Handbook of Hypertension, Vol 14: Blood Pressure Measurement
E. O'Brien and K. O'Malley, editors

1. The history of indirect blood pressure measurement

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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 (Fig. 1). That the discovery of blood pressure was virtually ignored by the scientific community for almost a century is somewhat 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.

This chapter will consider the subject under the following headings which outline only in the broadest sense the development of thought in blood pressure measurement:

I. Direct Measurement of Systolic Blood Pressure ca. 1733
II. Indirect Measurement of Systolic Blood Pressure ca. 1855
III. Measurement of Systolic and Diastolic Blood Pressure by Oscillometry ca. 1900
IV. Auscultatory Measurement of Systolic and Diastolic Blood Pressure ca. 1905
V. Development of Automated Techniques ca. 1940
VI. Ambulatory Measurement of Blood Pressure ca. 1960

The development of blood pressure 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 centers. 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 blood pressure measurement.

I. DIRECT MEASUREMENT OF SYSTOLIC BLOOD PRESSURE

The ancient Egyptians, as the Ebers papyrus of 1500 B.C. show, 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 (1). Egyptian physicians, moreover, regarded

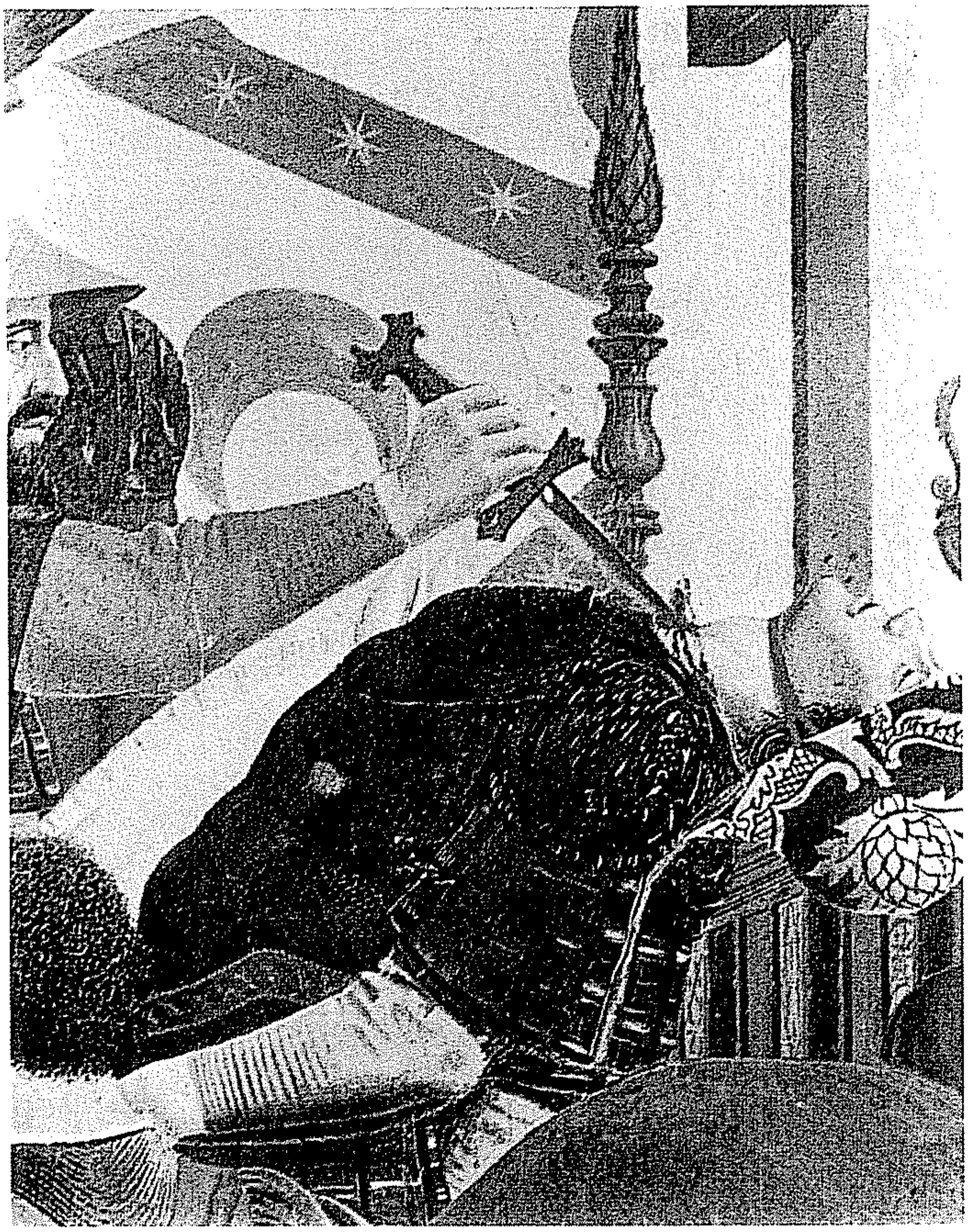

Fig. 1. The legend of the true cross. Detail from *The Battle between Heraclius and Chosroes* by Piero della Francesca (1415/20 – 1492). Arezzo: Church of S. Francesco. Reproduced from: Murray P, de Vecchi P. *The complete paintings of Piero della Francesca.* Penguin Classics of World Art. Middlesex: Penguin Books, 1987.

measurement an an indispensable aspect of clinical assessment, but the measurement of blood pressure had necessarily to await the discovery of the circulation by William Harvey (1578 – 1657) in 1628 (2). In fact, over a century had to pass 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 (Fig. 2). He went on to show that exsanguination reduced this pressure and he also did a number of intriguing experiments on the velocity of

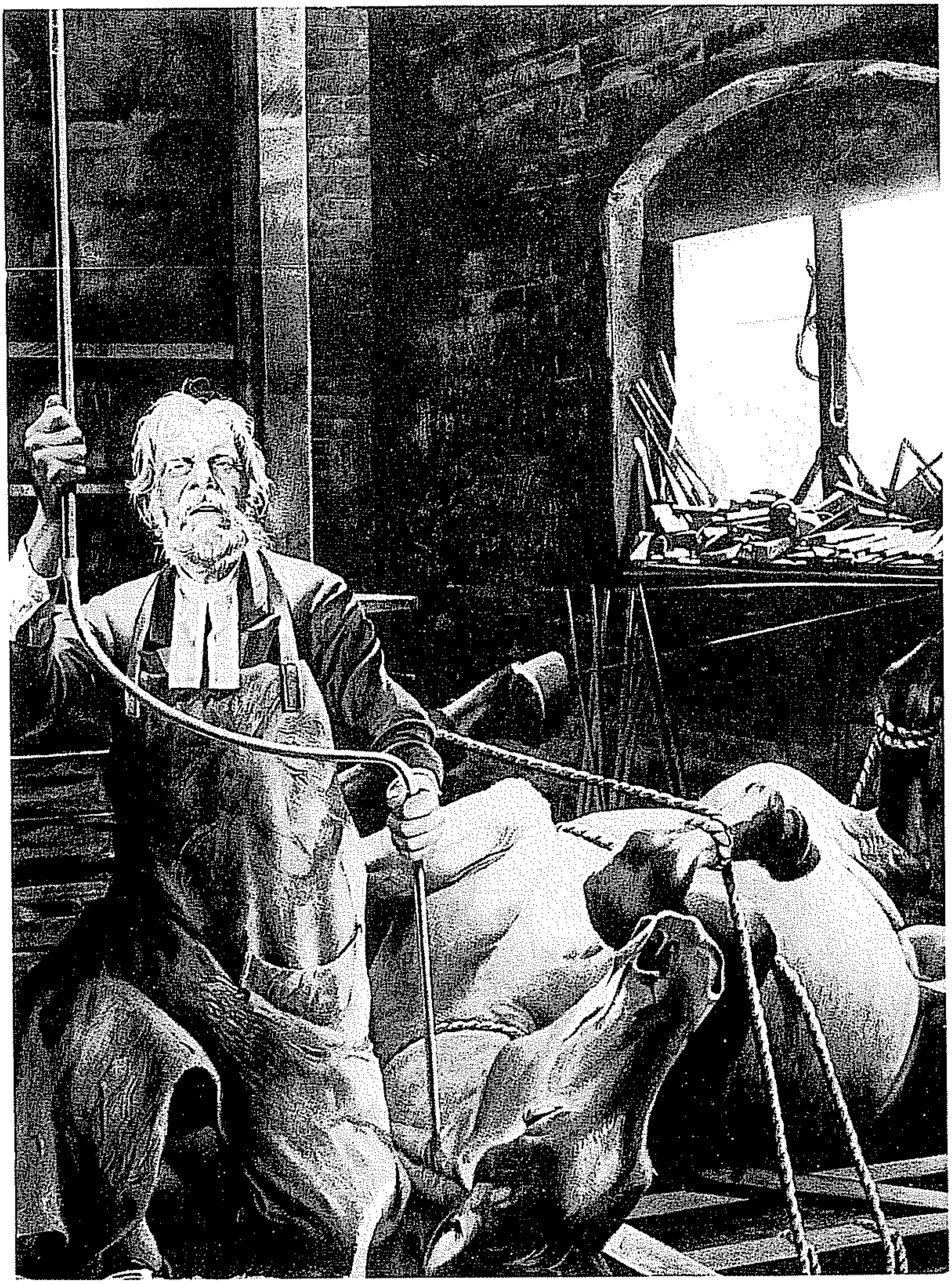

Fig. 2. The Reverend Hales demonstrating blood pressure in a horse. Reproduced from: *History of hypertension series*. Sandwich, Kent: Pfizer Ltd., 1980.

blood flow (3). Hales, a divine and humanitarian, had a profound influence on social mores (4, 5) and scientific thought but, once again, his remarkable discovery of blood pressure was to lie fallow for nearly a hundred years. The failure of physiologists to apply Hales's 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 blood pressure (5) — was not likely to meet with general acceptance. A more acceptable measuring device was needed. This was provided by Jean-Léonard Marie Poiseuille (1799 – 1869) who reported the measurement of blood pressure with a mercury sphygmomanometer in 1828 (6), thereby

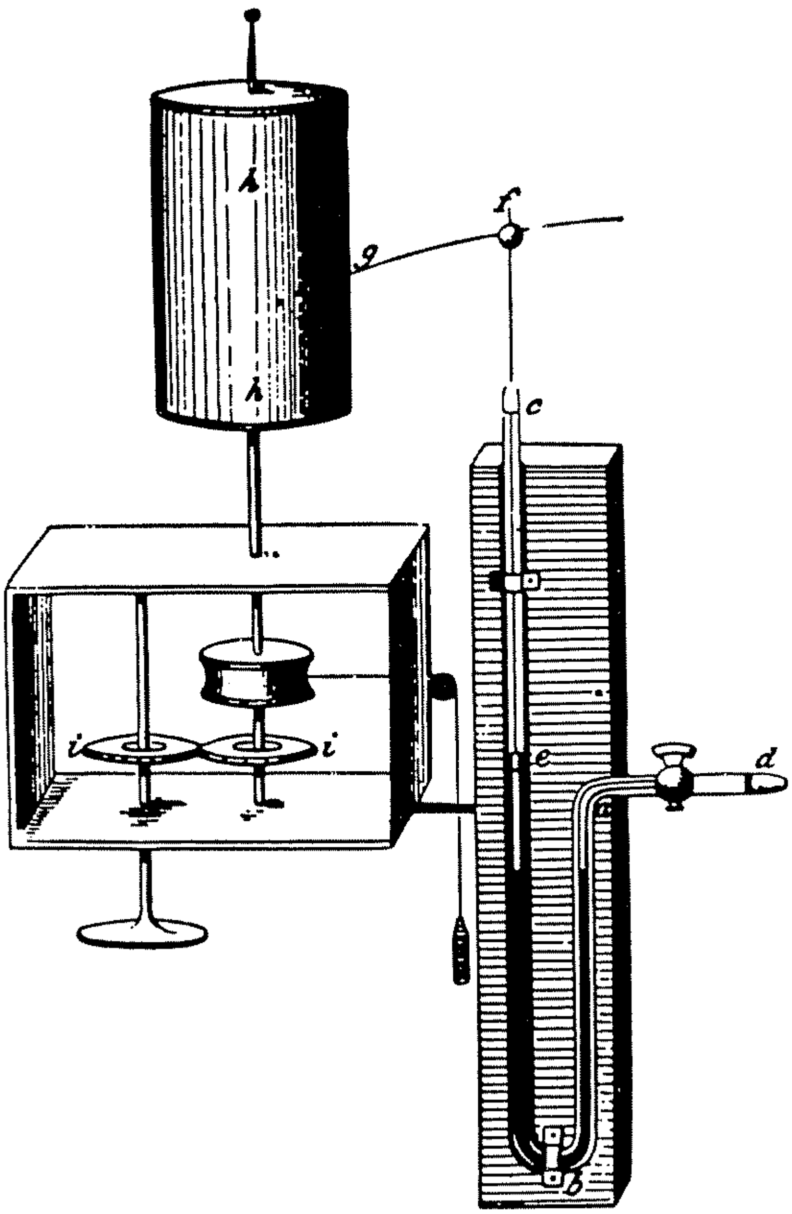

Fig. 3. Ludwig kymograph. Reproduced from: de Moulin D. A short history of blood pressure measurement. In: Arntzenius AC, Dunning AJ, Snellen HA, eds. *2nd Einthoven meeting on past and present cardiology: blood pressure measurement and systemic hypertension.* Breda: Medical World Press, 1981; 20.

winning a gold medal from the Royal Academy of Medicine in Paris (7). Poiseuille recorded blood pressure in a variety of arteries in animals by connecting his U-shaped mercury manometer to the artery with leaden cannulas. He prevented the coagulation of blood by filling the tube leading from the artery with potassium carbonate. Poiseuille's device, or modifications of it, were widely used to study the effect of physiological maneuvers and drugs on systolic blood pressure (8). In fact, as Lawrence has pointed out, the technique of direct measurement of arterial blood pressure in animals had become quite sophisticated in the second half of the nineteenth century (9).

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 (10) which was to find wide application in physiological studies (11) (Fig. 3). This instrument was used by Faivre during a limb amputation to record systolic blood pressure for the first time in man (12). So dawned the next phase in the history of blood pressure measurement — the development of methods for indirectly measuring blood pressure in man.

II. INDIRECT MEASUREMENT OF SYSTOLIC BLOOD PRESSURE

The first device for measuring blood pressure indirectly is usually attributed to Karl Vierordt (1818 – 1864) who invented the first of many sphygmographs in 1855 (13) (Fig. 4). However, credit for the first instrument capable of measuring blood pressure 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 (Fig. 5). The mercury bulb was compressed against the radial artery until oscillations ceased in the mercury column at which point systolic pressure was estimated. Herrison described an association between a full

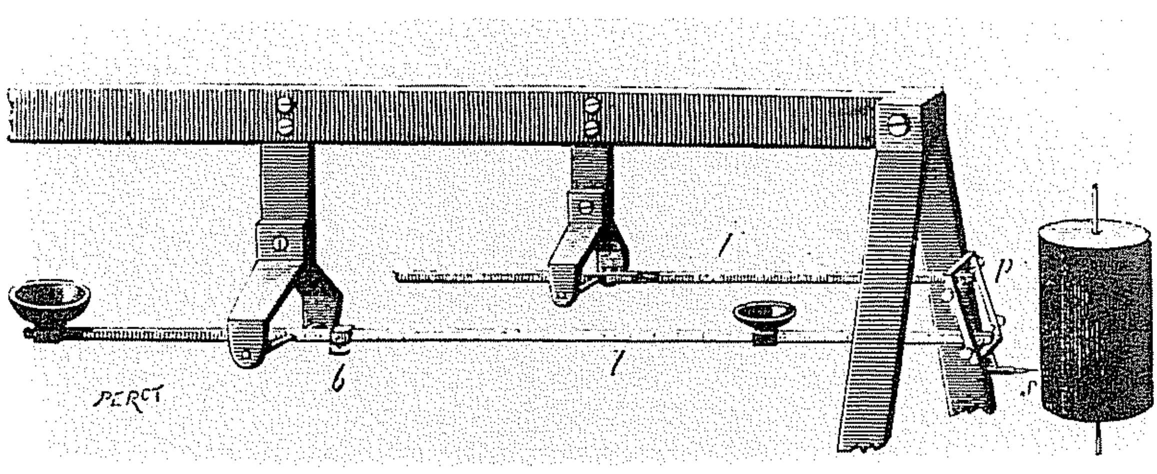

Fig. 4. Vierordt sphygmograph. Reproduced from: Snellen HA. *E.J. Marey and cardiology.* Rotterdam: Kooyker Scientific Publications, 1980; 131.

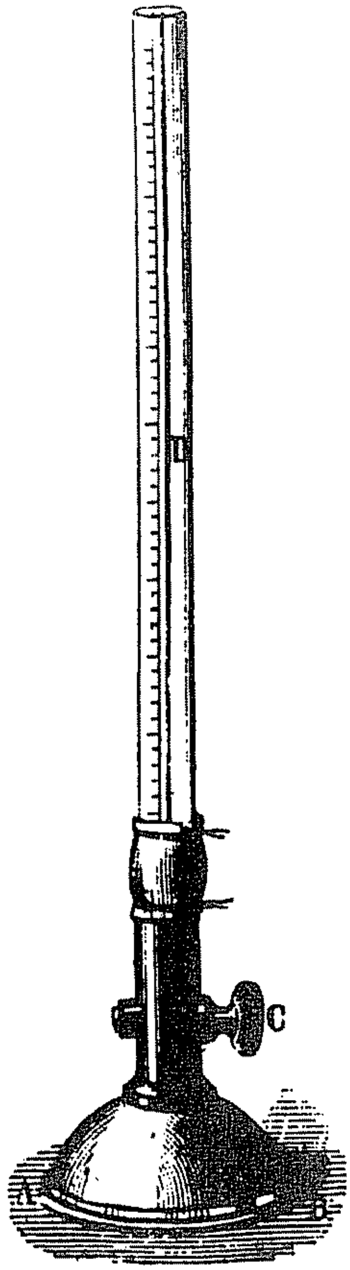

Fig. 5. Herrison device. Reproduced from: Snellen HA. *EJ Marey and cardiology.* Rotterdam: Kooyker Scientific Publications, 1980; 129.

pulse, left ventricular hypertrophy and apoplexy but inexplicably gives no blood pressure measurements in such patients (14). Vierordt and Herrison's instruments were each to influence the development of many blood pressure measuring devices in the nineteenth century.

Instruments based on the Vierordt sphygmograph

Vierordt's sphygmograph was a large (168 cm long) instrument consisting of a levered system that recorded the movements of a weight resting on the radial artery.

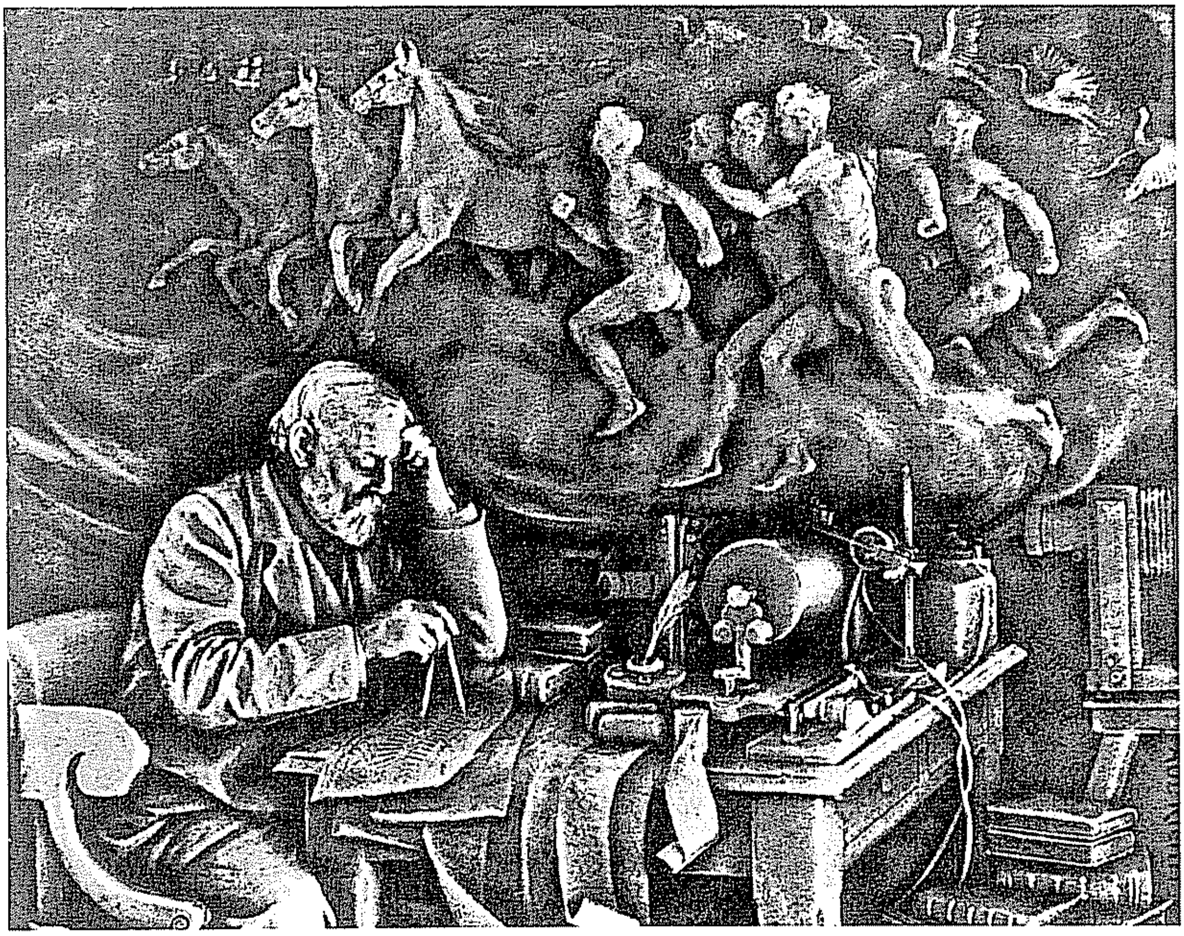

Fig. 6. Silver medal of Etienne Jules Marey by Paul Richer, Musée d'Histoire de la Médicine, Paris. Reproduced from: *The graphic method and cardiovascular research: Etienne Jules Marey (1830 – 1904).* VIII European Congress of Cardiology, Paris, 1980. Medtronic France S.A./JLR Graphics, France, 1980; 11.

This provided pulse wave recordings similar to intra-arterial recordings and an estimate of blood pressure was obtained by determining the weight required to obliterate the pulse (11). Understandably, this instrument was inaccurate.

The talented and versatile French physiologist, Etienne Jules Marey (1830 – 1904) (Fig. 6), quickly recognized the potential of Vierordt's instrument which he simplified and made more accurate (15). A number of modifications of this device became available, a good collection of which is to be found at the Wellcome Museum (16). In Marey's sphygmograph, the lever system and weights of Vierordt's device were replaced by a metal spring, the tip of which overlay the artery (Fig. 7). An adjustable screw altered the pressure exerted by the spring and a recording system wrote on smoked paper driven by a clockwork mechanism. The device, which was light, was strapped to the wrist with a laced bandage. Recordings were remarkably similar to direct intra-arterial tracings with the diacrotic notch being clearly visible. Marey was more interested in the pulse wave form than the actual blood pressure and his original device could only give an inaccurate estimate of blood pressure. Balthazar

Foster modified the instrument in an attempt to overcome its inaccuracy deficiency by calibrating the pressure screw to provide an estimate of the pressure required to obtain a maximal pulse tracing (17). A number of other modifications were made to Marey's sphygmograph (16), the most elaborate being those of the young physician from Guy's Hospital, Frederick Mahomed (1849 – 1884) (18) (Fig. 8). He was the first to make a serious study of the association of raised blood pressure with other illnesses, most notably Bright's disease (19). At the same time Thomas Lauder Brunton was using the Marey sphygmograph to study the effects of drugs on blood pressure (20). Important though the Marey sphygmograph was as a landmark in sphygmomanometry, it was difficult to use, likely to give varying results between observers, and it was inaccurate because it measured total pressure applied to the artery rather than pressure per unit of surface, as Theodore Janeway pointed out

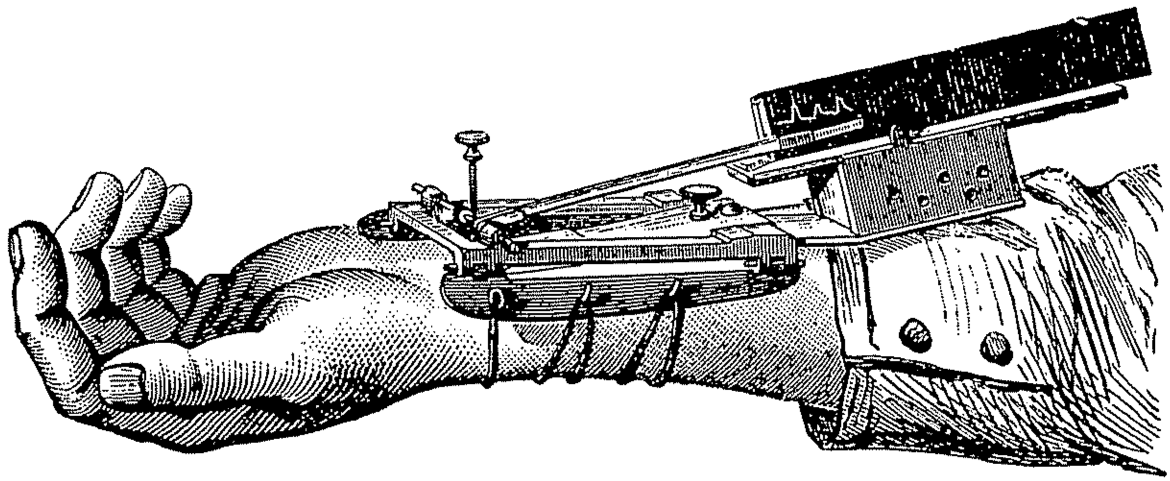

Fig. 7. Sphygmograph of Marey. Reproduced from: Snellen HA. *E.J. Marey and cardiology.* Rotterdam: Kooyker Scientific Publications, 1980; 214.

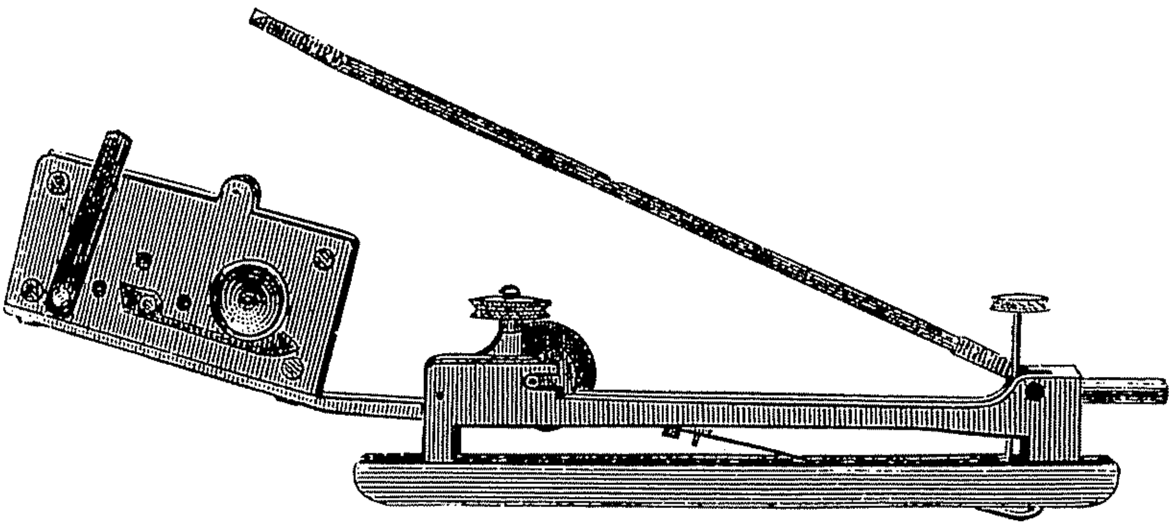

Fig. 8. Mahomed sphygmograph. Old illustration (source unknown).

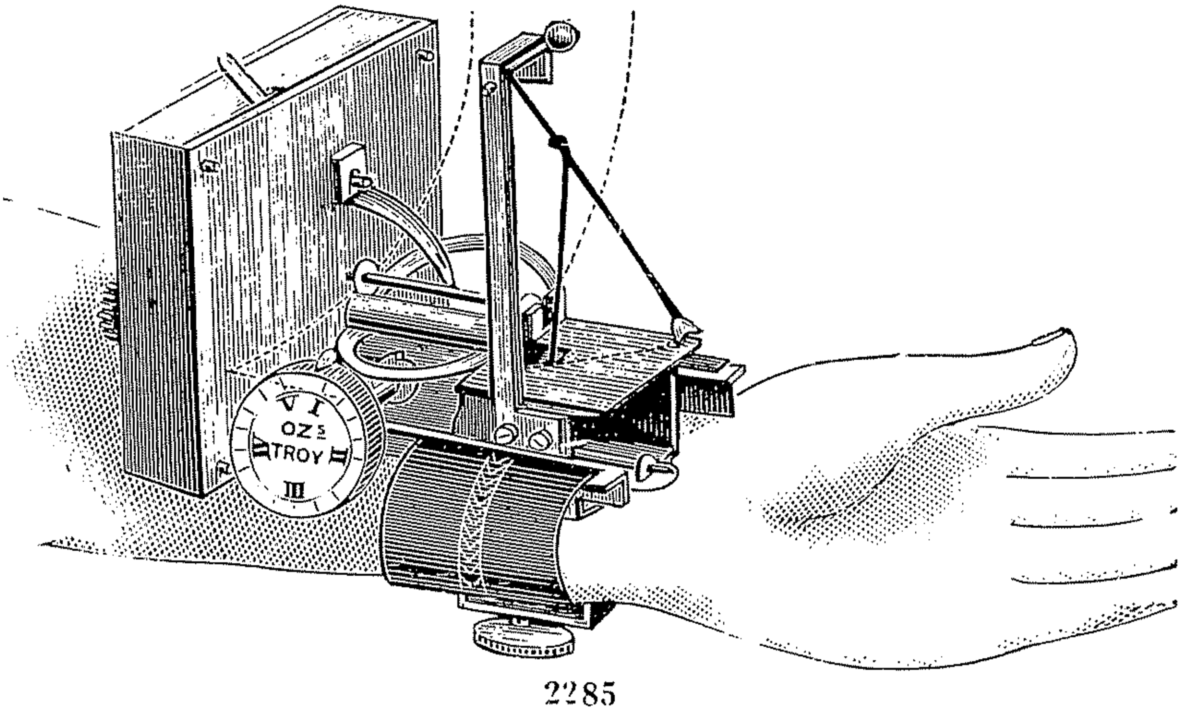

Fig. 9. Dudgeon sphygmograph. Reproduced from: *Wholesale illustrated catalogue of surgical instruments and medical appliances*. Dublin: Fannin and Co., 1908; 314.

in his comprehensive review of the history of blood pressure measurement written in 1904 (21). Not surprisingly, therefore, its use was confined to the laboratory and it did not achieve clinical popularity.

The Marey sphygmograph was finally replaced by a simpler and more accurate device introduced by Robert Ellis Dudgeon (1820 – 1904), a homeopath, in 1882 (22) (Fig. 9). This lightweight device which could be carried in the pocket (it weighed 4 ounces and measured 2'' × 2½'') 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 clockwork motor drove a strip of smoked paper under an oscillating metal tip to provide a record of the pulse wave. This device, which proved extremely popular, was modified by Mortimer Granville (1833 – 1900) so that it could be folded to lie flat when not in use (23) and in 1885 Benjamin Ward Richardson improved the recording facility (24). The Dudgeon sphygmograph or one of its modifications soon became an essential piece of equipment for the physiologist or scientifically minded clinician. Many of the observations of Thomas Lewis, F.A. Mahomed, Sir James Mackenzie and Lauder Brunton are based on these devices (23).

However, the sphygmograph, in general, was a disappointment (9). It was capable of giving a pulse wave tracing but was not an accurate device for measuring blood pressure, if for no other reason than it failed to take into account the size of the arterial surface being compressed (9). 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' (25).

Instruments based on palpatory occlusion

As far back as 1833 Herrison had attempted to measure blood pressure by applying pressure directly to the radial artery (14) and now some 35 years later this principle was to be adopted again. These devices, of which there were many varieties (9), contained a springed mechanism which registered the pressure that had to be exerted either on a finger palpating the radial artery or directly on the artery to cause arterial occlusion. The spring of the device either moved a pointer along a scale as in the Batten sphygmomanometer (26) or pushed a calibrated cylinder out of the top of the instrument as in the Bloch sphygmomanometer (27). These instruments were difficult to use as the palpating finger, which had the important role of denoting obliteration of the pulse, had to remain totally passive and this was not easily achieved. Moreover, they were flawed in the same way as the sphygmographs of Marey and Dudgeon in that they applied pressure directly to the artery. Though these devices remained popular well into the twentieth century, they were soon to be replaced by the next generation of blood-pressure-measuring devices which depended on arterial occlusion by counter-pressure applied directly to the artery through a fluid medium rather than by direct pressure. Blood pressure was determined by palpation of the artery distal to the point of occlusion or by attached manometers. These devices were to become the direct forerunners of the modern sphygmomanometer.

Arterial occluding devices

It is now necessary to go back some years to determine how this new approach to blood pressure measurement evolved. 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 (28). Around the same time Marey, using air to compress an arm in a glass box, demonstrated the blanching of the arm occurred when systolic pressure was exceeded (29). Later Marey substituted water for air as the compressing medium and he recorded oscillations in plethysmographic pressure using a tambour writing system (9). 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 (30) (Fig. 10), which was the first reasonably accurate device for clinical measurement of blood pressure.

Using an experimental system of rubber tubes connected to cadaver arteries he showed that the pressure required to occlude the lumen of an artery was equal to the pressure within the vessel plus that required to overcome the rigidity of its wall. As the rigidity of arteries was small, the occlusion pressure was a good estimate of intra-arterial pressure. 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

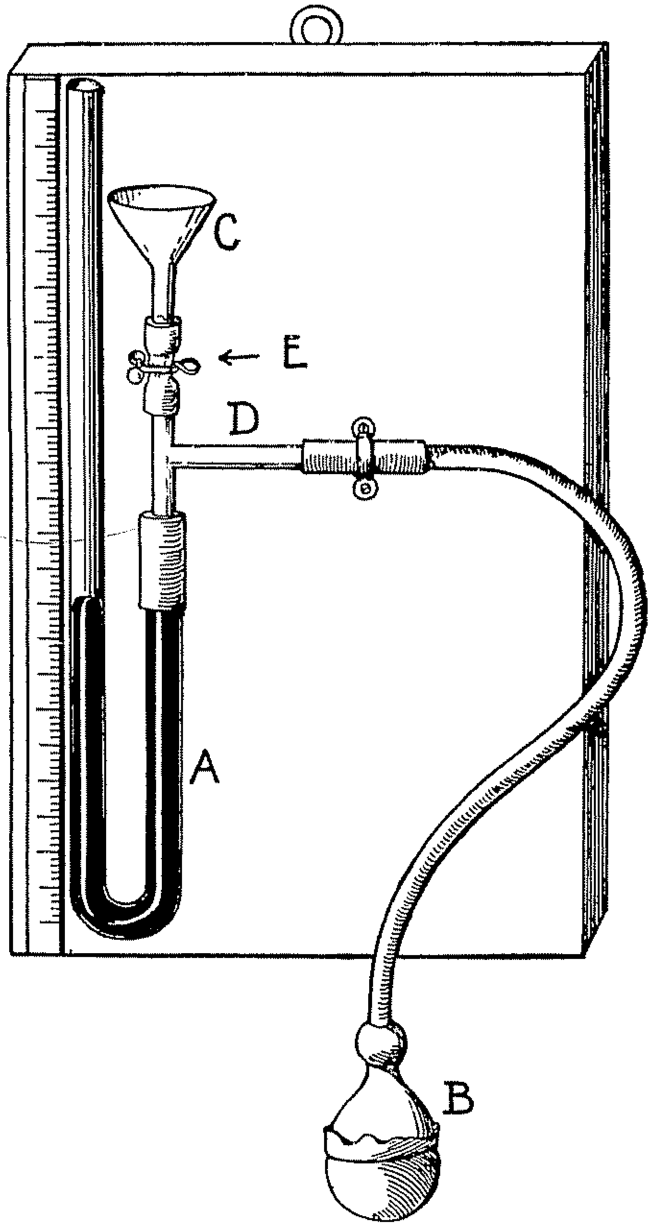

Fig. 10. von Basch sphygmomanometer. Reproduced from: Janeway TC. *The clinical study of blood-pressure.* New York and London: D. Appleton & Co., 1904; 46.

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, designed by Lucien Vidie (1805 – 1866) (9) and it was eventually refined to portable dimensions making it suitable for clinical use (Fig. 11). Extensive physiological and clinical observations were made with von Basch's

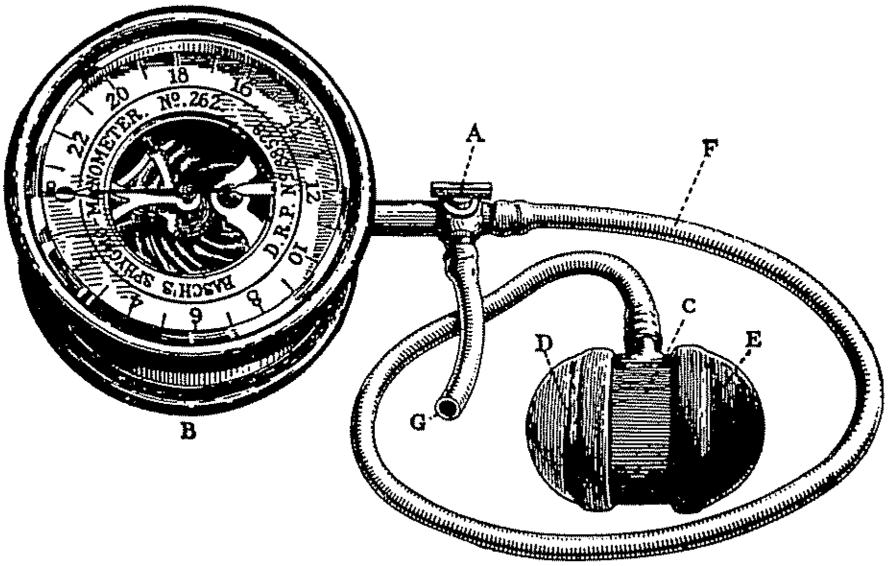

Fig. 11. Portable von Basch sphygmomanometer. Reproduced from: de Moulin D. A short history of blood pressure measurement. In: Arntzenius AC, Dunning AJ, Snellen HA, eds. *In: Proceedings, 2nd Einthoven meeting on past and present cardiology: blood pressure measurement and systemic hypertension.* Breda: Medical World Press, 1981; 28.

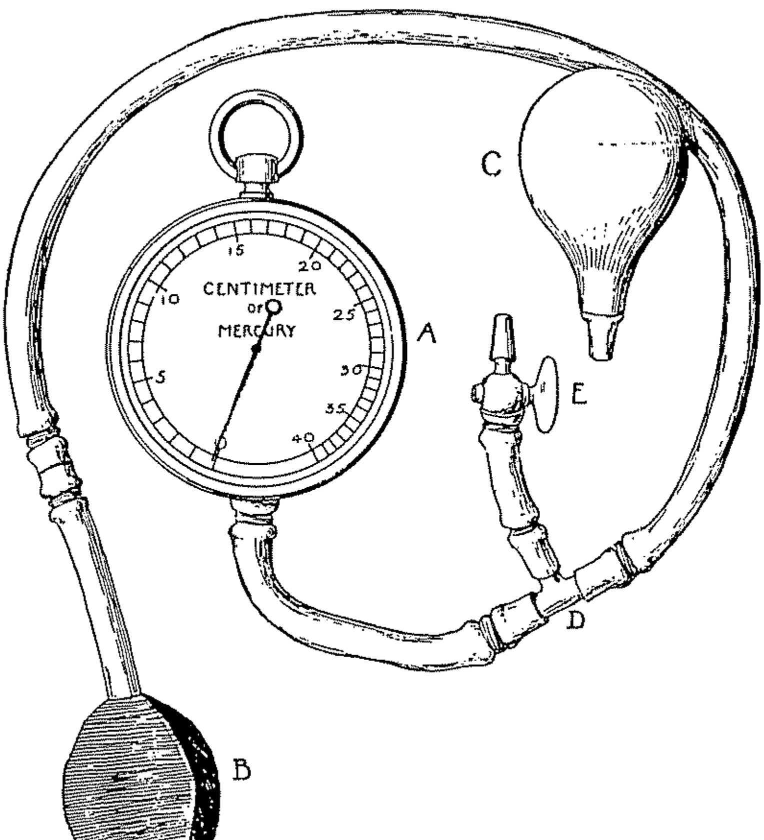

Fig. 12. Potain sphygmomanometer. Reproduced from: Janeway TC. *The clinical study of blood-pressure.* New York and London: D. Appleton & Co., 1904; 48.

sphygmomanometer by Ignaz Zadek, who in 1880, was probably the first to observe the variability of blood pressure under different circumstances (31).

Pierre Carl Edouard Potain (1825 – 1907), Professor of Clinical Medicine at the Charité in Paris, made a further significant modification to von Basch's instrument by substituting air for water as the compressing medium in the pelotte (Fig. 12). The pressure of air in the pelotte was raised to 30 mmHg through a side arm of the manometer tube and the zero position of the manometer was adjusted. Initially Potain used a U-tubed mercury manometer attached to the waistcoat button-hole of his junior doctor but later replaced this with an aneroid manometer.

In 1898 Leonard Hill (1866 – 1952) and Harold Barnard (1868 – 1908) published a modification of the von Basch/Potain sphygmomanometer in which pressure was recorded in a tube arising vertically from a modified pelotte, thus making the device easily portable (33). In 1898, George Oliver, produced a 'haemodynamometer' in which the movements of a pelotte membrane were amplified by a needle which moved a pointer across a scale (34).

These devices which owe their origin to von Basch, whom Janeway credits as 'the inventor of clinical sphygmomanometry', were flawed in that it was assumed that the artery could be uniformly compressed against underlying bone — a serious source of error (35).

The *fin de siècle* stage was dominated by the Austrians and French who had contributed substantially to the developing speciality, not least through Marey, whose contribution is detailed in an interesting book published in 1886 by Ozanam who himself made a number of modifications to existing sphygmomanometers (36). The Italians, however, would soon take the limelight.

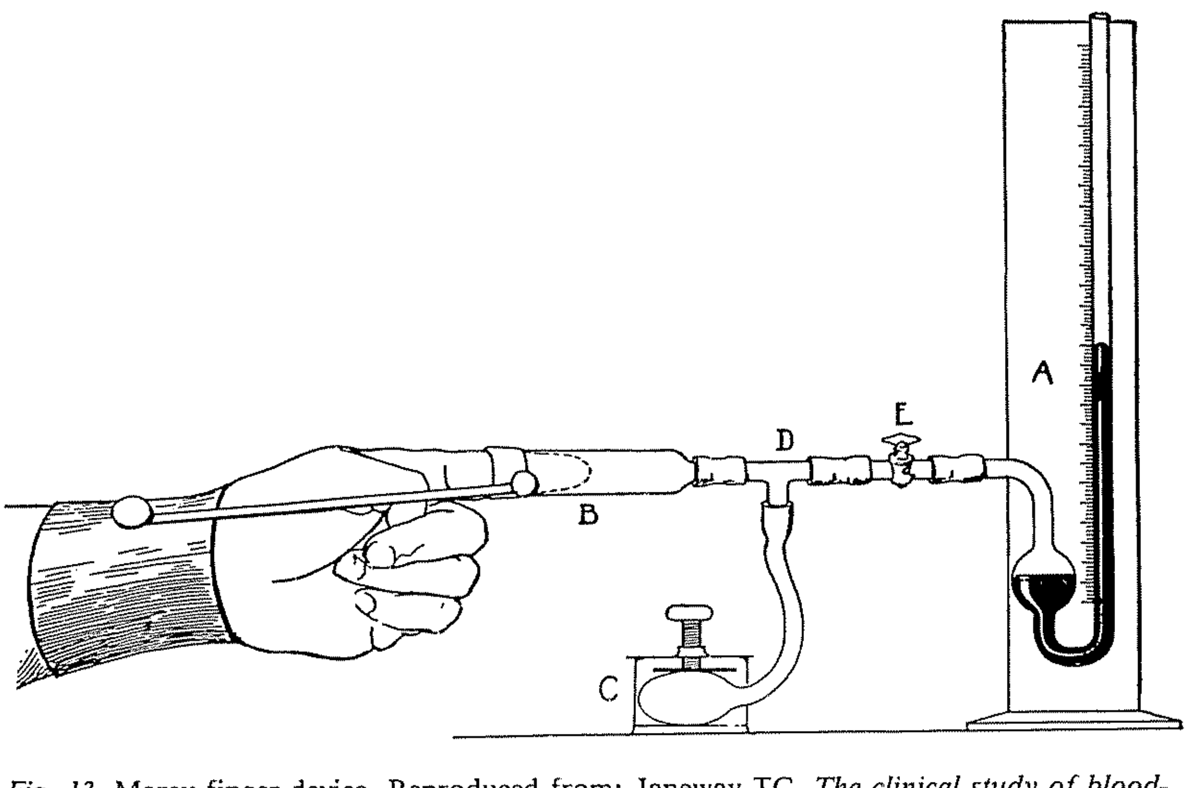

Fig. 13. Marey finger device. Reproduced from: Janeway TC. *The clinical study of blood-pressure.* New York and London: D. Appleton & Co., 1904; 51.

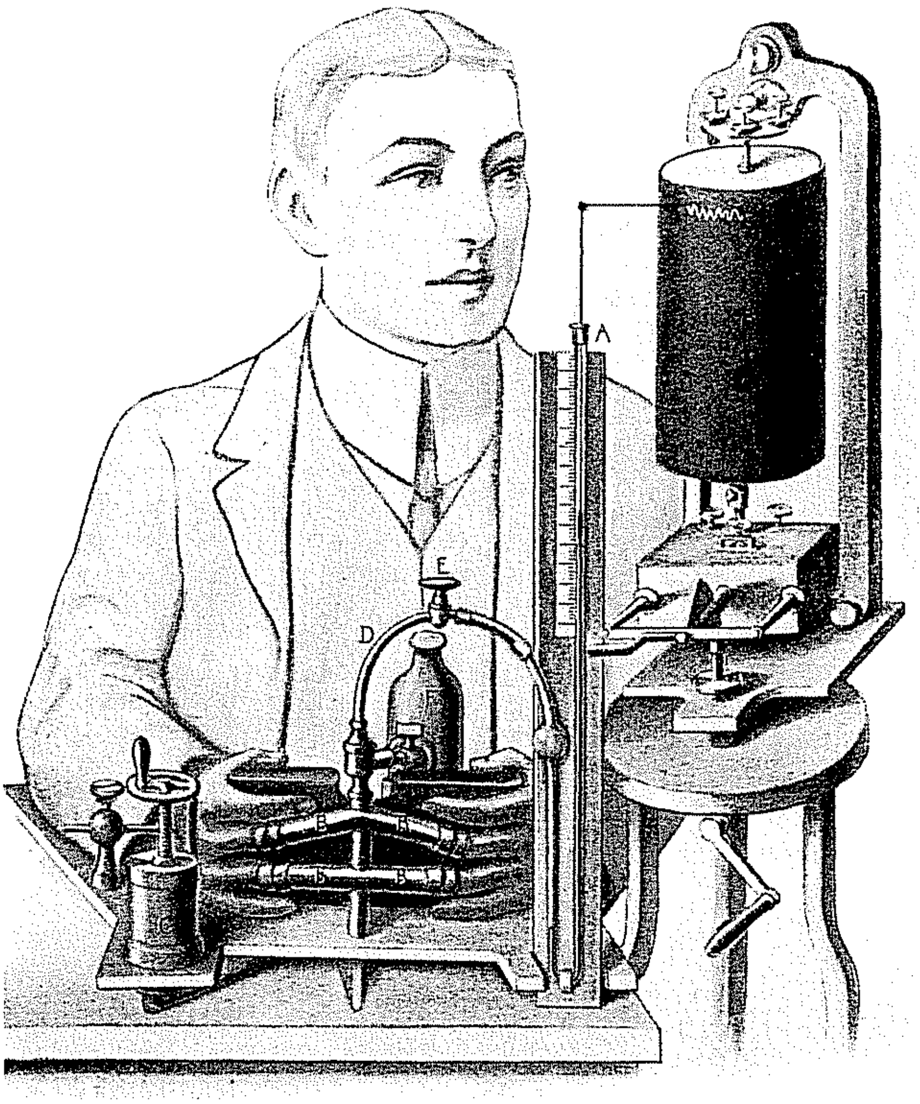

Fig. 14. Mosso sphygmograph. Reproduced from: Janeway TC. *The clinical study of blood-pressure.* New York and London: D. Appleton & Co., 1904; 52.

Limb-occluding devices

In some of his early experiments on blood pressure measurement Marey had used a water-filled plethysmograph to apply pressure to the entire arm (29) and he later modified this apparatus for the finger instead of the arm (37) (Fig. 13). However, the oscillations recorded were small and to overcome this problem, Mosso, in 1985, applied pressure to four fingers of each hand inserted into rubber stalls within metal tubes (38) (Fig. 14). This apparatus, though cumbersome, was quite accurate.

The next step to an occluding arm cuff was made by Scipione Riva-Rocci (1863 – 1939) in 1896 (39) (Fig. 15). 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 (Fig. 16).

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 (40) (Fig. 17). Shortly afterwards Gaertner applied the same principle, namely, that of circular compression of an extremity, to the finger with an instrument which he called a 'tonometer' (41, 42) (Fig. 18). These techniques removed the

Fig. 15. Scipione Riva-Rocci (1863 – 1939). Reproduced from: de Moulin D. A short history of blood pressure measurement. In: Arntzenius AC, Dunning AJ, Snellen HA, eds. *Proceedings, 2nd Einthoven meeting on past and present cardiology: blood pressure measurement and systemic hypertension.* Breda: Medical World Press, 1981; 28.

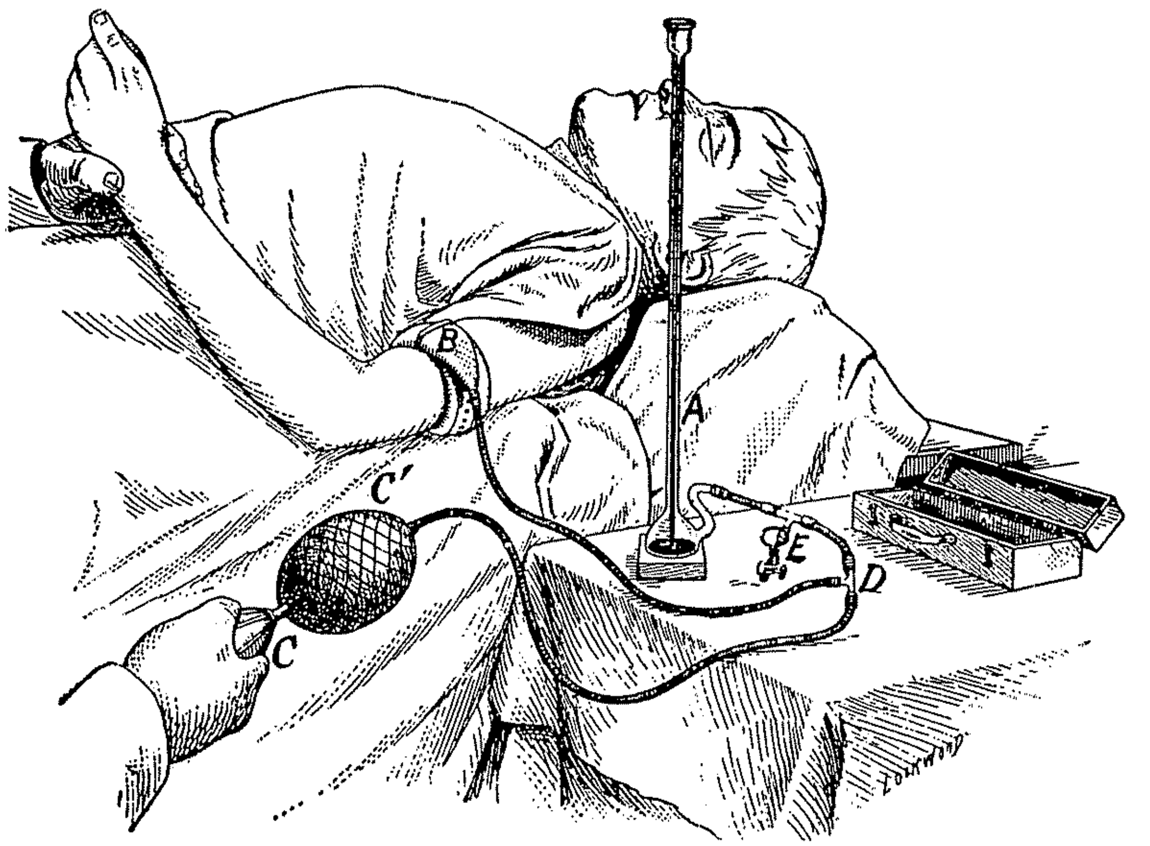

Fig. 16. Riva-Rocci sphygmomanometer. Reproduced from: Janeway TC. *The clinical study of blood-pressure.* New York and London: D. Appleton & Co., 1904; 79.

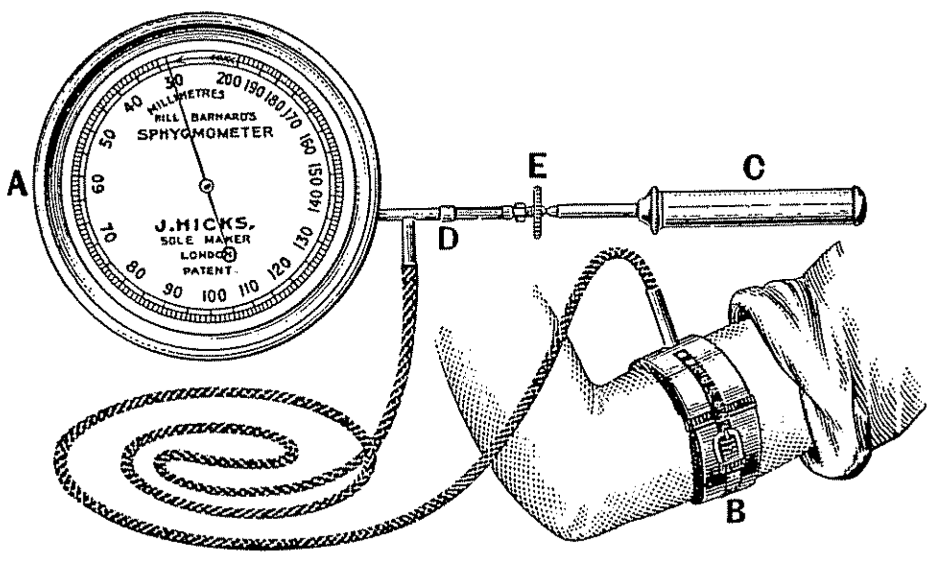

Fig. 17. Hill and Barnard's sphygmomanometer. Reproduced from; Janeway TC. *The clinical study of blood-pressure.* New York and London: D. Appleton & Co., 1904; 85.

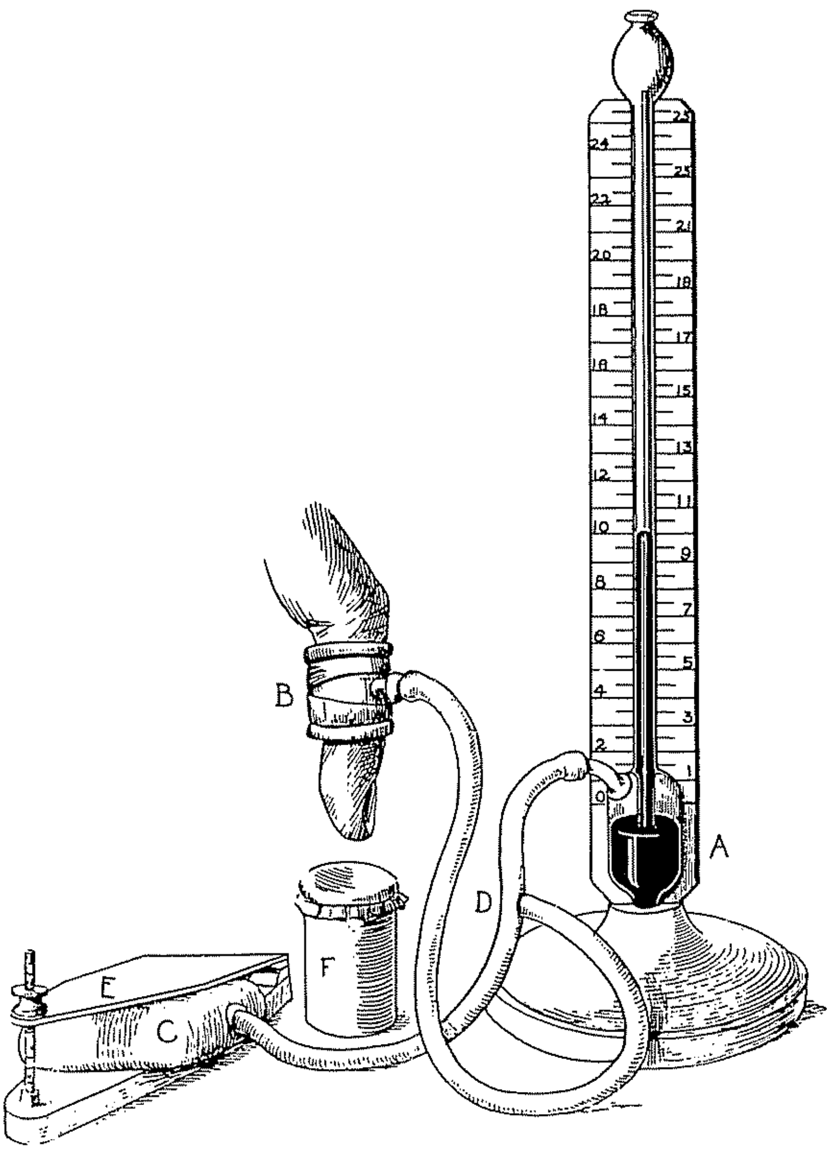

Fig. 18. Gaertner tonometer. Reproduced from: Janeway TC. *The clinical study of blood-pressure.* New York and London: D. Appleton & Co., 1904; 83.

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. Heinrich von Recklinghausen (not to be confused with Friedrich von Recklinghausen of eponymic 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 (43) and this was later confirmed by Janeway (44) and Erlanger (45).

The stage was now set for the next major development in blood pressure measurement, namely the measurement of both systolic and diastolic pressure. Though the instruments of Mosso (38) and Hill and Barnard could be used to estimate diastolic pressure by observing the point of maximum oscillation, mean and diastolic pressures were often confused with each other and the significance of the latter was not clearly recognized at the close of the nineteenth century (46).

III. MEASUREMENT OF SYSTOLIC AND DIASTOLIC BLOOD PRESSURE BY OSCILLOMETRY

It is salutary to note that a century ago Theodore Caldwell Janeway (1872 – 1917), Visiting Physician to the City Hospital in New York, was as fully aware of the sources of error in the blood pressure 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' (47). Janeway also anticipated the expansion that was about to take place in clinical sphygmomanometry and he 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' (48).

As is often inevitable in the research of medical history, the issue of priority for a particular discovery arises and in blood pressure measurement we find a number of such conundrums. The first of consequence is whether Riva-Rocci (39) or Hill and Barnard (40) should be accredited with inventing the forerunner to the modern sphygmomanometer. Janeway took the view that, though Riva-Rocci published first, 'it is questionable whether the credit of the new device does not belong to Hill' (49). This view can hardly be sustained, but perhaps by allowing the credit for this discovery to rest with the Italians, we can attribute, without fear of contention, a discovery of possibly greater importance to the London scientists, namely the development of a device capable of recording both systolic and diastolic blood pressure (40). It is of interest to note, however, that though Hill and Barnard mention diastolic blood pressure in their original publication (40), they confuse mean pressure for diastolic pressure and it was left to other workers, such as Janeway (50), to describe the correct use of the device by demonstrating that the point of maximum oscillation of the needle corresponded to diastolic and not to mean pressure.

The main disadvantage of Hill and Barnard's sphygmomanometer was that the gauge became inaccurate with use and frequent recalibration was necessary, an occurrence which led Janeway to draw attention to a difficulty with which we are all too familiar with to-day: 'The manometer is also difficult of repair in this country, a considerable drawback to so costly an apparatus (U.S. $40)' (51). To overcome this weakness, attention was directed to determining diastolic blood pressure by observing the oscillations in a mercury manometer rather than on an aneroid gauge and Janeway produced a sphygmomanometer incorporating for the first time most of the features that are found in contemporary sphygmomanometers (52). The Janeway instrument had an extendible U-tube mercury manometer, it was portable,

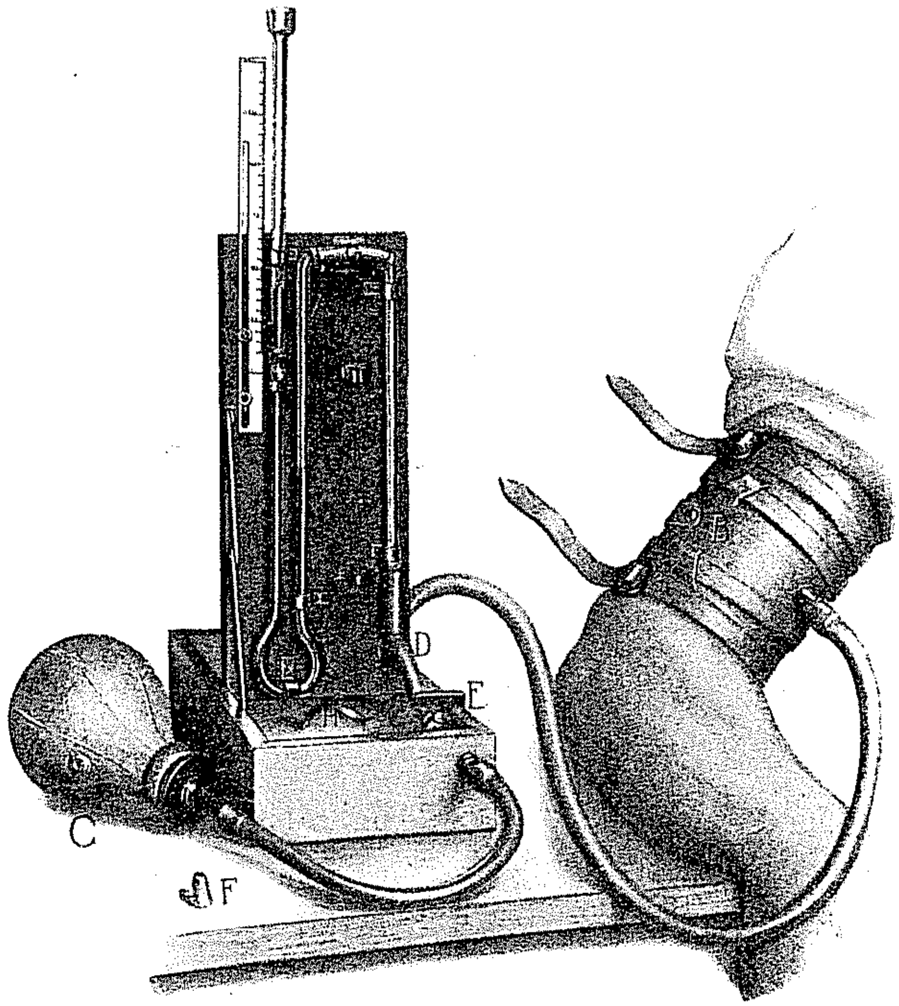

Fig. 19. Janeway sphygmomanometer. Janeway TC. *The clinical study of blood-pressure.* New York and London: D. Appleton & Co., 1904; 90.

the armlet contained an inflatable bladder measuring 12 × 18 cm, and it was reasonably priced at U.S. $14 (Fig. 19).

In the early years of the twentieth century the most accurate research device for measuring systolic and diastolic blood pressure was an instrument invented by a physiologist at Johns Hopkins Hospital and future Nobel prizewinner, Joseph Erlanger, which incorporated all the recent developments, but in addition oscillations within the cuff were recorded across a membrane by means of an ingenious stop-cock and observer bias was removed by using a kymograph to record the oscillations of the mercury column (45, 53) (Fig. 20). It was, of course, too bulky for clinical use. In England, Gibson modified Erlanger's device by using circular compression to estimate the systolic pressure and the oscillations of mercury to measure diastolic pressure (54) and Singer produced a further modification in 1910 (55) (Fig. 21).

In 1906, von Recklinghausen published details on diastolic blood pressure measurement using an aneroid tonometer (56) 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 (57). Known initially as a 'sphygmo-oscillometer' and later simply as an 'oscillometer' (Fig. 22), this instrument enjoyed popularity for many years and is prominently listed in catalogues of the thirties (Price £5 5s.0d.) (58).

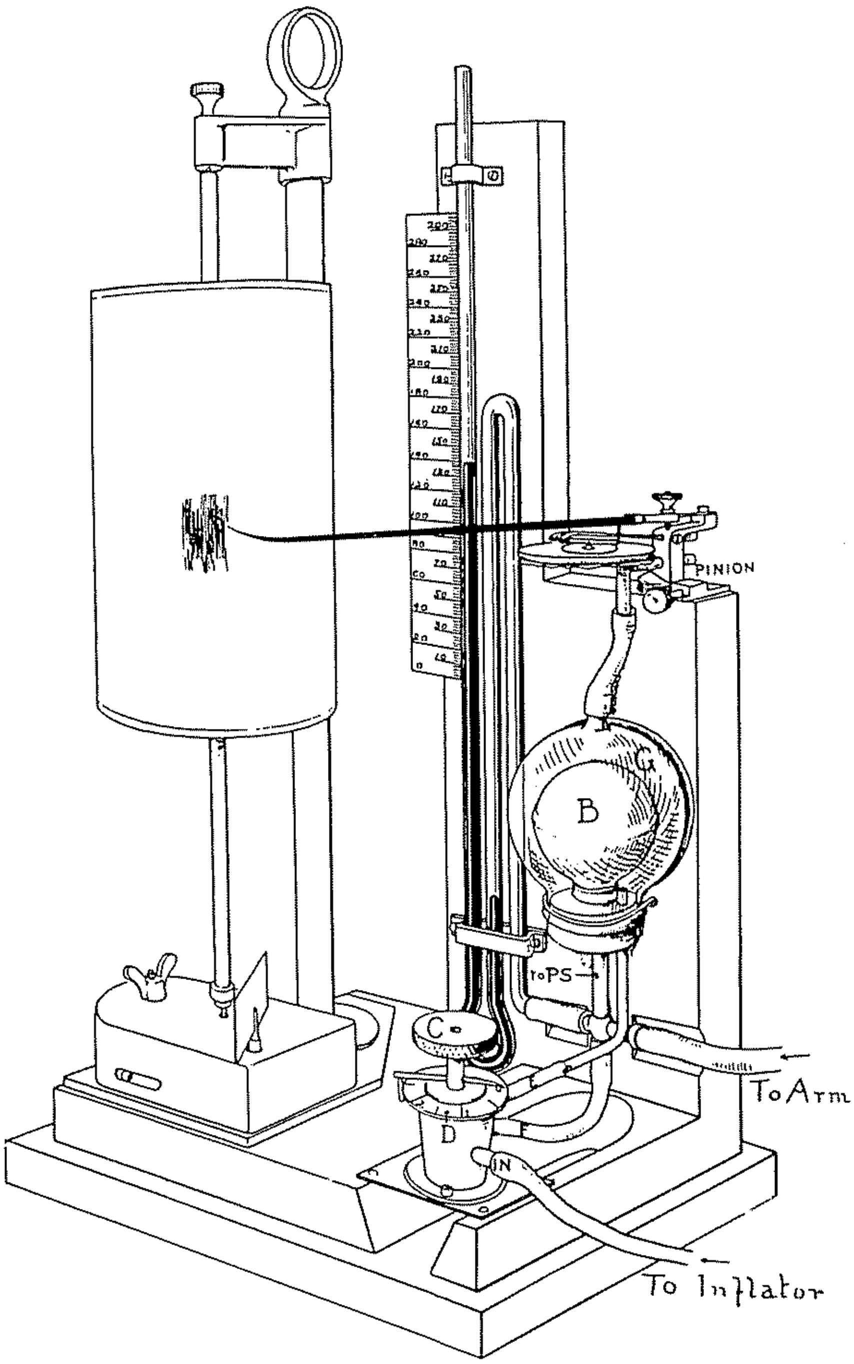

Fig. 20. Erlanger sphygmograph. Reproduced from: Janeway TC. *The clinical study of blood-pressure.* New York and London: D. Appleton & Co., 1904; 94.

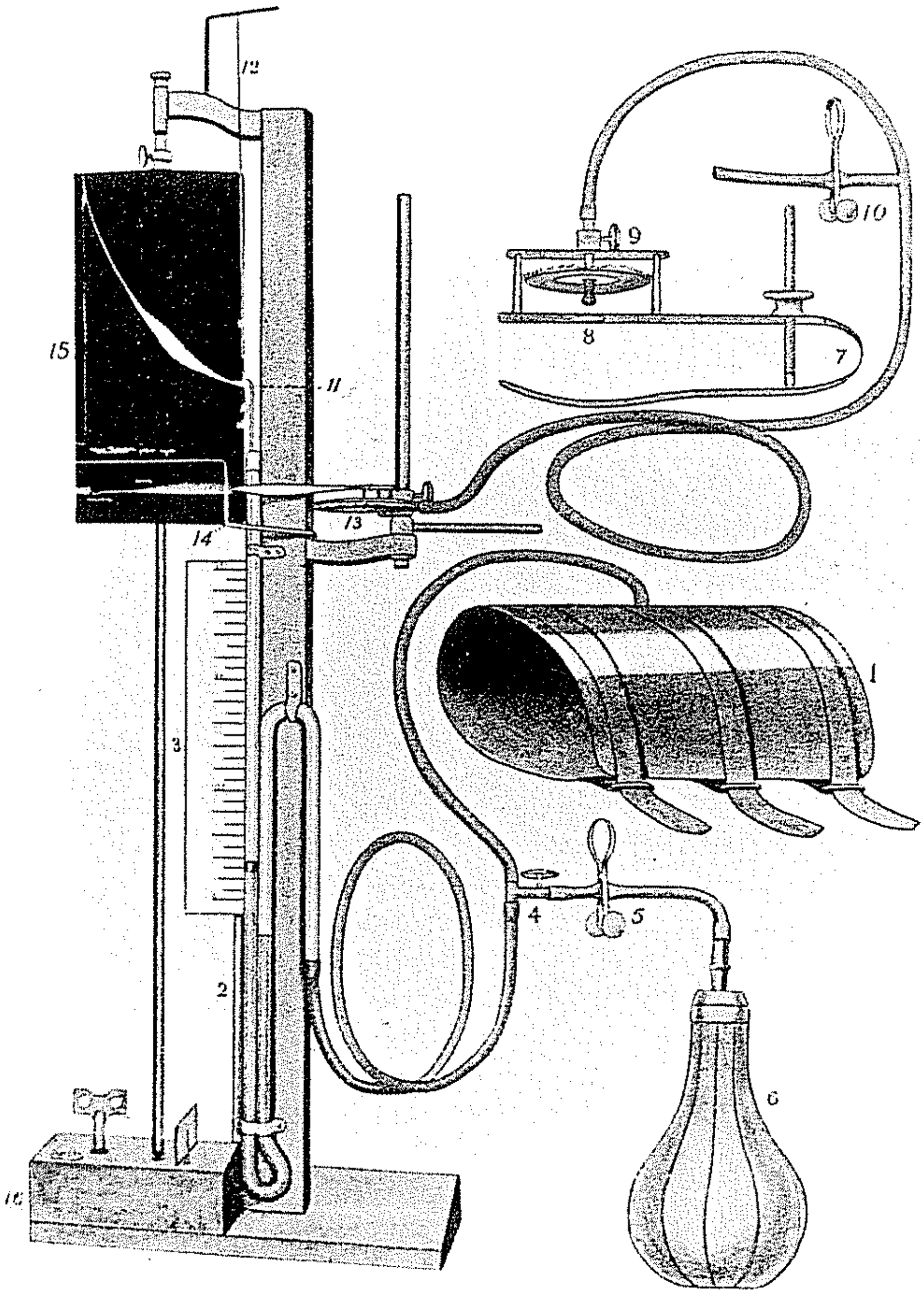

Fig. 21. Gibson's recording sphygmomanometer. Reproduced from: Halls Dally JF. *High blood pressure: its variations and control, 2nd ed.* London: W Heinemann, 1926; 248.

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.,

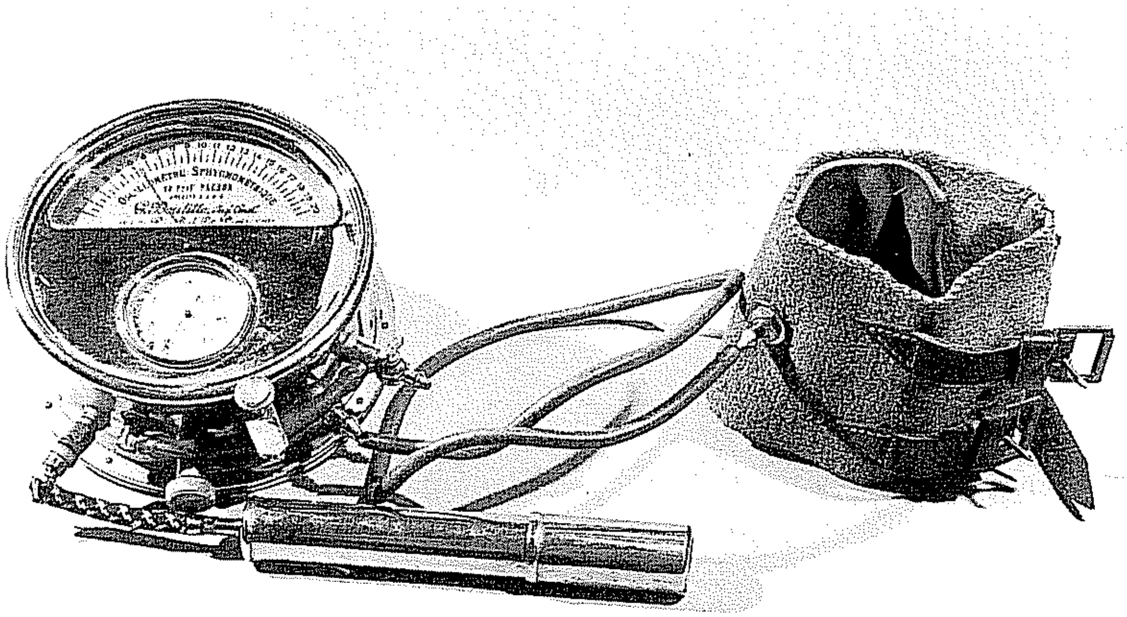

Fig. 22. Pachon sphygmo-oscillometer. Reproduced from: Halls Dally JF. *High blood pressure: its variations and control 2nd ed.* London: W Heinemann, 1926; 46.

etc., . . . ' (59). Harvey Cushing was probably the first to advocate the charting of blood pressure on the bedside chart together with the temperature and pulse rate (60).

IV. 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 which founded the technique of auscultatory measurement of systolic and diastolic blood presure (61) (Fig. 23):

The cuff of the Riva-Rocci is placed on the middle third of the upper arm; the pressure within the cuff is quickly raised up to complete cessation of circulation below the cuff. Then, letting the mercury of the manometer fall one listens to the artery just below the cuff with a children's stethoscope. At first no sounds are heard. With the falling of the mercury in the manometer down to a certain height, the first short tones appear; their appearance indicates the passage of part of the pulse wave under the cuff. It follows that the manometric figure at which the first tone appears corresponds to the maximal pressure. With the further fall of the mercury in the manometer one hears the systolic compression murmurs, which pass again into tones (second). Finally, all sounds disappear. The time of cessation of sounds indicates the free passage of the pulsewave; in other words, at the moment of the disappearance of the sounds the minimal blood pressure within the artery *predominates over the pressure in the cuff. It follows that the manometric figures at this time correspond to the minimal pressure.* (62)

William Dock has commented that 'the most remarkable fact about the Korotkoff sound is that it was discovered' (63). 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 blood pressure measurement in the *New York University Bulletin of the Medical Sciences* in which he wrote: ' . . . that certain experiments in a number of cases concerning the pressure tone and murmur in the brachial, to be described later, show that the pro-

Fig. 23. Nicolai Sergeivich Korotkov. Reproduced from: Segall HN. Discussion of Dr. de Moulin's presentation on the 'History of blood pressure measurement'. In: Arntzenius AJ, Dunning AJ, Snellen HA, eds. *Proceedings, 2nd Einthoven meeting on past and present cardiology: blood pressure measurement and systemic hypertension.* Breda: Medical World Press, 1981; 35.

duction of the tone always occurs at a lower pressure than the point in question (disappearance of secondary waves)' (64). He concluded the paper with another tantalizing statement that undoubtedly indicates that 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'. 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 (65). Yanovski verified the accuracy of the technique and the technique was known for some time as the Korotkov-Yanovski Method (66). Ettinger is credited with describing the 5 phases of Korotkov sounds audible on cuff deflation (67). The 'silent gap' was described in the English literature by Cook and Taussag (68) in 1917 and according to Geddes and colleagues this did not inspire confidence in the technique (69). Gibson (70) attributed the first description of this phenomenon to a Frenchman, Tixier, who considered it to be a manifestation of mitral stenosis.

The Korotkov technique apparently became popular in Germany immediately, but there was a delay of some years before it reached the American and British literature. The technique was first introduced to British practice by George Oliver (without acknowledgement to Korotkov) in 1910 at a meeting of the Royal Society of Medicine which was reported briefly in *The Lancet* (71). The first detailed account of the new method (again without acknowledgement to Korotkov) was by Lauder Brunton later in 1910 (72). The technique was not accepted readily, and in the year following these first descriptions Gibson expressed the view that 'the auscultatory determination cannot replace the previous tactile determination' (73). In America a comprehensive description of the method was published in the *Archives of Internal Medicine* by J.C. Gittings in 1910 (74). In this paper he acknowledged the growing controversy as to whether muffling or disappearance 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 the muffling of sounds rather than their disappearance was advocated (75). Measurement of diastolic blood pressure 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 (76), a view which he endorsed in the third edition of his influential book in 1934 (77). This view was to persist until comparatively recently when Korotkov's original recommendation was once again adopted (78). A more recent controversy has focused on the need to measure diastolic blood pressure at all. Systolic blood pressure, 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 (79 – 81). This issue remains to be resolved.

The source of the Korotkov sounds has been debated since they were first described. Korotkov, defending his technique, was of the opinion that the sounds were of local origin and not transmitted from the heart (61). Krilov studied the sounds in a number of experiments and concluded that they were produced by the fluctuating or centrifugal movement of the blood particles and the simultaneous vibration of the vessel wall (65). Ettinger, to whom may be attributed the clear delineation of the 5 phases of the Korotkov sounds in 1907, summarized the early and very important literature on the Korotkov technique and supported Korotkov in his opinion that the sounds were of local rather than transmitted origin (67). In this eloquent scientific paper he attempted to define the clinical significance of Phases II and III, and in 1911, Goodman and Howell also described the alterations in these phases that might occur in disease, in terms of both force and duration (82). Interestingly, contemporary clinical investigators in hypertension have been content to ignore the

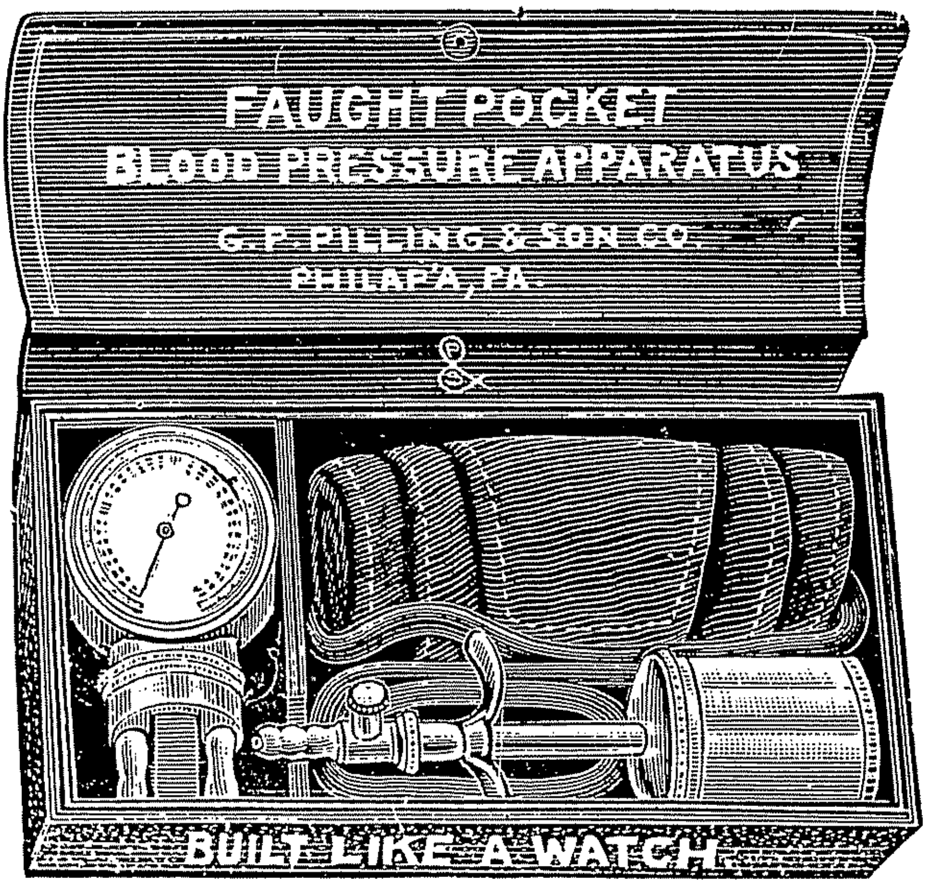

Fig. 24. Faught pocket sphygmomanometer. Reproduced from: Faught FA. *Blood-pressure primer: the sphygmomanometer and its practical application*. Philadelphia: GP Pilling, 1918; 30.

significance of these forgotten phases of the Korotkov sound phenomenon. Both flow phenomena and the transmission of sonic vibrations from the artery are now considered to contribute to the production of the sounds (83, 84), but their precise origin is complex and difficult to elucidate (70). The subject has been reviewed comprehensively by Geddes (85).

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 blood pressure, 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 (86). We might well ponder how these aspects of the technique of blood pressure measurement were obscured in the mists of time.

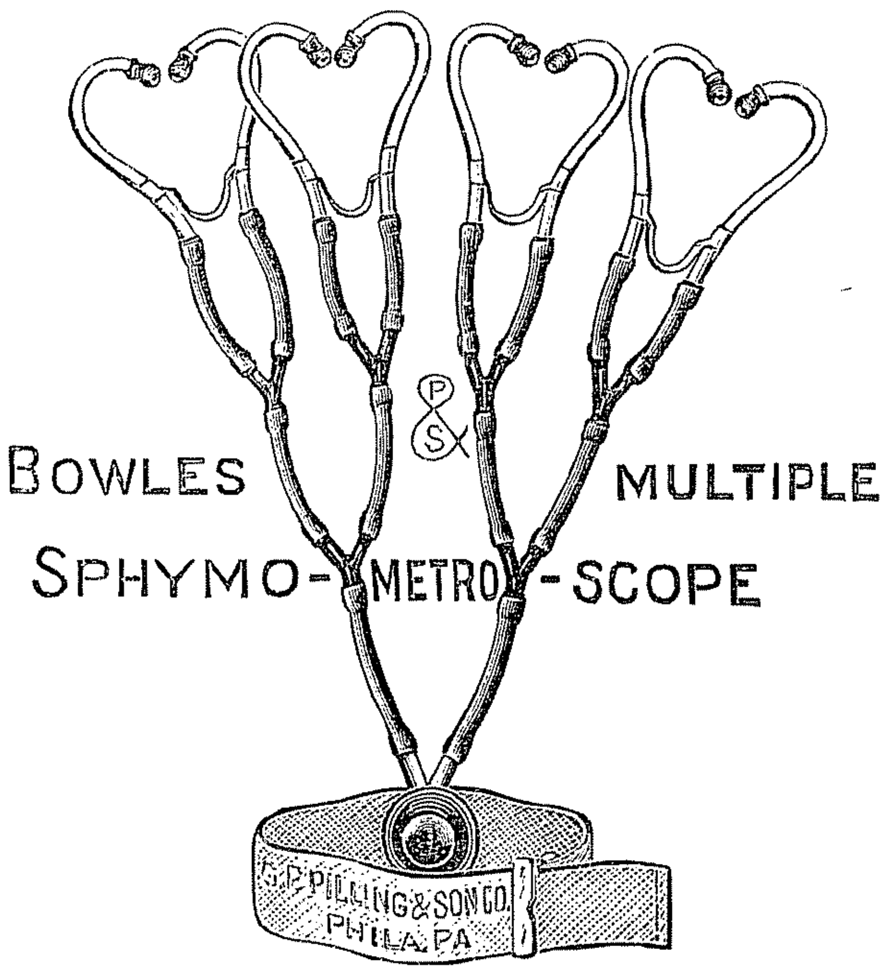

Fig. 25. Multiple sphygmometroscope. Reproduced from: Faught FA. *Blood-pressure primer. The sphygmomanometer and its practical application.* Philadelphia: GP Pilling, 1918; 42.

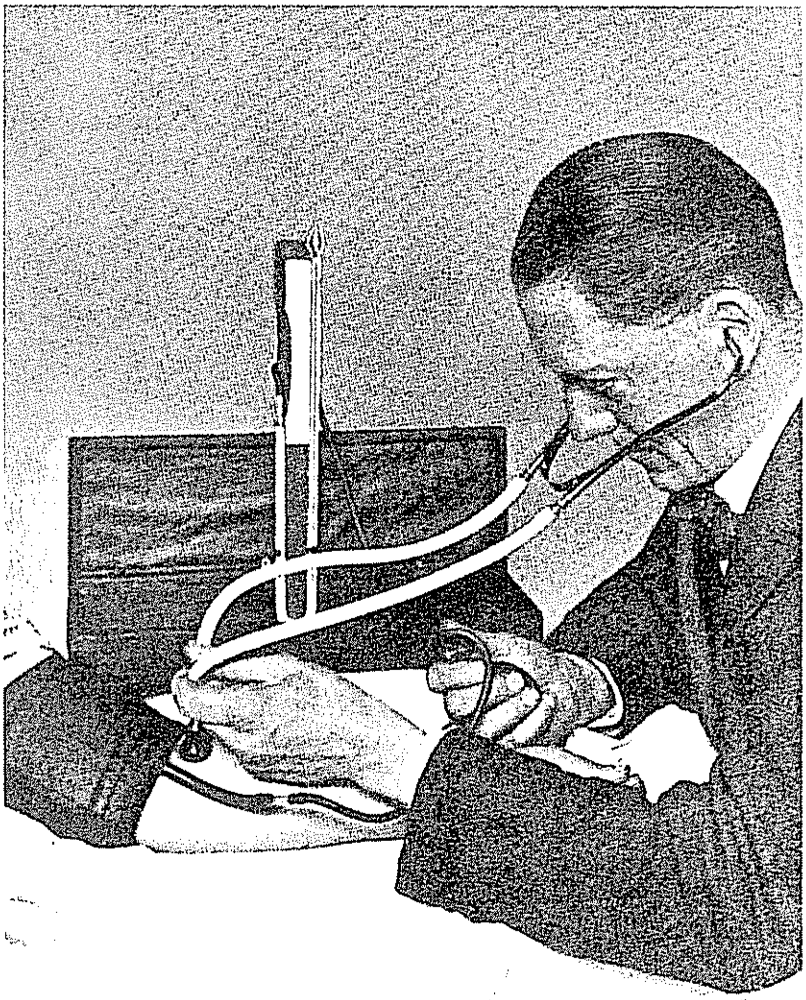

Fig. 26. Professor C.J. Martin's sphygmomanometer. Reproduced from: Halls Dally JF. *High blood pressure: its variations and control, 2nd ed.* London: W Heinemann, 1926; 252.

The age of clinical sphygmomanometry now began in earnest and with it came a problem which 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 . . . ' (87). There were mercury instruments with manometers incorporating a mercury reservoir and others with a U-tube similar to that first described by Poiseuille; there were a variety of aneroid devices which were marketed as 'pocket sphygmomanometers (Fig. 24); in addition, there were specially designed stethoscopes for measuring blood pressure and a 'Multiple Sphygmometroscope' for training observers was also available (86) (Fig. 25).

By 1926 modern sphygmomanometry had been well established and a large variety of U-tube mercury and aneroid sphygmomanometers were available (88). Simple U-tube mercury manometers, such as that designed by Professor C.J. Martin (Fig. 26), were popular (89), but an important modification was introduced in the 'Baumanometer' which utilized for the first time a modified U-tube and mercury

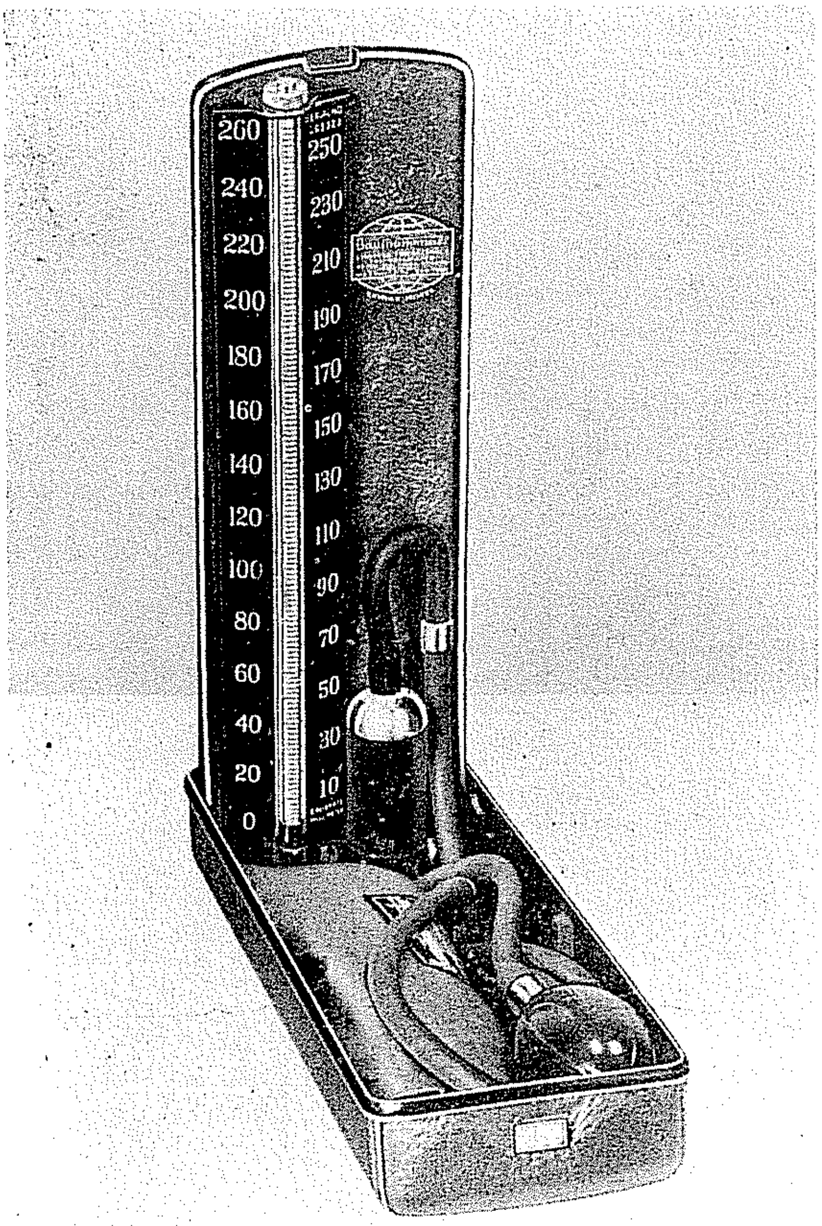

Fig. 27. Baumanometer. Reproduced from: Halls Dally JF. *High blood pressure: its variations and control, 2nd ed.* London: W Heinemann, 1926; 37.

reservoir (Fig. 27). The manufacturers marketed the instrument with the claim that every instrument was individually calibrated against a standard mercurial manometer, the accuracy of which had been checked against the U.S. Bureau of Standards manometer in Washington. Halls Dally, being of the opinion that such a claim was so important 'that it needs substantiation', submitted the Baumanometer to the National Physics Laboratory at Teddington, which confirmed the manufacturer's claim (90). Would that we exercised such cautious scepticism to-day!

In 1928, Pachon's sphygmo-oscillometer was still in use and was combined with auscultation to provide both auscultatory and oscillometric readings. Indeed Boulitte devised an aneroid sphygmomanometer which, by using a stethoscope attached to an armband, could be used to measure blood pressure by the Korotkov auscultatory, the oscillometric technique and the old palpatory method (91).

In the 1934 edition of Halls Dally's book a variety of aneroid devices were featured — the improved Brunton sphygmomanometer, the Boulette sphygmomanometer, the Tycos aneroid sphygmomanometer and a particularly robust device, the arteriotensiometer of Donzelot (92) (Fig. 28). Some of these devices utilized Gallavardin's armlet containing two rubber bladders overlapping by about one third of their widths to give an overall width of 12 cm, which it was claimed gave more uniform compression of the artery than a single bladder. It was recommended that aneroid devices should be tested against a standard mercury manometer every 2 years because of loss of accuracy.

A number of interesting devices for obtaining graphic recordings of blood pressure are described by Halls Dally (93). The Tonoscillograph of Plesch consisted of two manometers and a rotating drum with a graduated paper disk on which the blood pressure was recorded by a writing pen. Boulitte's Portable Recording Oscillometer (Fig. 29) utilized a clockwork recording system and aneroid manometer. The Tycos Recording Sphygmotonograph (Fig. 30), an elaborate disc recording device, is an indication of the importance that was being attached to blood pressure measurement at this time. In research, equipment was being adapted for the direct recording of intra-arterial blood pressure, as with the Boulittograph (94) (Fig. 31).

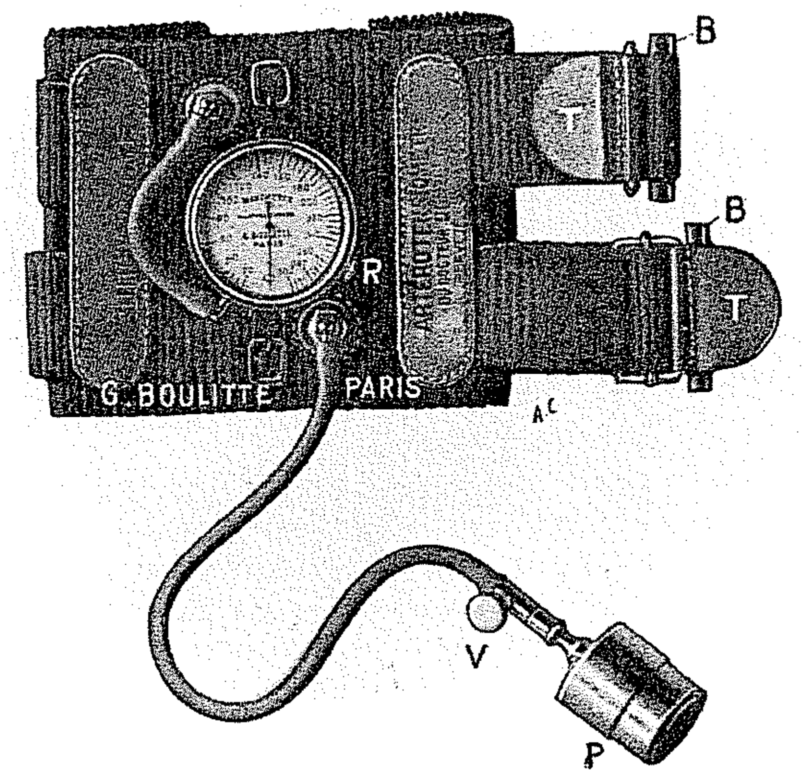

Fig. 28. Arteriotensiometer of Donzelot. Reproduced from: Halls Dally JF. *High blood pressure: its variations and control, 2nd ed.* London: W Heinemann, 1926; 45.

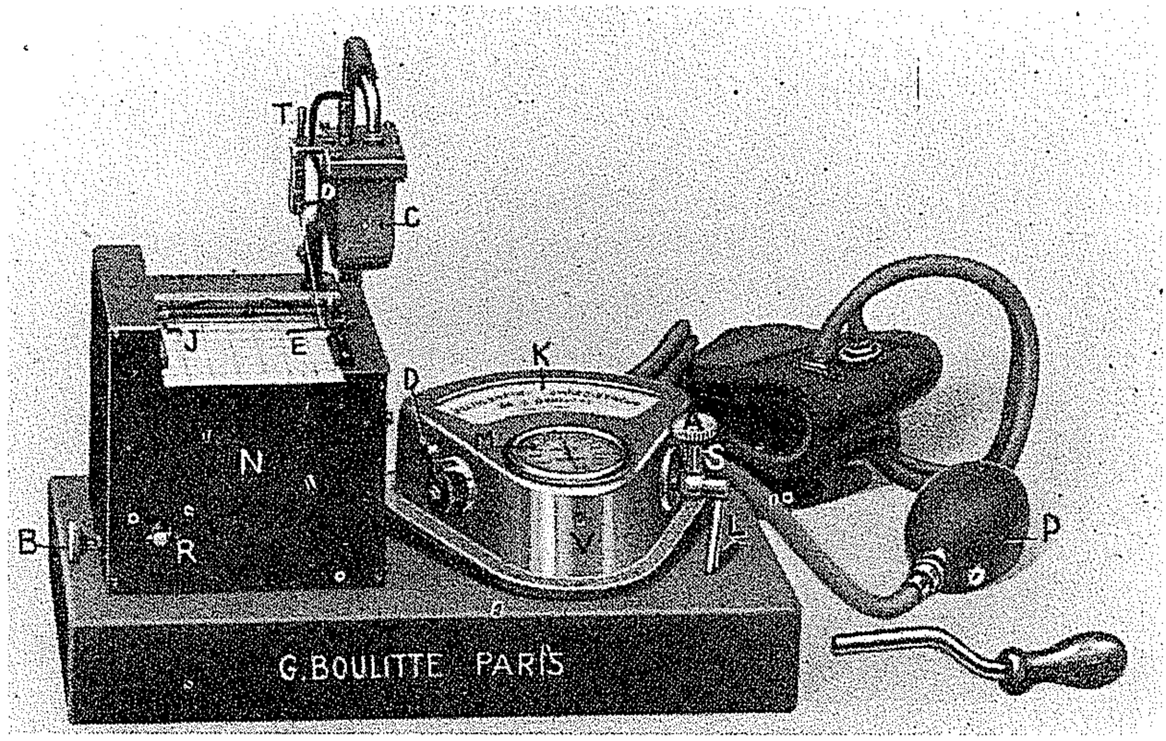

Fig. 29. Boulitte's portable recording oscillometer. Reproduced from: Halls Dally JF. *High blood pressure: its variations and control, 2nd ed.* London: W Heinemann, 1926; 62.

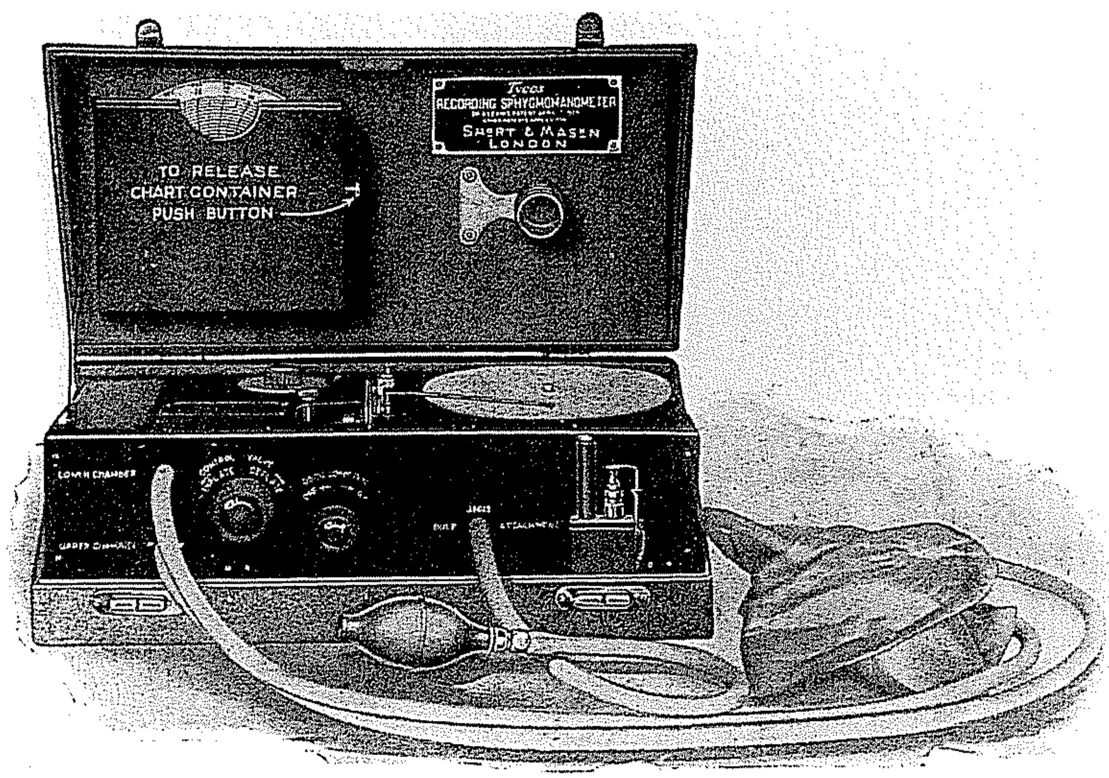

Fig. 30. Tycos recording sphygmotonograph. Reproduced from: Halls Dally JF. *High blood pressure: its variations and control, 2nd ed.* London: W Heinemann, 1926; 64.

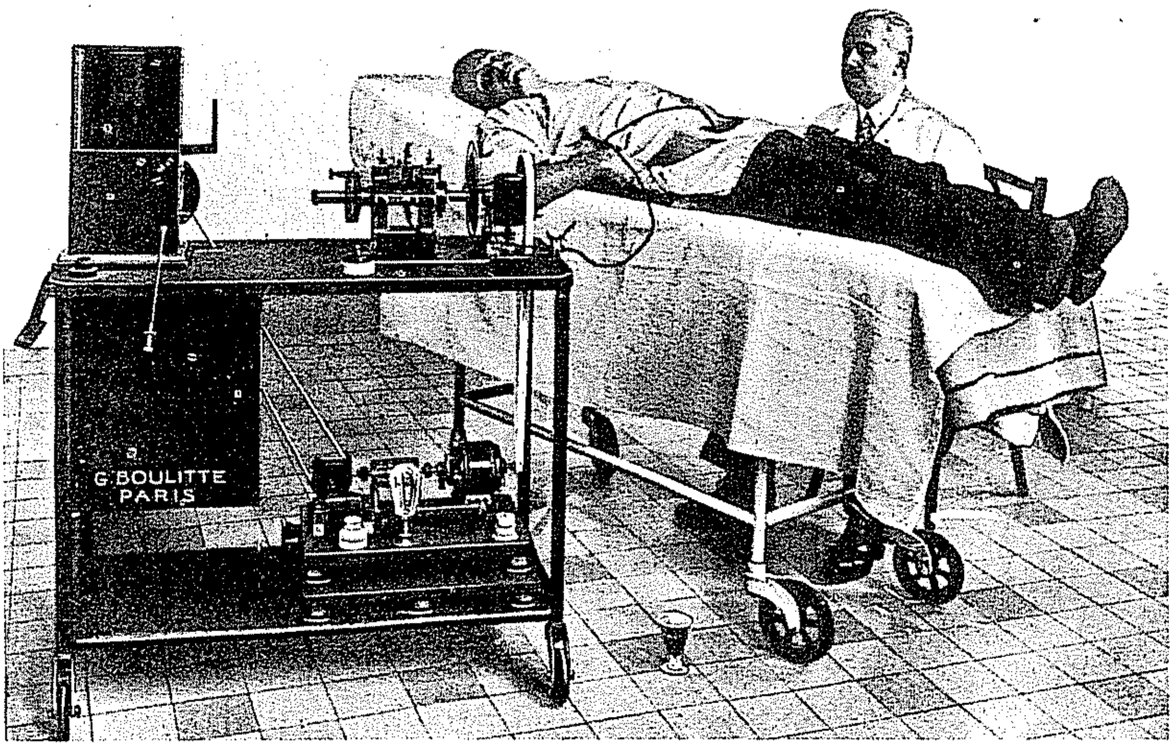

Fig. 31. Boulittograph. Reproduced from: Halls Dally JF. *High blood pressure: its variations and control, 2nd ed.* London: W Heinemann, 1926; 66.

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 blood pressure measurement (95). There have been many critical evaluations of the technique (96) and a series of recommendations for greater accuracy has been made by official bodies, such as the British Hypertension Society (97) and the American Heart Association (98). The sources of inaccuracy of blood pressure measurement have been reviewed elsewhere (99), but two sources of error are of historical importance in that they have influenced sphygmomanometer design, namely bladder size and observer error.

Inflatable bladder dimensions

Of the many controversial issues in hypertension few can rival that of determining the optimal bladder dimensions for a particular arm circumference. The problem is as old as the technique of blood pressure measurement itself. When Scipione Riva Rocci introduced the technique of cuff occlusion for the measurement of systolic blood pressure in 1896 (39), he used a very narrow cuff. Von Recklinghausen soon recognized that this was causing error and he recommended that the bladder should have a width of 12 – 13 cm (43). For the first quarter of this century it would seem

TABLE 1. *Recommended bladder dimensions*

Dimensions (cm)	Subject	Maximum arm circumference
13 × 4	Small children	17 cm
18 × 8	Medium-sized children	26 cm
35 × 12.5	Grown children and adults	42 cm

Accurate readings may be obtained in adults with arm circumferences greater than 42 cm by placing a cuff with a 35 cm bladder so that the center of the bladder is over the brachial artery. Reprinted from *Blood Pressure Measurement* by permission of the *British Medical Journal*.

that sphygmomanometers were provided with bladders that completely encircled the arm (100) and, indeed, such was the recommendation of the World Health Organisation in 1959 (101). However, during the next decade or so manufacturers began to reduce bladder size without consideration of the clinical inaccuracy caused by such a modification (102). An unnecessary controversy, that has consumed much energy and research resources, has raged ever since. It is fair to say that a review of the sizable literature on the subject (99) often serves to confuse rather than clarify.

It is generally agreed that the width of the bladder is not as critical as the length, provided bladder length is adequate and the bladder is not excessively narrow. The overwhelming opinion from the literature is for bladders with greater lengths (32 – 42 cm) so that the arm is encircled by the bladder in most subjects; the British Hypertension Society (97) and the British Standards Institution (103) have each decided to recommend only 3 cuffs for routine clinical use, with the proviso that for very large arms care should be taken to ensure that the center of the bladder is placed over the brachial artery (Table 1). This topic has been reviewed in depth by King (96) and Geddes (104).

Observer error

Blood pressure measurement by an observer using a standard mercury sphygmomanometer and stethoscope is subject to observer prejudice and terminal digit preference. These limitations can introduce error which is unacceptable for research work. Two devices have been designed specifically for research use — the random zero sphygmomanometer, which reduced observer prejudice, and the London School of Hygiene sphygmomanometer, which reduced 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 (105). 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 (Fig. 32). The problems of terminal digit preference and

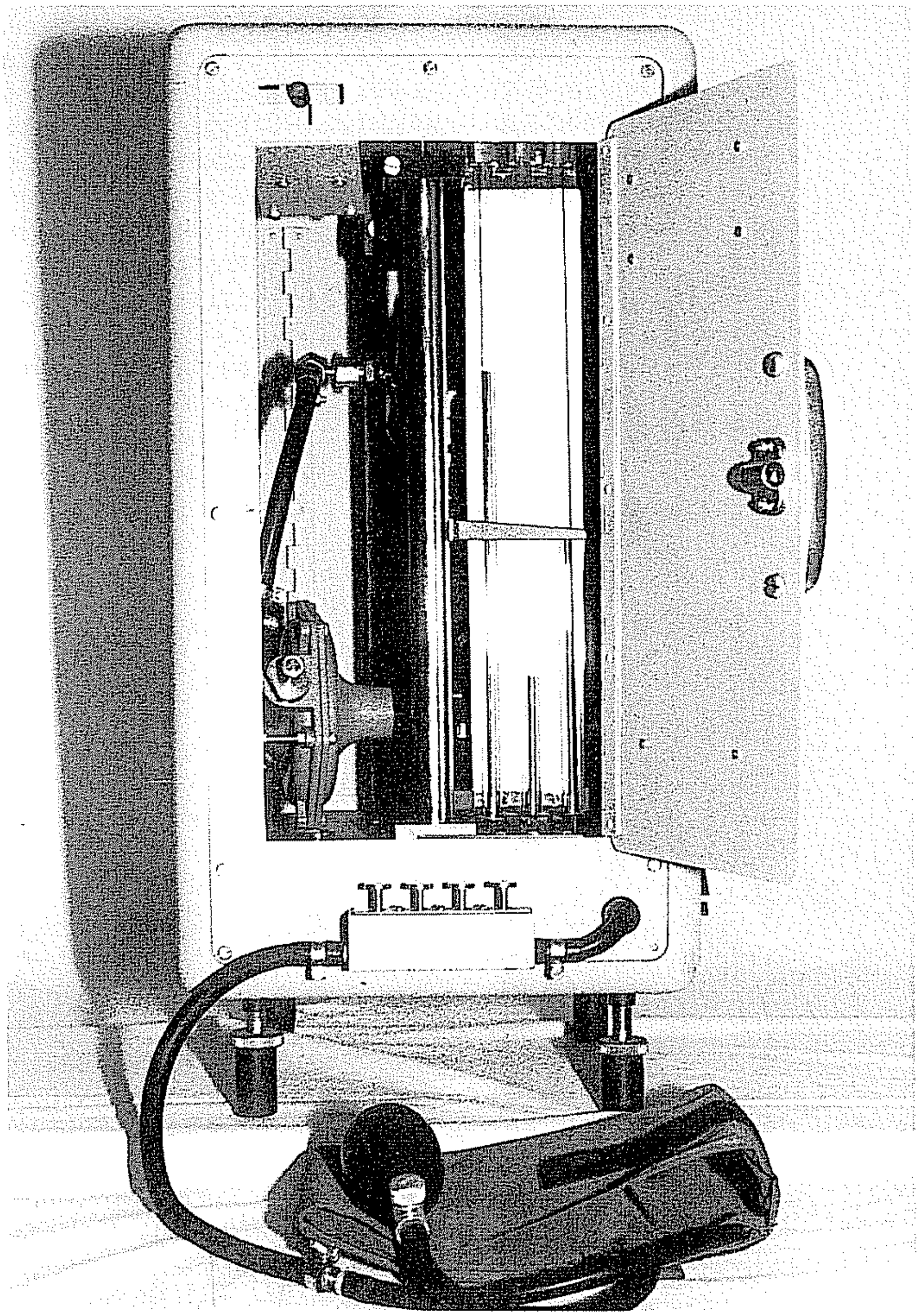

Fig. 32. London School of Hygiene sphygmomanometer. Photograph of model in the author's possession.

observer prejudice were thus removed and the instrument became popular in epidemiological and research studies for many years (99). Rather surprisingly it was accepted as the standard for blood pressure measurement without being subjected to validation. In 1982 a calibration error was demonstrated (106) which has not been rectified and the instrument is not now much used. The London School of Hygiene sphygmomanometer was modified by Nyberg (107) but this adaptation never became available for widespread use.

Random-zero sphygmomanometer

In 1963, Garrow described a 'zero-muddler for unprejudiced sphygmomanometry' (108) which was modified by Wright and Dore in 1970 (109) and produced commercially by Hawksley and Sons (Fig. 33). It is larger than a conventional sphygmomanometer and some 10 times more expensive. The manometer function is similar to

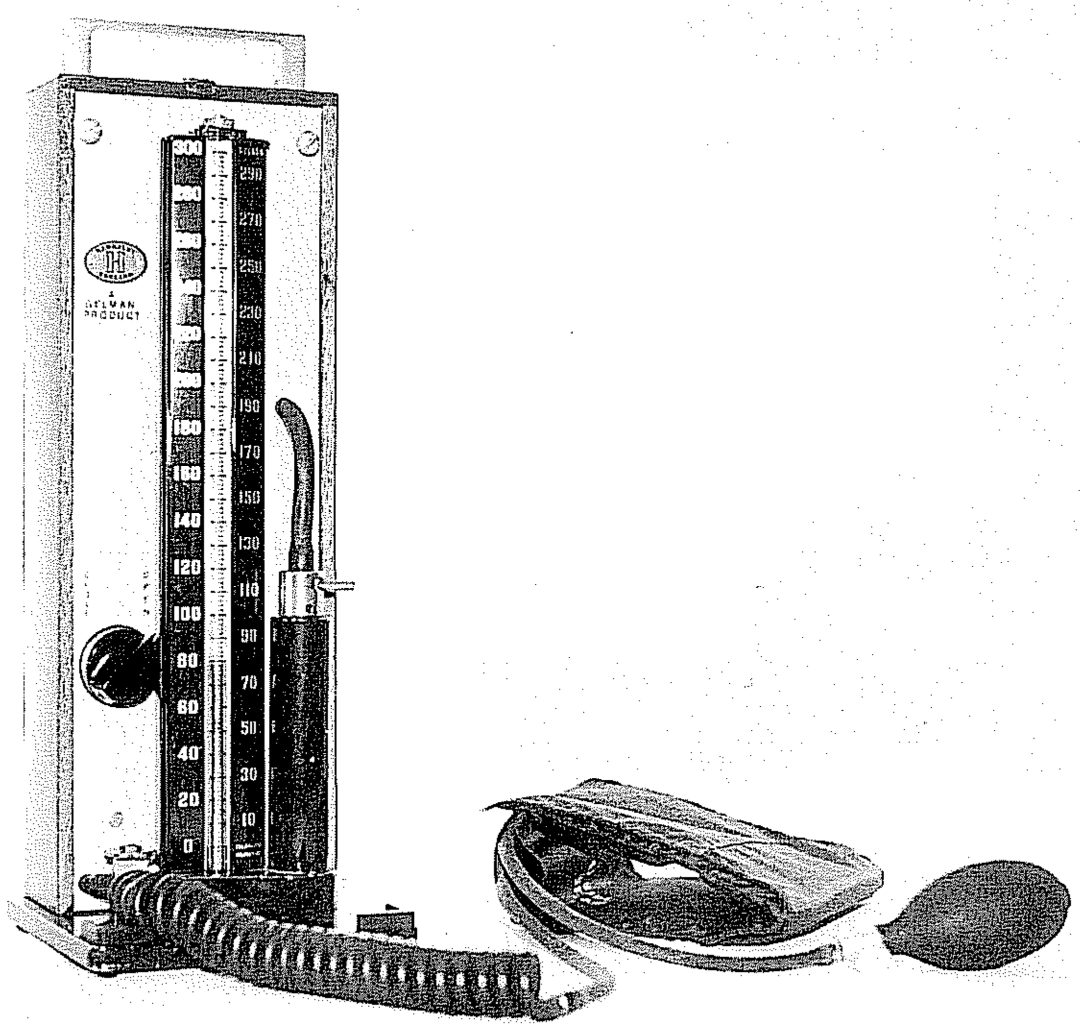

Fig. 33. Random-zero sphygmomanometer. Photograph of model in the author's possession.

the mercury sphygmomanometer, but a wheel is spun before each measurement to adjust the zero to an unknown level. Once the blood pressure 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 is generally accepted as the instrument of choice for epidemiological and research studies because it reduces observer bias and obscures digit preference, though the facility of the device to reduce terminal digit preference has been questioned (99). Because the random-zero sphygmomanometer is basically a mercury sphygmomanometer, its accuracy has been accepted rather uncritically and it has replaced the London School of Hygiene sphygmomanometer as the standard against which other devices are assessed (99). However, a number of recent studies have demonstrated that the instrument systematically gives lower readings than the standard mercury sphygmomanometer and it is no longer recommended in its present design for research and epidemiological studies (110).

Hoyt and Wolf modified the random-zero sphygmomanometer in 1984 (111), but, as with Nyberg's modification of the London School of Hygiene sphygmomanometer (107), it does not appear to have been developed commercially.

V. 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 would be outside the compass of this review which will attempt only to indicate major developments.

Janeway had recognized the variability of blood pressure in 1904 and had stressed the importance of making repeated observations of blood pressure (112). In 1917 Bernard Fantus devised an automatic recorder consisting of an Erlanger oscillometric manometer which was capable of automatically recording blood pressure, but it was never used in clinical studies (113). In 1921, Marian Blankerhorn (1885 – 1957) described an instrument for measuring blood pressure both repeatedly and automatically. Essentially it consisted of a double Ludwig kymograph and electrical motor by which it was possible to control inflation from a pressurized air source. Blankenhorn, who was fascinated by the effects of sleep on blood pressure, used this device to observe the behavior of blood pressure during sleep and made the interesting observation that he had difficulty in differentiating the 20 mmHg fall in blood pressure that may occur in normal subjects when turning from the supine to lateral position from that which occurs with sleep (114). It is interesting to reflect on the importance these early workers in clinical sphygmomanometry attached to the physiological variations in blood pressure that occurred with sleep, and in 1900 Walden compared the effects of natural and hypnotic sleep on blood pressure (115).

Since Blankenhorn's innovative device there have been many attempts at designing accurate automated devices capable of recording blood pressure at pre-set intervals automatically. The majority of such devices depend on Korotkov sound detection with a microphone, or the detection of arterial blood flow by oscillometry or ultrasound. However, a variety of devices dependent on alternative mechanisms have been developed in recent years; these include flush-dependent techniques, 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.

Palpatory technique

The first attempts to assess systolic blood pressure were by estimating the amount of digital pressure required to obliterate the radial or other pulse and many physicians took such pride in this skill that they resented the introduction of the sphygmomanometer (59, 73). Palpation of systolic pressure is still recommended as a preliminary technique in routine sphygmomanometry to exclude the presence of an auscultatory gap (99). Segall has described the palpation of diastolic blood pressure which he found accurate, but it never gained wide acceptance clinically (116). The technique does have some practical relevance for observers with poor hearing and is defended by Geddes (117).

Korotkov sound detection

With improving technology it is hardly surprising that manufacturers have attempted to design an automated device for routine clinical use. Indeed, the market for such devices has grown substantially with the increasing popularity of home measurement of blood pressure following the introduction of this technique by Brown in 1930 (118) and subsequent studies by a number of workers (see Chapter 5). Quite apart from market considerations an accurate semi-automated device would have the advantage of eliminating errors of interpretation together with observer bias and terminal digit preference. A number of semi-automated devices based on Korotkov sound detection are available (119 – 121). In the majority an electronic microphone shielded from extraneous noise in the pressure cuff is used to detect the Korotkov sounds and blood pressure may be recorded on a chart, or indicated on a digital display. The microphones are sensitive to movement and friction, however, and may be difficult to place accurately. Manual or automatic inflation and deflation, or both, may be available (99). Refinements, such as ECG gating, whereby auditory signals from the artery are only recorded when a transmitted pulse is anticipated, have helped to reduce the noise of artefactual sounds (122, 123). However, in spite of remarkable technological advances and production of an array of devices sphygmomanometry has been bedevilled, as in the past, by inaccuracy which is unacceptable in clinical practice and at the time of writing a semi-automated or automated device of proven accuracy is not available for the routine clinical measurement of blood pressure (99). In fact, dramatic though technological developments have been it must surely be a salutary indictment of biomedical engineering that nearly a century after Riva-Rocci and Korotkov introduced the technique of clinical sphygmomanometry, the only acceptable standard for blood pressure measurement is a trained observer using a standard mercury sphygmomanometer and stethoscope (99).

Oscillometry

The oscillometric technique, which enjoyed a considerable vogue around the turn of the century, is now becoming popular again. Oscillometric detection is based on the principle that as cuff pressure decreases from above systolic to below diastolic pressure, oscillations in the bladder are transmitted to either a mercury or, more usually, an aneroid manometer or other recording system. Two cuffs are often employed for oscillometric measurement; the lower one acting as a sensing cuff is inflated to pressure well below systolic pressure and as the pressure in the upper cuff is decreased systolic pressure is registered by the appearance of the first oscillations in the distal cuff. The detection of diastolic pressure has been a source of controversy, but it is now accepted as being the point of abrupt decrease in amplitude of the maximum oscillations (124). The development of oscillometry has been well reviewed by Geddes (125).

Complex devices that record blood pressure automatically at pre-set intervals have been designed for intensive care units and theatres. Examples of such systems are the Dinamap (126) and Vita-Stat (127). Such devices may use two methods of measurement, most commonly Korotkov sound detection and oscillometry, but often the mode being used is not indicated and assessments of accuracy for each mode are sometimes not available from the manufacturers. Moreover, these units do not always lend themselves to independent assessment because of their complex design. Reports of accuracy from independent units, each using a different validation protocol, makes comparison of results difficult and it may be many years before there is sufficient evidence to enable prospective buyers to make a confident judgement (99).

Flush techniques

Gaertner used a flush method of measuring systolic pressure in the finger which was popular for a time (41), but the only lasting application of the flush technique has been in pediatrics for measuring blood pressure in neonates and small children. The technique is based on the principle that if an extremity, usually the foot, is made bloodless by wrapping it in a bandage and a distally inflated cuff is slowly deflated, the point of flushing of the extremity indicates systolic pressure (128). The technique has been rendered obsolete by newer methods of ultrasonic measurement.

Ultrasonic devices

Arterial wall motion may be detected by the change in frequency of reflected ultrasonic waves transmitted by a transducer positioned over the brachial artery. Changes in arterial wall movement are detected by changes in ultrasonic frequency at the point of systolic and diastolic pressures — the Doppler shift phenomenon (129). The technique is particularly suited for measuring blood pressure in neonates and states of shock (128, 130) in which Korotkov sound detection may be difficult, but the accuracy of the technique is dependent on accurate placement of the transducer. Two features make ultrasound particularly attractive: namely, it is applicable to infants as well as to adults, and it records pressure in hypotensive states (131).

Infrasonic devices

The infrasonic method of blood pressure measurement depends on the detection of very-low-frequency acoustic wave energy generated during movement of the arterial wall which is converted to an audible signal. Results with this technique generally have been disappointing (132, 133).

Impedance plethysmography

With impedance plethysmography changes in limb volume are detected by alterations in tissue impedance. During deflation of an upper arm cuff changes in impedance measured by two electrodes, placed on the skin of the forearm, are detected at the point where the pulse first appears below the cuff leading to a change in arm volume (134). This method, which has been used mostly in neonates, is generally restricted to detection of systolic pressure as measurement of diastolic pressure tends to be variable.

Tonometry

Tonometry means simply the measurement of force. It does not require the use of occluding cuffs, being based on the principle that displacement of a force-sensitive transducer over a superficial artery can be made linearly proportional to the arterial blood pressure (135). Tonometry can provide a continuous read-out of pulse pressure, but its application is greatly limited by the need for critical placement of the instrument as any displacement leads to marked fluctuations in recording amplitude necessitating repositioning and recalibration. A new application of tonometry utilizing multiple transducers in a single diaphragm may overcome many of the shortcomings of tonometry and the system will soon be marketed (136).

Finger blood pressure

The finger was first used by for measuring blood pressure by Marey in 1880 who attempted to measure pressure by oscillometry (37). In 1895, Mosso used all the fingers of one hand to amplify finger oscillations (38). Four years later Gaertner measured what he thought was mean blood pressure by observing the point of flushing during cuff deflation in a finger that had been made bloodless with an occluding ring (41, 42).

A number of finger measuring systems based on the detection of a volume changes in a digit by double cuff systems have been developed for clinical blood pressure measurement, but accuracy studies have yielded conflicting results (121, 137) and the techniques are subject to the problems caused by vasoconstriction. However, new finger measuring techniques are being developed for the measurement of ambulatory blood pressure and are described below.

Phase shift method

Various techniques have been developed to detect volume changes dependent on pulse wave velocity. The phase shift technique measures blood pressure by detecting the time taken for blood to travel between 3 occluding cuffs — the phase shift — as the pressure decreases in the cuffs (138). This interesting technique merits further development.

Wideband external pulse recording

Recently Blank and colleagues, using a transducer with a wide frequency response, have separated the external pulse recorded during cuff deflation into 3 components which can be used to determine systolic and diastolic pressure (139).

Many of the innovative techniques referred to in this section hold promise for the future, but the results of validation studies have often been disappointing. It is essential that new instruments for measuring blood pressure are fully evaluated before being introduced for clinical practice (140) if they are to gain a permanent place in future reviews of the history of blood pressure measurement.

VI. AMBULATORY MEASUREMENT OF BLOOD PRESSURE

For 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 blood pressure and the striking response to stresses, such as surgery, tobacco and anxiety (141). A quarter of a century later Smirk and his colleagues attempted to assess blood pressure behavior in the individual by measuring basal blood pressure (142), and in 1940 Ayman and Goldshine showed that blood pressure measured at home was lower than in the clinic (143). Using a non-invasive apparatus which employed a Gallavardin double cuff, the late George Pickering and his group at Oxford showed for the first time how constant and profound was the fall in blood pressure recorded during sleep. They also demonstrated the fluctuations in pressure during the course of 24 hours (144).

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 (145) (Fig. 34). The first intra-arterial ambulatory blood pressure measurement was performed in Oxford in 1966 and the first publication reporting blood pressure changes in unrestricted man was in 1969 (146) (see Chapter 16).

Intra-arterial measurement of ambulatory blood pressure

The Oxford system has been adopted by other centers to provide important information on blood pressure behavior (147, 148). It soon became apparent that blood pressure 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 (147, 149), lecturing, driving a motor car (150), and having sexual intercourse (151). Furthermore, ambulatory measurement made it possible to determine, not alone the blood-pressure-lowering efficacy of antihypertensive drugs, but also their duration of action (152). Perhaps, most exciting-

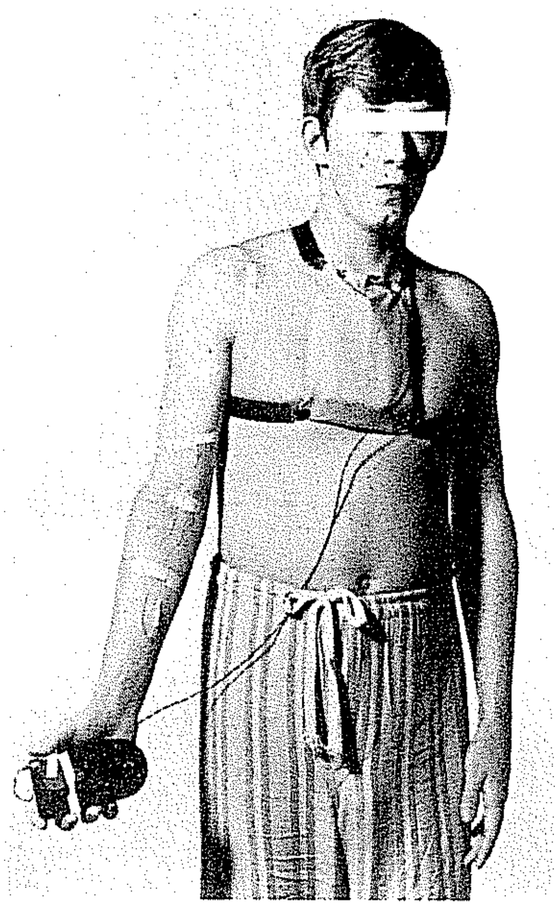

Fig. 34. The Oxford intra-arterial system for 24-hour blood pressure measurement. Reproduced from: Pickering G. *High blood pressure, 2nd ed.* London: J & A Churchill, 1968; (facing p. 21).

ly of all, 24-hour ambulatory recordings of blood pressure provided sufficient data for the characterization of nocturnal blood pressure (153) and the diurnal pattern of blood pressure (154), a subject reviewed with characteristic clarity by Pickering in 1964 (155).

These studies, though offering new insights into blood pressure behavior, 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 (145, 156). Attention was turned, therefore, towards developing a device that would measure ambulatory blood pressure non-invasively. The early history of ambulatory blood pressure measurement has been reviewed by Pickering and Stott (145) and Horan and his colleagues (157).

Non-invasive intermittent measurement of ambulatory blood pressure

Day-time ambulatory blood pressure

In the 1960s a number of attempts were made to provide a non-invasive alternative to direct intra-arterial measurement of ambulatory blood pressure. These early developments in the technique have been reviewed by Pickering (158). In 1962, two instruments were devised for measuring systolic pressure in a digital artery, but, as with all finger measuring devices, the problems associated with vasoconstriction limited their application. Two instruments using cuff inflation and Korotkov sounds were also developed at this time but were of limited application because of their size. A more portable system utilizing a Gallavardin double cuff and detecting the phase shift of pressure has already been referred to (144). In 1968, Schneider and his colleagues described a fully automatic portable blood pressure recorder which was reasonably accurate (159). None of these instruments was developed commercially and, therefore, never became established in clinical practice.

1962, Hinman and his colleagues described the first truly portable ambulatory system for the non-invasive measurement of blood pressure (160). The Remler Company of California developed this system commercially (161) (Fig. 35) and so began an important era in hypertension management, the effects of which are only now being fully appreciated; it has been used by a number of workers who validated its accuracy (162 – 165).

Fig. 35. The Remler ambulatory blood pressure recorder. Reproduced from: Kain HK, Hinman AT, 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.

The Remler consisted of a battery-operated recorder worn by the patient, a cuff which was inflated by the patient at pre-determined intervals and a microphone strapped over the brachial artery. Blood pressures were recorded on a magnetic tape which could be later decoded and the pressure plotted over the period of recording (163). Because the device depended on inflation by the subject, recordings were confined to waking hours and rarely lasted more than 12 – 14 hours. Moreover, unlike direct intra-arterial ambulatory blood pressure, the Remler system, in common with most of its successors, measured blood pressure intermittently at pre-set intervals and not continuously as with the direct technique and subjects were required to pause in their activities so that the arm may be held steady during recording of pressure. Moreover, the Remler system required the subject to inflate the cuff at pre-determined intervals. These disadvantages were offset to a large extent, however, by the safety of non-invasive measurement.

As with intra-arterial measurement, the Remler system provided new insights into blood pressure behavior (166) and new data on antihypertensive drug efficacy and duration of effect (167, 168). Among the most important aspects of hypertension studied with the Remler was the demonstration by Sokolow and his colleagues that ambulatory blood pressure was a better predictor of morbidity and mortality than casual office pressure (169, 170).

Twenty-four-hour ambulatory blood pressure

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 (163).

In 1979, Harshfield and his colleagues at Cornell validated the Del Mar Avionics Pressurometer II Ambulatory ECG and Blood Pressure Recording System (171). This system, which was fully automated, permitted the measurement of blood pressure throughout the 24 hours non-invasively. Early models were bulky and noisy, but the Del Mar system has been modified and made more portable over the years. By providing a non-invasive profile of blood pressures over the 24-hour period, it has been used extensively in assessing circadian patterns in normotensive (172) and hypertensive subjects (173) and in demonstrating the duration of action of antihypertensive drugs (157). The Avionics system was followed by a number of automated devices for the measurement of 24-hour blood pressure (174). Systems, such as the latest SpaceLabs device, the 90207 (Fig. 36), are pocket-sized with an almost noiseless pump (175). Some systems measure blood pressure by Korotkov sound detection, with or without ECG gating, and others use oscillometry (174). These instruments are expensive and strict accuracy criteria are being demanded from manufacturers (176).

Being non-invasive and almost completely free of adverse effects, these automated systems, capable of giving accurate profiles of blood pressure behavior over 24 hours, have found much wider use in research and clinical practice than was

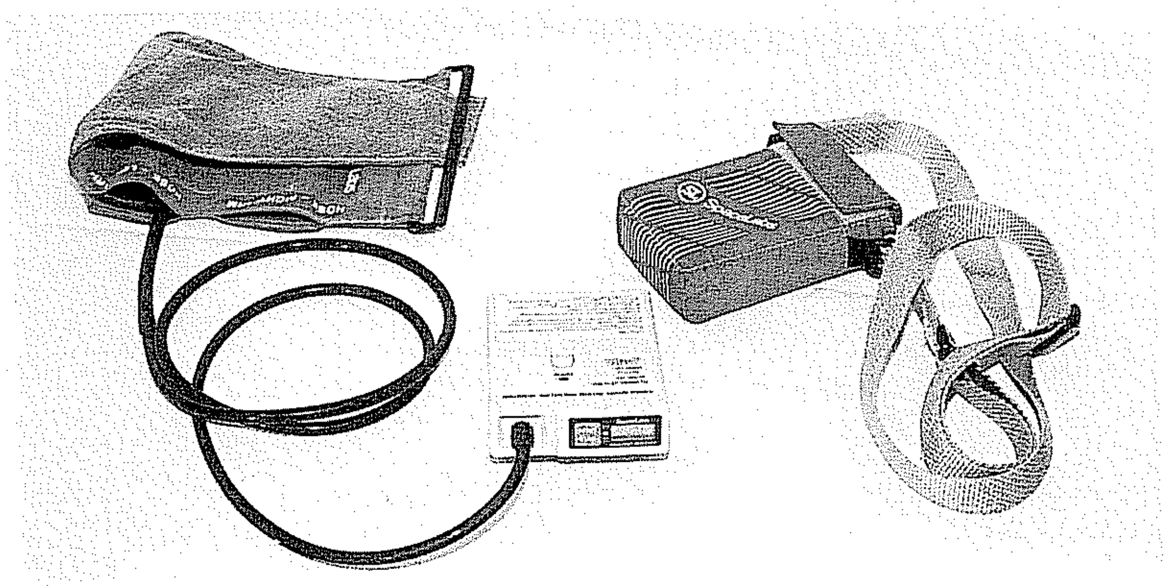

Fig. 36. SpaceLabs 90207. Photograph of model in the author's possession.

ever possible with invasive techniques. The concept of white coat hypertension, the phenomenon whereby blood pressure recorded by doctors and nurses is much higher than ambulatory day-time 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 (177). Recently profiles of 24-hour blood pressure in normal subjects have been characterized in population studies (178). It may now be anticipated that ambulatory blood pressure will become indispensable in the assessment of patients with elevated blood pressure (179).

Non-invasive continuous measurement of ambulatory blood pressure

The main disadvantages of the above systems are that they only provide intermittent measurement of 24-hour blood pressure and that the subject has to cease activity during the measurement of blood pressure. Though intermittent blood pressures give circadian blood pressure patterns which are surprisingly close to intra-arterial pressures (180), 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 practice, therefore, ambulatory measurements are usually made at 15-minute or 30-minute intervals. The disturbing effect of cuff inflation on sleep has also to be considered with these systems and their accuracy during exercise has been questioned (181). The next advance in blood pressure measurement is likely to be the development of accurate systems that will provide continuous 24-hour blood pressure allowing detailed waveform scrutiny and beat-to-beat analysis — in short, the equivalent of direct intra-arterial measurement without the inherent dangers of invasive catheterization.

In 1968, Peñáz patented a servo-plethysmomanometer based on the vascular unloading principle using a light source and photocell in a finger cuff (182). In 1973, he presented the technique at Dresden (183). 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. Peñáz's technique has been modified by Wesseling in The Netherlands (184), 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 blood pressure (185, 186) (see Chapter 11).

Another technique based on the Peñáz principle of vascular unloading has been described by Yamakoshi and colleagues (187). Using a hydraulic servo-control system, counterpressure is applied to the finger to equalize arterial pressure and arterial pressure is indirectly estimated by measuring the counterpressure. More recently Yamakoshi and his colleagues have elaborated on this technique describing two methods of measuring blood pressure continuously utilizing arterial elastic properties — a volume-oscillometric and a volume-compensation method (188), each based on the vascular unloading principle of Peñáz (183). These techniques may also prove to be an alternative means of obtaining continuous blood pressure recordings non-invasively.

Technological advances must soon provide accurate alternatives to the traditional techniques of blood pressure measurement. Recently, the Association for the Advancement of Medical Instrumentation (189) and the British Hypertension Society (176) have produced strict criteria for the evaluation of blood-pressure-measuring devices, most especially ambulatory systems. It will be necessary, therefore, in future for manufacturers to provide evidence of independent validation of the many innovative techniques which the future promises. Writing in 1987, Garrett and Kaplan stated that 'ambulatory blood pressure monitoring on a 24-hour basis is an idea whose time has come' (190). This is an appropriate note on which to close this section on the history of ambulatory measurement signalling, as it does, the end of an era and the beginning of a new epoch, that in which assessment of the individual with suspected blood pressure elevation will no longer be dependent on isolated measurements made under strange circumstances but dependent rather on evaluation of a 24-hour profile of blood pressure behavior 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 blood pressure.

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

VII. ENVOI

It is just over 250 years since the Reverend Hales discovered blood pressure and provided the crude principles of direct measurement (3). It is a little over 100 years since

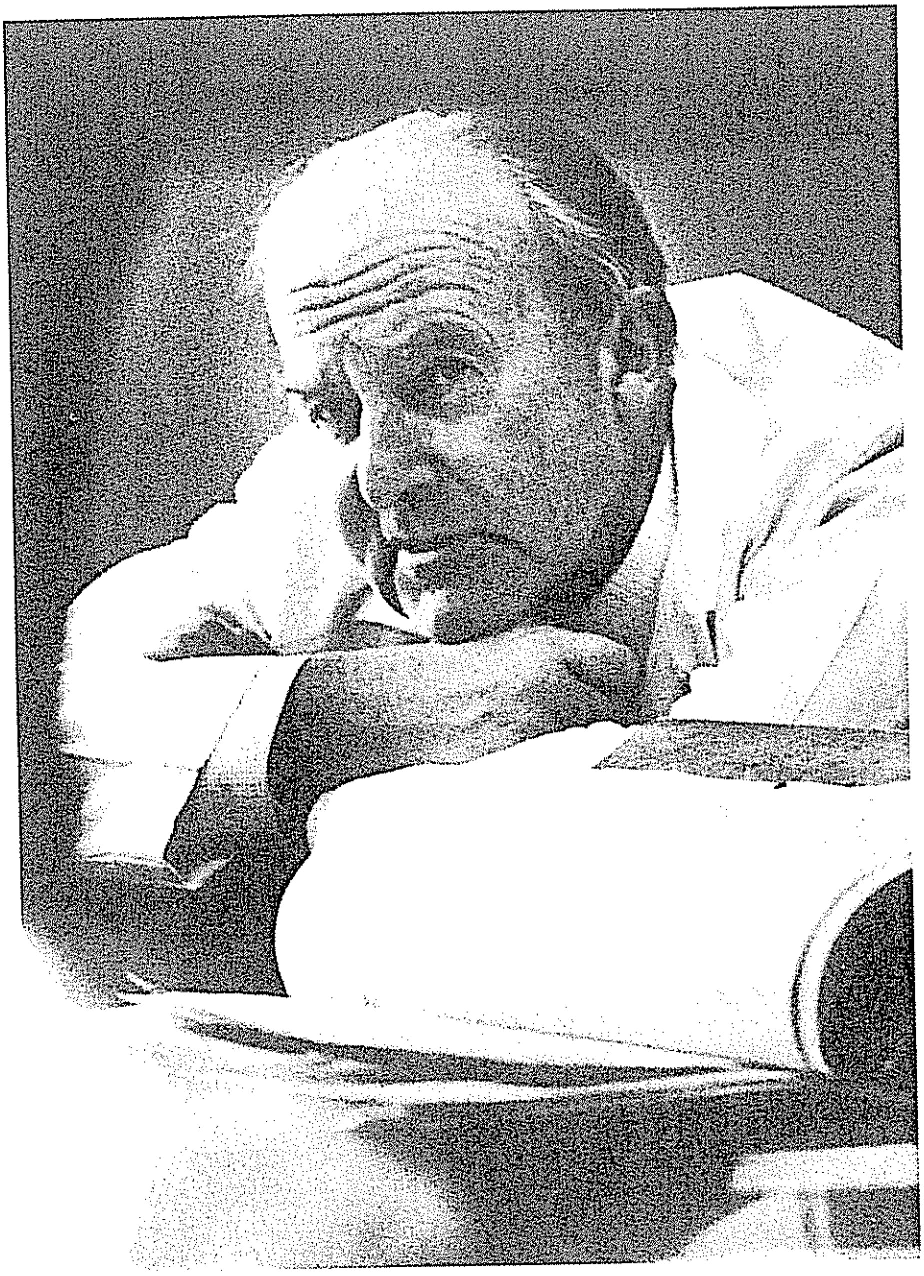

Fig. 37. Sir George Pickering. Reproduced from: Pickering G. *The nature of essential hypertension*. London: J & A Churchill Ltd., 1961, reprinted 1981 (frontispiece).

von Basch 830) and Riva-Rocci (39) devised instruments enabling the measurement of systolic blood pressure in clinical practice and just 85 years since Nicolai Korotkov (61) introduced the auscultatory technique of blood pressure measurement which 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 (2) and Hales's description of blood pressure (3) and the similar delay before blood pressure measurement was applied to man. 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 a secure connection between pressure-detecting systems and a manometer, did more to advance blood pressure measurement than did the development of scientific ideas.

No such reasoning can vindicate the paucity of development in blood pressure 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 blood pressure 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 being developed in the light of advances in knowledge. That the past decade should witness a revival of the criteria so clearly laid down by Faught (86) and Janeway (47) 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; if scientific vigilance had been exercised, this eventuality need never have been.

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 of future generations will be directed at our insistence in permitting isolated blood pressure measurements to dictate diagnostic and management policies in hypertension in the light of an abundance of evidence, beginning with Janeway's studies in 1904 (141), and emphasized by Pickering's (Fig. 37) Oxford group in the 1960s (145), showing the variability of blood pressure and the effect of doctors themselves on the very quantity they were attempting to measure. How many have been subjected to unnecessary or inappropriate therapy, and continue to be 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 and to acknowledge that the lessons of history can alert us to our ineptitudes and direct our future endeavors.

REFERENCES

1. Gispen JG. 'Measuring' the patient in ancient medical texts. *Acta Clin Belg* 1974; *29:* 224 – 227.
2. Harvey W. *Exercitatio anatomica de motu cordis et sanguinis in animalibus.* A fascimile of the 1628 Francofurti edition with the Keynes English translation of 1928. Birmingham, Alabama; The Classics of Medicine Library, 1978.
3. Hales S. *Statical essays: containing haemostaticks, Vol. ii.* London: 1733; W. Innys & R. Manby. p. 1 *et seq.*
4. Clark-Kennedy AE. Stephen Hales, DD,FRS. *Br Med J* 1977; *ii*; 1656 – 1658.
5. Burget GE. Stephen Hales. *Ann Med Hist* 1925; *7:* 109 – 116.
6. Poiseuille JLM. Recherches sur la force du coeur aortique. Thesis no. 166. Paris: Didot, 1828 (and *J Physiol Exp* 1828; *8:* 272).

7. Klopp EH. Poiseuille's contributions to medical science. *Surg Gynec Obstet* 1974; *139:* 95 – 96.
8. Blake J. Observations on the physiological effects of various agents introduced into the circulation, as indicated by the haemadynamometer. *Edinburgh Med Surg J* 1839; *51:* 330 – 345.
9. Lawrence C. Physiological apparatus in the Wellcome Museum. 3. Early sphygmomanometers. *Med Hist* 1979; *23:* 474 – 478.
10. Ludwig C. Beiträge zur Kenntniss des Einflusses der Respirationsbewegungen auf den Blutlauf im Aortensysteme. *Müllers Arch Anat Physiol Wissensch Med* 1847; 242 – 302.
11. Booth J. A short history of blood pressure measurement. *Proc Roy Soc Med* 1977; *70:* 793 – 799.
12. Faivre J. Etudes expérmentales sur les lésions organiques du coeur. *Gaz Med Paris* 1856: 727.
13. Vierordt K. *Die Lehre vom Arterienpuls.* Braunschweig: F. Vieweg, 1955.
14. Herrison J (translated by ES Blundell). *The sphygmomanometer, an instrument that makes the arteries apparant to the eye.* London: Longman, Rees, Orme and Brown, 1835.
15. Marey EJ. *Physiologie médicale de la circulation du sang.* Paris: 1863; Adrien Delahaye, 176.
16. Lawrence C. Physiological apparatus in the Wellcome Museum. 1. The Marey sphygmograph. *Med Hist* 1978; *22:* 196 – 200.
17. Foster B. Note on the regulation of the pressure on the artery in the application of the sphygmograph. *Br for Med Chir Rev* 1867; *40:* 240 – 242.
18. Mahomed FA. The physiology and clinical use of the sphygmograph. *Med Times Gaz* 1872; *i:* 62 – 64.
19. Mahomed FA. The aetiology of Bright's disease and the pre-albuminuric stage. *Med Chir Trans* 1874; *39:* 187 – 228.
20. Brunton TL. Lectures on the experimental investigation of the action of medicines. *Br Med J* 1871; *i:* 581 – 583.
21. Janeway TC. *The clinical study of blood-pressure.* New York and London: D. Appleton & Co., 1904; 45.
22. Dudgeon RE. *The sphygmograph.* London: Bailliere, Tindall & Cox, 1882.
23. Lawrence C. Physiological apparatus in the Wellcome Museum. 2. The Dudgeon sphygmograph and its descendants. *Med Hist* 1979; *23:* 96 – 101.
24. Richardson BW. Standard pulse readings. *Asclepiad* 1885; *2:* 193 – 203.
25. Albutt C. *Diseases of the arteries including angina pectoris, vol. 1.* London: Macmilllan, 1915: 65.
26. Batten RD. On a clinical pulse manometer. *Med Press Circ* 1892; *105:* 549 – 551.
27. Bloch AM. Nouveau sphygmomètre. *Paris Soc Biol Mém* 1888; *40:* 84 – 86.
28. von Kries N. Ueber den Druck in den Blutcapillaren des menschlichen Haut. *Leipzig Math Phys Ber* 1875; *27:* 149 – 160.
29. *Physiologie expérimentale: travaux du laboratoire de M. Marey, vol. 2.* Paris: G. Masson, 1876; 309 – 331.
30. von Basch S. Ueber die Messung des Blutdrucks am Menschen. *Z Klin Med* 1880; *2:* 79 – 96. English translation in: Arthur Ruskin, *Classics in arterial hypertension.* Springfield, IL: Charles C Thomas, 1956; 83 – 102.
31. Zadek I. Die Messung des Blutdrucks am Menschen mittelst des Basch'schen Apparates. *Z Klin Med* 1880/1881; *2:* 509 – 551.
32. Potain PCE. Du sphygmomanomètre et de la mesure de la pression artérielle chez l'homme. *Arch Physiol Norm Pathol* 1889; *i:* 556 – 569.

33. Hill L, Barnard H. A simpler and accurate form of sphygmomanometer or arterial pressure gauge contrived for clinical use. *Br Med J* 1897; *ii:* 904.
34. Oliver G. *A contribution to the study of the blood and blood-pressure.* London: HK Lewis, 1901; 121 – 127.
35. Janeway TC. *The clinical study of blood-pressure.* New York and London: D. Appleton & Co., 1904; 48 – 49.
36. Ozanam C. *La circulation et le poid.* Paris: J.B. Baillière, 1886.
37. *Physiologie expérimentale: Travaux du laboratoire de M. Marey, vol. 4.* Paris: G. Masson, 1880; 253 – 257.
38. Mosso A. Sphygmomanomètre pour mesurer la pression du sang chez l'homme. *Arch Ital Biol* 1895; *23:* 177.
39. Riva-Rocci S. Un nuovo sfigmomanometro. *Gazz Med Torino* 1896; *50:* 981 – 996; *51:* 1000 – 1017.
40. 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.
41. Gaertner G. Ueber einen neuen Blutdruckmesser (Tonometer). *Wien Med Wochenschr* 1899; *49:* 1411 – 1418.
42. Janeway TC. *The clinical study of blood-pressure.* New York and London: D. Appleton & Co., 1904; 66 – 69, 82 – 84.
43. von Recklinghausen H. Ueber Blutdruckmessung beim Menschen. *Arch Exop Pathol Pharmakol* 1901; *xlvi:* 78.
44. Janeway TC. *The clinical study of blood-pressure.* New York and London: D. Appleton & Co., 1904; 58.
45. Erlanger J. A new instrument for determining the minimum and maximum blood-pressures in man. *Johns Hopkins Hosp Rep* 1904; *12:* 53 – 110.
46. Janeway TC. *The clinical study of blood-pressure.* New York and London: D. Appleton & Co., 1904; 69 – 74.
47. Janeway TC. *The clinical study of blood-pressure.* New York and London: D. Appleton & Co., 1904; 59 – 66, 77.
48. Janeway TC. *The clinical study of blood-pressure.* New York and London: D. Appleton & Co., 1904; 77.
49. Janeway TC. *The clinical study of blood-pressure.* New York and London: D. Appleton & Co., 1904; 54.
50. Janeway TC. *The clinical study of blood-pressure.* New York and London: D. Appleton & Co., 1904; 84 – 87.
51. Janeway TC. *The clinical study of blood-pressure.* New York and London: D. Appleton & Co., 1904; 86.
52. Janeway TC. *The clinical study of blood-pressure.* New York and London: D. Appleton & Co., 1904; 87 – 93.
53. Janeway TC. *The clinical study of blood-pressure.* New York and London: D. Appleton & Co., 1904; 93 – 100.
54. Halls Dally JF. *High blood-pressure: its variations and control, 3rd ed.* London: W. Heinemann, 1934; 14 – 15, 247 – 248.
55. Singer C. A clinical apparatus for obtaining graphic records of blood pressure. *Lancet* 1910; *i:* 365 – 367.
56. Von Recklinghausen H. Unblutige Blutdruckmessung. *Arch Exp Pathol Pharmakol* 1906; *55:* 375 – 504.
57. Pachon V. Papers of 1909 in *Comptes rendus de la Société de Biologie* 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.
58. *Sphygmomanometers and polygraphs.* London: Catalogue of Hawlsley & Sons, Ltd., ca. 1931; 14.

59. Blake E. Recent British researches on arterial tension. *Med Times Gaz* 1895; *23:* 29 – 30.
60. Cushing H. On the routine determination of arterial tension in the operating room and clinic. *Boston Med Surg J* 1903; *148:* 250.
61. Korotkov NC. To the question of methods of determining the blood pressure (from the clinic of Professor CP Federoff). *Rep Imp Mil Acad* 1905; *11:* 365 – 367.
62. Laher M, O'Brien E. In search of Korotkoff. *Br Med J* 1892; *285:* 1796 – 1798.
63. Dock W. Korotkoff sounds. *N Engl J Med* 1980; *302:* 1264 – 1267.
64. Janeway TC. Some observations on the estimation of blood pressure in man, with especial reference to the value of the results obtained with the newer sphygmomanometers. *NY Uni Bull Med Sci* 1901; *1:* 106 – 126.
65. Krilov DO. On measuring the blood pressure by the sound method of Dr. NS Korotkov. *Bull Imp Mil Med Acad (St. Petersburg)* 1906; *13:* 221.
66. Mobchanor NW, Mishtenko AS, Silvertov VP. New stage in cardiology. *J Surg Anaesthesiol (Moscow)* 1971; *4:* 6 – 9.
67. Ettinger W. Auskultatorische Methode der Blutdruckbestimmung und ihr praktischer Wert. *Wien Klin Wochenschr* 1907; *20:* 992 – 996.
68. Cook JE, Taussig AE. Auscultatory blood pressure determination. *J Am Med Assoc* 1917; *68:* 1088.
69. Geddes LA, Hoff HE, Badger AS. Introduction of the auscultatory method of measuring blood pressure — including a translation of Korotkoff's original paper. *Cardiovasc Res Cent Bull* 1966; *5:* 57 – 74.
70. Gibson PC. Silent gap in auscultatory estimation of blood pressure. *Lancet* 1927; *2:* 1003.
71. Report. *Lancet* 1910; *ii:* 101.
72. Brunton L. Clinical measurement of diastolic blood pressure and cardiac strength. *Br Med J* 1910; *i:* 1389 – 1393.
73. Gibson GA. Arterial pressure. *Trans Med Chir Soc Edingburgh* 1911; *30:* 43 – 78.
74. Gittings JC. Auscultatory blood-pressure determinations. *Arch Intern Med* 1910; *6:* 196 – 204.
75. Warfield LM. Studies in auscultatory blood-pressure phenomena. *Arch Intern Med* 1912; *10:* 258 – 267.
76. Halls Dally JF. *High blood pressure: its variations and control, 2nd ed.* London: W Heinemann, 1926; 13, 19 – 22.
77. Halls Dally JF. *High blood pressure: its variations and control, 3rd ed.* London: W Heinemann, 1934; 14 – 15, 22 – 24.
78. O'Brien E. O'Malley K. Blood pressure measurement: technique. In: *ABC of hypertension*. London: British Medical Journal; 1981; 9.
79. Fisher CM. The ascendency of diastolic blood pressure over systolic. *Lancet* 1985; *ii:* 1349 – 1350.
80. Ramsay LE, Waller PC. Strokes in mild hypertension: diastolic rules. *Lancet* 1986; *ii:* 854 – 856.
81. Weismann DN. Systolic or diastolic blood pressure significance. *Prediatrics* 1988; *82:* 112 – 114.
82. Goodman EH, Howell AA. Further clinical studies in the auscultatory method of determining blood pressure. *Am J Med Sci* 1911; *142:* 334 – 352.
83. Travel M, Faris J, Nasser WK, Feigenbaum H, Fisch C. Korotkoff sounds. Observations on pressure-pulse changes underlying their formation. *Circulation* 1969; *39:* 465.
84. Ur A, Gordon M. Origin of Korotkoff sounds. *Am J Physiol* 1970; *218:* 524.
85. Geddes LA. *The direct and indirect measurement of blood pressure.* Chicago: Year Book Medical Publishers, 1970; 109 – 122.

86. Faught FA. *Blood-pressure primer: the sphygmomanometer and its practical application*. Philadelphia: GP Pilling, 1918; 24 – 50.
87. Faught FA. *Blood-pressure primer: the sphygmomanometer and its practical application*. Philadelphia: GP Pilling, 1918: 24.
88. Halls Dally JF. *High blood pressure: its variations and control, 2nd ed.* London: W Heinemann, 1926; 13, 31 – 41.
89. Martin CJ. The determination of arterial blood pressure in clinical practice. *Br Med J* 1905; *i:* 865 – 870.
90. Halls Dally JF. *High blood pressure: its variations and control, 2nd ed.* London: W Heinemann, 1926; 13, 33 – 34.
91. Halls Dally JF. *High blood pressure: its variations and control, 3rd ed.* London: W Heinemann, 1934; 49 – 50.
92. Halls Dally JF. *High blood pressure: its variations and control, 3rd ed.* London: W Heinemann, 14 – 15, 40 – 53.
93. Halls Dally JF. *High blood pressure: its variations and control, 3rd ed.* London: W Heinemann, 1934; 14 – 15, 53 – 65.
94. Halls Dally JF. *High blood pressure: its variations and control, 3rd ed.* London: W Heinemann, 1934; 14 – 15, 65 – 69.
95. O'Brien E, O'Malley K. Blood pressure measurement. In: *ABC of Hypertension, 2nd ed.* London: British Medical Association, 1987; 1 – 19.
96. King G. *Some sources of error in the clinical measurement of blood pressure.* Thesis for Doctorate of Medicine, University of London, 1967.
97. Petrie JC, O'Brien ET, Littler WA, de Swiet M. Recommendations on blood pressure measurement. British Hypertension Society. *Br Med J* 1986; *293:* 611 – 615.
98. Kirkendall WM, Feinleib M, Fries ED, Mark AL. Recommendations for human blood pressure determination by sphygmomanometers. *Hypertension* 1981; *3:* 509A – 519A.
99. O'Brien E, O'Malley K. Clinical blood pressure measurement. In: Birkenhäger WH, Reid JL, ser. eds. *Handbook of hypertension, vol. 15.* Robertson JIS, ed. *Clinical hypertension.* Amsterdam: Elsevier, 1991; in press.
100. Orma E, Karvonen MJ, Keys A. 'Cuff' hypertension. *Lancet* 1960; *ii:* 51.
101. World Health Organisation. Report of the Expert Committee on Cardiovascular Disease and Hypertension. *World Helath Org Techn Rep Ser* 1959; *168.*
102. Orma E, Punsar S, Karvonen MJ. Cuff hypertension. *Duo Decim* 1960; *76:* 460.
103. *Specification for aneroid and mercury non-automated sphygmomanometers (Revision of BS 2743).* London: British Standards Institution, 1990.
104. Geddes LA. *The direct and indirect measurement of blood pressure.* Chicago: Year Book Medical Publishers, 1970; 101 – 109.
105. Rose GA, Holland WW, Crowley EA. A sphygmomanometer for epidemiologists. *Lancet* 1964; *i:* 296 – 300.
106. 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.
107. Nyberg G. Indirect blood pressure and heart rate measured quickly observer bias using a semi-automatic machine (auto-manometer) — response to isometric exercise in normal healthy males and its modification by beta-adrenoceptor blockade. *Br J Clin Pharmacol* 1977; *4:* 275 – 281.
108. Garrow JS. Zero-muddler for unprejudiced sphygmomanometry. *Lancet* 1963; *iv:* 1205.
109. Wright BM, Dore CF. A random-zero sphygmomanometer. *Lancet* 1970; *i:* 337 – 338.
110. O'Brien E, Mee F, Atkins N, O'Malley K. Inaccuracy of the Hawksley random zero sphygmomanometer. *Lancet* 1990; *336*; 1465 – 1468.
111. Hoyt K, Wolf HK. An electronic instrument for indirect blood-pressure measurement. *Lancet* 1984; *ii:* 552 – 553.

112. Janeway TC. *The clinical study of blood-pressure*. New York and London: D. Appleton & Co., 1904; 107 – 132.
113. Fantus B. An automatic method of prolonged serial blood pressure registration in man. *J Am Med Assoc* 1917; *48:* 1807.
114. Blankenhorn MA. An automatic method for serial blood pressure observation in man. *J Am Med Assoc* 1921; *77:* 90 – 93.
115. Walden EC. A plethysmographic study of the vascular conditions during hypnotic sleep. *Am J Physiol* 1900; *12:* 124 – 161.
116. Segall HN. A note on the measurement of diastolic and systolic blood pressure by the palpation of arterial vibrations (sounds) over the brachial artery. *Can Med Assoc J* 1940; *42:* 311.
117. Geddes LA. *The direct and indirect measurement of blood pressure*. Chicago: Year Book Medical Publishers, 1970; 82 – 83.
118. Brown GE. Daily and monthly rhythm in the blood pressure of a man with hypertension: a three year study. *Ann Intern Med* 1930; *3:* 1177 – 1189.
119. Labarthe DR, Hawkins CM, Remington RD. Evaluation of performance of selected devices for measuring blood pressure. *Am J Cardiol* 1973; *32:* 546 – 53.
120. Hunyor SN, Flynn JM, Cochineas C. Comparison of performance of various sphygmomanometers with intra-arterial blood pressure readings. *Br Med J* 1978; *2:* 159 – 62.
121. O'Brien E, Mee F, Atkins N, O'Malley K. Inaccuracy of seven popular sphygmomanometers for home measurement of blood pressure. *J Hypertens* 1990; *8:* 621 – 634.
122. Lewis FW, Walker DC, Lee B, Quinn ML. Indirect blood-pressure measurement as part of a computer-controlled patient-monitoring system. *Biomed Comput Technol* 1976; *1:* 39 – 44.
123. Lagerwerff JM, Luce RS. Artifact suppression in indirect blood pressure measurements. *Aerosp Med* 1970; *41:* 1157.
124. Benson H. Blood pressure measurement and definition of hypertension. Part. 1. Methods of blood pressure recording: 1733 – 1971. In: Onesti et al., eds. *Hypertension: mechanisms and management. The 26th Hahnemann Symposium*. New York: Grune and Stratton, 1973; 1 – 8.
125. Geddes LA. *The direct and indirect measurement of blood pressure*. Chicago: Year Book Medical Publishers, 1970; 87 – 98.
126. Chia F, Ang AT, Wong T-W, Tan KW, Fung K, Lee J, Khin K. Reliability of the Dinamap non-invasive monitor in the measurement of blood pressure of ill Asian newborns. *Clin Pediatr* 1990; *29:* 262 – 267.
127. Salaita K, Whelton PK, Seidler AJ. A community-based evaluation of the Vita-Stat automatic blood pressure recorder. *Am J Hypertens* 1990; *3:* 366 – 372.
128. Moss AJ. Indirect methods of blood pressure measurement. *Pediatr Clin North Am* 1978; *25:* 3 – 14.
129. Morgan JL, Kemmerer WT, Halber MD. Doppler shifted ultrasound. History and application in clinical medicine. *Minn Med* 1969; *52:* 503.
130. George CF, Lewis PJ, Petrie A. Clinical experience with use of ultrasound sphygmomanometer. *Br Heart J* 1975; *37:* 804 – 807.
131. Geddes LA. *The direct and indirect measurement of blood pressure*. Chicago: Year Book Medical Publishers, 1970; 126 – 127.
132. Edwards RC, Bannister R, Goldberg AD, Raftery EB. The infrasound blood-pressure recorder: a clinical evaluation. *Lancet* 1976; *i:* 398 – 400.
133. Zezulka AV, Sloan PMJ, Davies P, Beevers DG. Clinical evaluation of the Infrasonde D4000 blood pressure monitor. *Postgrad Med J* 1985; *61:* 321 – 323.

134. Herscovici H, Roller DR. Noninvasive determination of central blood pressure by impedance plethysmography. *IEEE Trans Biomed Eng* 1986; *BME-33;* 617 – 625.
135. Stein PD, Blick EF. Arterial tonometry for the atraumatic measurement of arterial blood pressure. *J Appl Physiol* 1971; *30:* 593.
136. Terry S, Eckerle JS, Kornbluh D, Low T, Ablow CM. Silicon pressure transducer arrays for blood-pressure measurement. *Sens Actuators* 1990; *A21 – A23:* 1070 – 1079.
137. Close A, Hamilton G, Muriss S. Finger systolic pressure: its use in screening for hypertension and monitoring. *Br Med J* 1986; *293:* 775 – 778.
138. Gruen W. An assessment of present automated methods of indirect blood pressure measurement. *Ann NY Acad Sci* 1968; *147:* 109 – 126.
139. Blank GS, West JE, Nuller FB, Cody RJ, Harshfield GA, Pecker MS, Laragh JH, Pickering TG. Wideband external pulse recording during cuff deflation: a new technique for evaluation of the arterial pressure pulse and measurement of blood pressure. *Circulation* 1988; *77:* 1297 – 1305.
140. O'Brien E, O'Malley K, Sheridan J. The need for a standardized protocol for validating non-invasive ambulatory blood pressure measuring devices. *J Hypertens* 1989; *7 (Suppl. 3):* S19 – S20.
141. Janeway TC. *The clinical study of blood-pressure.* New York and London: D. Appleton & Co., 1904; 112 – 132.
142. Smirk JF. 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.
143. Ayman D, Goldshine AD. Blood pressure determination by patients with essential hypertension. *Am J Med Sci* 1940; *200:* 465 – 474.
144. Richardson DW, Honour AJ, Fenton GW, Stott FD, Pickering GW. Variations in arterial blood pressure throughout the day and night. *Clin Sci* 1964; *26:* 445 – 460.
145. Pickering G, Stott FG. Ambulatory blood pressure — a review. In: Pickering G, Stott F, eds., *ISAM. Proceedings, Third International Symposium on Ambulatory Monitoring.* 1979; 135 – 145.
146. Bevan AT, Honour AJ, Stott FH. Direct arterial pressure recording in unrestricted man. *Clin Sci* 1969; *36:* 329 – 344.
147. 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.
148. Millar-Craig MW, Hawes D, Whittington J. A new system for recording ambulatory blood pressure in man. *Med Biol Eng Comput* 1978; *16:* 727 – 731.
149. Pickering G. *High blood pressure, 2nd ed.* London: J. & A. Churchill, 1968; 12.
150. Littler WA, Honour AJ, Sleight P. Direct arterial pressure and electrocardiogram during motor car driving. *Br Med J* 1973; *2:* 273 – 277.
151. Littler WA, Honour AJ, Sleight P. Direct arterial pressure, heart rate and electrocardiogram during human coitus. *J Reprod Fertil* 1974; *40:* 321 – 331.
152. Millar-Craig MW, Kenny D, Mann S, Bala Subramanian V, Raftery EB. Effect of once daily atenolol on ambulatory blood pressure. *Br Med J* 1979; *1:* 237 – 238.
153. Littler WA, Honour AJ, Pugsley DJ, 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.
154. Millar-Craig MW, Bishop CN, Raftery EB. Circadian variation of blood pressure. *Lancet* 1978; *1:* 795 – 797.
155. Pickering G. *High blood pressure, 2nd ed.* London: J. & A. Churchill, 1968; 47 – 58, 92 – 101.
156. Mann S, Jones RI, Millar-Craig MW, Wood C, Gould BA, Raftery EB. The safety of ambulatory intra-arterial pressure monitoring: a clinical audit of 1000 studies. *Int J Cardiol* 1984; *5:* 585 – 597.

157. Horan MJ, Padgett NE, Kennedy HL. Ambulatory blood pressure monitoring: recent advances and clinical application. *Am Heart J* 1981; *101:* 843 – 847.
158. Pickering G. *High blood pressure, 2nd ed.* London: J. & A. Churchill, 1968; 19 – 20.
159. Schneider RA, Odle J, Linstead C. A fully automatic portable blood pressure recorder. *J Appl Physiol* 1968; *24:* 115 – 118.
160. Hinman AT, Engel BT, Bickford AF. Portable blood pressure recorder. Accuracy and preliminary use in evaluating intradaily variations in pressure. *Am Heart J* 1962; *63:* 663 – 668.
161. Kain HK, Hinman AT, Sokolow M. Arterial blood pressure measurements with a portable recorder in hypertensive patients. I. Variability and correlation with causual pressures. *Circulation* 1964; *30:* 882 – 892.
162. Clement DL, De Pue N, Packet L, Bobelyn M, Van Maele GO. Performance of noninvasive ambulatory blood pressure recordings. *J Hypertens* 1983; *1 (Suppl 2):* 296 – 298.
163. Fitzgerald DJ, O'Callaghan WG, 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.
164. Gould BA, Hornung RS, Kieso HA, Altman DA, Cashman PMM, Raftery EB. 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.
165. Brunner HR, des Combes BJ, 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.
166. Riess WF, Werdegar D, Sokolow M. Blood pressure responses to daily life events. *Trans Assoc Life Insur Med Dir Am* 1967; *51:* 116 – 129.
167. O'Malley K, O'Brien E, Brennan M. The contribution of non-invasive ambulatory blood pressure measurement to antihypertensive drug evaluation. In: Dal Palú C, Pessina AC, eds. *ISAM 1985. Proceedings of the Fifth International Symposium of Ambulatory Monitoring.* Italy: Cleup Editore, 1986; 255 – 263.
168. Brunner HR, Waeber B, Nussberger J. Clinical use of non-invasive ambulatory blood pressure recording. *J Hypertens* 1985; *3 (Suppl 2):* S13 – S17.
169. Sokolow MD, Werdegar HK, Kain HK, Hinman AT. Relationship between level of blood pressure measured casually and by portable recorders and severity of complications in essential hypertension. *Circulation* 1966; *34:* 279 – 298.
170. Perloff D, Sokolow M, Cowan R. The prognostic value of ambulatory blood pressures. *J Am Med Assoc* 1983; *240:* 2792 – 2798.
171. Harshfield GA, Pickering TG, Laragh JH. A validation of the Del Mar Avionics ambulatory blood pressure system. *Ambul Electrocardiogr* 1979; *1:* 7 – 12.
172. Weber MA, Drayer JIM, Nakamura DK, Wyle FA. The circadian pressure pattern in ambulatory normal subjects. *Am J Cardiol* 1984; *54:* 115 – 119.
173. Pickering TG, 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.
174. 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.
175. O'Brien E, Mee F, Atkins N, O'Malley K. Accuracy of the SpaceLabs 90207 determined by the British Hypertension Society protocol. *J Hypertens* 1991; *9:* 573 – 574.
176. O'Brien E, Petrie J, Littler WA, Padfield PL, O'Malley K, Jamieson M, Altman D, Bland M, Atkins N. British Hypertension Protocol: evaluation of automated and semi-automated blood pressure measuring devices with special reference to ambulatory systems. *J Hypertens* 1990; *8:* 607 – 619.

177. Pickering TG, James GD, Boddie C, Harshfield GA, Blank S, Laragh JH. How common is white coat hypertension? *J Am Med Assoc* 1988; *259:* 225–228.
178. 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:* 355–360.
179. O'Brien E, Fitzgerald D, O'Malley K. Blood pressure measurement: current practice and future trends. *Br Med J* 1985; *290:* 729–734.
180. 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.
181. O'Brien E, O'Malley K. Evaluation of blood pressure measuring devices with special reference to ambulatory systems. *J Hypertens* 1990; *8 (Suppl 7):* S133–S139.
182. Molhoek PG. Evaluation of the Penaz servo-plethysmo-manometer for continuous, non-invasive measurement of finger blood pressure. In: Arntzenius AC, Dunning AJ, Snellen HA, eds. *Blood pressure measurement and systemic hypertension.* Breda: Medical World Press, 1981; 157–162.
183. Peňáz J. Photoelectric measurement of blood pressure, volume and flow in the finger. In: *Digest of the International Conference on Medicine and Biological Engineering, Dresden* 1973; 104.
184. Wesseling KH. Finapres, continuous noninvasive finger arterial pressure based on the method of Peňáz. In: Meyer-Sabellek W, Anaulf M, Gotzen R, Steinfeld L, eds. *Blood pressure measurements: new techniques in automatic and 24-hour indirect monitoring.* Darmstadt: Steinkopff Verlag; New York: Springer-Verlag, 1990; 161–172.
185. Imholz BPM, van Montfrans GA, Settels JJ, van der Hoeven GMA, Karemaker JM, Wieling W. Continuous non-invasive blood pressure monitoring: reliability of Finapres device during Valsalva manoeuvre. *Cardivasc Res* 1988; *22:* 390–397.
186. 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.
187. Yamokoshi K-I, Shimazu H, Togawa T. Indirect measurement of instantaneous arterial blood pressure in the human finger by the vascular unloading technique. *IEEE Trans Biomed Eng* 1980; *BME-27*; 150–155.
188. Yamakoshi K, Rolfe P, Murphy C. Current developments in non-invasive measurement of arterial blood pressure. *J Biomed Eng* 1988; *10:* 130–137.
189. Association for the Advancement of Medical Instrumentation. *American National Standard for Electronic or Automated Sphygmomanometers.* Washington, DC: AAMI, 1987.
190. Garrett BN, Kaplan N. Ambulatory blood pressure monitoring: a question for now and the future. *J Clin Hypertens* 1987; *3:* 378–380.