AN EXPERIMENTAL STUDY OF THE ERRORS OF THE AUSCULTATORY METHOD FOR MEASURING BLOOD PRESSURE

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CHAPTER I

THE PROBLEM AND ITS BACKGROUND

A. INTRODUCTION

1. Reason for the study. Since the introduction in 1905 of the auscultatory method of measuring arterial pressure in humans, observations obtained by its use have formed the basis for many clinical and statistical studies and they continue to be an important guide to treatment and prognosis. Because of this it is desirable to have a clear understanding of the meaning of such measurements but only recently has attention been focused on the errors of the method. Although investigations conducted in the past fifteen years have shown that it has grave defects, there is, as yet, no general understanding of either the factors which may affect the measurements or of the magnitude of the errors they introduce.

2. Statement of the problem. This study was undertaken to determine the more important factors affecting the auscultatory measurement of the arterial pressure, to gain some insight into their mode of operation, and to evaluate their influence. It was hoped that such information would enable correction formulae to be established. Accordingly this report deals simply with the technique of measurement to the exclusion of any consideration of the limitations imposed on the interpretation of pressure estimations by the essentially variable nature of the pressure.

B. DEFINITIONS

3. <u>General description of circulatory system</u>. The circulatory system consists of a continuous series of vessels of which the arteries are the most important to the present study and the heart, acting as a pump, is responsible for the generation of energy in the system. The energy at any point in the arterial system has several components, the energy of position, the energy of pressure, and the energy of flow. As the first of these is not reflected in the measurements it will not be further discussed. The latter two contribute to measurements of arterial pressure to a variable extent depending on the technique of measurement.

4. <u>Various pressures existing in the system</u>. The energy of pressure, usually termed lateral pressure when speaking of arterial pressure, is the pressure exerted against the walls of the artery when the flow is unimpeded. The energy of flow is not measured as such but it is a component of end pressure, which is the pressure when the flow is stopped. End pressure consists of lateral pressure plus the pressure arising from the conversion of kinetic energy into static energy. It may be noted that this conception of end pressure is partly theoretical because it is impossible to prevent movement of fluid in the living system, and consequently end pressure as measured in any vessel tends to reflect the lateral pressure of the more proximal vessels in which the flow continues. As the circulatory system is pulsatile in nature, four further definitions are necessary. Systolic pressure is the maximum

and diastolic pressure is the minimum developed during a pulse cycle, while pulse pressure is the difference between systolic and diastolic pressures. Mean pressure is the average pressure present during a pulse cycle and therefore is dependent not only on the systolic and the diastolic pressure, but also on the shape of the pulse curve. These pressures may be either end or lateral.

C. MAJOR FACTORS AFFECTING THE PRESSURES IN THE ARTERIAL SYSTEM

5. Enumeration of factors. The mean arterial pressure is chiefly dependent upon the cardiac output which governs the rate of entry of the blood into the arterial system and upon the peripheral resistance which determines the rate of emptying of the system. However the distribution of pressure in time, that is, through a pulse cycle, will also depend upon the volume elasticity of the vessels. The bearing of these factors on the present problem can be briefly indicated.

6. Cardiac output. Cardiac output is a function of the frequency and the stroke volume of the heart. If the cardiac output and the peripheral resistance remain constant, the frequency of the heart will determine the stroke volume which will in turn determine the contour of the pulse. Under these conditions a change in frequency will cause large changes in the systolic and diastolic pressure, but the mean pressure will remain constant.

7. Peripheral Resistance. Peripheral resistance is determined by the viscosity of the blood and by friction. For the purposes of this

study the first may be considered constant, while friction is a variable factor and depends on the calibre of the terminal vessels. Dilatation of these vessels produces an increase in the velocity of flow which will cause a decrease in lateral pressure. Obviously the end pressure will not be affected if the vasodilatation occurs distal to the point of measurement.

8a. The volume elasticity. The volume elasticity of the arteries is highly important to the dynamics of the system. As the central arteries have a large capacity and elastic walls they serve the function of a reservoir, indeed half the systolic discharge is stored in the aorta, to be moved onward during diastole by the elastic recoil of the arterial walls (Wiggers 1944). This property of the arterial walls is expressed by the volume elasticity coefficient, which states the relationship between the changes in pressure and the changes in volume caused by alterations in either of these factors.

8b. Hallock and Benson (1937) have provided an example of the importance of this coefficient. They plotted the volume elasticity curves of aortas, obtained post mortem, for various age groups. From these curves shown in Figure 1, it is seen that the distensibility decreases progressively with age, while in Figure 2 it is seen that at the same time the size of the aorta and its branches increases, thus partly offsetting the effect of a decreased distensibility. If no change in volume had occurred it is obvious that very high pulse pressures would be produced by the loss of elasticity.

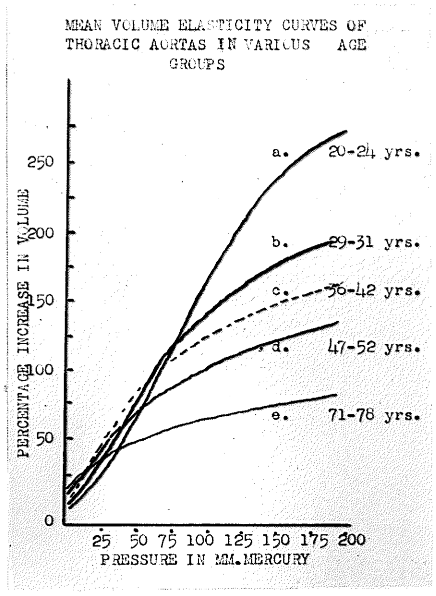

FIGURE 1

VOLUME ELASTICITY CURVES
(Redrawn from Hallock and
Benson: J.Clin.Investig.
16:597,1937.)

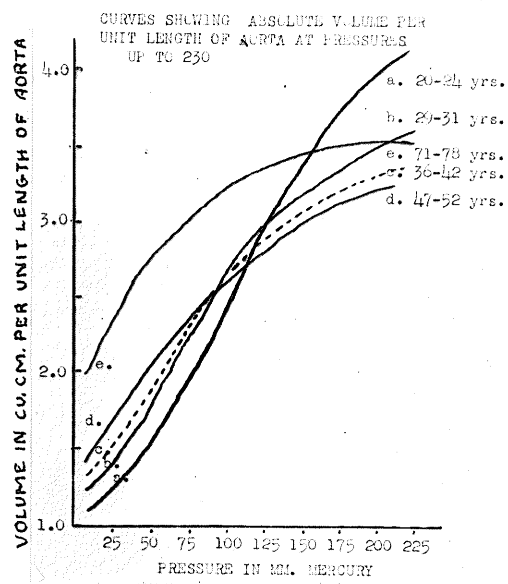

FIGURE 2

VOLUME PRESSURE CURVES
(Redrawn from Hallock and
Benson: J.Clin.Investig.
16:597,1937.)

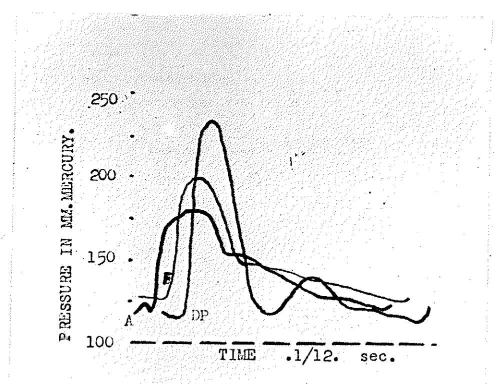

FIGURE 3

SIMULTANEOUS DIRECT ARTERIAL PRESSURE READINGS IN THE AXILLARY (A)
FEMORAL (F) AND DORSALIS PEDIS (DP) IN MAN (HYPERTENSIVE SUBJECT)
(Redrawn from Hamilton, Woodbury, and Harper: J.A.M.A. 107:856,1936.)

8c. Volume elasticity has another important influence on arterial pressure through its control of the pulse wave velocity. The velocity of the pulse wave has been shown by Bramwell and Hill (1922) to depend to a small degree on the velocity of the blood, but chiefly on the elasticity of the arterial wall. These authors studied the velocity of the arterial pulse in humans and their results were incorporated in the following equation:

$$v(\text{velocity}) = \frac{3.57}{\sqrt{\%\ \text{increase in volume per mm. Hg. increase in pressure}}}$$

The volume elasticity coefficient, as shown in Figure 1 decreases at high pressures. This will cause the crest of the pulse wave to travel at a faster rate than the initial part of the pulse wave, and this redistribution of energy will cause the wave to become steeper in its progress towards the periphery. This is evident in Figure 3, where simultaneous tracings from the axillary, femoral, and from the dorsalis pedis arteries are shown.

9. Other factors. Despite the simplicity of the concepts underlying the hemodynamics of the arterial system the various factors are difficult to measure. Therefore the importance of the reflected waves and the natural resonance of the system which has been stressed by Hamilton (1944) is difficult to evaluate.

D. THE DEVELOPMENT OF THE AUSCULTATORY METHOD

10. Early methods of measuring arterial pressure. Stephen Hales (1733)

was the first to measure arterial pressure. This was accomplished by connecting the crural artery of a horse with a long glass tube. Although his contribution is now regarded as being highly important, it is remarkable that it did not directly stimulate any other workers and he himself was diverted by his concern with botany and with the ventilation of ships and jails. It was not until 1828 that Poiseuille (Garrison 1917), starting from Hales's original experiment, improved upon it by substituting a mercury manometer for the inconvenient long tube. The connection with the artery was established by means of a lead cannula filled with potassium carbonate. Carl Ludwig (Hill 1900 a) in 1847 added a float carrying a writing stylus to the mercury manometer and recorded the variations in arterial pressure on a smoked drum or "Kymographion". Systolic and diastolic pressure could not be accurately estimated because of the low frequency of the mercury manometer, which was only 2 cycles per second, but a close approximation of mean pressure was obtained. The last advance in direct methods of measuring arterial pressure before the development of the auscultatory method came with the introduction by Hurthle (Hill 1900 b) in 1888 of a manometer which combined a spring resistance with a heavy rubber membrane, the movements of the membrane being amplified by a mechanical lever. The system was considered to be able to respond to variations having a frequency up to 40 cycles per second, but because a cannula was required it was not very satisfactory for the measurement of arterial pressure in man.

11. Clinical methods leading to the auscultatory method. The first indirect measurement of arterial pressure was attempted by Vierodt (Faught 1916 a) in 1855 who placed a series of weights over the radial artery until the pulse wave obliterated. Von Basch (Faught 1916 a) in 1876 placed a water filled pelotte connected to a mercury manometer over the radial artery. The pelotte was pressed against the arm until the pulse distal to it was obliterated. Only systolic pressure could be measured with this instrument and it is chiefly important because it was the direct forerunner of all modern instruments. In 1889 Potain (Janeway 1904) replaced the water in the earlier instrument with air and altered the pressure in the circuit by means of a bulb connected to the apparatus by a side tube. He also modified the apparatus by using the chamber of an aneroid barometer instead of a mercury column for measuring pressure. In 1896 Riva-Rocci (Lewis 1941) developed a better method for occlusion of the artery. This consisted of a rubber bag or tube within an inelastic cuff which encircled the arm and which was inflated by a bulb or pump. This improvement surmounted the most serious defect in the earlier instruments which was the difficulty of accurately adapting the small round pelotte to the underlying artery.

12. The introduction of the auscultatory method. Using a Riva-Rocci cuff to apply pressure to the artery, Korotkoff (Lewis 1941) in 1905 found that a series of sounds could be heard with a stethescope placed over the brachial artery below the cuff as the pressure was gradually

allowed to fall. He reasoned that the first sound indicated that a part of the pulse wave had passed under the cuff, and considered that the reading of the manometer at this time corresponded to the systolic blood pressure. He reasoned further that the disappearance of all sounds should indicate the free flow of blood, and therefore the cuff pressure at this stage should correspond to the diastolic pressure.

13. <u>The Korotkoff sounds</u>. Korotkoff described three sound phases, but Gittings (1910) and subsequent observers recognized five, which Wiggers (1923) has enumerated as follows:

> First phase: The sudden appearance of a clear sound, lasting for a fall of approximately 14 mm. of mercury.
> Second phase: The acquisition of a murmurish character, lasting while the pressure falls approximately 20 mm. of mercury more.
> Third phase: The replacement of the murmur by a sound becoming progressively louder and lasting during the next 25 mm. of pressure fall.
> Fourth phase: The muffling of sounds, lasting while the pressure falls 5 to 6 mm. more.
> Fifth phase: The disappearance of all sounds.

E. INVESTIGATIONS PRECEDING THE ADOPTION OF THE STANDARD AUSCULTATORY PROCEDURE

14. <u>Enumeration of factors</u>. It was generally considered that since the auscultatory indices employed for the detection of systolic and diastolic pressures were dependent upon the penetration of the pulse waves through the segment of artery compressed by the cuff, several factors might influence the relationship between the intra-arterial pressure and the pressure applied externally. Several noteworthy

investigations have been made concerning the effect of the width of the cuff, the girth of the arm, and the rigidity of the arterial wall. In addition much attention has been paid to the criteria to be employed in determining systolic and diastolic pressures.

15. Width of the cuff. Concerning the width of the cuff, von Recklinghausen (1901) found that measurements of arterial pressure made with the 4.5 centimeter cuff of Riva-Rocci were higher than those made with wider cuffs. He postulated that this was due to the fact that the pressure applied to a small area must overcome not only intra-arterial pressure but also the resistance of the tissues to compression; whereas, if the same pressure per unit area was applied over a wider space, only the outer pressures were concerned in overcoming tissue resistance, while the central pressure was transmitted directly to the arterial wall. Using cuffs ranging in width from 4.5 to 32 centimeters, he found a progressive fall in measured pressure as the cuffs were increased up to 10 centimeters, but beyond this there was no further effect. Erlanger (1903), using cuffs ranging from 5 to 17 centimeters in width, found that the lowest measurement of arterial pressure was obtained with a cuff 17 cm. wide, but that one of 12 to 13 cm. yielded measurements very nearly the same as those obtained by the use of the wider and more cumbersome cuff. These studies formed the basis for the acceptance of the 13 centimeter cuff of the present day auscultatory procedure and they were not seriously questioned until the development of modern methods of directly recording the intra-arterial pressure permitted by Robinow et al. (1939), to demonstrate that measurements obtained using the 13 centimeter cuff, did not necessarily correspond to intra-arterial pressures.

16. Girth of the arm. The effect of the girth of the arm on the measurement of pressure was first noted by von Basch (Faught 1916 a) who found that the pressures obtained with the pelotte method varied with the thickness of the soft tissues separating the pelotte from the artery. Von Recklinghausen (1901) noted that the lowest measurement of pressure for an arm 24 centimeters in girth was obtained using a cuff 10 centimeters wide whereas, if the arm were of larger girth, a cuff 15 centimeters in width was necessary to obtain the lowest measurement of pressure.

17. Arterial wall. Von Recklinghausen (1901) again was the first to investigate the influence of the arterial wall. He noted that occlusion of the brachial artery resulted in the collapse of arteries distal to the point of occlusion and concluded that the vessels did not possess any stiffness influencing pressure measurements. MacWilliam and Kesson (1913) examined the resistance to compression of excised arteries which still retained their contractility, under pulsatile and non-pulsatile conditions of internal pressure. Completely relaxed or dead arteries offered only a few millimeters of mercury resistance to compression, and repetition of the compression made no appreciable difference. Contracted arteries or arteries showing arteriosclerotic changes required an excess of extra over intra-arterial pressure varying from 5 to 50 millimeters of mercury to cause collapse. Repeated compression usually reduced this to a few millimeters of mercury. In humans, with a compression cuff about

each upper arm, simultaneous blood pressure readings were made. In one arm the cuff was repeatedly compressed and decompressed. In certain individuals this produced an appreciable lowering of pressure compared to the control arm. It was concluded that normal arteries seldom offered any resistance to compression and that where spasm or moderate arteriosclerosis was present, its effect could be minimized by repeated compression of the armlet or massage of the vessel. The conclusions of MacWilliam and Kesson seem to be based on sound experimental data but they require confirmation by modern methods. Nevertheless, it is reasonable to assume that the error due to the influence of the vessel wall can with proper procedure be reduced to insignificance.

18a. Indices employed for systolic and diastolic pressure. Auscultatory criteria are based on three sound changes which occur as the pressure in the cuff is allowed to fall, the first appearance of sounds, the muffling of sounds, and the disappearance of sounds. The point at which sounds first appear is readily ascertained, the muffling of sounds is more difficult to detect, and the point at which all sounds disappear is often very difficult to determine.

18b. Korotkoff (Lewis 1941) assumed that the first sounds heard below the cuff indicated systolic pressure, and the disappearance of all sounds indicated diastolic pressure. The validity of this assumption was difficult to evaluate at that time because devices capable of measuring actual arterial pressure in humans had not been developed.

18c. The palpatory method, which was the original indirect method, gave readings which averaged 5 to 10 millimeters of mercury below those obtained by auscultation (Faught 1916 b, Gittings 1910). Therefore it was considered that auscultation was a more sensitive index of systolic pressure than was palpation. The use of other indirect methods to check the accuracy or inaccuracy of the auscultatory indices, such as the oscillometric method were unsatisfactory because there was no unanimity of opinion concerning the accuracy of these methods. The majority of observers considered that the first appearance of sounds was an accurate index of systolic pressure, but opinions differed as to the auscultatory index to be employed for diastolic pressure.

18d. Various approaches have been made to the study of correct diastolic index. MacWilliam and Melvin (1914) on the basis of their experiments performed with schemata of the circulation using excised sheep's arteries in a compression chamber, considered that the sounds owed their origin to vibration of the arterial wall when the normal circular form of the vessel in the compression chamber was more or less distorted by external pressure. Sudden diminution of sound, which might or might not be followed by its extinction, was found to occur in these experiments at a level of external pressure which exceeded the internal diastolic by a small amount. This diminution of sound was taken as the index of diastolic pressure.

18e. Erlanger (1916, 1921) in experiments on the exposed ilio-femoral arteries of dogs found that the first sound was heard at the instant the blood in the artery below a compression chamber showed brusque acceleration with each pulse, and muffling of sound occured at the instant the compression chamber no longer obstructed the blood flow. He attributed the origin of the Korotkoff sounds to what he termed the preanacrotic phenomenon. This phenomenon was considered to be due to changes in the contour of the pulse wave as it passed through the compression chamber. These changes consisted of small negative and positive waves preceding the upstroke or the anacrotic limb of the pulse wave, and they developed only when the artery was in the partly flattened state, that is between systolic and diastolic pressures.

18f. Bramwell and Hickson (1926), on the basis of work on the velocity of the pulse wave in the arterial system and experiments with elastic tubes, considered that the preanacrotic phenomenon could be explained by the hypothesis that the pressure applied by the pneumatic cuff brought about a decrease in the volume elasticity coefficient of the system with consequent changes in the velocity of the foot and the crest of the pulse wave. The resulting instability of the wave gave rise to a redistribution of energy with the production of the preanacrotic phenomenon. However, Brewer et al. (1934) cast doubt on this explanation of the origin of the sounds. Using a high frequency recording apparatus they showed that the waves described as the preanacrotic did not appear, whereas they appeared if recording apparatus of a lower frequency was used under the same conditions. The authors attributed the occurence of the preanacrotic waves to artifacts produced by the recording apparatus and they believed that the Korotkoff sounds were produced by the sudden movements of the artery.

18g. The results of experiments on animals, although they probably had an important effect upon the criteria adopted for the standard procedure, are difficult to interpret because sounds are present even over the unobstructed artery of the dog, which was the experimental animal usually employed, and because the size and the shape of the limbs of the dog and man are in no way comparable.

F. THE STANDARD PROCEDURE FOR AUSCULTATORY MEASUREMENT

19. Need for standardization. Wright et al. (1938), in a survey of the methods of teaching and interpretation of measurements of arterial pressures, found that there was a serious lack of agreement amongst individual observers as to the indices to be used in the measurement of both systolic and diastolic pressure. A part of these differences could be accounted for on the basis of the wide variation in the teaching of the auscultatory method in the medical schools. Committees for the standardization of methods of blood pressure measurement appointed by the American Heart Association and the Cardiac Society of Great Britain and Ireland attempted to secure a crystallization of the best available thought on the subject and in (1939) made the following recommendations:

20. STANDARD METHOD FOR TAKING AND RECORDING BLOOD PRESSURE READINGS
By: The Committee for the Standardization of Blood Pressure Readings of the American Heart Association, and the Committee for the Standardization of Blood Pressure Readings of the Cardiac Society of Great Britain and Ireland.

1. Blood Pressure Equipment.—The blood pressure equipment to be used, whether mercurial or aneroid, should be in good condition and calibrated at yearly intervals for accuracy, and more

often if defects are suspected (mercurial preferred by British committee).

2. The Patient.-The patient should be comfortably seated (or lying-British committee) with the arms slightly flexed and the whole forearm supported at the heart level on a smooth surface. If readings are taken in any other position, a notation should be made. The patient should be allowed time to recover from any recent exercise or excitement. There should be no constriction of the arm due to clothes or other objects.

3. Position and Method of Application of the Cuff.-A standard sized cuff containing a rubber bag from 12 to 13 cm. in width should be used. A completely deflated cuff should be applied snugly and evenly around the arm with the lower edge about 1 inch above the antecubital space and with the rubber bag applied over the inner aspect of the arm. The cuff should be of such a type and applied in such a manner that inflation causes neither bulging nor displacement.

4. Significance of Palpatory and Auscultatory Levels.-In all cases palpation should be used as a check on auscultatory readings. The pressure in the cuff should be quickly increased in steps of 10 mm. of mercury until the radial pulse ceases and then allowed to fall rapidly. If the radial pulse is felt at a higher level than that at which the auscultatory sound is heard, the palpatory reading should be accepted as the systolic pressure; otherwise the auscultatory reading should be accepted.

5. Position and Method of Application of Stethoscope.-The stethoscope should be placed over the previously palpated brachial artery in the antecubital space, not in contact with the cuff. No opening should exist between the lip of the stethoscope and the skin; this should be accomplished with the minimum pressure possible. The hand may be pronated or supinated according to the position yielding the clearest brachial pulse sounds.

6. Determination of the Systolic Pressure.-The cuff should be rapidly inflated to a pressure about 30 mm. above the level at which the radial pulse can be palpated. The cuff should then be deflated at a rate of from 2 to 3 mm. of mercury per second. The level at which the first sound regularly appears should be considered the systolic pressure unless, as already described, the palpatory level is higher, in which event the palpatory level should be accepted. This should be noted.

7. Determination of the Diastolic Pressure and the Pulse Pressure.-With continued deflation of the cuff, the point at which the sounds suddenly become dull and muffled should be known as the diastolic pressure. If there is a difference between that point and the level at which the sounds completely disappear, the American committee recommends that the latter reading should be regarded also as the diastolic pressure. This should then be recorded in the following form: RT (or LT) 140/80-70 or 140/70-0.

If these two levels are identical, the blood pressure should be recorded as follows: 140/70-70. The cuff should be completely deflated before any further determinations are made.
The British committee believes that except in aortic regurgitation it is nearly always possible to decide the point at which the change comes and this is the only reading that should be recorded.

21. Discussion. It is to be noted that the recommendations of these committees allow the acceptance of either of two criteria for both systolic and diastolic indices. The criteria most commonly used are the first appearance of sounds as the index of auscultatory systolic pressure and the muffling of sounds as the index of diastolic pressure. The fact that even after forty years of use there are still differences of opinion suggests that there is something basically unsound in the auscultatory method. The modern investigations to be reviewed indicate some of the reasons for this unsatisfactory situation.

G. MODERN METHODS OF RECORDING INTRA-ARTERIAL PRESSURE

22. General requirements. A recording apparatus which is to follow the pulsatile changes in pressure taking place in the arterial system must be sensitive and capable of responding rapidly. These two requirements, as Green (1944) has shown, tend to be mutually exclusive and the type of manometer used represents a compromise between the maximum sensitivity and the minimum distortion.

23. Theoretical postulates of Wiggers and Frank. Wiggers (1917) postulated that in order to obtain adequate details of the pressure

changes in the arterial system the natural frequency of the recording system should be about five times the tenth harmonic of the fundamental frequency to be recorded. For example, to record arterial pressure at a heart rate of two per second, the natural frequency of the manometer should be 2 x 11 x 5 or 110 cycles per second. The natural frequency can be calculated from Frank's formula (Green 1944):

$$N \text{ (Frequency)} = \frac{1}{2\pi}\sqrt{\frac{E \text{ (Volume elasticity)}}{M \left(\text{Mass} = \frac{(L)}{s(Q)}\right)}}$$

where s equals the density of the solution with which the manometer is filled in grams per cm.3, where L equals the length of the manometer tube in cm., and Q equals the cross section of the liquid column in the manometer in cm.

It is seen that the highest frequency will be obtained in a manometer which has a diaphragm as rigid as possible, and in which the shortest and broadest liquid column is used.

24. Optical Manometers. The first improvement over the Hurthle type of manometer was the development of the optical manometers of Frank and Wiggers (Green 1944). These were perfected about 1925 and utilized a segment capsule, that is, where a segment of the diaphragm or membrane is fixed to a light rigid plate upon which a mirror is mounted. Increased magnification was obtained by the use of a beam light as a recording lever, and this enabled the diaphragm to be increased in rigidity and so raised the natural frequency of the recording system. The frequency of such manometers lay between 50 and 150 cycles per second, depending upon the characteristics of the individual instrument.

They still required that a relatively large bore cannula be fastened into the artery and hence their use in humans was technically difficult.

25. Later modifications. Brömser (von Bonsdorff 1932) in 1927 developed an optical manometer utilizing a glass capsule which Wolf and von Bonsdorff (von Bonsdorff 1932) used in 1931 for the first successful comparison of direct and indirect measurement of arterial pressure in humans. Hamilton et al. (1934) constructed manometers which had a rigid metallic diaphragm and utilized an improved lighting system to obtain greater magnification. Longer tubing from the patient to the manometer and smaller cannulae or needles could be used in this system. The frequency of the manometric system was calculated to be between 130 and 250 cycles per second for the various manometers constructed. Gregg (1937) modified Hamilton's manometer and used a rubber diaphragm in place of the metal one and found the frequency of the instrument to lie between 130 and 300 cycles per second, depending upon the tension of the diaphragm. A combined optical and electrical manometer was developed by Lilly (1942). Such an instrument has a rigid metal diaphragm, utilizes an electrical system for amplification, and requires an exceedingly small displacement to produce measurable deflections on the record. The manometers developed by Hamilton, Gregg and Lilly have a high frequency and are responsive to small changes in fluid displacement, hence a fine bore needle can be utilized for arterial puncture. Such a needle causes a negligible interference with blood flow and can be considered to measure lateral pressure in the vessel into which it is introduced.

H. STUDIES PERFORMED USING MODERN RECORDING SYSTEMS

26a. Importance of the studies. A summary of the findings of investigations in the past fifteen years with modern recording devices, gives some estimate of the magnitude of the errors involved in the auscultatory method and reveals the factors which are operative in producing these errors.

26b. Wolf and von Bonsdorff (von Bonsdorff 1932) in 1931 performed forty-four comparisons of direct and auscultatory measurements of arterial pressure, using the Brömser manometer. The first appearance of sound was taken as the index of systolic pressure and the end of the third sound phase as the index of diastolic pressure. Direct and indirect measurements were found to deviate unpredictably from one another. It is to be noted that the measurements were often not taken simultaneously and that the position of the patient varied from one determination to the other. However other investigators found similar deviations as is shown in Table I. These and other investigators have attributed some of the deviations to the effect of arm girth and pulse contour.

27. Girth of arm. Robinow et al. (1939), working with children, found that the standard 13 centimeter cuff might give readings that were too low in comparison with direct pressures. This was tentatively attributed to the ease with which the compressible soft tissue of the child's arm was displaced laterally by the compressing cuff and the effective diameter of the arm thus reduced. In general they found the

TABLE I.

AUSCULTATORY AND INTRA-ARTERIAL MEASUREMENTS OF PRESSURE

(Measured in mm. of mercury)

Investigator	Number of Subjects	Mean deviation of auscultatory from intra-arterial measurements. (Lateral pressure)		
		Systolic	Diastolic	
			muffling of sound	cessation of sound
Hamilton et al.(1936)	30	- 3 or - 4	+ 9	
Ragan and Bordley(1941)	40	+ 0.1 range -20 to +47	+ 8 range -12 to +39	
Steele(1942)	41	-10 range -40 to +16	+ 8.8 range - 1 to +26	+ 0.8 range -10 to + 8

smaller the diameter of the compressed arm, the narrower the width of the cuff necessary to give agreement between direct and auscultatory systolic readings. Ragan and Bordley (1941) found that there appeared to be a definite trend in using the standard 13 centimeter cuff in adults; with arms of small circumference, auscultatory measurements, both systolic and diastolic tended to be too low, while with large arms they tended to be too high in comparison with simultaneously obtained direct estimations. While this general trend was noted, there were numerous exceptions which could not be explained on the basis of the effects produced by compression of the soft tissues, nor on the width of the cuff employed.

28. <u>Contour of the pulse</u>. Another factor which was considered to influence auscultatory measurements was the contour of the pulse wave. Ragan and Bordley (1941) noted that in arms of average size, when there was a relatively broad pulse, the auscultatory readings agreed very closely with intra-arterial readings. However, when the pulse was peaked, the auscultatory readings tended to be too low. This effect had also been observed by Bazett and La Place (1933) and Hamilton, Woodbury and Harper (1936). Ragan and Bordley considered that the peaked type of pulse was not sufficiently well sustained to force its way through the compressed artery until the compressing pressure was reduced considerably below the "true" systolic level. A further complicating effect of pulse contour on auscultatory measurements is indicated by the observations of Robinow et al. (1939). They found that occlusion of an artery such as is produced when taking an auscultatory measurement, caused a variable

distortion of the contour of the pulse wave. In their series, intra-arterial systolic pressures were increased by occlusion of the artery below the manometer needle and the greatest increase occurred where the contour of the pulse had been peaked.

I. SUMMARY

The auscultatory method described by Korotkoff in 1905 was the outgrowth of the many indirect methods proposed at the turn of the century. By virtue of the fact that it was one of the few procedures available to the clinician of the time whereby objective measurements could be made, and because it appeared to give fairly reliable results as judged by the criteria then available, it became almost universally accepted as a routine clinical procedure. It is noted, however, that methods by which measurements obtained by the auscultatory method could be compared to pressures existing in the arterial system did not become available for 30 years although their theoretical basis had been established by Otto Frank in 1903. It is, therefore, not surprising that Wright et al. in 1938 found a serious lack of agreement among observers as to what indices should be employed in measuring systolic and diastolic pressure by the auscultatory method. The committees for standardization of blood pressure measurements proposed different indices for diastolic pressure, the British committee believed that the point at which the sounds became dull and muffled was the diastolic index while the American committee recommended that the point at which the sounds completely disappear should also be regarded as diastolic pressure.

From the studies which have been conducted it appears that the contour of the arterial pulse, the girth of the arm, and the width of the compressing cuff are important and interrelated factors influencing the measurements obtained by the auscultatory method. The experiments that have been reported in this study were designed to provide additional information about these particular factors.

CHAPTER II

EXPERIMENTAL METHODS

1. <u>Introduction</u>. Besides the standard auscultatory procedure three experimental methods were employed in this study. The first was used to measure intra-arterial pressure, the second to determine the effect of cuff size and arm girth on auscultatory measurements and the third to ascertain the distribution of pressure in the tissues under the cuff. These three methods are described below.

THE METHOD OF MEASURING INTRA-ARTERIAL PRESSURE

A. APPARATUS

2. <u>Choice of apparatus</u>. The choice of apparatus was determined by the necessity of recording sustained pressures as well as superimposed fluctuations. For this purpose the apparatus described by Lilly (1947) seemed most suited. This consisted of three units, a variable capacitor for the conversion of arterial pressure into an electrical signal, an electrical circuit for amplification and rectification of the electrical signal, and a recording system.

3. <u>Capacitor</u>. The capacitor first employed is shown in Figure 4A, and that used in the experiments reported here in Figure 4B. Both models consisted of a deflectable diaphragm and a fixed electrode. The diaphragm was a circle of phosphor-bronze, 0.5 inches in diameter, 0.008 inches in thickness, clamped at the edges and at ground potential.

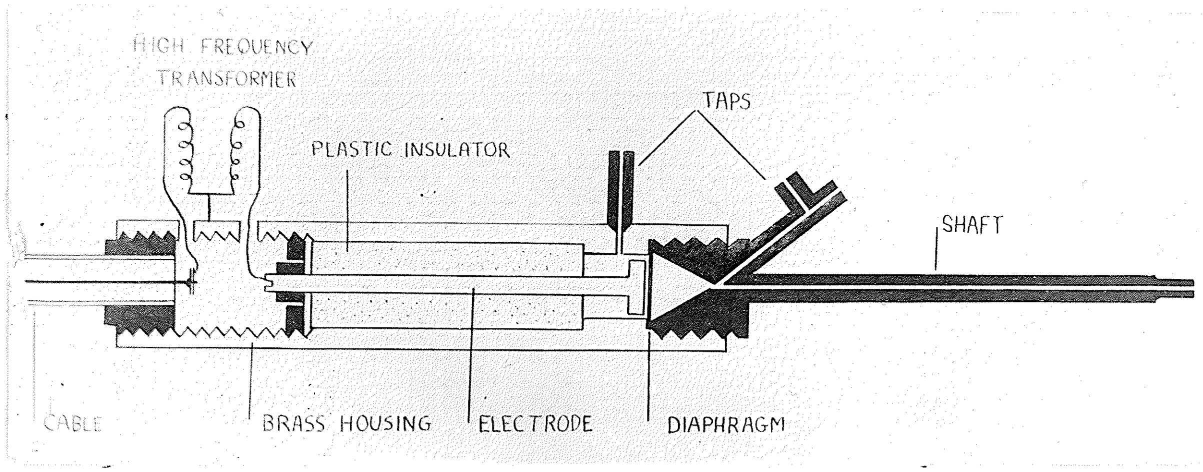

FIGURE 4A

A VARIABLE CAPACITOR FOR MEASUREMENT OF PRESSURE

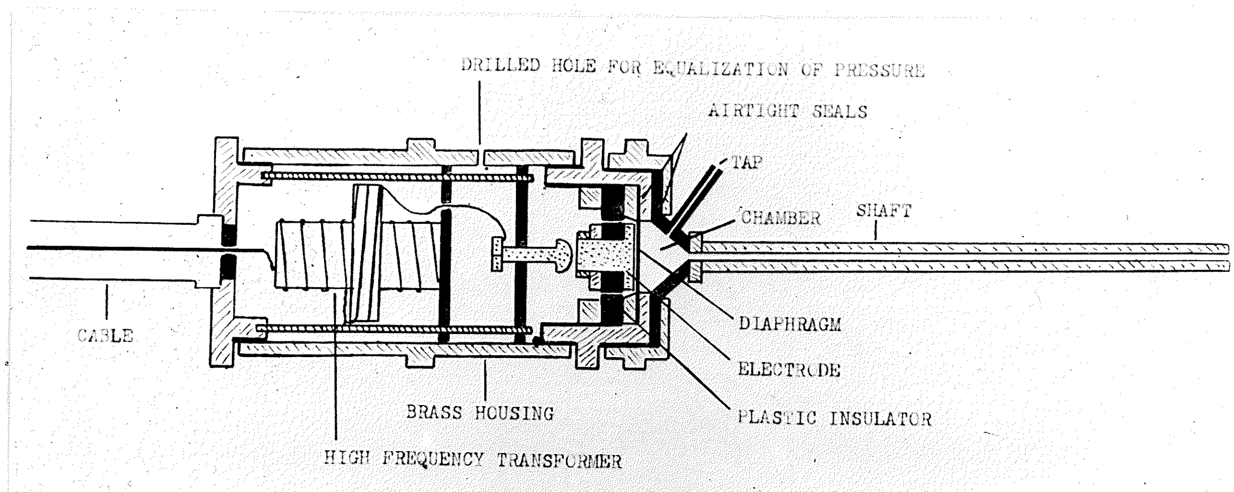

FIGURE 4B

A VARIABLE CAPACITOR FOR MEASUREMENT OF PRESSURE

The electrode, which was at a high alternating current potential, had a plane surface parallel to the undeflected diaphragm, but separated from it by an air gap of about 5×10^{-4} centimeters. The chamber and the shaft of the capacitor were filled with citrate solution which served to transmit pressure from the artery to the diaphragm.

4. Characteristics of the capacitor. Several difficulties arose in the use of the first model of capacitor shown in Figure 4A:

1. The long plastic insulator which had to be placed under tension to prevent leakage of fluid from the chamber slowly changed its position with the result that the air gap was diminished, causing changes in the strength of the electrical signal. This made the instrument unstable.
2. Thermal effects on the dimensions of the instrument due to alterations in room temperature and the effects of handling caused uncontrollable changes in the air gap.
3. For easy manoeuvrability the capacitor was separated from the amplification system by a length of coaxial cable. In order to accomplish this a transformer was incorporated in the capacitor. In the original model where it was mounted on the brass housing it was found to be improperly shielded and its operation was affected by changes in the electrical field about it.

These difficulties were largely overcome in the later model shown in Figure 4B. The insulator was greatly reduced in length and the tension on it more evenly distributed. By decreasing the length of the brass housing temperature effects were minimized. The transformer was mounted inside the housing which was at ground potential so that changes in the external electrical field no longer affected its function.

5. Electrical system for amplification. The electrical system for amplification consisted of a rectifier to provide a constant source of direct current, and a series of electrical circuits which operated on the principle of a Wheatstone bridge whose sensitivity was controlled by tuning condensers. A point of maximum sensitivity was found by trial and error. In use these condensers were tuned to one or other side of this point, in which range it was found that a nearly linear amplification was obtained for changes in applied pressure. For a change in applied pressure of 150 millimeters of mercury an increase in output of approximately 20 milliamperes was obtained. The circuit diagram is shown in Figure 5.

6. Recording system. The recording system consisted of a Heiland type C oscillograph galvanometer, a light source, and a Kipp and Zonen camera with a horizontal slit. The oscillograph galvanometer was oil damped and would respond to at least 200 cycles per second without a decrease in sensitivity. From the mercury vapor lamp, used as a source of light, a narrow vertical beam of light was focused on the mirror of the galvanometer and reflected to the camera. A current of 20 milliamperes caused the beam of light to be deflected 10 centimeters when the camera was at a distance of 60 centimeters from the galvanometer.

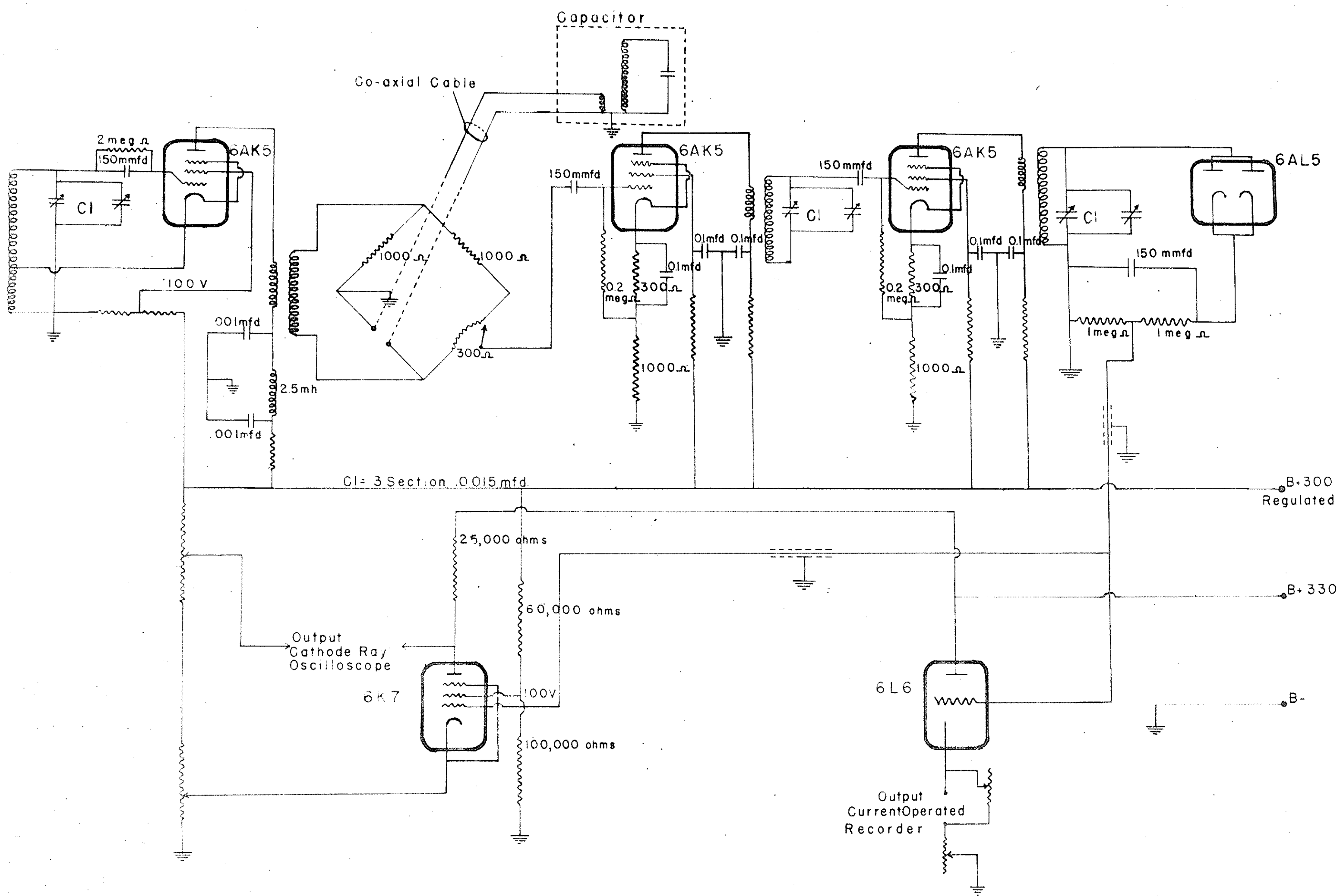

FIGURE 5

AMPLIFYING SYSTEM

Two Thorens constant speed motors were connected to the camera so that the paper speed could be changed almost instantaneously. The two speeds which were found most suited to this work were 10 and 180 centimeters per minute.

7. Deflection time. The deflection time of the whole manometric system was determined by sudden decompression of the fluid filled chamber and shaft. This was accomplished by inserting the needle attached to the shaft into a glass capsule through a small rubber stopper. Air was carefully excluded from the chamber, shaft and capsule, and a pressure of about 200 millimeters mercury applied to the liquid system through the tap. After closing the tap and starting the camera at a speed of 600 centimeters of paper per minute, the glass capsule was broken by striking it sharply. The measured deflection time at an applied pressure of 200 millimeters of mercury was 20 milliseconds, which compares favorably with the values obtained by Lilly (1947),who considered that it indicated a natural frequency well above that demanded by Wiggers.

8. Calibration of the apparatus. The apparatus for calibration consisted of four pressure bottles which could be connected to a reservoir of 6 percent citrate solution. This reservoir in turn could be connected to the fluid filled chamber, shaft and needle of the capacitor. A stopcock, inserted between the shaft of the capacitor and the needle used for puncture, enabled calibration to be performed while the needle was in the artery. Calibration was performed approximately every three minutes during the course of an experiment. By means of

stopcocks the pressure bottles were serially connected to the fluid system of the capacitor and this resulted in the step-like tracing similar to that shown in Figure 6. From the distance in millimeters of these steps from the signal line, and from the known applied pressure corresponding to each step, calibration curves were constructed which were similar in form to that shown in Figure 7. As a rule all calibrations made during the course of an experiment checked closely with one another. Signal and time lines were produced by two mirrors placed in the beam of light from the mercury vapor lamp and focused on the camera slit so that the lines would appear close together at the bottom of the finished record. The first mirror could be caused to deflect by closing an electrical circuit. The line of light from the second mirror was interrupted every second by a timing disc to produce second intervals on the finished record.

B. PROCEDURE

9. Preliminary procedures. The procedure was explained to the subject and his cooperation obtained. The circumference of the arm was measured at a point halfway between the acromion and the olecranon, and the patient was placed in the recumbent position, arms relaxed at the sides and at approximately heart level. With the center of a standard 13 centimeter cuff overlying the point at which the circumference of the arm was measured, preliminary measurements of auscultatory pressure were made on both arms. On the basis of these readings the recording system was adjusted so that the tracing of the pressure pulses would fall

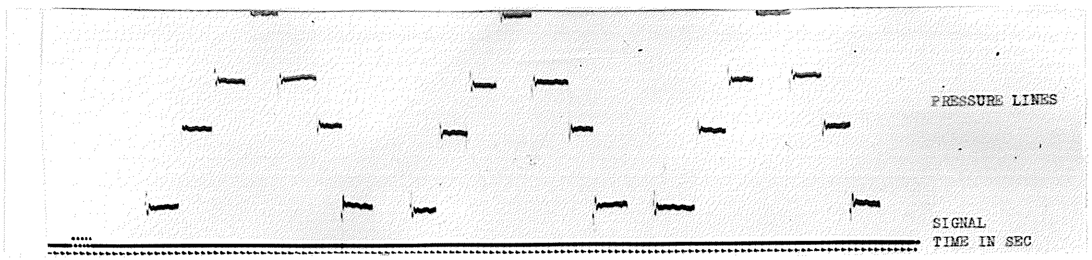

FIGURE 6

CALIBRATION TRACING

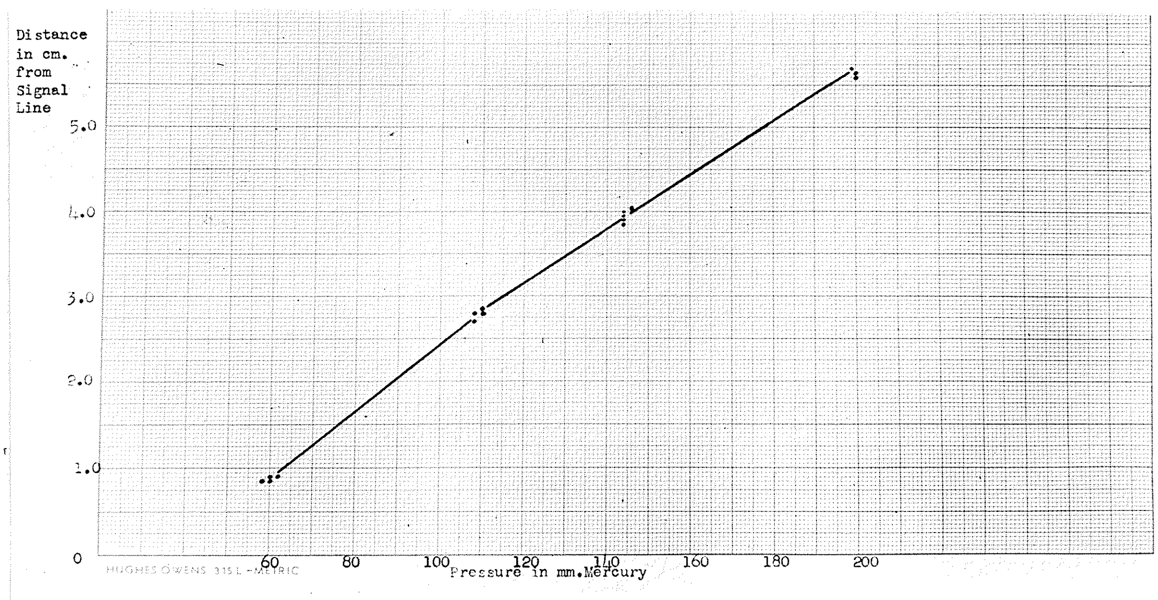

FIGURE 7

CALIBRATION CURVE

just above the time and signal lines. If the preliminary measurements obtained in the two arms did not differ by more than 5 millimeters of mercury, it was thought justifiable to compare the auscultatory measurements on one arm with the intra-arterial pressures of the other. If the difference was more than 5 millimeters of mercury, another subject was selected.

10. Duties of investigators. The actual procedure required three investigators. One took auscultatory measurements on one arm and signalled their exact time. The second investigator performed the arterial puncture and controlled the tap and the stopcock of the capacitor. The third operated the camera and the amplification system, performed the calibrations and kept a written record of the progress of the experiment.

11. Arterial puncture. The chamber and the shaft of the capacitor, the stopcock and the needle were filled with citrate. The tap to the reservoir was closed, and the stopcock between the shaft and the needle opened. The brachial artery in the antecubital fossa was punctured without the use of local anesthetic. Successful puncture was indicated by regular oscillations of the beam of light. The camera was started, the system calibrated as previously detailed, and the tracing taken. Records could be taken for 10 to 15 minutes before clotting interfered with the procedure.

C. SUBJECTS

12. Selection of subjects. Ten patients on the medical and surgical wards of the Winnipeg General Hospital were studied. There were nine males

and one female, their ages ranged from 21 to 76 years and the circumference of their arms ranged from 21 to 30 centimeters. The group selected was relatively homogeneous with regard to girth of arm and preference was given to those subjects without obvious cardiovascular disorders. The procedure was well tolerated and in no instance did a hematoma develop though in some cases the artery was punctured three or four times in the course of an hour. Fifty-two sets of simultaneous measurements of auscultatory and intra-arterial pressures were made on these ten subjects. In addition, on five subjects the effect of occluding the circulation was observed eight times.

THE METHOD FOR ASSESSING THE INFLUENCE OF CUFF SIZE AND ARM GIRTH ON AUSCULTATORY MEASUREMENTS

A. APPARATUS

13. Cuffs and manometer. Four widths of compression cuff were used: 8, 12, 16 and 20 centimeters. These cuffs were of the same thickness of rubber and covered by the same inelastic material as the standard 13 centimeter cuff. The measurements were made with a standard Tycos mercury manometer.

B. PROCEDURE

14. Measurements. All auscultatory measurements were taken with the patient at rest in the recumbent position. The procedure was explained to the patient while preliminary measurements were being taken to establish the general level of pressure. The circumference of the arm

was measured as previously described. One of the four widths of cuff was placed about the upper arm, at the level at which the circumference had been measured and two determinations each of systolic and diastolic pressures were made. The other cuffs were substituted in turn and the readings repeated. Twenty-four measurements of systolic and diastolic pressure, six for each size of cuff, were made on an individual.

C. SUBJECTS

15. Selection of subjects. Twenty-two patients on the medical and surgical wards of the Winnipeg General Hospital were studied. There were fourteen males and eight females, their ages ranged from 23 to 74 years and the circumference of their arms from 21 to 40 centimeters. These subjects were selected so that this group in contrast to the previous one was heterogeneous in regard to girth of the arm. None exhibited cardiac arrhythmia or edema of the soft tissues.

THE METHOD FOR MEASURING THE DISTRIBUTION OF APPLIED CUFF PRESSURE IN THE UNDERLYING TISSUES.

A. APPARATUS

16. Tissue pressure manometer. In order to measure the pressure in the tissues under a blood pressure cuff, a modification of the apparatus described by Wells et al. (1938) was used. This consisted of a 20 gauge spinal needle, 7.5 centimeters in length, connected to one end of a glass capillary tube, 20 centimeters in length. To the other end of the capillary tube was connected a glass T-tube attached to a standard

mercury manometer and to the compression bulb of the manometer. All connections were made with heavy rubber pressure tubing.

B. PROCEDURE

17a. Measurements of tissue pressure. All measurements of pressure were taken with the subject in the recumbent position. The spinal needle and the glass capillary tube were filled with isotonic saline solution in such a manner as to leave an air bubble in the capillary tube. The needle was inserted into the tissues from below the lower edge of a cuff which had previously been placed around the arm. The position of the point of the needle in the tissues with reference to the cuff was established by measuring the angle and the distance of insertion of the needle and the distance of the point of insertion from the lower edge of the cuff. The measurements were supplemented by observations made of the depth at which bone was struck. The depth and position of the bone in relation to the cuff was determined by soft tissue X-rays and these were also used to measure the effective diameter of the arm. Despite these attempts to ascertain the exact position of the point of the needle it is probable that an accuracy of not better than 0.5 centimeters in any direction was obtained except when the needle was vertical to the edge of the cuff or in contact with bone.

17b. After insertion of the needle the pressure within the cuff was raised and the pressure within the needle varied until a point was reached at which a few millimeters of mercury of additional pressure in the needle caused the air bubble in the capillary tube to move inwards and a few millimeters less pressure caused the bubble to move outwards. This pressure was taken to indicate the tissue pressure which was in equilibrium with the applied cuff pressure. The procedure was repeated with the needle in twenty-nine different positions under the 12 centimeter cuff, nine under the 8 centimeter cuff and twenty-six under the 4 centimeter cuff.

C. SUBJECT

18. Selection. The subject chosen for this experiment was a mortally ill comatose female of 72 years of age. The arm was soft and flabby and the measured circumference was 30 centimeters. The effective circumference as determined from X-ray films was 24 to 26 centimeters.

CHAPTER III

RESULTS

1. Introduction. In common with those of other investigators the present results have shown certain discrepancies between auscultatory and intra-arterial pressure measurements and it appears that these are determined by the contour of the pulse, the width of the cuff, the girth of the arm, and the auscultatory indices employed. As these factors differ in relative importance in regard to systolic and diastolic measurements the results concerned with these two measurements will be detailed separately.

A. SYSTOLIC MEASUREMENTS

2. Agreement of auscultatory measurements with lateral pressures. In Table II are recorded all the simultaneous measurements of auscultatory and intra-arterial pressure made on ten subjects. Subjects were designated as "Cold" when they were at nearly basal conditions of circulation though they were not purposefully cooled, and as "Hot" when the blood flow had been increased by general body heating and exercise of the arm prior to the arterial puncture. Three subjects were observed under both conditions and they appear twice in the Table because as will be seen the relationship between auscultatory and intra-arterial measurements varied with the blood flow. Columns 5 and 6 of the Table show the auscultatory and the lateral pressure measurements, while Column 8 shows the difference between them. It is seen that auscultatory

TABLE II

SIMULTANEOUS AUSCULTATORY AND INTRA-ARTERIAL PRESSURES

(Measured in mm. mercury)

Subject Age	Circ. of arm in cm.	Width of pulse wave in mm.		Systolic pressure					Diastolic pressure				
		Lateral	End	Auscultatory	Lateral	End	Ausc. minus lat.	Ausc. minus end	Auscultatory	Lateral	End	Ausc. minus lat.	Ausc. minus end
1	2	3	4	5	6	7	8	9	10	11	12	13	14
D.C.	25	3.5		148	163		-15		80	65		15	
76		3.5		150	163		-13		80	61		19	
Cold		4.0		148	158		-10		78	59		19	
				148	158		-10		78	63		15	
				145	155		-10		78	61		17	
				142	153		-11						
							-11.5					17.0	
E.L.	23	4.0	2.5	120	122		- 2		70	58		12	
36		4.0	2.5	120	122		- 2		70	72		2	
Cold		4.0	2.5										
							- 2.0					7.0	
V.M.	26	4.5	4.0	130	147		-17		70	70		0	
66		5.0	3.0	132	143		-11		70	70		0	
Cold		5.0	3.0										
							-14.0					0.0	
H.J.	23	5.0		135	134		1		80	55		25	
21		5.0		120	119		1		80	42		38	
Cold		5.0		122	125		- 3		80	60		20	
							- 0.3					27.6	
H.K.	23	6.0	6.0	104	108		- 4		68	56		12	
64		6.0	5.0	108	107		1		70	54		14	
Cold		6.0	6.0	104		106		-2	70		60		10
				94	101		- 7		70	60		10	
				100	105		- 5		65	54		11	
				100	103		- 3		65	54		11	
							- 3.6					11.6	
M.G.	21	6.0	6.0	150	149		1		60	58		2	
75		6.0	6.0	150	152		- 2		58	58		0	
Cold		6.0	6.0	148	143		5		58	56		2	
				150	148		2		42	59		-17	
				150	148		2		45	54		- 9	
				158	148		10						
							3.0					- 4.4	
G.T.	26	6.0		165	160		5		80	57		23	
50		6.0		165	163		2		80	60		20	
Cold		6.0		165	163		2		80	60		20	
							3.0					21.0	
R.F.	27	6.5		118	119		- 1		78	64		14	
36		6.0		118	121		- 3		78	64		14	
Cold		6.0											
							- 2.0					14.0	
P.B.	27	6.5		120	118		2		78	65		13	
39		6.5		128	124		4		80	65		15	
Cold		7.0											
							3.0					14.0	
V.M.	26	8.0	8.0	140	138		2		80	55		25	
66		9.5	8.0	132	124		8		76	58		18	
Hot		9.0	8.0										
							5.0					21.5	
H.K.	23	9.0	6.0	100	96		4		70	58		12	
64		9.0	6.0	102	96	104	6		70	56		14	
Hot		9.0	6.0	100				-4	72		62		10
				102	96		6		70	58		12	
							5.3					12.6	
T.K.	30	9.5	7.0	136	131		5		86	81		5	
34		10.0	7.5	130		128		2	80		78		2
Cold		10.0	7.5	124	117		7		80	68		12	
				126		114		12	80		68		12
				120	114		6		78	68		10	
				122	111		11		80	70		10	
				120	108		12		80	67		13	
				120		111		9	80		65		15
							8.2	7.0				10.0	9.6

							-11.5					17.0	
E.L.	23	4.0	2.5	120	122		- 2		70	58		12	
36		4.0	2.5	120	122		- 2		70	72		2	
Cold		4.0	2.5										
							- 2.0					7.0	
V.M.	26	4.5	4.0	130	147		-17		70	70		0	
66		5.0	3.0	132	143		-11		70	70		0	
Cold		5.0	3.0										
							-14.0					0.0	
H.J.	23	5.0		135	134		1		80	55		25	
21		5.0		120	119		1		80	42		38	
Cold		5.0		122	125		- 3		80	60		20	
							- 0.3					27.6	
H.K.	23	6.0	6.0	104	108		- 4		68	56		12	
64		6.0	5.0	108	107		1		70	54		14	
Cold		6.0	6.0	104		106		-2	70		60		10
				94	101		- 7		70	60		10	
				100	105		- 5		65	54		11	
				100	103		- 3		65	54		11	
							- 3.6					11.6	
M.G.	21	6.0	6.0	150	149		1		60	58		2	
75		6.0	6.0	150	152		- 2		58	58		0	
Cold		6.0	6.0	148	143		5		58	56		2	
				150	148		2		42	59		-17	
				150	148		2		45	54		- 9	
				158	148		10						
							3.0					- 4.4	
G.T.	26	6.0		165	160		5		80	57		23	
50		6.0		165	163		2		80	60		20	
Cold		6.0		165	163		2		80	60		20	
							3.0					21.0	
R.F.	27	6.5		118	119		- 1		78	64		14	
36		6.0		118	121		- 3		78	64		14	
Cold		6.0											
							- 2.0					14.0	
P.B.	27	6.5		120	118		2		78	65		13	
39		6.5		128	124		4		80	65		15	
Cold		7.0											
							3.0					14.0	
V.M.	26	8.0	8.0	140	138		2		80	55		25	
66		9.5	8.0	132	124		8		76	58		18	
Hot		9.0	8.0										
							5.0					21.5	
H.K.	23	9.0	6.0	100	96		4		70	58		12	
64		9.0	6.0	102	96	104	6		70	56		14	
Hot		9.0	6.0	100				-4	72		62		10
				102	96		6		70	58		12	
							5.3					12.6	
T.K.	30	9.5	7.0	136	131		5		86	81		5	
34		10.0	7.5	130		128		2	80		78		2
Cold		10.0	7.5	124	117		7		80	68		12	
				126		114		12	80		68		12
				120	114		6		78	68		10	
				122	111		11		80	70		10	
				120	108		12		80	67		13	
				120		111		9	80		65		15
							8.2	7.0				10.0	9.6
T.K.	30	12.0	7.0	120	110		10		80	74		6	
34		12.0	7.5	120		117		3	80		77		3
Hot		12.0	7.5	122	112		10		82	75		7	
				124		122		2	82		80		2
				126	115		11		82	77		5	
				120	112		8		84	77		7	
							9.7	2.5				6.2	2.5
Mean of average values:							0.3					12.2	

systolic measurements averaged 0.3 millimeters of mercury above lateral systolic pressure, with a range of difference from - 17 to + 12 millimeters of mercury, which is in accord with the findings of other investigators (Hamilton et al. 1936, Ragan and Bordley 1941, Steele 1942). As this group of subjects was fairly homogeneous with respect to measured arm circumference it is not likely that deviations of this magnitude can be wholly accounted for on the basis of this factor.

3. Contour of the lateral pressure pulses. Information as to one of the causes of the observed discrepancies was obtained by analysing the contour of the lateral pressure pulses in the individual cases. The shape of the pulses, as is seen in Figures 8 to 19, differed from individual to individual and in the same individual with changes in blood flow. There were two extreme types, those with narrow peaked crests, for example Figure 8, and those with broad rounded crests, for example Figure 19. As each of these curves had a different pressure scale, but a similar time base, comparison was simplified by measuring the width of the pulse in millimeters at a point equivalent to 15 millimeters of mercury below the systolic peak. Measurements were made of three representative pulses within five minutes of the time pressure readings were made. In Table II the subjects have been arranged so that they progress from those with the most peaked to those with the most rounded contours. The measurements of the width of the lateral pressure pulses appear in Column 3 of the Table, while Column 8 shows the difference between auscultatory and intra-arterial measurements. It is seen that

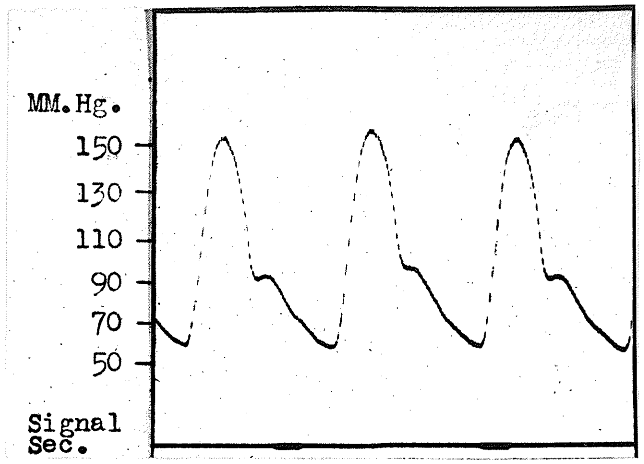

FIGURE 8

LATERAL PRESSURE PULSE TRACING, SUBJECT D.C. "COLD"

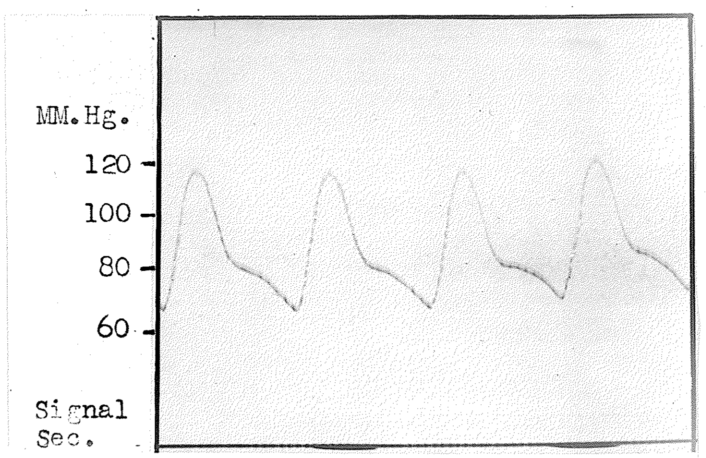

FIGURE 9

LATERAL PRESSURE PULSE TRACING, SUBJECT E.L. "COLD"

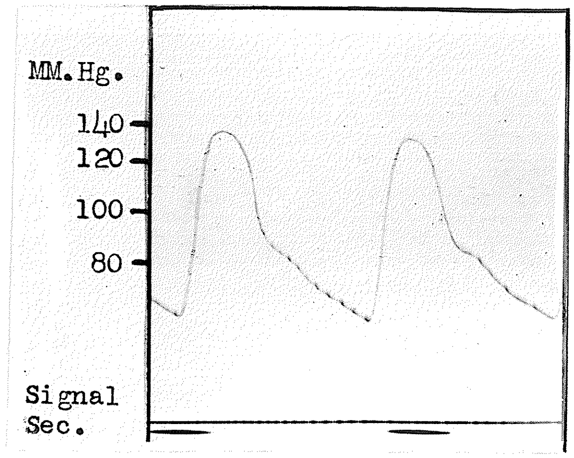

FIGURE 10

LATERAL PRESSURE PULSE TRACING, SUBJECT V.M. "COLD"

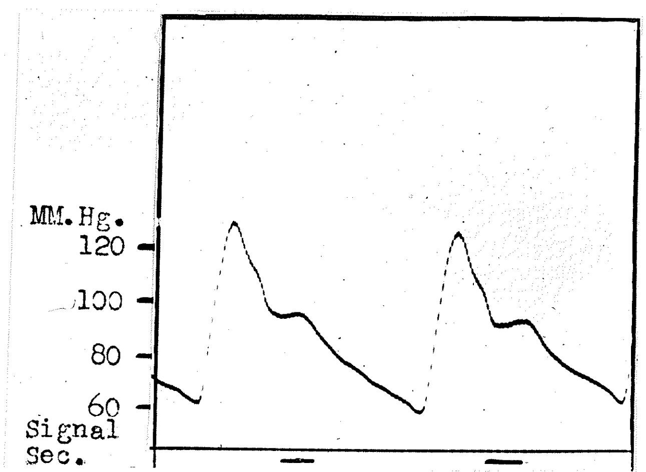

FIGURE 11

LATERAL PRESSURE PULSE TRACING, SUBJECT H.J. "COLD"

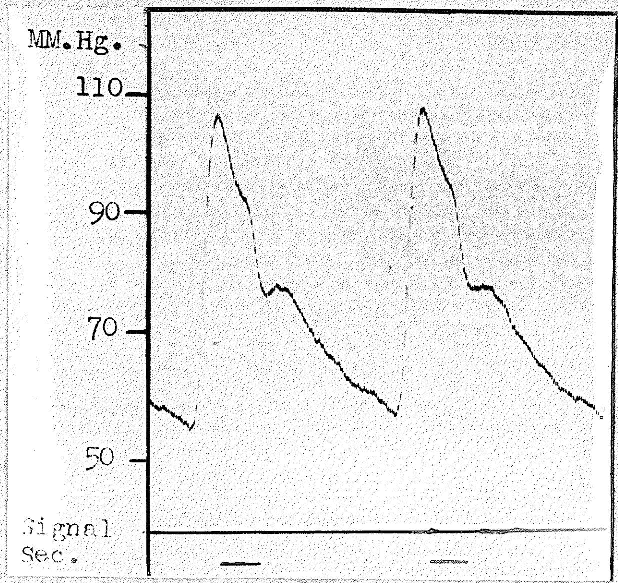

FIGURE 12

LATERAL PRESSURE PULSE TRACING, SUBJECT H.K. "COLD"

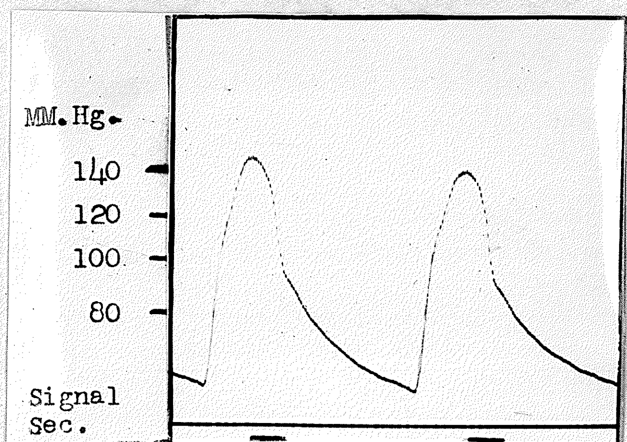

FIGURE 13

LATERAL PRESSURE PULSE TRACING, SUBJECT M.G. "COLD"

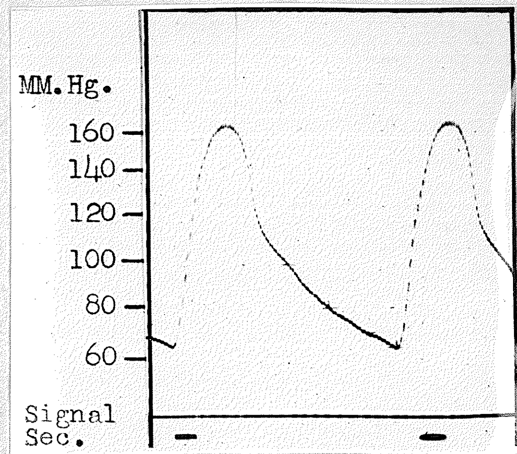

FIGURE 14

LATERAL PRESSURE PULSE TRACING, SUBJECT G.T. "COLD"

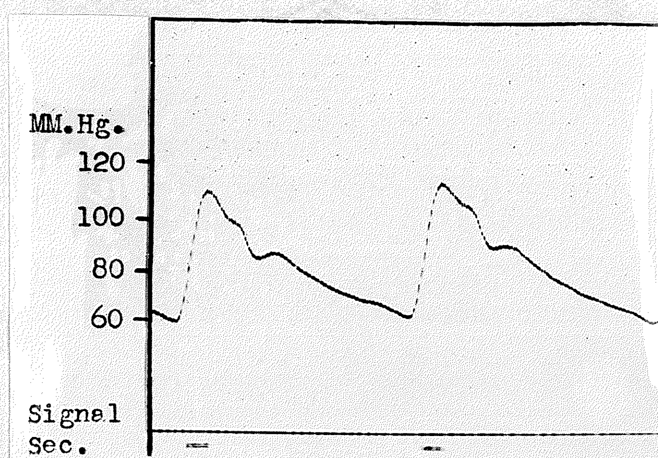

FIGURE 15

LATERAL PRESSURE PULSE TRACING, SUBJECT R.F. "COLD"

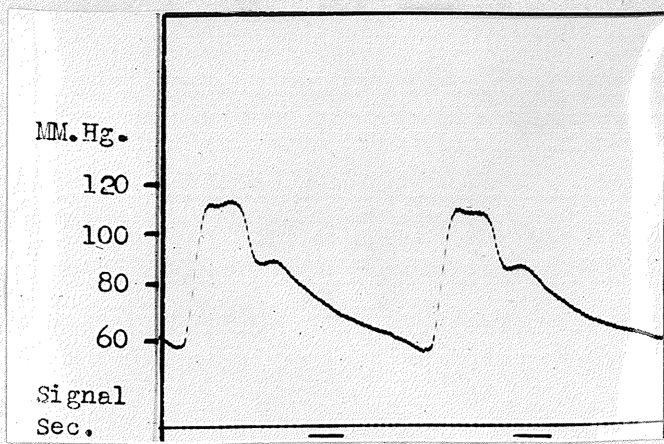

FIGURE 16

LATERAL PRESSURE PULSE TRACING, SUBJECT P.B. "COLD"

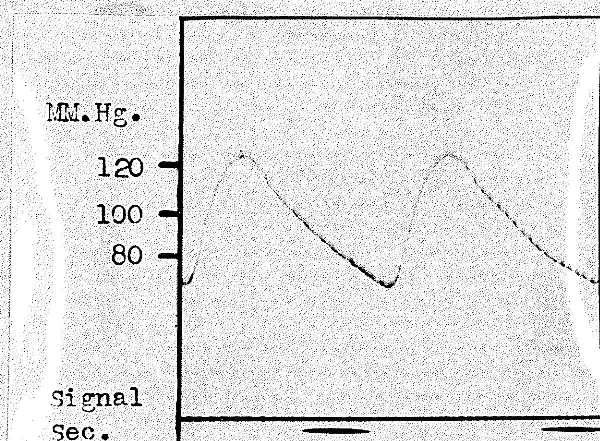

FIGURE 17

LATERAL PRESSURE PULSE TRACING, SUBJECT V.M. "HOT"

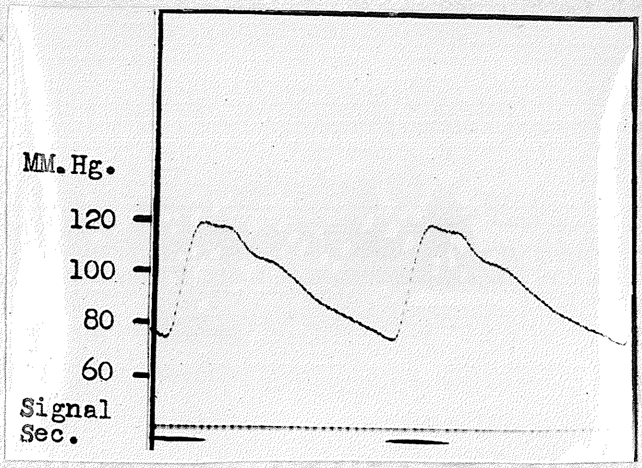

FIGURE 18

LATERAL PRESSURE PULSE TRACING, SUBJECT T.K. "COLD"

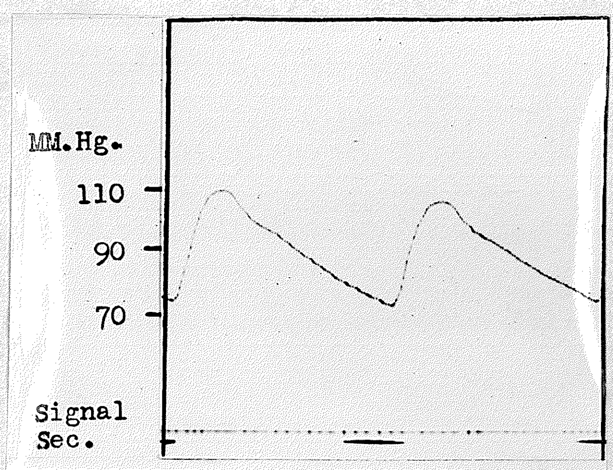

FIGURE 19

LATERAL PRESSURE PULSE TRACING, SUBJECT T.K. "HOT" in individuals with narrow peaked pulse curves auscultatory systolic measurements were much below lateral systolic pressures, in individuals with intermediate curves the auscultatory measurements were closer to lateral systolic pressures, while in individuals with very broad curves the auscultatory measurements were above lateral systolic pressures. These observations indicate that the discrepancies between auscultatory and lateral pressures are related to the contour of the lateral pressure pulses.

4. Pressure at the time of auscultatory measurement. Auscultatory systolic measurements are made at a time when the blood pressure cuff is inflated and therefore they would be expected to approximate end rather than lateral pressures. The possibility that end pressures existed at the time of measurement was investigated in four subjects. After making auscultatory measurements a cuff, previously placed around the forearm, was inflated to beyond systolic pressure and the measurements repeated. Three series of such alternate readings were made and the differences between readings before and during occlusion of the circulation averaged. As it was found that this method of producing end pressures in the artery had little effect on the measurements an attempt was made to accentuate any possible difference. To do this the whole procedure was repeated after vigorous exercise of the forearm in order to increase blood flow. These readings, after exercise, are shown in Table III. It is seen that stopping the circulation even in these circumstances did not materially alter the auscultatory measurements.

TABLE III

AUSCULTATORY MEASUREMENTS BEFORE AND AFTER OCCLUSION OF THE CIRCULATION

(Measured in mm. mercury)

Subject	Systolic pressure			Diastolic pressure		
	Cuff on	Cuff off	Difference	Cuff on	Cuff off	Difference
T.B.	120	122	-2	76	82	-6
	120	118	2	76	80	-4
	120	120	0	76	78	-2
			0			-4
A.T.	130	126	4	76	80	-4
	128	126	2	80	78	2
	126	122	4	78	80	-2
			3.3			-1.3
A.B.	128	128	0	70	68	2
	128	124	4	66	64	2
	130	126	4	62	62	0
			2.6			1.3
M.B.	112	108	4	78	76	2
	112	108	4	76	68	8
	110	108	2	74	76	-2
			3.3			2.6
Mean:			2.3			0.4

Note: All measurements were taken after exercise and the diastolic index employed was the muffling of sounds.

5. Difference between end and lateral pressures. Having established that auscultatory measurements were made under conditions where end pressures existed it was necessary to ascertain if end pressures were actually significantly different from lateral pressures and the changes taking place in the contour of the pulse when end pressures were produced. This was done in five subjects by inflating an occluding cuff just distal to the site of arterial puncture. Under these circumstances simultaneous lateral and end pressures were not available for measurement, so to assess the difference between them three measurements of pressure were made just prior to the inflation of the cuff and three measurements during inflation in apparently the same phases of respiration. The effect of occlusion of the circulation below the needle of the manometer is shown in Figures 20 and 21, and the observed pressures are recorded in Table IV, Columns 3 and 6. Column 8, showing the change in pressure, demonstrates that in every instance a rise in systolic pressure occurred, averaging 9 millimeters of mercury with a range of 2 to 19 millimeters. This rise in systolic pressure was accompanied by a change in the contour of the pulse as is shown in Figure 22 and in Columns 2 and 5 of the Table. The most marked rises occurred where the contour of the pulses was proportionately most narrowed, for example subjects E.L."Cold" and V.M. "Cold". In those with only a small rise, for example subjects H.K."Cold" and M.G."Cold" the contour, although changed, did not show narrowing detectable by the method of measurement employed here. These findings are in accord with those of Robinow et al. (1939) and indicate that end

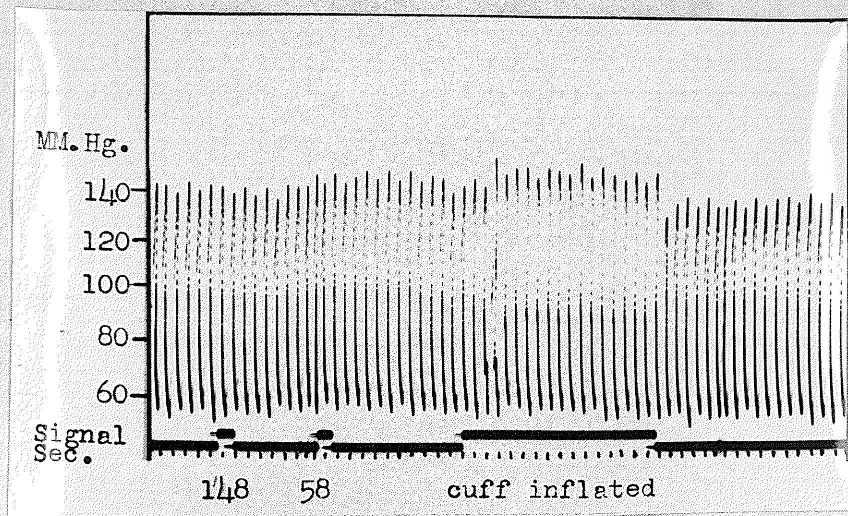

FIGURE 20

PRESSURE PULSE TRACING, SUBJECT M.G. "COLD"

(Signals indicate auscultatory measurements made on the other arm and the period of occlusion of the circulation.)

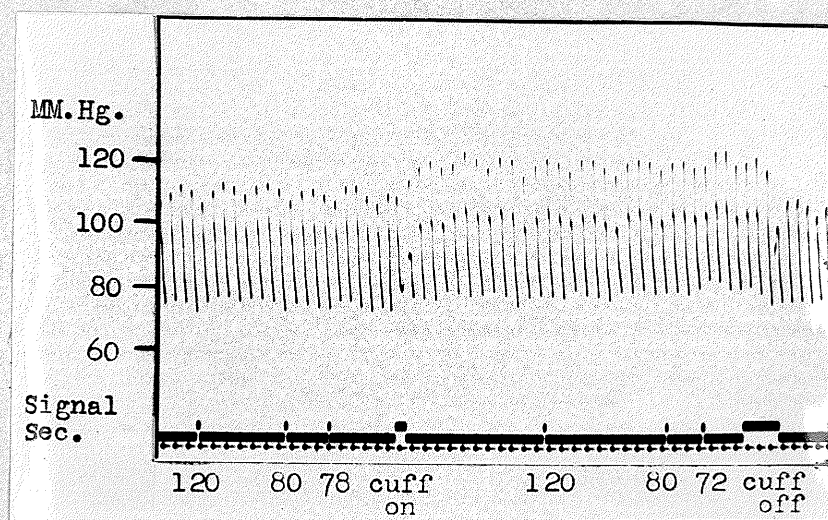

FIGURE 21

PRESSURE PULSE TRACING, SUBJECT T.K. "HOT"

(Signals indicate auscultatory measurements made on the other arm. The circulation was occluded between cuff signals.)

TABLE IV

INTRA-ARTERIAL LATERAL AND END PRESSURES

(Measured in mm. mercury)

Lateral pressure				End pressure			Difference End minus Lateral	
Subject Temp.	Width of pulse wave in mm.	Sys-tolic	Dias-tolic	Width of pulse wave in mm.	Sys-tolic	Dias-tolic	Sys-tolic	Dias-tolic
1	2	3	4	5	6	7	8	9
E.L. Cold	4.0	125	60	2.5	140	63	15	3
	4.0	125	60	2.5	140	63	15	3
	4.0	125	63	2.5	140	63	15	0
							15.0	2.0
V.M. Cold	4.5	147	62	4.0	166	66	19	4
	5.0	151	64	3.0	166	70	15	6
	5.0	148	64	3.0	166	67	18	3
							17.0	4.3
H.K. Cold	6.0	112	57	6.0	115	58	3	1
	6.0	114	55	5.0	116	60	2	5
	6.0	112	55	6.0	116	59	4	4
							3.0	3.3
M.G. Cold	6.0	145	56	6.0	149	57	4	1
	6.0	146	58	6.0	148	59	2	1
	6.0	146	58	6.0	149	59	3	1
							3.0	1.0
V.M. Hot	8.0	114	66	8.0	119	69	5	3
	9.5	114	69	8.0	122	69	8	0
	9.0	111	66	8.0	117	66	6	0
							6.3	1.0
H.K. Hot	9.0	98	57	6.0	110	62	12	5
	9.0	98	60	6.0	109	61	11	1
	9.0	97	61	6.0	109	61	12	0
							11.7	2.0
T.K. Cold	9.5	113	70	7.0	117	73	4	3
	10.0	111	70	7.5	117	73	6	3
	10.0	113	70	7.5	117	73	4	3
							4.6	3.0
T.K. Hot	12.0	111	80	7.0	120	82	9	2
	12.5	114	78	7.5	123	80	9	2
	12.0	114	79	7.0	120	82	6	3
							8.0	2.3
Mean							9.0	2.0

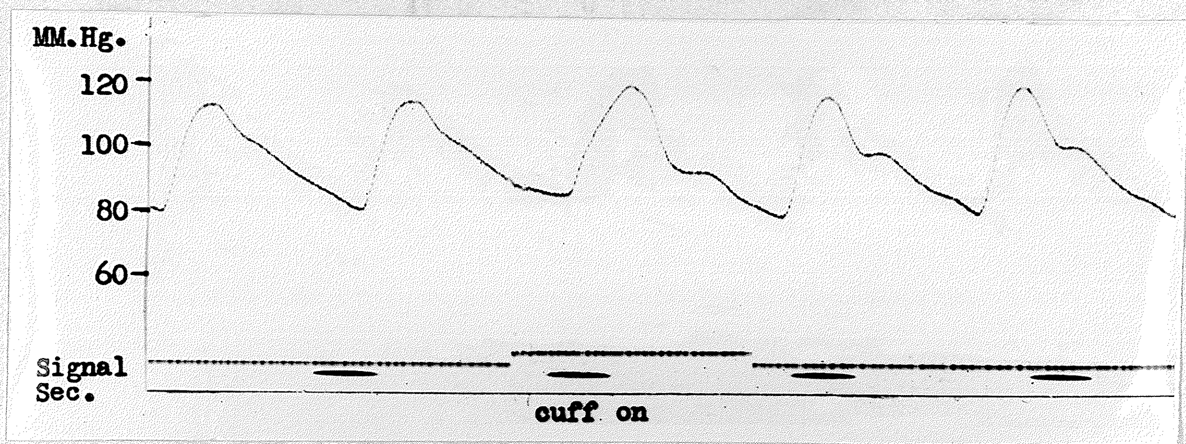

FIGURE 22

PRESSURE PULSE TRACING, SUBJECT T.K. "HOT"

(Lateral pressure pulses are before signal and end pulses after.)

pressure may be significantly above lateral pressure and that the greatest difference is associated with the greatest narrowing of the peak of the pulse wave.

6. Agreement of auscultatory measurements with end pressures. In subjects with narrow peaked contours the auscultatory measurements, which were below lateral pressures, were naturally even further below end pressures. Thus subject V.M."Cold" is shown in Table IV, Column 8 to have had an end pressure 17 millimeters of mercury above the lateral, while in Table II, Column 8 it is seen that his auscultatory measurements were 14 millimeters below the lateral. In subjects with very broad contours in whom the end-lateral pressure differences were small, and in whom auscultatory measurements were above lateral pressures, it would be expected that auscultatory measurements would also exceed end pressures. This was observed in subject T.K."Cold" and "Hot" whose simultaneous auscultatory and end intra-arterial measurements are shown in Table II, Columns 5 and 7 and the difference between them in Column 9. It is clear therefore that despite theoretical considerations auscultatory measurements show little better agreement with end pressures than they do with lateral pressures and in cases where the pulse waves are narrow the disagreement is even greater.

7. Influence of cuff width on auscultatory measurements. In order to show the influence of cuff width on auscultatory measurements, a group of subjects was chosen in which there was a much wider variation in regard

to measured girth of arm than in the group just considered. The mean values of the auscultatory measurements made with the four different widths of cuffs are shown in Table V where it is seen that the highest measurements of both systolic and diastolic pressures were obtained using a cuff 8 centimeters in width. The use of wider cuffs gave lower readings. When the differences between the measurements obtained with a 20 centimeter cuff and each of the other three cuffs was calculated it was found that the difference between measurements made with the 8 centimeter and the 12 centimeter cuffs was greater than the difference between the 12 centimeter and the 16 centimeter cuffs which in turn was greater than the difference between the 16 centimeter and the 20 centimeter cuffs. These differences, while not strictly related to arm size, were greatest in subjects having the largest girth. The width of the cuff therefore has an important influence on auscultatory measurements, but this is modified by the girth of the arm.

8. Relationship of arm girth to cuff width. To demonstrate the relationship between the influence of the girth of the arm and that of the width of cuff on auscultatory measurements, the group was divided into three classes, those with arm circumferences from 20 to 25 centimeters, from 25 to 30 centimeters, and those over 30 centimeters. The auscultatory measurements of the individuals in each of these classes are shown graphically in Figure 23 for systolic and Figure 24 for diastolic pressures. For each class mean values for each width of cuff have been joined. The resultant curves show that in general the greater the girth

TABLE V.

MEAN AUSCULTATORY BLOOD PRESSURE VALUES OBTAINED WITH CUFFS OF DIFFERENT WIDTHS.

(Measured in mm. mercury).

Subject	Age	Arm Circ. in cm.	Mean Systolic Values							Mean Diastolic Values						
			Cuff width in cm.				Difference between 20 cm. cuff value and others			Cuff width in cm.				Difference between 20 cm. cuff value and others		
			8	12	16	20	8	12	16	8	12	16	20	8	12	16
A.K.	68	21	147	138	131	126	21	12	5	77	70	65	60	10	5	7
A.T.	25	21	116	106	101	98	18	8	3	66	60	59	57	9	3	2
J.K.	68	22	137	132	128	125	12	7	3	77	74	72	68	9	6	4
H.K.	64	23	114	108	103	97	17	11	6	81	73	68	64	17	9	4
E.W.	23	23	208	198	195	191	17	7	4	148	141	140	136	12	5	4
A.B.	65	24	120	114	112	109	11	5	3	92	86	81	75	17	11	6
M.T.	50	25	129	128	125	122	7	6	3	82	71	64	64	18	7	0
V.M.	66	26	131	121	112	111	20	10	1	73	62	58	56	17	6	2
D.A.	23	27	128	115	114	109	19	6	5	78	71	66	57	21	14	9
T.S.	54	28	184	177	173	167	17	10	6	100	90	82	76	24	14	6
B.C.	27	28	124	115	113	110	14	5	3	72	65	58	55	17	10	3
M.B.	52	28	107	102	98	96	11	6	2	78	67	63	63	15	4	0
A.B.	58	28	165	160	158	148	17	12	10	115	107	103	100	15	7	3
P.O.	28	28	136	118	116	110	26	8	6	81	70	65	62	19	8	3
T.C.	47	29	144	134	135	130	14	4	5	87	85	84	83	4	2	1
J.F.	73	30	180	168	172	166	14	2	6	112	94	94	90	22	4	4
C.S.	48	30	130	113	109	107	23	6	2	84	68	64	63	21	5	1
M.L.	44	31	208	178	178	167	41	11	11	131	110	107	101	20	9	6
D.B.	25	31	119	95	94	91	28	4	3	82	71	64	54	28	17	10
M.K.	74	35	220	180	175	166	54	14	9	108	88	84	79	29	9	5
A.G.	47	36	228	195	183	180	48	15	3	162	141	140	130	32	11	10
J.B.	42	40	123	106	93	84	39	22	9	85	70	61	59	26	11	2
Mean:							23	11	5					18	8	4

Note: Each mean pressure value is computed from 6 observed values. The total number of observations was 1076. Subjects are arranged in order of arm size and the diastolic index employed was the muffling of sounds.

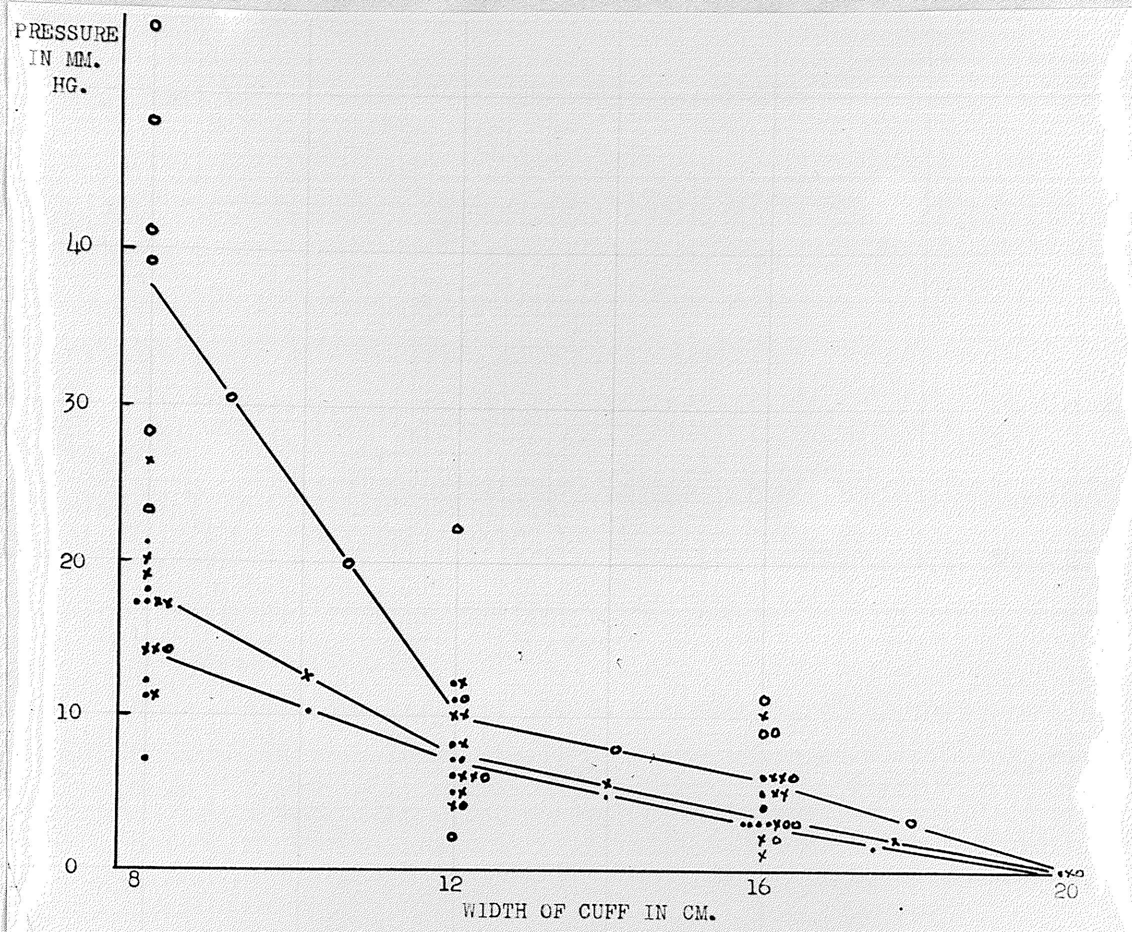

FIGURE 23

MEAN SYSTOLIC PRESSURES WITH VARIOUS WIDTHS OF CUFF FOR ARMS OF DIFFERENT CIRCUMFERENCE

(Open circles indicate mean systolic values obtained on individual subjects with arm circumference of over 30 cm. The line —o— joins the average values of this group for various cuff sizes. Similarily the closed circles and the crosses represent individuals with arm circumferences 25 to 30 cm., and 20 to 25 cm. respectively.)

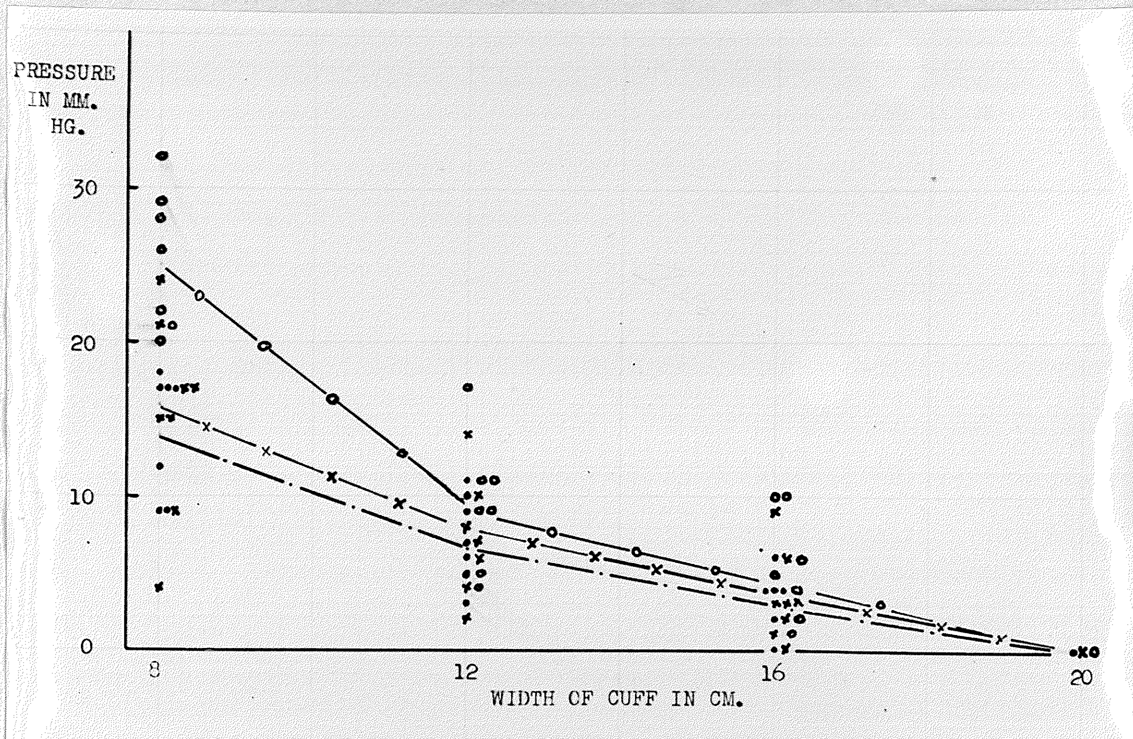

FIGURE 24

MEAN DIASTOLIC PRESSURES WITH VARIOUS WIDTHS OF CUFF FOR ARMS OF DIFFERENT CIRCUMFERENCE

(Open circles indicate mean diastolic values obtained on individual subjects with arm circumference of over 30 cm. The line —o— joins the average values of this group for various cuff sizes. Similarily the closed circles and the crosses represent individuals with arm circumferences 25 to 30 cm., and 20 to 25 cm. respectively.)

of the arm the greater the effect of changing the width of the cuff, the initial slope of the curves being steepest in the subjects with the greatest arm girths.

9. Measurements of arm girth. As the above results indicated the importance of arm girth an attempt was made to ascertain the relationship of measured girth to the effective girth; effective girth being considered to be that present when the cuff was inflated. To determine the effective girth X-ray films, using soft tissue technique, were taken before and after inflation of a standard blood pressure cuff to systolic pressure. This was done on three subjects whose soft tissue consistency was different. The measured arm circumferences were 29, 30 and 34 centimeters respectively for a "muscular","flabby" and a "fat" arm. Circumferences calculated from X-ray films before inflation of the cuff were 29, 30 and 35 centimeters and after inflation 27, 26 and 31 centimeters. As would be expected it was found that the circumference at the center of the cuff was more affected than at the edges. It is therefore seen that effective circumference can differ from measured circumference and this difference appears to depend upon the consistency of the soft tissues.

10. Relation of the level of cuff pressure to tissue pressure. Preliminary to a study of the distribution of pressure in the tissues underlying the cuff it was necessary to ascertain the influence of different cuff pressures. The tissue pressure was measured at four to six cuff pressures between 20 and 200 millimeters of mercury at eight points under the 12 centimeter cuff and at nine points under the 8 centimeter cuff.

Figures 25 and 26 show the observations made at four positions of the needle under each of these cuffs. In these Figures it is seen that for each position of the needle the ratio of tissue pressure to applied pressure remains constant. This held in a similar fashion for the observations not charted. Therefore the distribution of the pressure under the cuff is independent of the applied pressure and the relationship between tissue pressure and applied pressure for any point can be expressed as a percentage of the cuff pressure.

11. Distribution of pressure in the tissues under the cuff. Having shown that the relationship of the tissue pressure to the applied pressure is independent of the cuff pressure it was possible to study the geographical distribution of the pressure beneath the cuff using a single cuff pressure for each point. The cuff pressures used were between 150 and 200 millimeters of mercury and the measurements made were converted to percentage values which are shown in Figures 27, 28 and 29 for cuffs 12, 8 and 4 centimeters in width. Comparison of these Figures suggested that the relationship of these values to the edge of the various cuffs was similar and independent of the total width of the cuff. To test this all the observations were incorporated in the diagram shown in Figure 30 and were located keeping constant their relationship to the nearest edge of the cuff and their depth in the tissues. Because the discrepancies between the measurements made with different cuffs were no greater than between the measurements made with the same cuff it was concluded that the pattern of the pressure distribution

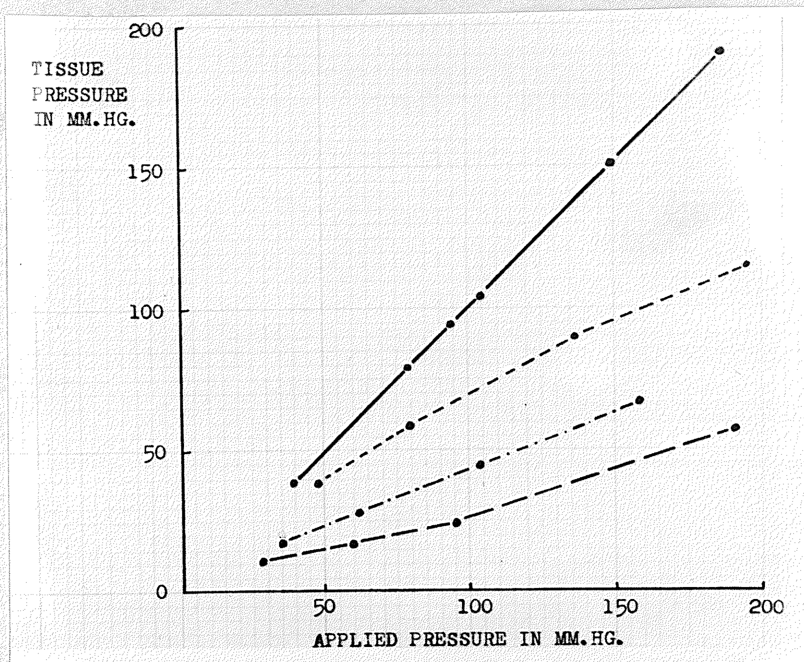

FIGURE 25

APPLIED PRESSURE AND TISSUE PRESSURE

AT FOUR POSITIONS UNDER THE 12 CENTIMETER CUFF

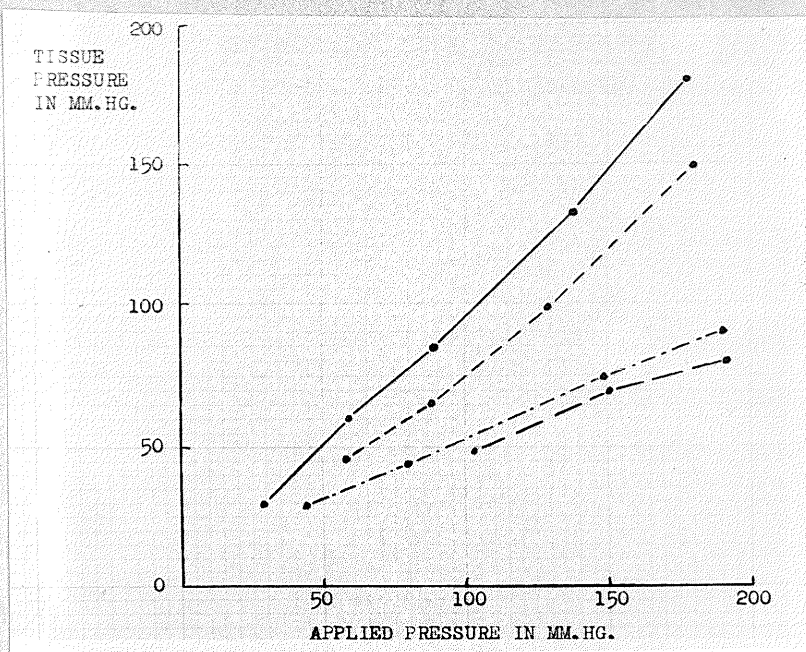

FIGURE 26

APPLIED PRESSURE AND TISSUE PRESSURE

AT FOUR POSITIONS UNDER AN 8 CENTIMETER CUFF

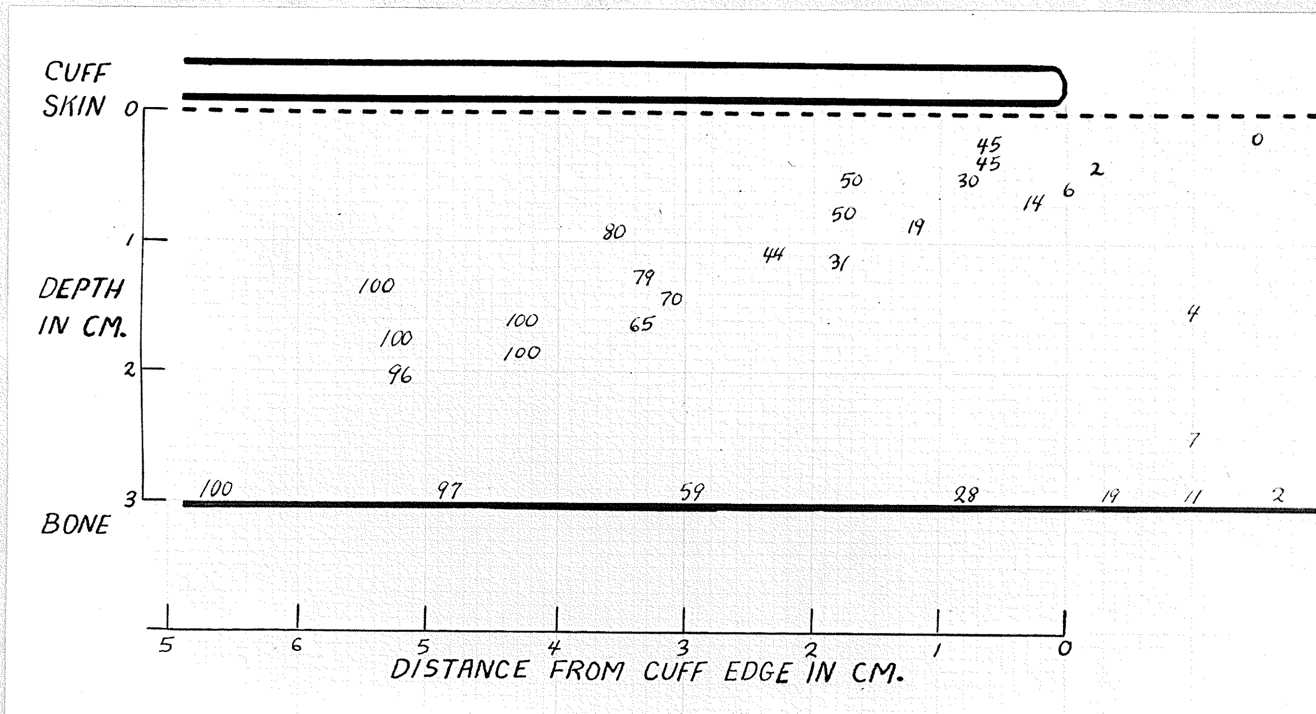

FIGURE 27

DISTRIBUTION OF PRESSURE IN THE TISSUES UNDER A 12 CENTIMETER CUFF

62

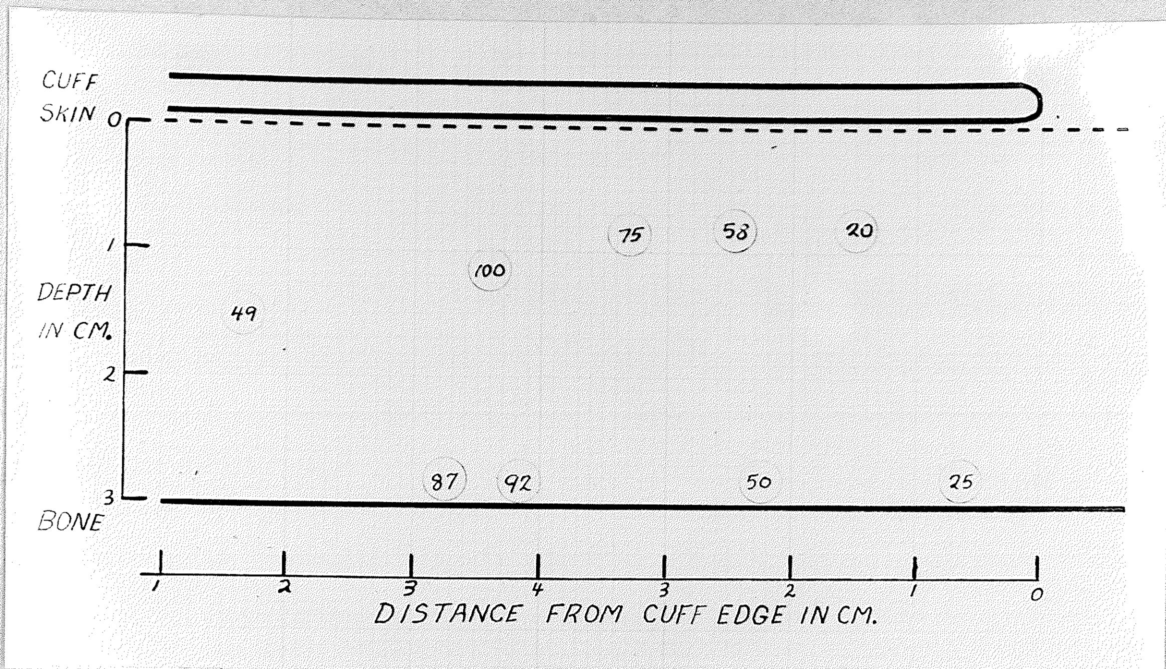

FIGURE 28

DISTRIBUTION OF PRESSURE IN THE TISSUES UNDER AN 8 CENTIMETER CUFF

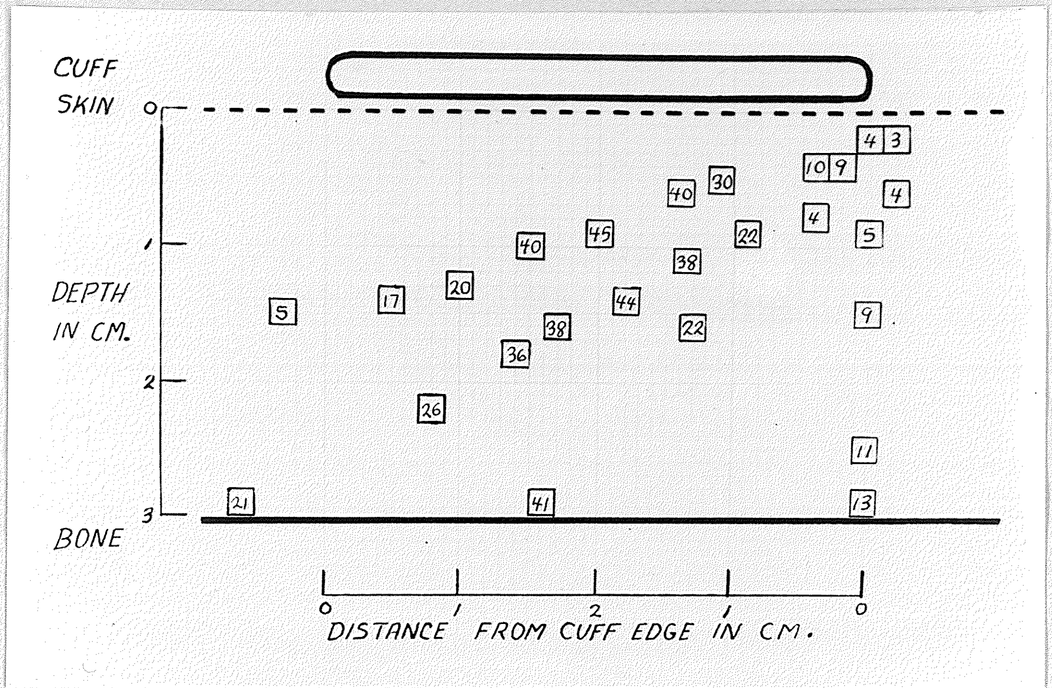

FIGURE 29

DISTRIBUTION OF PRESSURE IN THE TISSUES UNDER A 4 CENTIMETER CUFF

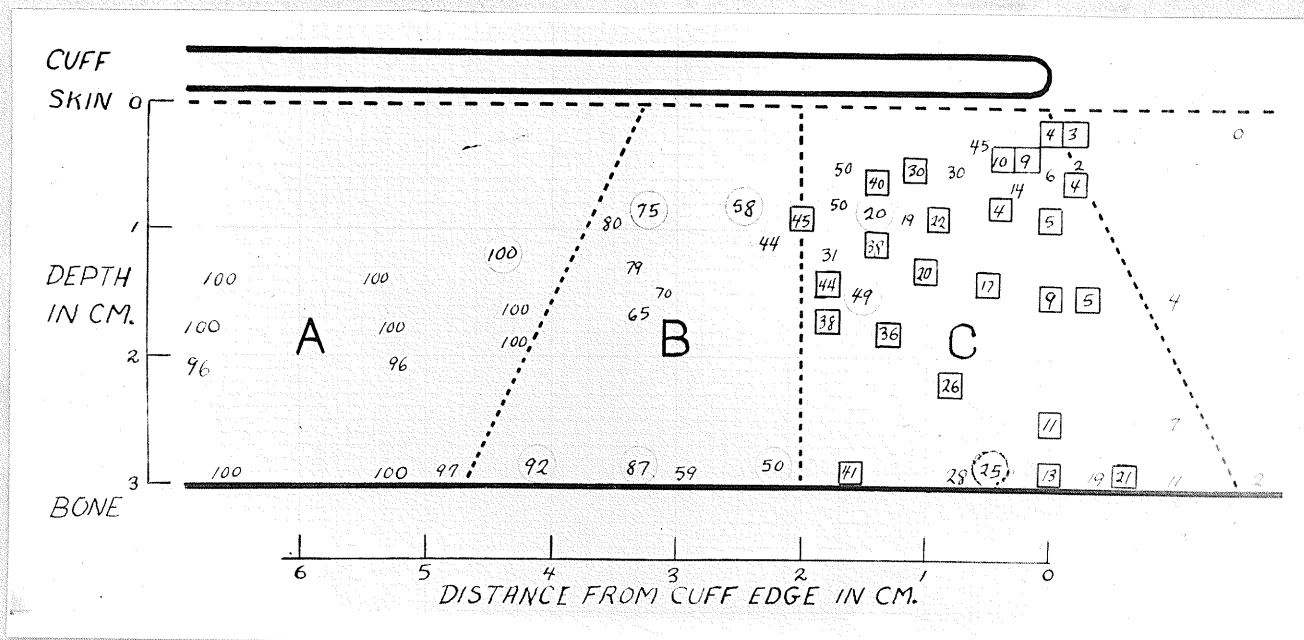

FIGURE 30

DISTRIBUTION OF PRESSURE IN THE TISSUES UNDER THE EDGE OF A CUFF

(Values within circles and within squares are obtained from measurements made with an 8 centimeter and a 4 centimeter cuff respectively. Other values are obtained from measurements made with a 12 centimeter cuff.)

was similar for the various cuffs except beneath the wider cuffs where a wider central zone of high pressure was present. The total number of observations was insufficient to enable exact isobaric lines to be drawn, but certain general trends were noted. The highest relative pressures were found near the center of the cuff and the zone occupied by these values, although fairly extensive immediately beneath the cuff became less so at greater depths in the tissues. With the 4 centimeter cuff, as shown in Figure 29 the 100 percent zone was not detected. Lowest relative pressures were found towards the edge of the cuff and the area occupied by these values was definitely greater at increasing depths in the tissues. The zone in which intermediate values were present lay between the low and the high relative pressure zones and appeared to broaden at greater depths in the tissues at the expense of the high pressure zone.

B. DIASTOLIC MEASUREMENTS

12. Agreement of auscultatory measurements with lateral pressures. In Table II, Columns 10 and 11 are listed the simultaneous measurements of auscultatory and lateral diastolic pressures. The auscultatory values were obtained using the muffling of sounds as the index. In Column 13 is shown the difference between the measurements and it will be seen that the auscultatory values average 12.2 millimeters of mercury above lateral diastolic pressure with a range of difference of - 12 to + 38 millimeters. This is in agreement with the findings of other investigators (Hamilton et al. 1936, Ragan and Bordley 1941, and Steele 1942.)

The fact that only two negative differences were found in the forty-three comparisons, both of these being on the same subject, indicates that the measurements obtained using this index are usually considerably above lateral diastolic pressure. The detection of the point of cessation of all sounds depends upon the acuteness of the hearing of the individual observer, and with the employment of no other index is there such a wide variation in measurement from observer to observer. In the few instances in this study where a sharp end point could be elicited it agreed well with lateral diastolic pressure, but this occurence was so infrequent that the cessation of sounds was of little use in obtaining measurements of diastolic pressure.

13. Agreement of auscultatory measurements with end pressures. Because sounds are still being produced at the point of muffling of sounds it is logical to assume that the flow of blood is at least partly obstructed by the compressing cuff. Measurements obtained, using this index, might therefore be closer to end than to lateral diastolic pressure. The procedure used to measure end diastolic pressure was identical to that used for end systolic pressures, and the observations made are shown in Table IV, Columns 4 and 7. It is seen that end diastolic pressures averaged 2 millimeters of mercury above lateral diastolic pressures with a range of difference from 0 to 6 millimeters. These small differences when considered in relation to the large differences between auscultatory and lateral measurements indicate that auscultatory measurements, using the muffling of sounds as an index, do not agree with end diastolic pressures.

14. Other factors. No relationship between the contour of the pulses and the discrepancies between auscultatory diastolic measurements and intra-arterial pressures could be demonstrated. The width of cuff and girth of arm influenced the measurements in the same manner as they influenced auscultatory systolic measurements.

CHAPTER IV

DISCUSSION

1. Introduction. The purpose of this study has been to ascertain the factors which determine the values obtained by the auscultatory method of measuring arterial pressure and if possible to elaborate formulae to correct for variations in these factors. In discussing the results it will first be necessary to consider an explanation of the various phenomena observed and then to show how these bear upon the problem.

A. EXPLANATION OF THE OBSERVED PHENOMENA

2. Dependency of auscultatory measurements upon the contour of the pulse. It has been shown that auscultatory systolic measurements were made at a time when end pressures existed in the artery and that the observed deviations of auscultatory measurements from intra-arterial pressures were related to the contour of the lateral and end pulses. An explanation for this relationship is to be found in a consideration of the method of measurement. The production of audible sounds depends upon the penetration of the peaks of the pulse waves through the segment of artery compressed by the cuff. A certain amount of energy is necessary to overcome the pressure exerted by the cuff. A pulse which is broad and rounded will have considerably more energy available for a longer period of time to penetrate the compressed segment than will a narrow pulse.

Thus, when broad pulses were found the auscultatory measurements approximated or exceeded intra-arterial pressures. When narrow pulses were found, auscultatory measurements were below intra-arterial pressures. It was also observed that narrow lateral pressure pulses underwent marked systolic elevation when converted into end pulses and the pulses became much narrower. Because of the counter effect of this change in contour auscultatory measurements, although made when end pressures are present, may still be much below lateral pressures.

3. Dependency of auscultatory measurements upon the width of cuff. When auscultatory measurements were made on the same subject, with cuffs ranging from 8 to 20 centimeters in width, progressively lower readings of both systolic and diastolic pressure were obtained as the width of the cuff was increased. Plotting these measurements gave curves which had an initial steep slope when narrower cuffs were used and which became less steep as the width of the cuff was increased. These findings can be explained by using as a specific example the observations made on the subject in whom the distribution of the applied pressure in the tissues beneath various widths of cuff was determined. It was shown that the ratio of tissue pressure to applied pressure was constant at any given position in the tissues, within the pressure range of 20 to 200 millimeters of mercury, and that the general pattern of the distribution of applied pressure throughout the tissues was the same for each cuff. However the depth to which the central high relative pressure zone extended was found to depend upon the width of the cuff employed. Beneath the

center of the 4 centimeter cuff only 50 percent of the applied pressure was transmitted to the depth of the bone and thus available for compressing the artery. On this basis auscultatory measurements made with the 4 centimeter cuff would be expected to yield much higher values than would be obtained with wider cuffs which projected 100 percent zones to the depth of the bone. Accordingly systolic and diastolic measurements made with cuffs from 4 to 20 centimeters in width were obtained and are charted in Figure 31. Estimates of relative pressure at the level of bone taken from Figure 30 are also shown in Figure 31. It will be seen that the steep part of the curve corresponds to the transition from a cuff which does not project a high relative pressure zone to the bone to a cuff which does. The less steep parts of the curve correspond to increases in width of the high pressure zone, produced by changing to wider cuffs. These observations suggest that the auscultatory blood pressure measurements are affected by the width of the cuff because of two factors. Firstly, narrow cuffs project considerably less than the applied pressure to the depth of the artery and secondly, that once the width of the cuff has been increased to that necessary to project a high relative pressure to the depth of the artery, further increases in the width of the cuff cause increasingly longer segments of artery to be occluded, adding to the difficulty of penetration by the pulse wave.

4. <u>Dependency of auscultatory measurements upon arm girth</u>. It was observed that the greater the girth of the arm the steeper the initial slope of the curve representing decreases in auscultatory measurements,

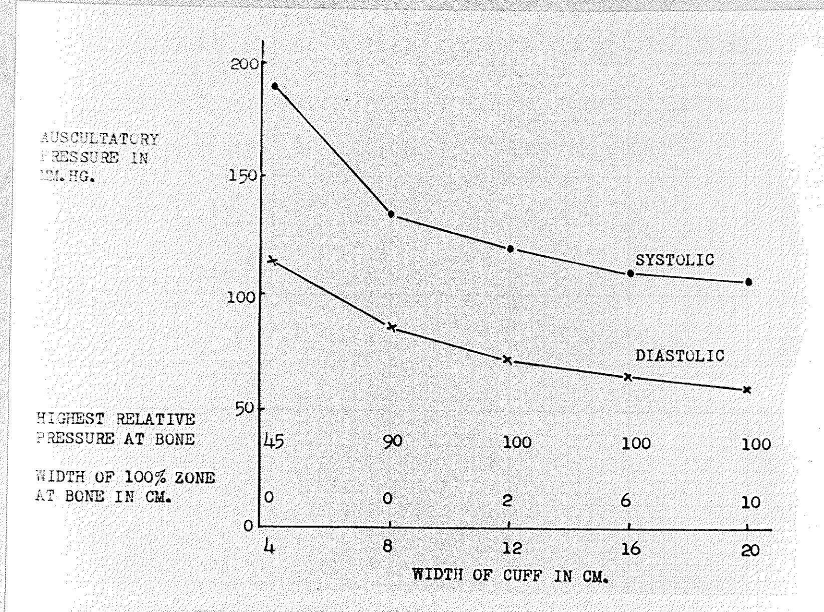

FIGURE 31

SYSTOLIC AND DIASTOLIC PRESSURES WITH VARIOUS WIDTHS OF CUFF

SUBJECT, M.S.

(Estimates of relative pressure and width of the 100 percent zone at the level of bone are taken from Figure 30.)

obtained when cuffs of increasing width were used. These observations indicate that the girth of the arm relative to the width of the cuff used is important. They can be explained on the basis of the distribution pattern of the applied pressure in the tissues underlying the cuff. It was shown that the greater the depth of tissue under the cuff the narrower was the zone of high pressure. Thus the girth of the arm will determine the percentage of the applied pressure which is transmitted to the artery and the length of the segment of artery which is affected by this pressure.

5. Dependency of effective girth upon the consistency of the soft tissues. It was observed that the effect on auscultatory measurements of changing the width of cuff was not strictly related to the measured girth of the arm. A possible reason for this was supplied by the observation that the measured girth of the arm was found to be a poor index of the girth when the cuff was inflated. Even if the effective girth were readily measured individual variations in the position of the artery would exert an important influence. Furthermore the consistency of the soft tissues besides determining the effective girth might also exert a great but as yet undetermined influence on the distribution of pressure within the tissues.

6. Dependency of auscultatory measurements upon the indices employed. The first appearance of sound is generally accepted as indicating auscultatory systolic pressure and the factors which influence the closeness of the association of this index with intra-arterial pressure have been

discussed. The auscultatory index most widely employed for the detection of diastolic pressure is the muffling of sounds, that is the beginning of the fourth sound phase. The findings of this study, in accord with those of other investigators, showed this index to yield measurements which varied greatly above lateral diastolic pressure, averaging + 12 millimeters of mercury with a range of − 17 to + 38 millimeters. The mean elevation of the measurements obtained with this index above intra-arterial pressures suggests that it is not a measure of diastolic pressure, however if it could be shown to bear a predictable relationship to diastolic pressure it would be a valuable index. The wide range of observed values might have been due either to the influence of factors which were shown to affect the systolic index or to the difficulty in the detection of the change in sounds. No relationship between the muffling of sounds and the contour of the pulse was demonstrated. The factors influencing the distribution of applied pressure in the tissues underlying the cuff, that is the width of the cuff and the girth of the arm, had similar but less marked effects to those exerted on the auscultatory systolic index. However the subjects which showed the wide range of differences between auscultatory and intra-arterial measurements formed a relatively homogeneous group with regard to the girth of the arm so it is unlikely that these differences can be accounted for on the basis of the influence of these factors. Therefore it would appear that the muffling of sounds is an unreliable index of diastolic pressure. The detection of the point at which all sounds cease was extremely difficult to determine and the bearing of the factors found to influence other auscultatory indices was not established with regard to this index.

B. APPLICATION OF THE OBSERVED PHENOMENA

7. Auscultatory measurement of systolic pressure. The estimation of systolic pressure by the auscultatory method is dependent upon the penetration of pulse waves through a segment of artery compressed by the cuff of the blood pressure apparatus. The factors which have been shown to influence auscultatory measurements act either to modify the amount of applied pressure effective at the depth of the artery and the length of the segment of artery compressed or to determine the capacity of the pulse waves to penetrate the compressed segment. The width of the cuff and the girth of the arm, determining the effective pressure and the length of the segment of artery compressed remain constant in a given individual, but the contour of the pulses, determining the ease with which the pulse waves penetrate the segment varies widely from individual to individual and in the same individual at different times.

8. Auscultatory measurement of diastolic pressure. Measurements obtained using the muffling of sounds as an auscultatory index vary widely and unpredictably from intra-arterial pressures and cannot be considered as reliably indicating diastolic pressure either lateral or end. The point of cessation of sounds, while agreeing with lateral diastolic pressure is usually very indefinite and not a practical index.

9. Standard auscultatory procedure. The major factors which affect the measurements obtained by the auscultatory method are known and in regard to systolic measurements it would be possible by extending the

observations to elaborate a correction formula. However in such a formula would be incorporated factors representing the contour of the pulse, depth of the artery and the consistency of the soft tissues, none of which can be readily measured and therfore such a formula would be of little use. In regard to diastolic measurements which have been found to deviate unpredictably from intra-arterial pressures it would be impossible to devise any method of correction. The above considerations suggest that the auscultatory procedure gives results which depend upon numerous factors the sum of which for clinical purposes may provide a measurement of great significance. However the measurements are not those of systolic and diastolic pressure and whether or not the terminology is changed the distinction is real.

CHAPTER V

SUMMARY AND CONCLUSION

1. Summary. A study has been made of the factors affecting the auscultatory measurements of arterial blood pressure. By comparison of auscultatory and intra-arterial pressures in a group of subjects with similar girths of arm it was found that the contour of the pulse exerted a great influence on auscultatory systolic measurements; when the contour was narrow auscultatory measurements were too low whereas when it was broad they were too high. Auscultatory measurements appeared to agree better with lateral than end intra-arterial pressures, averaging 0.3 millimeters of mercury above lateral systolic with a range of difference from - 17 to + 12 millimeters. The measurements obtained using auscultatory indices for diastolic pressure were unaffected by the contour of the pulse and varied unpredictably from intra-arterial diastolic pressures, the discrepancy averaging + 12 millimeters of mercury with a range of difference from - 17 to + 38 millimeters. By taking auscultatory measurements with different widths of cuff in a series of subjects with a variety of arm sizes it was found that auscultatory systolic and diastolic measurements were dependent upon the relationship between cuff size and arm girth; narrow cuffs and large arms tended to give the highest measurements. By taking X-ray films it was found that the effective girth of the arm was modified by the pressure in the cuff depending upon the consistency of the soft

tissues. By measuring tissue pressures under the cuff it was found that the girth of the arm and the width of the cuff determined the pressure acting on the artery and on the length of the artery occluded.

2. Conclusion. It was concluded that auscultatory systolic measurements are dependent upon various factors which if methods of measurement were available could be corrected for to yield measurements closely approximating intra-arterial systolic pressures, whereas auscultatory diastolic measurements which were found to vary unpredictably from intra-arterial pressures could not be corrected in such a manner.

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