Journal of Human Hypertension (1994) 8, 73–84

The history of blood pressure measurement

Eoin O'Brien and Desmond Fitzgerald
Blood Pressure Unit, Beaumont Hospital, Dublin 9

Keywords: *Blood pressure measurement*

That the phenomenon of blood spurting from a severed artery failed to excite the minds of scientists until relatively recently may be seen as an indictment of the development of scientific reasoning (Figure 1). That the discovery of BP was virtually ignored by the scientific community for almost a century is even more remarkable. This essay which opens, therefore, on a critical note will be seen to end on one of scepticism – scepticism at the tardiness of scientific thinking, even today, to grasp the obvious and thereby advance science. Such are the lessons that may be learned from the study of history.

The development of BP measurement should not be viewed as a clear progression from one principle or device to the next; many of the instruments described in this review often developed simultaneously and, at times, independently in different centres. Moreover, the introduction of a superior technique did not necessarily result in the demise of its predecessor for many years but it is helpful to impose a scheme which permits us to assess the progression of scientific ideas in BP measurement.[1]

Figure 1 The Legend of the True Cross. Detail from *The Battle between Heraclius and Chosroes* by Piero della Francesca (1415/20-1492). Arezzo, Church of St. Francesco. Source: Murray, P. & de Vecchi, P. *The Complete Paintings of Piero della Francesca*, Penguin Classics of World Art, Penguin Books, Middlesex, 1987.

Direct measurement of systolic blood pressure

The yellow Emperor of China, Huang-Ti, was undoubtedly aware of the importance of changing characteristics of the pulse 4000 years ago. With remarkable prescience, he commented that people who eat too much salt had hard pulses and tended to suffer strokes.[2] The ancient Egyptian, as the Ebers papyrus of 1500 BC shows, were undoubtedly aware of the pulsations in different parts of the body even if they did not actually go as far as to count the pulse.[3] Egyptian physicians, moreover, regarded measurement as an indispensable aspect of clinical assessment but the precise measurement of BP had necessarily to await the discovery of the circulation by William Harvey (1578–1657) in 1628.[4] In fact over a century had to pass after Harvey's empirical work before the Reverend Stephen Hales (1677–1761) performed his famous experiment in 1733 demonstrating that blood rose to a height of 8 feet 3 inches in a glass tube placed in the artery of a horse.[5] His remarkable discovery of blood pressure was to lie fallow for nearly a hundred years. The failure of physiologists to apply Hales' discovery to human physiology is, perhaps, not surprising as the insertion of glass tubes measuring seven and a half feet, such was Hales's overestimation of human BP, was not likely to meet with general acceptance. A more acceptable measuring device was needed. This was provided by Jean-Leonard Marie Poiseuille (1799–1869) who reported the measurement of BP with a mercury sphygmomanometer in 1828.[6]

In 1847, Carl Ludwig (1816–1895), Professor of Comparative Anatomy at Marburg, made an even more significant advance than Poiseuille when he floated a writing pen on the mercury column of Poiseuille's manometer and using a revolving smoked drum introduced the kymograph[7] which was to find wide application in physiological studies.[8] This instrument was used by Faivre during a limb amputation to record systolic blood pressure for the first time in humans.[9] So dawned the next phase in the history of BP measurement – the development of methods for indirectly measuring BP in humans.

Indirect measurement of systolic blood pressure

The first device for measuring BP indirectly is usually attributed to Karl Vierordt (1818–1864) who invented the first of many sphygmographs in 1855.[10] However, credit for the first instrument capable of measuring BP indirectly should go to Jules Herisson, who, in 1833, devised an instrument which consisted of a mercury reservoir covered by a rubber membrane from which a graduated glass column arose. The mercury bulb was compressed against the radial artery until oscillation ceased in the mercury column at which point systolic pressure was estimated. Herrison described an association between a full pulse, left ventricular hypertrophy and apoplexy but inexplicably gives no BP measurements in such patients.[11] Vierordt and Herrison's instruments were each to influence the development of many BP-measuring devices in the nineteenth century.

Instruments based on the Vierordt sphygmograph

The talented and versatile French physiologist, Etienne Jules Marey (1830–1904), quickly recognized the potential of Vierordt's instrument which he simplified and made more accurate.[12]

The Marey sphygmograph was eventually replaced by a simpler and more accurate device introduced by a homeopath, Robert Ellis Dudgeon (1820–1904), in 1882[13] (Figure 2). This lightweight device which could be carried in the pocket (it weighed 4 ounces and measured 2″ × 2.5″) incorporated many of the principles of the Marey instrument but it was less complicated. Pressure was applied to the radial artery using a calibrated screw and a

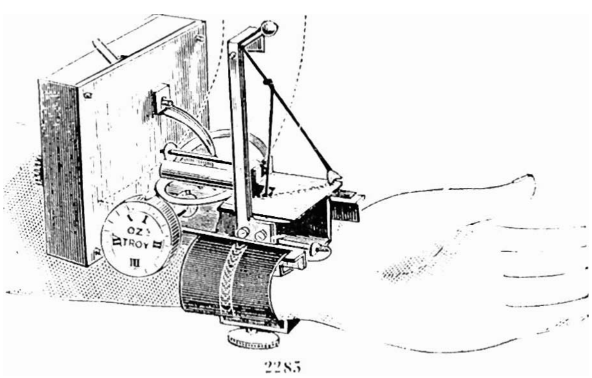

Figure 2 Dudgeon sphygmograph. Source: *Wholesale Illustrated Catalogue of Surgical Instruments and Medical Appliances*. Fannin & Co. Dublin, 1908, p. 314.

clockwork motor drove a strip of smoked paper under an oscillating metal tip to provide a record of the pulse wave. However, in general the sphygmograph was a disappointment. Clifford Albutt recognizing the problems of sphygmography advocated that physicians should be '. . . driven back upon the first, the readiest and still least dispensable of pulse gauges, namely the finger'.[14]

Arterial occluding devices

In 1875, von Kries, who worked in Ludwig's laboratory attempted to estimate the absolute pressure in skin capillaries by measuring the weight needed to blanch the skin.[15] Around the same time Marey, using air to compress an arm in a glass box, demonstrated that blanching of the arm occurred when systolic pressure was exceeded.[16] Later Marey substituted water for air as the compressing medium and he recorded oscillations in plethysmographic pressure using a tambour writing system.[17] These methods are, of course, inaccurate because the precise pressure level in the plethysmograph at which arterial pulsation disappears is difficult to determine. However, these techniques led Samuel Siegfried Ritter von Basch (1837–1905) to develop what he called the 'sphygmomanometer' in 1880.[18] This was the first reasonably accurate device for clinical measurement of BP. In von Basch's original instrument, the compressing medium, water, was enclosed in a rubber 'pelotte' or bulb which had a thin membrane on one side. Pressure was applied on the radial (or temporal) artery with the pelotte and as the pressure increased water was forced out of the pelotte into the closed arm of the manometer; the pulse was palpated with the fingers of the other hand, just beyond the point of compression, and the point of disappearance was taken as systolic pressure. Von Basch's instrument differed from those that had gone before in the important principle of providing pressure per unit of surface. Initially, the disappearance of the pulse was most easily determined by palpation but later von Basch connected the device to a sphygmograph to register the obliteration of the pulse. The instrument went through many modifications, the most significant of which was made by von Basch himself who substituted the mercury manometer with an aneroid manometer and it was eventually refined to portable dimensions making it suitable for clinical use (Figure 3).

The *fin de siecle* state was dominated by the Austrians and French who had contributed substantially to the developing speciality, not least through Marey. The Italians, however, would soon take the limelight.

Limb occluding devices

In some of his early experiments on BP measurement Marey had used a water-filled plethysmograph to apply pressure to the entire arm[16] and he later modified this apparatus for the finger instead

Physician to the City Hospital in New York, was as fully aware of the sources of error in the BP measuring technique to which we so frequently draw attention today, namely, the importance of ensuring that the arm is both relaxed and at heart level during measurement, that the cuff is deflated slowly, that an interval is allowed between measurements, and that 'an armlet of 12 cm width is adequate for any but the most enormous arms'.[24] Janeway also anticipated the expansion that was about to take place in clinical sphygmomanometry and recognized that this development would bring its own problems: 'The gradual development of various sphygmomanometers from which one may chose a clinical instrument to-day (1904), has been unfortunate in breeding more partisan bias and personal feeling than should find a place in the quest of scientific accuracy; but this evil has not been without its good side. It has led to the rigid scrutiny of each new instrument brought forward, and a diligent search for its faults'.[24]

In the early years of the twentieth century the most accurate research device for measuring systolic and diastolic BP was an instrument invented by a physiologist at Johns Hopkins Hospital and future Nobel prize-winner, Joseph Erlanger. It incorporated all the recent developments but in addition oscillations within the cuff were recorded across a membrane by means of an ingenious stopcock and observer bias was removed by using a kymograph to record the oscillations of the mercury column.[24] It was, of course too bulky for clinical use.

In 1906, von Recklinghausen published details on diastolic BP measurement using an aneroid tonometer[25] and three years later Dr V. Pachon, Chef du Laboratoire de Physiologie in the faculty of Medicine of Paris, successfully incorporated Erlanger's membrane in a portable recorder with an aneroid gauge.[26] Known initially as a sphygmo-oscillometer and later simply as an oscillometer, this instrument enjoyed popularity for many years and is prominently listed in catalogues of the 1930s (Price £5 5s. 0d.).[27]

Such devices brought sphygmomanometry into clinical medicine and so dawned a new era but not without protest. One commentator, while acknowledging that 'the middle-aged and successful physician may slowly and imperceptibly lose the exquisite sensitiveness of his finger tips through repeated attacks of gouty neuritis' doubted if the sphygmomanometer would be welcomed by 'the overworked and underpaid general practitioner, already loaded with thermometer, stethoscope, etc., etc., . . .'.[28] Harvey Cushing was probably the first to advocate the noting of BP on the bedside chart together with the temperature and pulse rate.[29]

Auscultatory measurement of systolic and diastolic blood pressure

In April 1905, a Russian surgeon, Nicolai Sergeivich Korotkov, presented a brief paper to the Imperial Military Academy in St. Petersburg and so founded the technique of auscultatory measurement of systolic and diastolic BP[30,31] (Figure 6).

William Dock has commented that 'the most remarkable fact about the Korotkov sound is that it was discovered'.[32] What is even more remarkable is that the sounds had been discovered some years before Korotkov published his masterly paper. In 1901, Theodore Janeway published a 20 page review of BP measurement in the *New York University Bulletin of the Medical Sciences* in which he wrote '. . . certain experiments in a number of cases concerning the pressure tone and murmur in the brachial, to be described later, show that the production of the tone always occurs at a lower pressure than the point in question (disappearance of secondary waves)'.[33] He concluded the paper with another tantalizing statement that undoubtedly indicates he was well on the way to making a notable discovery: 'It is to be hoped that some more satisfactory method for estimating mean arterial pressure may yet be devised. I have been making some experiments on the tone and murmur produced in the brachial artery by known pressures, thinking that some information might thus be obtained. The results will be reported in a subsequent article together with a consideration of the value of our present methods from a clinical standpoint'.

Figure 6 Nicolai Sergeivich Korotkov. Source: Segall, H.N. Discussion of Dr de Moulin's presentation on the History of Blood Pressure Measurement. *2nd Eithoven Meeting on Past and Present Cardiology: Blood Pressure Measurement and Systemic Hypertension*. Arntzenius, A.C., Dunning, A.J. & Snellen, H. A. (eds). Medical World Press, Breda, Holland, 1981, p. 35.

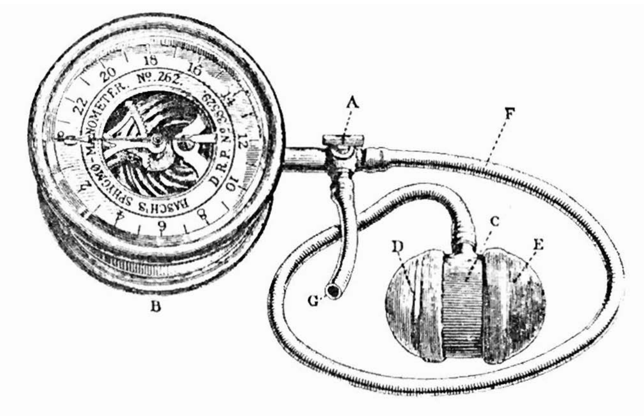

Figure 3 Portable von Basch sphygmomanometer. Source: de Moulin, D. A short history of blood pressure measurement. *2nd Eithoven Meeting on Past and Present Cardiology: Blood Pressure Measurement and Systemic Hypertension.* Arntzenius, A.C., Dunning, A.J. & Snellen, H. A. (eds) Medical World Press, Breda, Holland, 1981, p. 28.

of the arm.[19] However, the oscillations recorded were small and to overcome this problem, Mosso, in 1895, applied pressure to four fingers of each hand inserted into rubber stalls within metal tubes.[20] This apparatus, although cumbersome, was quite accurate.

The next step to an occluding arm cuff was made by Scipione Riva Rocci (1863–1939) in 1896[21] (Figure 4). Riva Rocci's cuff consisted of an inflatable rubber bladder enclosed in still leather encircling the upper arm. The bladder was inflated by a pump until the palpated pulse disappeared and the pressure was recorded by a mercury manometer.

Figure 4 Scipione Riva Rocci (1863–1939). Source: de Moulin, D. A short history of blood pressure measurement. *2nd Eithoven Meeting on Past and Present Cardiology: Blood Pressure Measurement and Systemic Hypertension.* Arntzenius, A.C., Dunning, A.J. & Snellen, H. A. (eds). Medical World Press, Breda, Holland, 1981, p. 28.

A year after Riva-Rocci's publication Hill and Barnard described an almost identical instrument except that an aneroid gauge was used instead of a mercury manometer.[22] These techniques removed the most serious error of their predecessors, namely, that associated with achieving uniform compression of the radial artery against bone with the small and awkward pelotte. However, it was not long before a serious source of error was identified in the new devices. Henrich von Recklinghausen (not to be confused with Friedrich von Recklinghausen of eponymous renown) in a series of elegant experiments in 1901 showed that the 5 cm wide cuff used by Riva-Rocci gave erroneously high systolic pressures which could be corrected by using a 12 cm wide cuff[23]; this was later confirmed by Janeway.[24]

The stage was now set for the next major development in BP measurement, namely, the measurement of both systolic and diastolic pressure. Although the existing instruments could be used to estimate diastolic pressure by observing the point of maximum oscillation, mean and diastolic pressure were often confused with each other and the significance of the latter was not clearly recognized at the close of the nineteenth century.[24]

Measurement of systolic and diastolic blood pressure by oscillometry

It is salutary to note that a century ago Theodore Caldwell Janeway (1872–1917) (Figure 5), Visiting

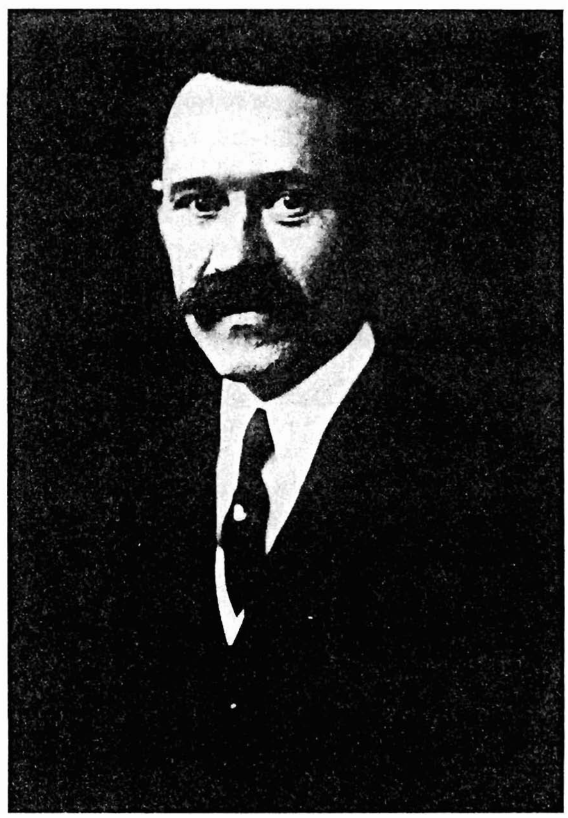

Figure 5 Theodore Caldwell Janeway. Source: National Library of Medicine, Bethesda, MD, USA.

Unfortunately Janeway did not elaborate on this intriguing statement and he makes no mention of auscultatory phenomena in his extensive monograph written in 1904. Had he done so we might now speak of 'Janeway sounds' but such is Korotkov's succinct description that eponymous approbation cannot be challenged.

Indeed, Korotkov's discovery might have languished in obscurity were it not for two of his contemporaries, D.O. Krilov and M.V. Yanovski. Within a year of Korotkov's presentation, Krilov published a paper entitled 'On measuring the blood pressure with the sound method of Korotkov' in which he described elaborate experiments attempting to elucidate the mechanism of Korotkov sound production.[34] Yanovski verified the accuracy of the technique which was known for some time as the Korotkov–Yanovski Method.[35] Ettinger is credited with describing the five phases of Korotkov sounds audible on cuff deflation.[36] The 'silent gap' was described in the English literature by Cook and Taussag[37] in 1917 and according to Geddes and colleagues this did not inspire confidence in the technique.[38] Gibson[39] attributed the first description of this phenomenon to a Frenchman, Tixier, who considered it to be a manifestation of mitral stenosis.

In America a comprehensive description of the Korotkov method was published in the *Archives of Internal Medicine* by J.C. Gittings in 1910.[40] In this paper he acknowledged the growing controversy as to whether muffling or disppearance of sounds should be taken as diastolic pressure but supported Korotkov and Ettinger in recommending the fifth phase. Such was to be the American view in the early years of the controversy but in Germany and Britain muffling of sounds rather than their disappearance was advocated.[41] Measurement of diastolic BP at the point of disappearance, as originally recommended by Korotkov, fell out of fashion within a few years and in 1926 we find Halls Dally quoting many studies demonstrating the superiority of muffling of sounds rather than disappearance as the most accurate measure of diastolic pressure,[42] a view which he endorsed in the third edition of his influential book in 1934.[43] This view was to persist until comparatively recently when Korotkov's original recommendation was once again adopted.[44] A more recent controversy has focused on the need to measure diastolic BP at all. Systolic BP, which is easier to measure accurately in clinical practice and does not require as complicated technology for automated measurement, may provide the same epidemiological information as measuring both pressures.[45–47] This issue remains to be resolved.

It is of interest to reflect that in 1918 the technique was treated as an important clinical procedure requiring considerable care and attention if accurate results were to be obtained. Among recommendations relating to patient anxiety, posture, arm level and an unequivocal direction to measure diastolic pressure at the disappearance of sounds, there is also a recommendation to withhold diagnostic decisions until a number of measurements have been made under varying conditions. In recording the results of measurement, the observer is asked to make note not only of the BP but also of the apparatus used, the width of the cuff, the limb examined and whether right or left and the time of day as well as the date.[48] We might well ponder how these aspects of the technique of BP measurement were obscured in the mists of time.

The age of clinical sphygmomanometry now began in earnest and with it came a problem that is all too familiar to-day: 'At the present time (1918) the market is flooded with instruments of all descriptions for estimating blood-pressure, so that it is important that the prospective purchaser should be able to separate the good from the bad . . .'.[48] There were mercury instruments with manometers incorporating a mercury reservoir and others with a U-tube similar to that first described by Poiseuille; there was a variety of aneroid devices which were marketed as 'pocket sphygmomanometers'; in addition a 'Multiple Sphygmometroscope' for training observers was also available.[48]

A number of interesting devices for obtaining graphic recordings of BP are described by Halls Dally.[42] In research, equipment was being adapted for the direct recording of intra-arterial BP, as with the Boulittograph[43] (Figure 7).

Development of the standard sphygmomanometer

The standard mercury and aneroid sphygmomanometers which are the mainstay of clinical sphygmomanometry have been improved over the years but their basic design does not differ greatly from the early models. However, in recent years there has been considerable concern about the inaccuracy of BP measurement.[49] There have been many critical evaluations of the technique[50] and a series of recommendations from official bodies, such as the British Hyptertension Society[51] and the American Heart Association,[52] for improving the accuracy of the method. The sources of inaccuracy of BP measurement have been previously reviewed[1,53] with two

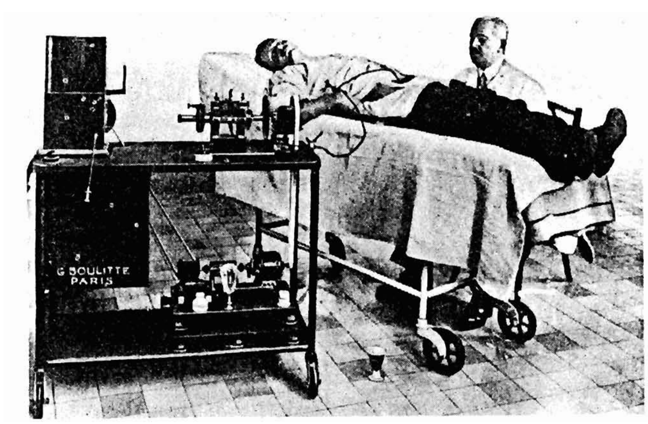

Figure 7 Boulittograph. Source: Halls Dally, J.F. *High Blood Pressure: Its Variations and Control*, 2nd edn. W. Heinemann, London, 1926, p. 66.

sources of error being emphasized, namely, bladder size and observer error.

Two devices were designed specifically for research use: the random zero sphygmomanometer that reduces observer prejudice and the London School of Hygiene sphygmomanometer that reduces both observer prejudice and terminal digit preference.

London School of Hygiene sphygmomanometer

The first such device to be introduced was the London School of Hygiene sphygmomanometer designed by Geoffrey Rose and his colleagues and often known as the 'Rose box'.[54] By means of a series of columns and plungers the observer records pressure by depressing the appropriate plunger at the end-points for systolic pressure and phases IV and V diastolic pressure without having any means of knowing the pressure in the cuff. The problems of terminal digit preference and observer prejudice were thus removed and the instrument became popular in epidemiological and research studies for many years. Rather surprisingly it was accepted as the standard for BP measurement without being subjected to validation. In 1982 a calibration error was demonstrated[55] which has not been rectified and the instrument is not now much used.

Random zero sphygmomanometer

In 1963, John Garrow described a 'zero-muddler for unprejudiced sphygmomanometry'[56] which was modified by Wright and Dore in 1970[57] and produced commercially by Hawksley and Sons. It is larger than a conventional sphygmomanometer and some ten times more expensive. The manometer function is similar to the mercury sphygmomanometer but a wheel is spun before each measurement to adjust the zero to an unknown level. Once the BP has been measured the level of zero may be determined and the pressure reading corrected. In this way observer prejudice is reduced but not digit preference. This device has been generally accepted as the instrument of choice for epidemiological and research studies on the basis that it reduces observer bias but recent studies have shown that it does not generate random numbers[58] and it has been shown to systematiclly give lower readings than the standard mercury sphygmomanometer.[59] It is therefore no longer recommended in its present design for research and epidemiological studies.

Development of automated techniques

However complex the evolution of sphygmomanometry may have been prior to the introduction of the Korotkov technique, the technological advances of the twentieth century have been such that many automated devices have been manufactured and a detailed history is outside the compass of this review. A variety of devices dependent on alternative mechanisms have been developed in recent years; these include devices dependent on Korotkov sound detection, oscillometry and ultrasonic techniques. Other techniques have utilized the phase-shift method, infrasound recording, wideband external pulse recording, plethysmography and tonometry but, as with other automated devices, the results of validation have often been disappointing. A review of these techniques may be found in the chapter on which this paper is based.[1] The most important consequence of technological and computer development in BP measurement has been the technique of 24-hour BP measurement.

Ambulatory measurement of blood pressure

or not the first time in this review we must turn to Theodore Janeway who, as far back as 1904, drew attention to the variability of BP and the striking response to stresses, such as surgery, tobacco and anxiety.[24] A quarter of a century later Horace Smirk and his colleagues attempted to assess BP behaviour in the individual by measuring basal BP[60] and, in 1940, Ayman and Goldshire showed that BP measured at home was lower than in the clinic.[61] Using a noninvasive apparatus that employed a Gallavardin double cuff, Sir George Pickering and his group at Oxford showed for the first time how constant and profound was the fall in BP recorded during sleep. They also demonstrated the fluctuations in pressure during the course of 24 hours.[62]

This system, which was not portable, did not permit measurement during unrestricted activity and Pickering's group went on to develop an ambulatory technique whereby pressure could be measured directly from the brachial artery with a small plastic catheter.[63] The first intra-arterial ambulatory BP measurement was performed in Oxford in 1966 and the first publication reporting BP changes in unrestricted humans was in 1969.[64]

Intra-arterial measurement of ambulatory blood pressure

The Oxford system has been adopted by other centres to provide important information on BP behaviour.[65,66] It soon became apparent that BP varied considerably in response to a variety of stresses which included the presence of a doctor, nurse or technician (any one of which was capable of inducing the orienting reflex or defense reaction),[67] lecturing, driving a motor car[68] and having sexual intercourse.[69] Furthermore, ambulatory measurement made it possible to determine not only the BP-lowering effects of antihypertensive drugs but also their duration of action.[70] Perhaps most excitingly of all, 24h ambultory recordings of BP provided sufficient data for the characterization of nocturnal BP[71] and the diurnal pattern of BP,[72] a subject reviewed with characteristic clarity by Pickering in 1964.[67]

These studies, although offering new insights into BP behaviour, had little if any effect on clinical practice chiefly due to the limitations of invasive intra-arterial measurement, not least being the dangers inherent in the procedure.[63,73] Attention was turned, therefore, towards developing a device that would measure ambulatory BP noninvasively. The early history of ambulatory BP measurement has been reviewed by Pickering and Stott[63] and Horan and his colleagues.[74]

Noninvasive intermittent measurement of ambulatory blood pressure

Daytime ambulatory blood pressure In the 1960s a number of attempts were made to provide a noninvasive alternative to direct intra-arterial measurement of BP. These early developments in the technique have been reviewed by Pickering.[67] In 1962, Hinman and his colleages described the first truly portable ambulatory system for the noninvasive measurement of BP.[75] The Remler Company of California developed this system commercially[76] (Figure 8) and so began an important era in hypertension management, the effects of which are only now being fully appreciated; the system was used by a number of workers who validated its accuracy.[77–80]

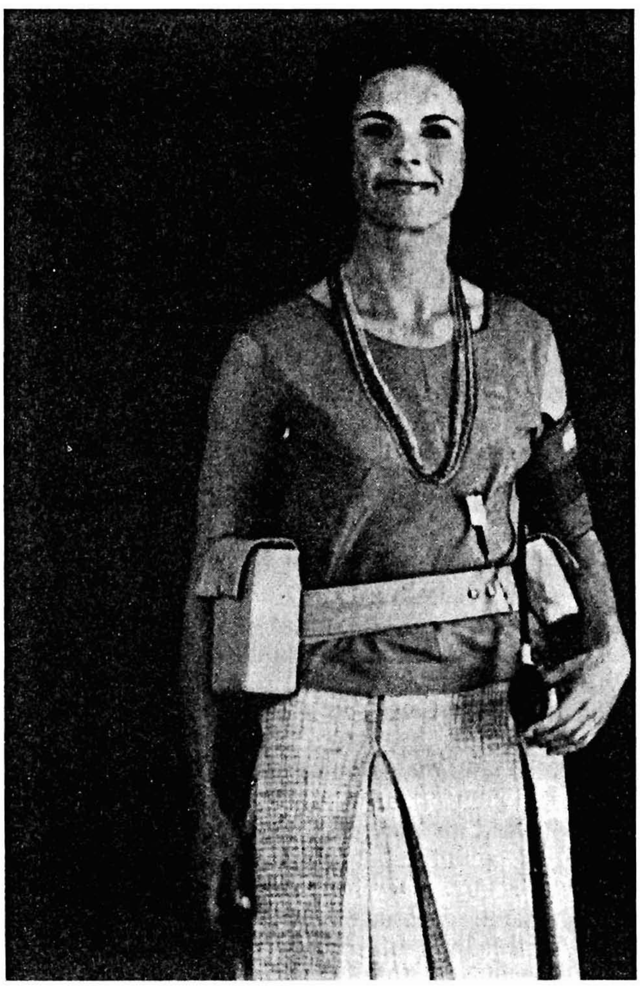

Figure 8 The Remler ambulatory blood pressure recorder. Source: Kain, H.K., Hinman, A.T. & Sokolow, M. Arterial blood pressure measurements with a portable recorder in hypertensive patients. I. Variability and correlation with 'casual' pressures. *Circulation* 1964, **30**: 882–892.

As with intra-arterial measurement, the Remler system provided new insights into BP behaviour[81] and new data on antihypertensive drug efficacy and duration of effect.[82,83] Among the most important aspects of hypertension studied with the Remler was the demonstration by Sokolow and his colleagues that ambulatory BP was a better predictor of morbidity and mortality than casual office pressure.[84,85]

24h ambulatory BP With the development of compact pumps and solid state memory systems, the Remler system was replaced by devices capable of automatically inflating the cuff and providing pressures intermittently over 24 hours. However, despite the many technological developments in equipment design, the Remler remains unique in having possessed one outstanding merit, namely, the facility that enabled the operator to listen to the recordings on tape and thereby distinguish between Korotkov sounds and artefactual noise.

In 1979, Harshfield and his colleagues at Cornell, validated the Del Mar Avionics Pressurometer II Ambulatory ECG and Blood Pressure Recording System.[86] This system, which was fully automated, permitted the measurement of BP throughout the 24 hours noninvasively. Early models were bulky and noisy but the Del Mer system has been modified and made more portable over the years. By providing a noninvasive profile of BPs over the 24h period, it has been used extensively in assessing circadian patterns in normotensive[87] and hypertensive subjects[88] and in demonstrating the duration of action of antihypertensive drugs. The Avionics system was followed by a number of automated devices for the measurement of 24h BP.[89] Systems, such as the latest SpaceLabs device, model 90207 (Figure 9), is pocket-sized with an almost noiseless pump.[90] Some systems measure BP by Korotkov sound detection, with or without ECG gating, and others use oscillometry.[89] These instruments are expensive and strict accuracy criteria are being demanded from manufacturers.[91]

Being noninvasive and almost completely free of adverse effects, these automated systems capable of giving accurate profiles of BP behaviour over 24 hours, have found much wider use in research and

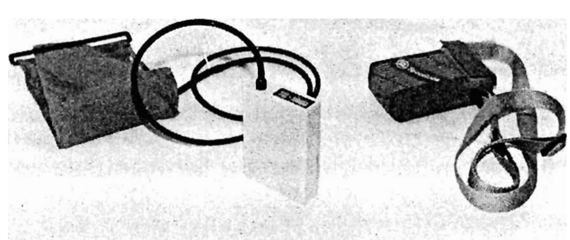

Figure 9 SpaceLabs 90207. Source: Photograph of model in the author's possession.

clinical practice than was ever possible with invasive techniques. The concept of white coat hypertension, the phenomenon whereby BP recorded by doctors and nurses is much higher than ambulatory daytime pressure, a theme so strikingly developed by Sir George Pickering in the 1960s in Oxford, has been elucidated by his son Professor Thomas Pickering at Cornell.[92] Recently profiles of 24h BP in normal subjects have been characterized in population studies.[93] It may now be anticipated that ambulatory BP will become indispensable in the assessment of patients with elevated BP.[94]

Noninvasive continuous measurement of ambulatory blood pressure

The main disadvantages of the above systems are that they only provide intermittent measurement of 24h BP and that the subject has to cease activity during the measurement of BP. Although intermittent BPs give circadian BP patterns that are surprisingly close to intra-arterial pressures,[95] there is a limit to the number of pre-set measurements a subject can be expected to tolerate and, moreover, there comes a point at which intermittent measurements interfere with normal ambulatory activity. In clinical studies ambulatory measurements are usually made at no less than 15 minute and in clinical practice at 30 minute intervals. The next advance in BP measurement is likely to be the development of accurate systems that will provide continuous 24h BP allowing detailed wave-form scrutiny and beat-to-beat analysis – in short, the equivalent of direct intra-arterial measurement without the inherent dangers of invasive catherization.

In 1968, Penaz patented a servo-plethysmomanometer based on the vascular unloading principle using a light source and photocell in a finger cuff.[96] In 1973, he presented the technique at Dresden.[97] The cuff of the instrument is inflated above systolic pressure and deflated until maximum unloading of the arterial wall occurs at the point of mean arterial pressure. This signal is used as a reference standard to vary cuff pressure with the pulse so that maximum unloading is maintained throughout arterial pressure recording. Penaz's technique has been modified by Wesseling in The Netherlands[98] and manufactured as the Finapres (FINger arterial PRESsure). This device may prove to be an acceptable alternative to direct intra-arterial measurement for the continuous recording of BP.[99,100]

Technological advances must soon provide accurate alternatives to the traditional techniques of BP measurement. Recently, the Association for the Advancement of Medical Instrumentation and the British Hypertension Society have published revisions of their earlier published criteria for the evaluation of BP-measuring devices.[91,101] It will be necessary, therefore, in future for manufacturers to provide evidence of independent validation of the many innovative techniques that the future promises. Writing in 1987, Garrett and Kaplan stated that 'ambulatory blood pressure monitoring on a 24h basis is an idea whose time has come'.[102] This is an appropriate note on which to close this section on the history of ambulatory measurement, signalling the end of an era and the beginning of a new epoch, that in which assessment of the individual with suspected BP elevation will no longer be dependent on isolated measurements made under strange circumstances but dependent rather on evaluation of a 24h profile of BP behaviour in more natural surroundings than the hospital clinic or family doctor's office. The future holds promise, moreover, for more rational selection of antihypertensive drug therapy so that treatment will be evaluated according to the individual pattern of diurnal BP.

Historically it is of interest to note that ambulatory measurement had its origins in a noninvasive technique, followed by an invasive era during which much valuable information on BP behaviour was gathered and now with developments in technology the technique has returned to noninvasive methodology.

ENVOI

It is just over 250 years since the Reverend Stephen Hales discovered BP and provided the crude principles of direct measurement. It is a little over 100 years since von Basch and Riva Rocci devised instruments enabling the measurement of systolic BP in clinical practice and just 85 years since Nicolai Korotkov introduced the auscultatory technique of BP measurement that remains the 'gold standard' of measurement to this day.

This review commenced in critical wonderment at the lapse of a century between Harvey's discovery of the circulation and Hales's description of BP and the similar delay before BP measurement was applied to humans. These lacunae in the development of scientific thought can be excused, at least to some extent, by the inadequacy of the technical facilities at the disposal of these pioneering scientists. The discovery of rubber, for example, by making possible secure connections between pressure detecting systems and a manometer, did more to advance BP measurement than did the development of scientific ideas.

No such reasoning can vindicate the paucity of development in BP measurement in this century, most especially, in the latter quarter, a period which future historians will refer to as 'the technological age'. It becomes evident from a historical review, such as this, that the indifference of practitioners of BP measurement (for the greater part doctors, a significant number of whom would wish to be judged as 'scientists') to the accuracy of the scientific principles of methodology so carefully enunciated by early researchers has resulted in those principles being relaxed rather than developed in the light of advances in knowledge. That the past decade should witness a revival of the criteria so clearly laid down by Theodore Janeway and others in the early years of the century or that resources need be expended on persuading manufacturers to restore the dimensions of the inflatable bladder to those which had been accepted as integral to the technique in the first half of the century must surely place a serious question mark against scientific reasoning.

Critical though historical analysis may force us to be of our failure to preserve the fundamental aspects of measurement and to capitalize on the elaborate technology (to which we are heirs) to improve the procedure, the sternest historical indictment from future generations will be directed at our insistence on permitting isolated BP measurements to dictate diagnostic and management policies of hypertension in the light of an abundance of evidence, beginning with Janeway's studies in 1904 and emphasized by Pickering's (Figure 10) Oxford group in the 1960s, showing the variability of BP and the effect of doctors themselves on the very quantity they are attempting to measure. How many patients have been subjected to unnecessary or inappropriate therapy, and continue to be so mismanaged at the time of writing, is a matter of such concern that we must bow in gratitude to those of our predecessors who perceived the way forward so clearly while acknowledging the lessons of history that can alert us to our ineptitudes and direct our future endeavours.

Acknowledgements

This paper is based on Chapter I, The history of indirect blood pressure measurement by E. O'Brien and D. Fitzgerald. In: Birkenhager WH, Reid JL (series eds) *Handbook of Hypertension*. Vol. 14, O'Brien E, O'Malley K (eds). *Blood Pressure Measurement*. Amsterdam, Elsevier, 1991, pp. 1–54. We are grateful to the editors of the series for permission to publish this short paper. The reader in search of more historical detail is referred to this chapter.

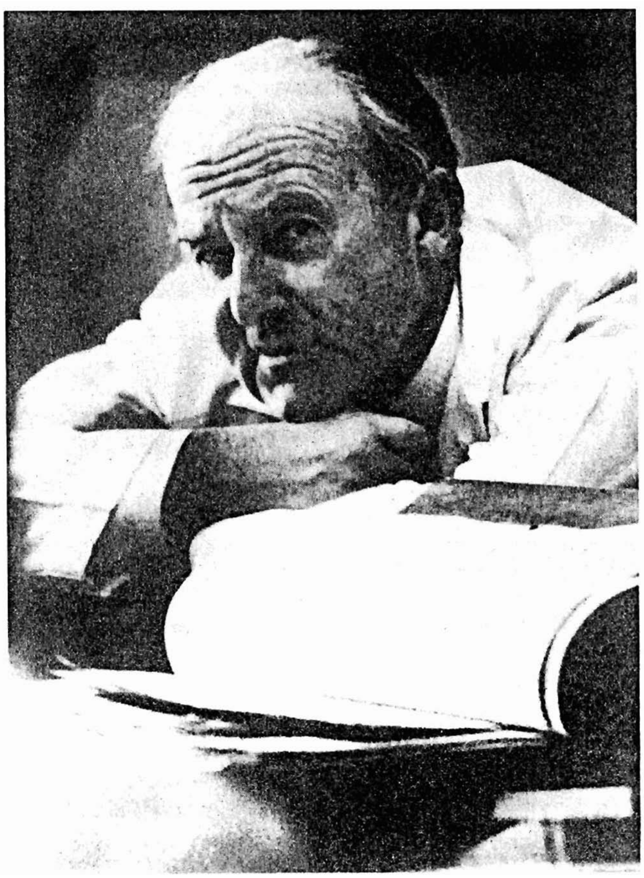

Figure 10 Sir George Pickering. Source: Pickering, G. *The Nature of Essential Hypertension*. J. & A. Churchill Ltd, London, 1961. Reprinted 1981. Frontispiece.

References

(Where work from books is cited more than once, the first reference number is given in the text but pagination citation is given in order of citation for the reference.)

1. O'Brien, E. & Fitzgerald, D. The history of indirect blood pressure measurement. In: Birkenhager WH, Reid JL. (series eds) *Handbook of Hypertension*. Vol. 14, O'Brien E., O'Malley K. (eds). *Blood Pressure Measurement*, Amsterdam, Elsevier, 1991, pp. 1–54.
2. Huang, T., Ching, N. & Wên, S. *The Yellow Emperor's Classic of Internal Medicine*. Translated by Veith, I, University of California Press, 1949.
3. Gispen, J.G. 'Measuring' the patient in ancient medical texts. *Acta Clin Belg* 1974, **29**: 224–227.
4. Harvey, W. *Exercitatio Anatomica de Motu Cordis et Sanguinis in Animalibus*. A Facsimile of the 1628 Francofurti Edition with the Keynes English Translation of 1928. The Classics of Medicine Library, Birmingham, Alabama, 1978.
5. Hales, S. *Statistical Essays: containing Haemostatics*. W. Innys & R. Manby, London, 1733, vol. ii. p. 1 *et seq*.
6. Poiseuille, J.L.M. Recherches sur la force du coeur aortique. Thesis No. 166, Didot, Paris, 1828 and *J Physiol Exp* 1828, **8**: 272.
7. Ludwig, G. Beitrage zur Kenntniss des Einflusses der Respirationsbewegungen auf den Blutlauf im Aortensysteme. *Mullers Archiv Anat Physiol Wissensch Med* 1847, pp. 242–302.
8. Booth, J. A short history of blood pressure measurement. *Proc R Soc Med* 1977, **70**: 793–799.
9. Faivre, J. Etudes experimentales sur les lesions organiques du coeur. *Gaz Med Paris* 1856, p. 727.
10. Vierordt, K. *Die Lehre vom Arterienpuls, F. Vieweg, Braunschweig*, 1855.
11. Herrison, J. (translated by ES Blundell). *The sphygmomanometer, an Instrument that makes the Arteries apparant to the Eye*. Longman, Rees, Orme and Brown, London, 1835.
12. Marey, E.J. *Physiologie medicale de la circulation du sang*. Adrien Delahaye, Paris, 1863, p. 176.
13. Dudgeon, R.E. *The Sphygmograph*. Bailliere, Tindall & Cox, London, 1882.
14. Albutt, C. *Diseases of the Arteries including Angina Pectoris*. Macmillan, London, 1915, vol. 1, p. 65.
15. Von Kries, N. Ueber den Druck in den Blutcapillaren den menschlichen Haut. *Leipzig Math Phys Ber* 1875, **27**: 149–160.
16. *Physiologie experimentale: Travaux du laboratorie de M. Marey*. G. Masson, Paris, 1876, vol. 2, pp. 309–331.
17. Lawrence, C. Physiological apparatus on the Wellcome Museum. 3. Early sphygmomanometers. *Med Hist* 1979, **23**: 474–478.
18. Von Basch, S. Ueber die Messung des Blutdrucks am Menschen *Zit Klin Med* 1880, **2**: 79–96. English translation In: Ruskin, A. *Classics in Arterial Hyper-*

tension. Charles C Thomas, Springfield, Ill, 1956, pp. 83–102.
19. *Physiologie experimentale: Travaux du laboratorie de M. Marey*. G. Masson, Paris, 1876, vol. 2, pp. 253–257.
20. Mosso, A. Sphygmomanometre pour mesurer la pression du sang chez l'homme. *Arch Ital Biol* 1895, **23**: 177.
21. Riva Rocci, S. Un nuovo sfigmomanometro. *Gazz Medi di Torino* 1896, **50**: 981–996; **51**: 1000–1017.
22. Hill, L. & Barnard, H. A simple and accurate form of sphygmomanometer or arterial pressure gauge contrived for clinical use. *Br Med J* 1897, **2**: 904.
23. Von Recklinghausen, H. Ueber Blutdruckmessung beim Menschen. *Arch Exper Pathol Pharmakol* 1901, **xlvi**: 78.
24. Janeway, T.C. *The Clinical Study of Blood-Pressure*. D Appleton & Co, New York and London, 1904, pp. 58, 69–74, 59–66, 77, 93–100, 112–132.
25. Von Recklinghausen, H. Unblutige Blutdruckmessung. *Arch Exp Path Pharm* 1906, **55**: 375–504.
26. Pachon, V. Papers of 1909 in *Comptes rendus de la Soc de Biol* cited by Halls Dally, JF. The clinical determination of blood pressure by means of Pachon's sphygmo-oscillator. *Br Med J* 1911, **2**: 813–814.
27. *Sphygmomanometers and Polygraphs*. Catalogue of Hawlsley & Sons Ltd, London, *c* 1931, p. 14.
28. Blake, E. Recent British researches on arterial tension. *Med Times Gaz* 1895, **23**: 29–30.
29. Cushing, H. On the routine determination of arterial tension in the operating room and clinic. *Boston Med Surg J* 1903, **148**: 250.
30. Korotkov, N.C. To the question of methods of determining the blood pressure (from the clinic of Professor CP Federoff). *Reports of the Imperial Military Academy* 1905, **11**: 365–367.
31. Laher, M. & O'Brien, E. In search of Korotkoff. *Br Med J* 1982, **285**: 1796–1798.
32. Dock, W. Korotkoff sounds. *New Engl J Med* 1980, **302**: 1264–1267.
33. Janeway, T.C. Some observations on the estimation of blood pressure in man, with especial reference to the value of the results obtained with the newer sphygmomanometers. *New York Univ Bull Med Sci* 1901, **1**: 106–126.
34. Krilov, D.O. On measuring the blood pressure by the sound method of Dr N.S. Korotkov. *Bull Imperial Mil Med Acad (St. Petersburg)* 1906, **13**: 221.
35. Mobchanor, N.W., Mishtenko, A.S. & Silvertov, V.P. New state in cardiology. *J Surg Anaesthesiol (Moscow)* 1971, **4**: 6–9.
36. Ettinger, W. Auskultatorische Methode der Blutdruckbestimmung und ihr praktischer Wert. *Wien Klin Woch* 1907, **20**: 992–996.
37. Cook, J.E. & Taussig, A.E. Auscultatory blood pressure determination. *JAMA* 1917, **68**: 1088.
38. Geddes, L.A., Hoff, H.E. & Badger, A.S. Introduction of the auscultatory method of measuring blood pressure – including a translation of Korotkoff's original paper. *Cariovasc Res Center Bull* 1966, **5**: 57–74.
39. Gibson, P.C. Silent gap in auscultatory estimation of blood pressure. *Lancet* 1927, **2**: 1003.
40. Gittings, J.C. Auscultatory blood pressure determinations. *Arch Intern Med* 1910, **6**: 196–204.
41. Warfield, L.M. Studies in auscultatory blood pressure phenomena. *Arch Int Med* 1912, **10**: 258–267.
42. Halls Dally, J.F. *High Blood Pressure: Its Variations and Control*. W Heinemann, London, 1926, 2nd edn., pp. 13, 19–22, 31–41.
43. Halls Dally, J.F. *High Blood Pressure: Its Variations and Control*. W Heinemann, London, 1934, 3rd edn, pp. 14–15, 22–24, 14–15.
44. O'Brien, E. & O'Malley, K. Blood pressure measurement: technique. In: *ABC of Hyptertension*. British Medical Journal, London, 1981, p. 9.
45. Fisher, C.M. The ascendency of diastolic blood pressure over systolic. *Lancet* 1985, **ii**: 1349–1350.
46. Ramsay, L.E. & Waller, P.C. Strokes in mild hypertension: diastolic rules. *Lancet* 1986, **ii**, 854–856.
47. Weismann, D.N. Systolic or diastolic blood pressure significance. *Pediatrics* 1988, **82**: 112–114.
48. Faught, F.A. *Blood-Pressure Primer: The Sphygmomanometer and its Practical Application*. G.P. Pilling, Philadelphia, 1918, p. 24–50, 24, 42.
49. O'Brien, E. & O'Malley, K. Blood pressure measurement. In: *ABC of Hypertension*. British Medical Association, London , 2nd edn, 1987, pp. 1–19.
50. King, G. Some sources of error in the clinical measurement of blood pressure. *Thesis for Doctorate of Medicine*, University of London, 1967.
51. Petrie, J.C., O'Brien, E.T., Littler, W.A. & de Swiet, M. Recommendations on blood pressure measurement. British Hypertension Society. *Br Med J* 1986, **293**: 611–615.
52. Kirkendall, W.M., Feinleib, M., Fries, E.D. & Mark, A.L. Recommendations for human blood pressure determination by sphygmomanometers. *Hypertension* 1981, **3**: 509A–519A.
53. O'Brien, E. & O'Malley, K. Clinical blood pressure measurement. In: Birkenhager, W.H. & Reid, J.L. (series eds). *Handbook of Hypertension*. Vol. 15, Robertson, J.I.S. (ed.) *Clinical Hypertension*. Amsterdam, Elsevier, 1992, pp. 14–50.
54. Rose, G.A., Holland, W.W. & Crowley, E.A. A Sphygmomanometer for epidemiologists. *Lancet* 1964, **i**: 296–300.
55. Fitzgerald, D., O'Callaghan, W., O'Malley, K. & O'Brien, E. Inaccuracy of the London School of Hygiene sphygmomanometer. *Br Med J* 1982, **284**: 18–19.
56. Garrow, J.S. Zero-muddler for unprejudiced sphygmomanometry. *Lancet* 1963, **iv**: 1205.
57. Wright, B.M. & Dore, C.F. A random-zero sphygmomanometer. *Lancet* 1970, **i**: 337–378.
58. Beevers, M., Beevers, D.G. & Churchill, D. *et al.* Random zero sphygmomanometer. *Am J Hypertens* 1993, **6**: 94–95 (letter).
59. O'Brien, E., Mee, F., Atkins, N. & O'Malley, K. Inaccuracy of the Hawksley random zero sphygmomanometer. *Lancet* 1990, **336**: 1465–1468.
60. Smirk, J.F. Casual and basal blood pressures. IV. Their relationship to the supplemental pressure with a note on statistical implications. *Br Heart J* 1944, **6**: 176–182.
61. Ayman, D. & Goldshine, A.D. Blood pressure determination by patients with essential hypertension *Am J Med Sci* 1940, **200**: 465–474.
62. Richardson D.W., Honour, A.J., Fenton, G.W., Stott, F.D. & Pickering, G.W. Variations in arterial blood pressure throughout the day and night. *Clin Sci* 1964, **26**: 445–460.
63. Pickering, G. & Stott, F.G. Ambulatory blood pressure – a review. *Proceedings of the Third International Symposium on Ambulatory Monitoring*. Academic Press, London 1979, pp. 135–145.
64. Bevan, A.T., Honour, A.J. & Stott, F.H. Direct arterial pressure recording in unrestricted man. *Clin Sci* 1969, **36**: 329–344.
65. Mancia, G., Bertinieri, G., Grassi, G., Pomidossi, G., Parati, G., Gregorini, L. & Zanchetti, A. Effects of blood pressure measurement by the doctor on patient's blood pressure and heart rate. *Lancet* 1983,

2: 695–698.
66. Millar-Craig, M.W., Hawes, D. & Whittington, J. A new system for recording ambulatory blood pressure in man. *Med Biol Eng Comput* 1978, **16**: 727–731.
67. Pickering, G. *High Blood Pressure*. J. & A. Churchill, London, 2nd edn, 1968, pp. 12, 92–101, 19–20.
68. Littler, W.A., Honour, A.J. & Sleight, P. Direct arterial pressure and electrocardiogram during motor car driving. *Br Med J* 1973, **2**: 273–277.
69. Littler, W.A., Honour, A.J. & Sleight, P. Direct arterial pressure, heart rate and electrocardiogram during human coitus. *J Reprod Fertil* 1974, **40**: 321–331.
70. Millar-Craig, M.W., Kenny, D., Mann, S., Bala Subramanian, V. & Raftery, E.B. Effect of once daily atenolol on ambulatory blood pressure. *Br Med J* 1979, **1**: 237–238.
71. Littler, W.A., Honour, A.J., Pugsley, D.J. & Sleight, P. Continuous recording of direct arterial pressure in unstricted patients: its role in the diagnosis and management of high blood pressure. *Circulation* 1975, **51**: 1101–1106.
72. Millar-Craig, M.W., Bishop, C.N. & Raftery, E.B. Circadian variation of blood pressure. *Lancet* 1978, **1**: 795–797.
73. Mann, S., Jones, R.I., Millar-Craig, M.W., Wood, C., Gould, B.A. & Raftery, E.B. The safety of ambulatory intra-arterial pressure monitoring: a clinical audit of 1000 studies. *Int J Cardiol* 1984, **5**: 585–597.
74. Horan, M.J., Padgett, N.E. & Kennedy, H.L. Ambulatory blood pressure monitoring: recent advances and clinical application. *Am Heart J* 1981, **101**: 843–847.
75. Hinman, A.T., Engel, B.T. & Bickford, A.F. Portable blood pressure recorder. Accuracy and preliminary use in evaluating intradaily variations in pressure. *Am Heart J* 1962, **63**: 663–668.
76. Kain, H.K., Hinman, A.T. & Sokolow, M. Arterial blood pressure measurements with a portable recorder in hypertensive patients. I. Variability and correlation wtih casual pressures. *Circulation* 1964, **30**: 882–892.
77. Clement, D.L., De Pue, N., Packet, L., Bobelyn M. & van Maele, G.O. Performance of noninvasive ambulatory blood pressure recordings. *J Hypertens* 1983, **1** (Suppl. 2): 296–298.
78. Fitzgerald, D.J., O'Callaghan, W.G., McQuaid, R., O'Malley, K. & O'Brien, E. Accuracy and reliability of two indirect ambulatory blood pressure recorders: Remler M2000 and Cardiodyne Sphygmolog. *Br Heart J* 1982, **48**: 572–579.
79. Gould, B.A., Hornung, R.S., Kieso, H.A., Altman, D.A., Cashman, P.M.M. & Raftery, E.B. Evaluation of the Remler M2000 blood pressure recorder: comparison with intraarterial blood pressure recordings both at hospital and at home. *Hypertension* 1984, **6**: 209–215.
80. Brunner, H.R., des Combes, B.J., Waeber, B. & Porchet, M. Accuracy and reproducibility of ambulatory blood pressure recordings obtained with the Remler system. *J Hypertens* 1983, **1** (Suppl. 2): 291–292.
81. Riess, W.F., Werdegar, D. & Sokolow, M. Blood pressure responses to daily life events. *Trans Assoc Life Ins Med Dir Am* 1967, **51**: 116–129.
82. O'Malley, K., O'Brien, E. & Brennan, M. The contribution of non-invasive ambulatory blood pressure measurement to antihypertensive drug evaluation. In: *ISAM 1985, Proceedings of the Fifth International Symposium of Ambulatory Monitoring*. Dal Palu, C. & Pessina, A.C. (eds) Cleup Editore, Italy, 1986, pp. 255–263.
83. Brunner, H.R., Waeber, B. & Nussberger, J. Clinical use of non-invasive ambulatory blood pressure recordings. *J. Hypertens* 1985, **3** (Suppl. 2): S13–S17.
84. Sokolow, M.D., Werdegar, H.K., Kain, H.K. & Hinman, A.T. Relationship between level of blood pressure measured casually and by portable recorders and severity of complications in essential hypertension. *Circulation* 1966, **34**: 279–298.
85. Perloff, D., Sokolow, M. & Cowan, R. The prognostic value of ambulatory blood pressures. *JAMA* 1983, **240**: 2792–2798.
86. Harshfield, G.A., Pickering, T.F. & Laragh, J.H. A validation of the Del Mar Avionics ambulatory blood pressure system. *Ambul Electrocard* 1979, **1**: 7–12.
87. Weber, M.A., Drayer, J.I.M., Nakamura, D.K. & Wyle, F.A. The circadian pressure pattern in ambulatory normal subjects. *Am J Cardiol* 1984, **54**: 115–119.
88. Pickering, T.G. & Gerin, W. Ambulatory blood pressure monitoring and cardiovascular reactivity testing for evaluation of the role of psychosocial factors and prognosis in hypertensive patients. *Am Heart J* 1988, **116**: 665–672.
89. O'Brien, E. & O'Malley, K. Twenty-four-hour ambulatory blood pressure monitoring: a review of validation data. *J. Hypertens* 1990, **8** (Suppl. 6): S11–S16.
90. O'Brien, E., Mee, F., Atkins, N. & O'Malley, K. An evaluation of the SpaceLabs 90207 ambulatory recorder according to the British Hypertension Society Protocol. *J Hypertens* 1991, **9**: 573–574.
91. O'Brien, E., Petrie, J., Littler, W., de Swiet, M., Padfield, P.L., Altman, D., Bland, M., Coats, A. & Atkins, N. The British Hypertension Society Protocol for the evaluation of blood pressure measuring devices *J Hypertens* 1993 (in press).
92. Pickering, T.G., James, G.D., Boddie, C., Harshfield, G.A., Blank, S. & Laragh, J.H. How common is white coat hypertension? *JAMA* 1988, **259**: 225–228.
93. O'Brien, E., Murphy, J., Tyndall, A., Atkins, N., Mee, F., McCarthy, G., Staessen, J., Cox, J. & O'Malley, K. 24-hour ambulatory blood pressure in men and women aged 17 to 65 years: the Allied Irish Bank study. *J Hypertens* 1991, **9**: 335–360.
94. O'Brien, E., Fitzgerald, D. & O'Malley, K. Blood pressure measurement: current practice and future trends. *Br Med J* 1985, **290**: 729–734.
95. Di Rienzo, M., Grassi, G., Pedotti, A. & Mancia, G. Continuous vs intermittent blood pressure measurements in estimating 24-hour average blood pressure. *Hypertension* 1983, **5**: 264–269.
96. Molhoek, P.G. Evaluation of the Penaz servo-plethysmo-manometer for continuous, non-invasive measurement of finger blood pressure. In: Arntzenius, A.C., Dunning, A.J. & Snellen, H.A. (eds). *Blood Pressure Measurement and Systemic Hypertension*. Medical World Press, Holland, 1981, pp. 157–162.
97. Penaz, J. Photoelectric measurement of blood pressure, volume and flow in the finger. *Digest of the International Conference on Medicine and Biological Engineering*. Dresden, Conference Committe of the Xth Internatonal Conference on Medicine and Biological Engineering, 1973, p. 104.
98. Wesseling, K.H. Finapres, continuous noninvasive finger arterial pressure based on the method of Penaz. In: Meyer-Sabellek, W., Anaulf, M., Gotzen, R., Steinfeld, L. (eds) *Blood Pressure Measurements: New Techniques in Automatic and 24-hour Indirect Monitoring*. Steinkopff Verlag, Darmstadt, Springer-Verlag, New York, 1990, pp. 161–172.
99. Imholz, B.P.M., van Montfrans, G.A., Settels, J.J., van der Hoeven, G.M.A., Karemaker, J.M. & Wieling, W. Continuous non-invasive blood pressure monitor-

ing: reliability of Finapres device during Valsalva manoeuvre. *Cardivasc Res* 1988, **22**: 390–397.
100. Parati, G., Casadei, R., Groppelli, A., Di Rienzo, M. & Mancia, G. Comparison of finger and intra-arterial blood pressure monitoring at rest and during laboratory testing. *Hypertension* 1989, **13**: 647–655.
101. White, W.B., Berson, A., Robbins, C., Jamieson, M.J., Prisant, M.L., Rocella, E. & Sheps, S. National standard for measurement of resting and ambulatory blood pressure with automated sphygmomanometers. *Hypertension* 1993, **21**: 504–509.
102. Garrett, B.N. & Kaplan N. Ambulatory blood pressure monitoring: a question for now and the future. *J Clin Hypertens* 1987, **3**: 378–380.