invasion of the body (skin, tissue and vessel wall) with a hollow needle. The measurement system usually consists of a long, thin liquid-filled catheter which can be positioned in the artery through the hollow needle. The catheter is connected to a pressure transducer outside the body at heart level. The accuracy of invasive measurements is

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† Finapres is a trade mark of Ohmeda Monitoring Systems, Louisville, CO, USA.

‡ Portapres is a trade mark of TNO-TPD BioMedical Instrumentation, Amsterdam, The Netherlands.

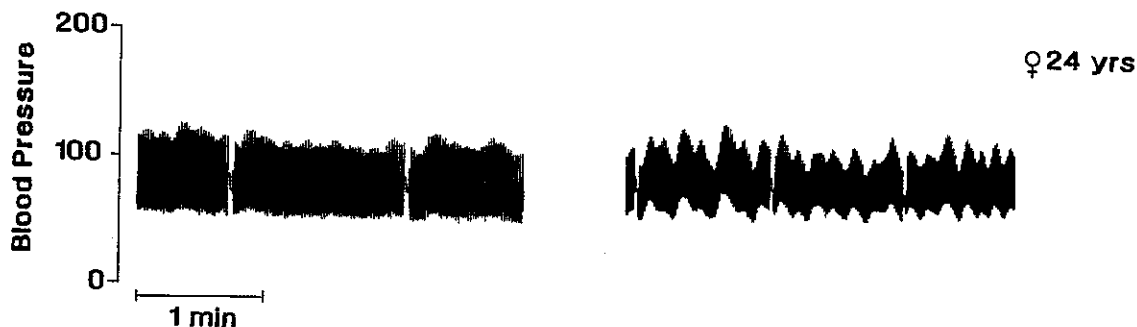


Figure 1. Blood pressure recording with Finapres in a healthy young subject in supine (left) and upright position (right). Note that the variability during standing is larger than during the supine position (Mayer-Traube-Hering waves). From Veerman [5].

determined by the frequency response of the catheter manometer system. The bandwidth of such a catheter manometer system should exceed 30 Hz in order to obtain an undistorted arterial pressure waveform. A catheter placed between the artery and the pressure transducer limits the bandwidth and thus the quality of the measurement. The ideal catheter is short, stiff and of a large diameter. In practice this is often not the case, which can lead to overestimation of systolic pressure. Also, small air bubbles may be present in the system, resulting in damping and distortion of the arterial pressure waveform [7]. Presently, catheter-tip pressure transducers of sufficiently small dimensions are available. These are usually positioned in the aorta. Such transducers have a larger bandwidth and give an undistorted and artefact-free pressure waveform. Bruner *et al.* [7] give an overview of the limitations of invasive methods.

Invasive measurements of blood pressure by means of a catheter in the brachial artery is an accepted method, although application is limited due to the invasiveness and the associated risks and ethical aspects. Therefore, such measurements are only indicated for seriously ill patients. This technique is also used for the evaluation of non-invasive blood pressure devices. It then requires careful quality control in order to obtain meaningful comparisons.

Indirect non-invasive measurements

Indirect measurements provide either a momentary value of blood pressure or a continuous waveform similar to invasive measurements, depending on the technique. Non-invasive measurements are mainly performed by three different techniques, namely:

- (a) the auscultatory method (Riva-Rocci/Korotkoff, RRK);
- (b) the oscillometric method (Marey);
- (c) the Peñáz/Wesseling-method (Finapres and Portapres).

The first two methods provide momentary values of systolic and diastolic blood pressure. The third method provides not only an absolute measure of blood

pressure in the finger but also the arterial blood pressure waveform. Ng and Small [8] recently presented an overview of non-invasive methods, for measuring blood pressure. They also paid attention to less frequently used methods such as arterial tonometry and the pulse wave velocity method. The latter is based upon the relation between the propagation velocity of the arterial pulse wave in the arteries and mean blood pressure.

The Riva-Rocci/Korotkoff-method. The technique described by Riva-Rocci in 1896, with the criteria of Korotkoff in 1905, is still the most frequently applied method for measuring blood pressure. Using a stethoscope it is possible to determine sounds over the brachial artery distal to an upper arm cuff. The nature of these sounds is used to determine systolic pressure (beginning of sounds; phase I in the Korotkoff sounds) and diastolic pressure (muffling, phase IV or the (preferred) disappearance of sounds, phase V) while cuff pressure readings are made from a mercury column or a manometer. The use of phase IV or phase V in the Korotkoff sounds for determining diastolic pressure is still debated [4].

When the results of RRK measurements are compared with intra-arterial measurements the differences vary between studies, ranging from an underestimation of 20 mmHg to an overestimation of 25 mmHg, whereby in most cases the RRK method tends to underestimate systolic and overestimate diastolic blood pressure.

Sources of error by the auscultatory method can be summarized as follows:

- The width of the cuff compared to the circumference of the upper arm. A cuff too narrow for the arm circumference usually results in a pressure value that is too high.
- The position of the arm during the measurement may introduce hydrostatic pressure differences. This has important implications on the variability of ambulatory measurements.
- Observer error and bias; physicians measure up to 30 mmHg higher blood pressure values than home-made measurements taken by the patient him/herself or by nurses in the hospital.

- Speed of inflation and deflation of the cuff.
- Cuff response, shortlasting pressure increase up to 40 mmHg during cuff inflation [5].
- Contamination of the mercury column if not regularly serviced.

Marey's oscillometric method. This technique was discovered by Marey in 1876. If the pressure in an upper arm cuff is measured continuously during deflation one can detect oscillations of which the amplitude at first increases, then decreases. The point of maximal amplitude of oscillation appears to correspond with mean arterial pressure. However, the oscillations begin at suprasystolic pressure levels and still continue at levels below diastolic blood pressure. This implies that systolic and diastolic pressure can only be obtained by approximation. Different manufacturers use different criteria, which are seldom made public.

The agreement between oscillometric measurements and intra-arterial measurements is of the same order of magnitude as that of the RRK method, although systolic pressures tend to show greater scatter. The advantage of the oscillometric method is that the cuff contains no sensors so that its placement is not critical. As a consequence patients can apply cuffs themselves, making home measurements possible. A disadvantage is that the weak cuff pulsations so detected are easily disturbed by movement artefacts.

Peñáz/Wesseling method. The volume-clamp method of Peñáz [10] is based on the principal of dynamic unloading of the arteries in the finger. The size of the finger arteries is gauged with an infrared transmission plethysmograph mounted inside an inflatable cuff. If the size of the finger arteries increases due to a blood pressure increase, the air pressure in the cuff also increases just enough to keep the arterial size constant. Since blood pressure changes can be as fast as 3500 mmHg/s during the upstroke, a pneumatic servo system is required to keep arterial size and transmural pressure constant by modulating cuff pressure in parallel with blood pressure in the finger. The pressure in the cuff can be measured with an electronic pressure gauge, thus providing an indirect measurement of the intra-arterial pressure waveform. The Physiological criteria of Wesseling [11] establish a setpoint value for arterial size to be used by the servo system. Ideally, cuff pressure should be identical to intra-arterial pressure. The arterial size at which cuff pressure equals blood pressure is its unstretched size at zero transmural pressure. The unstretched size is thus the ideal volume-clamp setpoint. Physiological calibrates this size by temporarily interrupting the measurement and opening the volume clamp servo loop. For one heartbeat the cuff pressure is kept constant at a level halfway between systolic and diastolic. Since blood pressure continues to pulse inside the artery, transmural pressure changes and a plethysmogram are observed and evaluated by a computer algorithm. From the amplitude and the shape of the plethysmogram the setpoint is then determined [11]. This procedure is repeated at regular intervals since the unstretched arterial size may change; thus, Finapres automatically

follows the size changes that are caused by changes in the tone of the smooth muscle in the finger arterial wall. The full calibrated pressure waveform becomes available and a pattern recognition program provides systolic and diastolic blood pressure per heartbeat. By integration of the pressure waveform over one heartbeat, mean pressure is computed. Additional Model-flow calculations provide aortic stroke volume, cardiac output and total peripheral resistance.

Intra-arterial and Finapres cuff pressures have been compared in a number of studies in anaesthetized and awake subjects. Blood pressure variations were induced by surgical manoeuvres [12-14], vasoactive drug administration [15], or cardiovascular manoeuvres such as Valsalva straining [16], orthostasis [17] and exercise to exhaustion [18]. Comparisons were made in adults [3], in the elderly [19] and in ambulant subjects [20]. For the latter a light-weight, battery-operated Finapres was developed having internal storage of the waveform for at least 24 h, i.e., the Portapres [21].

Summarizing the results [22] it appears that finger arterial mean pressure measured with Finapres is 5 to 10 mmHg lower than intra-arterial pressure in the brachial artery. This is now known to be caused by a pressure gradient due to flow in the arteries of the arm and hand as proven indirectly in [11] and elegantly demonstrated in [19]. The shape of the pressure pulsation in the finger differs from that in the brachial artery. Pulse pressure in the finger is greater in the young, about the same or slightly reduced in the elderly.

Portapres can track intrabrachial pressure over as much as a 24 h period without noticeable drift or change in accuracy (figure 2). Recording was switched automatically between two fingers every 30 min. During sleep pressure differences increased slightly, during the physical activities of walking and bicycling they decreased. Pressure in the ring finger appeared to be slightly higher than in the middle finger. Continuous monitoring for such long periods was atraumatic and no major limitations in behaviour of the subjects were observed.

Factors that influence the measurement of Finapres and Portapres are mainly related to the far peripheral finger site where sympathetic innervation is strong.

- The peripheral location causes finger blood pressure levels and pulse waveform to differ from pressures recorded at a more central location. As a consequence, finger pressure is lower than the more central pressure in the brachial artery which is most often used to record intra-arterial blood pressure. One can usually compensate for this effect by keeping the hand 10 cm below heart level;
- Sympathetic outflow to the finger arteries may at times be so strong as to cause full contraction of the smooth muscle in their walls, collapsing the arteries. This may be caused by circulatory changes due to psychological stress, severe blood loss or pain. At such times, finger pressure can no longer

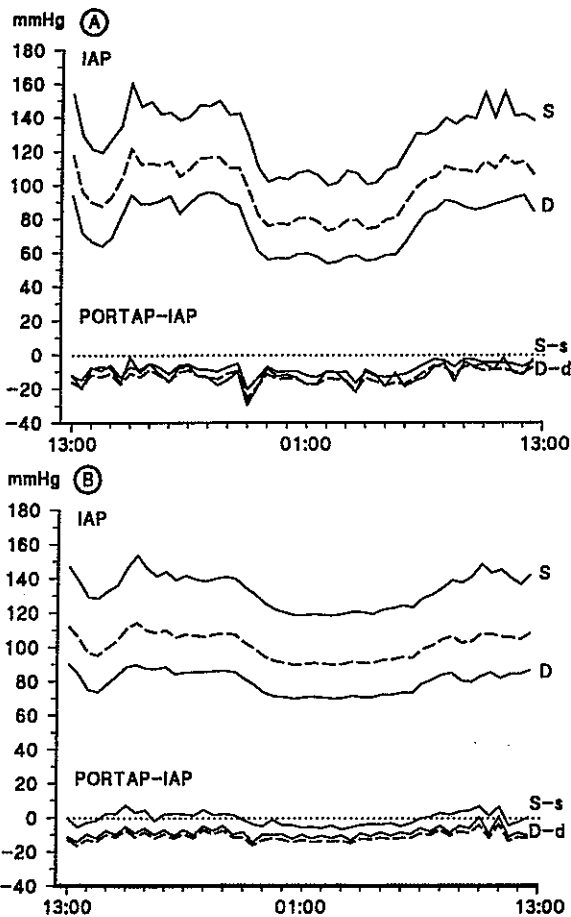


Figure 2. Systolic, mean and diastolic pressure levels derived from continuous intrabrachial pressure recordings in a single subject (panel A) and averaged for a group of 24 subjects (panel B). Finger pressure was also recorded and its differences with intrabrachial pressure are plotted each 30 min. Dashed lines represent mean arterial pressure. From Imholz *et al.* [20].

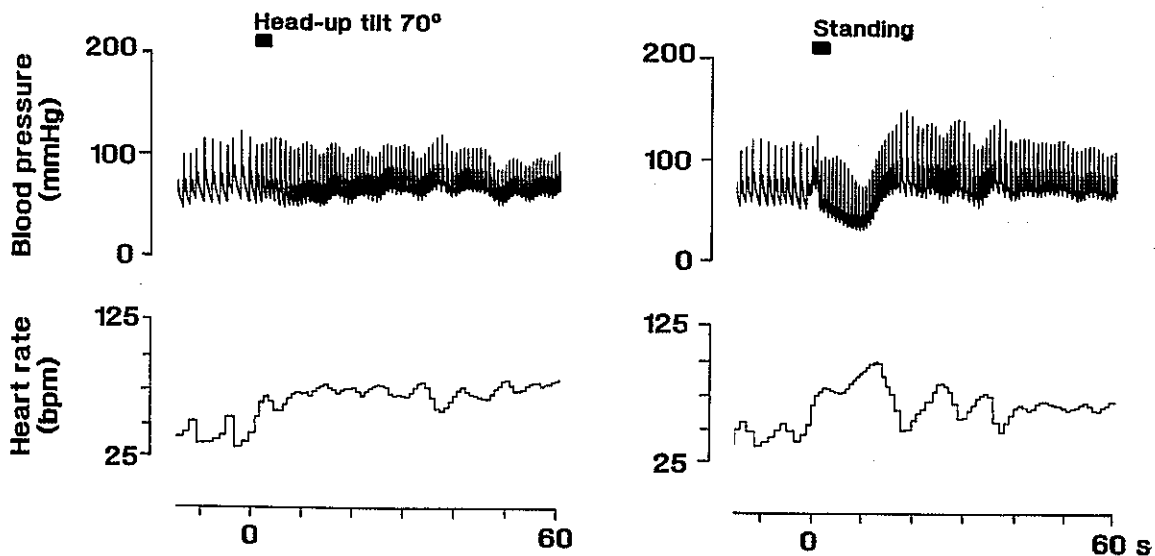


Figure 3. Blood pressure and heart rate changes as a result of orthostatic stress testing (standing up) compared to passive 70° head up tilt on a tilt table. From Van Lieshout [24].

be measured. A similar condition occurs in Raynaud's phenomenon.

- Cold fingers have been described as a problem situation [23]. Often, however, cold fingers are secondary to vasoconstriction and follow, rather than provoke, arterial contraction. Warming of the hand may help reverse the condition as the subject becomes more comfortable.
- When a single finger is monitored for a long time, the fingertip often turns blue and the feeling of reduced blood flow to the fingertip becomes unpleasant. Awake subjects appreciate switching to another finger every ½–2 h. Portapres does this automatically [21].

Clinical applications of Finapres and Portapres

The Peñáz/Wesseling-method is implemented in the stationary Finapres and in its portable version, Portapres. Typical areas of application for Finapres are

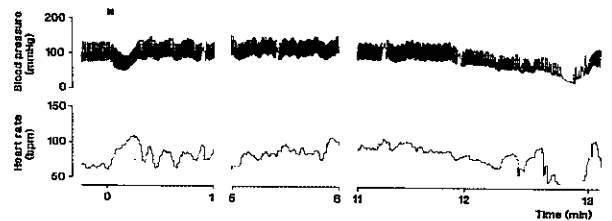


Figure 4. Vasovagal syncope in a 22-year-old male. After an initial normal response of blood pressure to standing up (at $t=0$) heart rate starts to increase after 6 min of standing. After 11–12 min of standing both blood pressure and heart rate decrease to very low values resulting in syncope. Recovery is nearly immediate after taking the supine position again. From Wieling and Shepherd [26].

situations in which short-term variability and changes in blood pressure are to be measured, such as orthostatic stress testing (standing up from a supine position) and the Valsalva manoeuvre (acute increase of pressure in the thorax) and the computation of baroreflex sensitivity is used more and more in such circumstances as an alternative to the placement of an intra-arterial line. Portapres provides the possibility of measuring the circadian rhythm in blood pressure and derived variables, even in ambulatory circumstances.

The orthostatic stress test and the Valsalva manoeuvre decrease the venous return to the heart and thus the cardiac output. By means of the baroreflex, regulatory mechanisms come into play, resulting in only a transitory decrease in blood pressure. Figure 3 shows an example of the blood pressure response to standing up. This response is different from the passive 70° head up tilt test of the same subject on a tilt table [24].

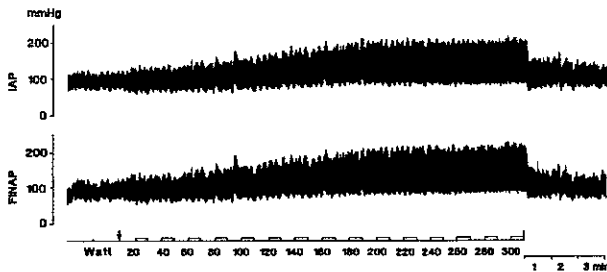


Figure 5. Representative example of intra-brachial pressure (IAP) and finger arterial pressure (FINAP) before, during and after stopping a staircase increase in power on a bicycle ergometer. Each level was maintained for 1 min, the level was then increased by 20 W. The starting point of the ergometer test is indicated by the arrow. From Imholz *et al.* [20].

Baroreflex sensitivity, the change in blood pressure relative to the simultaneous change in heart rate, is a measure of the quality of blood pressure control. Baroreflex sensitivity decreases with aging [25]. The baroreceptors also play a role in the response of blood

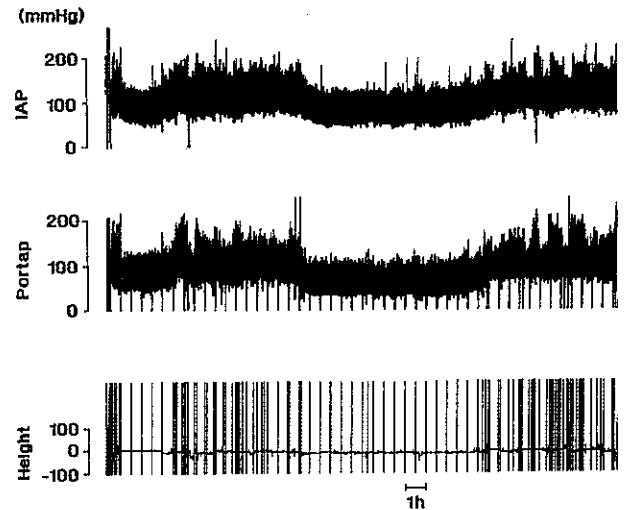


Figure 6. Typical example of a continuous 24 h intra-brachial pressure (IAP) and simultaneously measured finger arterial pressure with Portapres (Portap). The measurement runs from 13:00 h on the first day to 13:00 h on the second day. The downgoing 'spikes' in the Portap-signal indicate the half-hour switching periods where the measurement was automatically alternated between two fingers. The lower panel shows the changes in the hydrostatic pressure difference between the hand and the position of the intra-arterial pressure transducer (height). Superimposed on the height signal are coded status messages of Portapres. From Imholz *et al.* [20].

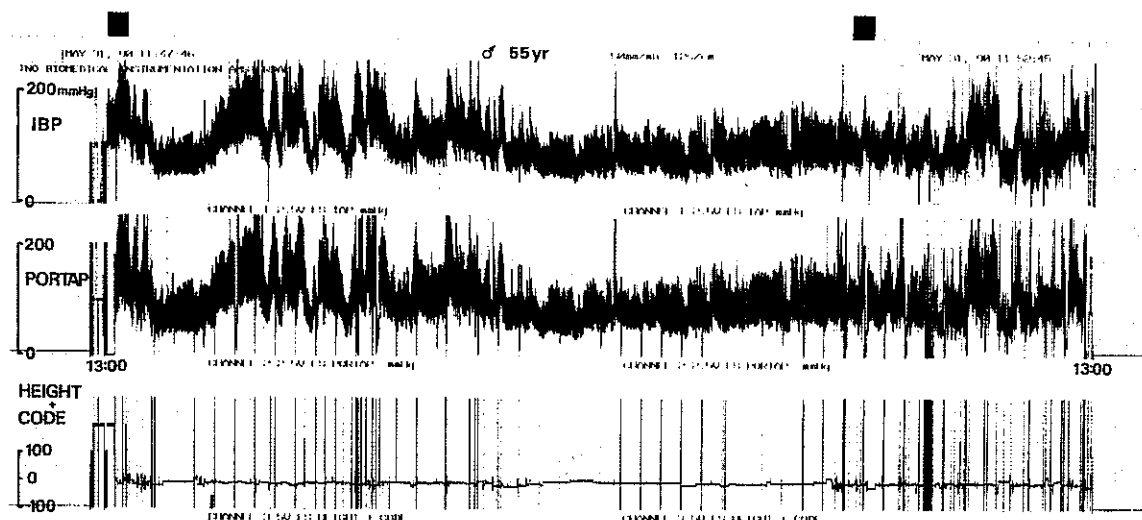


Figure 7. Example of a 24 h blood pressure profile in a 55-year-old male with a lesion in the afferent branch of the baroreflex arc. As a consequence blood pressure is highly variable. IBP is the invasively measured blood pressure with the Oxford system. PORTAP is the simultaneously measured blood pressure with Portapres. The lower panel shows the changes in the hydrostatic pressure difference between the hand and the position of the Oxford transducer (HEIGHT). Superimposed on the height signal are coded status messages of Portapres. The regular 'spikes' after each half hour indicate the automatic switching between two fingers. From TNO Applied Research, 35, 1991.

pressure to physical and mental activity. It is generally accepted that reactions such as dizziness and even syncope after standing up are due to a decrease in blood pressure (orthostatic hypotension). Figure 4 shows a typical example of the behaviour of blood pressure and heart rate in a young man after a period of standing, resulting in syncope. After lying down both blood pressure and heart rate return to normal almost instantaneously [26].

Finapres can also be used—with simple precautions—during exercise on a treadmill or a bicycle ergometer. Figure 5 shows an example of an exercise test on a bicycle ergometer with comparison of Finapres finger pressure and simultaneously measured intrabrachial pressure. In both pressure recordings similar changes are observed [27].

With the recently developed Portapres ambulatory blood pressure measurement device it is possible to record long-term 24 h blood pressure profiles to obtain diurnal variations in blood pressure and related cardiovascular parameters of healthy subjects and patients during their normal daily activities.

The device is well-accepted by the patient and can thus be applied repeatedly. Figure 6 shows a typical example of a 24 h measurement in comparison with a simultaneously measured intrabrachial pressure. Note that, although there are differences in detail, the overall appearance is one of close agreement between the two recordings [20].

Finally, figure 7 shows an example of a 24 h blood pressure profile measured with Portapres in a 55-year-old male patient with very labile blood pressure due to a lesion in the baroreflex arc. The simultaneously measured intrabrachial blood pressure with the Oxford system (IBP) is also shown. Note the remarkable agreement between these two recordings, even during those periods during the 24 h when blood pressure changed quite substantially.

Conclusion

We conclude that clinical blood pressure measurement with the RRK or oscillometric method only provides a momentary measure, the value of which is hampered by phenomena such as cuff response and white coat hypertension. Invasive methods are not an alternative due to their inherent, if small, risk and to ethical aspects. More recent developments of continuous non-invasive methods such as Finapres and Portapres provide new perspectives for medical practice, especially in areas in which beat-to-beat recording of blood pressure is needed to obtain further insight into the dynamics of the cardiovascular system.

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Book reviews

Bio-fluid Mechanics

Edited by H. Power, Computational Mechanics Publ. (UK, 1995), pp. 336. Price £97.00, \$150.00, ISBN 1853122866.

Fluid mechanics is one of the main topics of applied mathematics and physics and is one of the most challenging areas of computational mechanics. Since fluid is one of the major components of a living organism, it is logical that fluid mechanics play a major role in bioengineering, by analysing and simulating the fluid flow problem associated with physiological processes.

This book contains recent developments in the area of bio-fluid mechanics. The nine chapters in the book have been contributed by leading authors in the field. Each chapter concerns itself with a fluid flow problem. Chapter 1 is concerned with the fluid mechanics of abnormal heart valves as well as the flow phenomena associated with these conditions. Chapter 2 develops a computational method to conduct simulations of blood flow in the left ventricle during the contraction stage of the cardiac cycle which is called systole. Chapter 3 describes a numerical model for the coupled solution of the equations of motion for the flow and wall in the larger arteries. Chapter 4 describes a mathematical model for the simulation of arterial haemodynamics, as well as discussing several results obtained by the simulation, including the effects on axial velocity profiles, shear-stress and their time variation during a cardiac cycle.

In chapter 5 a computer model of the human cardiovascular system, for simulating the short-term regulatory processes that adapt the cardiac output of the heart to changing circulatory demands, is presented. A numerical model to calculate extra corporeal blood flow to describe a haemodialysis system and therapies is developed in chapter 6.

In chapter 7 simulation is used to study the dynamics of indicators interacting with the renal proximal convoluted tubule (PCT). The subject of chapter 8 is the numerical modelling of the complex mechanical system of lung respiration.

Finally, in chapter 9 the problem of determining the low Reynolds number flow of the cerebrospinal fluid through the subarachnoid space passing around the brain and spinal cord is formulated exactly as a system of linear Fredholm integral equations of the second kind.

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Biomechanics—Circulation: 2nd edition

By Y.C. Fung. Springer Verlag (Berlin, 1996). pp 560. Price £34, ISBN 0-387-94384-6.

Fung's seminal book on Biomechanics is accepted throughout the world as a standard reference text in the subject. It is widely used as the basis of undergraduate and postgraduate courses in bioengineering and biophysics. The coherence of his approach across the disciplines of biomechanics and biofluid mechanics casts light on the fundamental unity of the physical phenomena. It encourages students and professionals alike to develop a rigorous but intuitive approach to the descriptions of constitutive equations for solid and fluid continua. He uses mathematics to describe elegantly and concisely principles that he first explores and develops in the light of physical understanding and experience. The mathematical structures that underpin many physical phenomena thus become familiar friends as the reader negotiates the several aspects of human tissues, systems and physiology that Fung explores. The book on the circula-

tion focuses, as its title suggests, on the physics of the cardiovascular system. Once again the emphasis is on understanding, with mathematics used to illuminate and to tie together the diverse threads of investigation.

The eight chapters of the book are entitled: Physical Principles of Circulation, The Heart, Blood Flow in Arteries, The Veins, Microcirculation, Blood Flow in the Lung, Coronary Blood Flow and Blood Flow in Skeletal Muscle. Much of the physics and mathematics that describes these flows is common to many other fields, and so the reader will find the familiar developments of the Poiseuille equation and of the Navier Stokes equations for viscous flows. Laminar and turbulent flows are described, and the phenomena of boundary layers, separations and secondary flow structures are also addressed. The emphasis throughout is on the applications of these ideas in the circulation. In this context there are many problems that make the analysis of the circulation fraught with difficulty: in much of the arterial system the flow is pulsatile, in general the vessel walls are elastic and, with particular effect in the venous system, are collapsible, there are manifold bifurcations, pressure reflections, flow separations and self-excited oscillations. To compound the problem blood is inhomogeneous and certainly non-Newtonian in some instances, although in others a Newtonian treatment might be appropriate. Fung addresses all of these issues, expounding theory where possible and conjecture where necessary. The work is well-researched and up-to-date. He starts to lay the foundation of the links between the physical phenomena, such as fluid shear stress or wall tension, addressed in this work and clinical outcomes such as atherosclerosis.

Equations and figures are embedded in the text, as would be expected in any modern work.