Comparison of Indirect and Direct Methods of Measuring Arterial Blood Pressure

By Frederick H. Van Bergen, M.D., D. Stuart Weatherhead, M.D., Alan E. Treloar, Ph.D., Allan B. Dobkin, M.D., and Joseph J. Buckley, M.D.

Direct and indirect determinations of blood pressure have been recorded in 70 human subjects. Statistical analysis of the results is presented. A frequent discrepancy between direct and indirect readings is evident with the drift of the latter falling increasingly below the direct measurement as blood pressure rises. The greatest discrepancy is found in the young hypertensive subject and the possible clinical implications of this finding are discussed. An attempt is made to explain some of the factors contributing to the variable error by which auscultatory readings underestimate the true intraarterial pressure.

In the course of recording arterial pressures of patients subjected to hypotensive anesthesia, it was observed that blood pressures often were unobtainable by any of the indirect methods, while at the same time intra-arterial manometry demonstrated systolic levels of 60 to 70 mm. Hg. One frequently is impressed by the uncertainty, if not inadequacy, of blood pressure determinations upon patients in surgical shock when indirect methods alone are employed.

Clinicians, using the three indirect methods under customary conditions, have observed disturbing discrepancies among the results obtained. The usual practice of employing one technic only does not permit such revelations. False confidence in absolute values thus arises all too easily.

Conflicting opinions exist concerning the validity of auscultatory pressures. Several observers in studies of the inaccuracy of indirect determinations have enumerated factors contributing to the errors. Others report good agreement between blood pressures determined by the direct intra-arterial and the auscultatory methods.

Cognizant of the confusion existing in this basic physiologic measurement, we undertook the following investigation to compile data seeking to define the relative accuracy of the three indirect methods over a wide blood pressure range, and to identify some of the factors contributing to the current enigma.

**METHODS**

*Indirect Measurement of Blood Pressure.* Two to four trained observers participated sequentially in determining auscultatory systolic and diastolic levels, and oscillometric and palpatory systolic levels, on each patient, using a mercury manometer. Care was taken to insure that these observers did not see the intra-arterial pressure recordings. Another assistant entered each observer's indirect blood pressure findings on the tracings at the appropriate points.

In the determination of auscultatory systolic and diastolic pressure, the standards recommended by Bordley and his co-workers were followed. Oscillometric systolic pressure was recorded as the point on the manometer scale at which the meniscus of the pulsating mercury column became convex. Palpatory systolic pressures were determined by the perception of a pulse in the radial artery. Diastolic
levels were not recorded by either the oscillographic or the palpatory methods.

**Direct Measurement of Blood Pressure.** The intraarterial pressure was measured directly with high accuracy by means of a standard resistance wire pressure transducer (model P23A Statham strain gage) and registered by a direct-writing electronic recorder (Sanborn Polyviso). A 15 gage needle, connected directly to the face of the transducer by a double male adapter, was inserted into the brachial artery directly under the lower edge of the blood pressure cuff (fig. 1). This entire system was demonstrated to have a 100 per cent frequency response, flat to 17.5 cycles per second. There was a 105 per cent response at 23 cycles per second (fig. 2).

The system was calibrated statically against a mercury manometer before and after each recording. Square waves of 200 mm. Hg were passed before, during, and after each recording to detect damping due to clotting or malposition of the needle.

**Reading the Tracings.** The Sanborn Polyviso has a recording accuracy of ±0.5 mm. deflection within the inner 4 cm. of the recording paper. This increases an additional ±0.5 mm. deflection error in the remaining 0.5 cm. at each margin of the paper. With the attenuation used to cover the pressure ranges involved, the over-all reading accuracy was judged to be within ranges of ±2.5 mm. Hg in the center 4 cm. of the paper and within ±5 mm. Hg in the marginal 0.5 cm.

In quantifying the tracings an average of the individual systolic and diastolic levels for a period of 15 seconds immediately before beginning inflation of the cuff was used. This was deemed desirable so that effects of variations in blood pressure produced by respiration, irregular cardiac rhythm and such other minor factors might be minimized. Tracings immediately following deflation of the cuff were not used.

**Subjects**

The subjects in the present study consisted of 70 surgery patients ranging in age from 2.5 to 82 years (average of 52 years). In every instance the blood pressure comparisons were made in the immediate postoperative period while the subjects still were partially under the effects of general anesthesia. All measurements were made with the patients in a horizontal supine position.

The subjects used for these observations and the conditions prevailing were not normal. It may be inferred safely from the average age (52 years) that many of the patients were either mild or severe hypertensives. Many of the patients were afflicted with some form of cardiovascular disease other than hypertension. The postoperative and postanesthetic states are often accompanied by marked alterations in stroke volume output, blood volume, total peripheral resistance, pulse pressure and heart rate. Nevertheless, these subjects and these conditions represent a cross section of the surgical patients who require careful and accurate monitoring of their blood pressures during the operative and postoperative periods.

**Results**

Circumstances delimited both the period of observation and number of available observers for these blood pressure determinations on each patient. With 5 of the 70 subjects,
only one direct reading was secured, followed immediately by one each of the indirect measurements in four cases and only the auscultatory measurements in the other. For the remaining 65 subjects, 2 to 14 direct measurements were made, with varying numbers of indirect determinations.

In studying the relationship between the direct measurement and each of the indirect determinations of blood pressure, we have available 180 values for auscultatory systolic pressure, 133 auscultatory diastolic, 166 oscillometric systolic, and 132 palpatory systolic. Each indirect reading has its associated direct reading taken closely if not immediately in advance of it. Thus there are from 132 to 180 pairs of values defining the relationships, each of the 70 subjects contributing from 1 to 7 points for the 3 correlation surfaces.

The possibility of disturbing effects arising from the unequal representation of the 70 subjects led us to select one pair of values at random from each subject for each of these three associations, using a table of random numbers. Thus we established a sample of paired values for each association in which there was no possibility of disturbance arising from considering patients unequally.

The basic data need not be reproduced here in tabular form. Graphic methods will be adequate. Figures 3, 4 and 5 present the correlation scatters for the three relationships of indirect determination of blood pressure to the direct method of measurement. Each solid dot or open circle defines a pair of associated values for some patient; the corresponding direct and indirect blood pressure values may be ascertained by tracing these points to the horizontal and vertical scales, respectively.

The inscribed thicker straight lines define the average relationship of the indirect reading of blood pressure to the direct measure. Since the latter has negligible error in comparison with the indirect determination, it is appropriate to consider only this line for the average relationship when errors alone reduce the correlation below perfection. The full line is fitted to all available pairs of values (dots plus circles). The broken line is fitted only to the
random sample of 1 point per patient (defined by the circles). These heavy lines are the statistical regression lines. The light diagonal line is that of equal values on the two scales; the distribution of the point scatter in relation to this line defines the nature of the errors of the indirect method relative to the direct method over the range of values covered.

Certain features common to all three relationships are outstanding. First, over the entire range of observations, indirect readings of blood pressure fall below the direct measurement made as nearly as possible at the same time. There was only one case of equality in 611 paired observations, and relatively few approaches to equality. Second, the drift of indirect readings is to fall increasingly below the direct measurement as blood pressure increases. Third, no serious disturbance is introduced by considering all values (as opposed to one per patient for the random sample) in arriving at these average relationships. We therefore have chosen to use the total sample lines in further discussion.

The three regressions of indirect on direct readings (using all observations) are superimposed in figure 6. It will be observed that the oscillometric method makes the nearest approach on the average to equality with the direct reading. The palpatory method falls furthest from the equality line in these data, with auscultatory results holding the intermediate position. It would be unwise to conclude that these rather small divergences of the three regressions among themselves would persist if more extensive data were available. However, there would be no question about their departure in general (collectively) from the equality line.

Figure 6 also includes the regression of auscultatory diastolic reading. The full scatter of points, together with the regression and equivalence lines for the auscultatory diastolic data, is given in figure 7. It is interesting to note that the agreement of indirect and direct readings is even less satisfactory for diastolic pressures than for systolic pressures. The absolute errors of the indirect readings on the average are of the same general order of magnitude as for the auscultatory systolic pressure at each end of the line. Since the general level of diastolic pressures is much less than for systolic pressures, the errors become much more important in the relative sense.

It is of some interest to consider at this point the inter-relationships of the indirect readings, one to the other, for systolic pressure. The charts are reproduced as figures 8, 9 and 10. Since both variables are now subject to error, and one may presume more or less equally so, there is less justification for considering only one of the two regression lines which may be drawn for each surface. However, the amount of data available to us for this study is limited to not more than 47 points. We shall omit, therefore, regression analysis and be content to study the scatters alone.
It will be noted that there is comparatively good agreement between these indirect readings. As before, the thin diagonal line traces equal values by both methods. It will also be noted that the scatters of points are in closer agreement with this line than in figures 3, 4 and 5. This would be anticipated from the proximity of the regression lines in figure 6. Because of the restricted number of paired values we would not care to suggest that indications of somewhat closer agreement in one pair than another are suitable bases for claims that such better agreement does exist in general. However, it is noticeable that these readings agree with one another as individual pairs more closely, in general, than each indirect reading agrees with its direct associate. That is, the intensity of correlation in figures 8, 9 and 10 is greater than in figures 3, 4, and 5. This may arise from circumstances; the direct reading is unknown to an observer, whereas his indirect readings cannot very well be dismissed from mind immediately as each is made.

The Relationship of Body Build, Age and Pulse Pressure to Auscultatory—Direct Blood Pressure Measurement

1. Body Build. The patients were divided into three weight groups (48 slim, 88 medium and 39 heavy) to study whether there is any
influence of body build on the accuracy of systolic auscultatory determinations. Figure 11 presents the full scatters and regressions of auscultatory pressure on direct pressure for the three weight groups.

It is interesting to note that the three regressions form a systematic array of lines intersecting at essentially the same value of approximately 150 mm. Hg direct systolic pressure. Variation in blood pressure is very wide for both the heavy and medium build patients, and relatively restricted only for the thin persons. But the average divergence of auscultatory reading from direct determination is more variable for the thin than for the heavy, ranging from 0 to 45 mm. Hg for the former and 20 to 40 mm. Hg for the latter.

2. Age. The results of regrouping to study this relationship are given in figure 12. Since weight tends to increase with age, it is not surprising that there is some similarity between figures 11 and 12. Unfortunately our data are too scant to allow of age analysis within weight groups.

It is evident that the two older age groups could well be combined to present a sharper contrast with the younger group. Since the regression line of the young age group slopes rapidly away from the line of equivalence, one is challenged by the implication that serious errors exist in determining auscultatory pressures of young hypertensive patients.

3. Pulse Pressure. Auscultatory systolic pressure regression lines were computed to determine the influence of pulse pressure upon their slope (fig. 13). For this purpose the data were divided into two groups on the basis of the direct intra-arterial pulse pressures; the first group consisted of 76 observations in which the pulse pressures ranged from 14 to 49 mm. Hg, while the second consisted of 104 observations where the pulse pressure ranged from 50 to 151 mm. Hg.

The regression line of the low pulse pressure group slopes away from the line of equivalence more rapidly than the line of the high pulse pressure group. The suggestion is that, on the average, errors in auscultatory systolic readings are different for persons of low pulse pressure than for those with high pulse pressure.

Discussion

Accuracy of the Direct Recording System. Attention should be drawn to the importance of the fluid filled system used to conduct dynamic pressure changes to the diaphragm of the transducer. The frequency response characteristics of both the transducer and the recorder have been shown to be more than adequate for recording pressure pulse waves.9 The limiting factor of all such systems, then, is the needle or catheter and its connections to the pressure transducer. This is particularly true where accurate reproduction of the detailed components of a pressure pulse wave

![Fig. 12. Age as a factor in the correlation of indirect and direct systolic blood pressure readings.](http://circ.ahajournals.org/)

![Fig. 13. Effect of pulse pressure on the auscultatory regression lines (all samples).](http://circ.ahajournals.org/)
are desired. Even in this instance expert observers do not agree on the over-all frequency response required. Wood reports no significant differences in recorded pressure levels when measured by different manometer systems with uniform response out to 6 cycles per second and above.

In this particular study we have been concerned with the systolic and diastolic levels rather than the actual configuration of the pressure pulse waves. The system was underdamped at the higher frequencies since it produced a 100 per cent response flat to 17.5 cycles per second followed by overshoot as the frequency increased. To determine the accuracy of this recording system, a comparative test was carried out. A second recording system which produced a 100 per cent response flat to only 7.5 cycles per second (fig. 2) was arranged by using a 22.5 cm. length of small bore (0.5 mm. inside diameter) polyvinyl catheter. This catheter was threaded into the brachial artery through an 18 gage needle. A 15 gage needle was inserted beside it. The orifices of both catheter and needle were at the same level within the artery. Simultaneous recordings were made and analyzed. Figure 14 illustrates the findings. No appreciable difference exists in the pressure levels recorded by the two systems. The only noticeable alteration produced by the catheter was a phase lag of 0.03 second.

A second factor which conceivably could account for differences in direct and indirect pressure measurements was considered. The indirect methods determine the lateral pressure against the wall of the artery, whereas the direct method used here determined the end-on thrust of pressure against the diaphragm of the transducer. In the latter instance higher readings might result from the additive effect of kinetic energy imparted to the stagnant fluid column of the recording system. To determine the error introduced by measuring an end-on systolic pressure, a second comparative experiment was carried out. A simultaneous recording of end-on and end-away pressures was obtained by introducing two 15 gage needles in opposite directions into the brachial artery. The results are shown in figure 15. It will be noted that no appreciable difference exists between these two recordings.

Oscillometric Method. In observing oscillometric systolic pressures it is conceivable that the values obtained may be higher than the intra-arterial pressures. This may be explained by the pulsating column of blood proximal to the inflated cuff striking its upper edge and producing an oscillation of the mercury column. This condition was most apt to occur when measuring the systolic pressure of children with a small sized cuff.

Auscultatory Method. Contrary to the find-
ings of others\(^3\) the indirect auscultatory and palpatory systolic observations never exceeded the simultaneous direct pressure readings in our observations.

Although the mechanisms effecting the Korotkoff sounds are not wholly understood, the conclusions of Erlanger\(^4\) concerning a preanacrotic phenomenon seem tenable. He found that at a compression pressure just below the proximal endarterial pressure a small increment of blood is forced through the flattened segment of artery. This blood is insufficient in amount to distend the compressed segment and the segment remains flattened until the compression pressure is reduced further. The pulse then succeeds in penetrating the entire length of the segment and a \textit{diastolic residuum} results. Not until this diastolic residuum is formed is it possible for the preanacrotic phenomenon (fig. 16) to occur with its concomitant sounds of Korotkoff.

In one phase of our study endarterial and auscultatory readings were recorded simultaneously from the same arm and distal to a compression cuff (fig. 17). The procedure was as follows. The cuff was inflated rapidly to a level well above the endarterial systolic pressure, maintained there for several seconds and then slowly deflated. Prior to deflation the endarterial pressure level fell toward the equilibrium pressure of 20 mm. Hg. During deflation of the cuff a slow rise in the level of the direct tracing developed, followed by the appearance of small pressure waves. Shortly thereafter, sounds of Korotkoff could be obtained. It was noted that the initial slow rise in the endarterial pressure level occurred at a compression pressure approximately equal to the previously determined endarterial systolic pressure. Some workers\(^5,\,6\) have published similar tracings wherein it was demonstrated that the first small pressure waves distal to the compressing cuff could be synchronous with the first auscultatory sound.

We assume from these studies that these small pressure waves represent increments of blood penetrating the artery under the cuff during systole at a compression pressure which completely flattens the compressed segment during diastole. When the compressing pressure becomes low enough for the endarterial pressure to maintain a diastolic residuum, the preanacrotic phenomenon develops. And if this residuum develops with the first pulse wave to penetrate the cuff, the auscultatory and direct readings can be equal.

We are thus led to believe that, using the proper size of cuff and slow deflation, the
auscultatory method for measurement of systolic blood pressure can be of varying degrees less than (or equal to) the true direct systolic pressure reading, but can never exceed this direct reading.

Roberts and associates suggest that, as an index of diastolic pressure, the muffling of Korotkoff sounds is more accurate than the disappearance of the sounds. The frequency with which our diastolic readings grossly underestimate the intra-arterial pressure seems to support this view. We recorded levels according to the disappearance of sounds as recommended by Bordley and his colleagues.

Wave Summation. According to Wiggers a centripetal rebound wave of pressure summates upon the primary centrifugal systolic wave resulting in the peak systolic level. That the magnitude of the summation wave is a function of peripheral resistance has been demonstrated in a circulation model.

Direct tracings were recorded in which the peripheral resistance was increased by occlusion of the brachial artery distal to the needle (fig. 18). Invariably this increase in peripheral resistance resulted in an elevation of the direct systolic pressure of 20 to 30 mm. Hg. It is of interest to note that the values of auscultatory systolic pressures did not vary under the two conditions. From this observation one might assume that the difference between direct systolic and auscultatory systolic pressures could be the result of failure of the auscultatory method to register the summation waves. In turn this might mean that the appearance of the first sound of Korotkoff depends primarily upon the pressure of the centrifugal wave. If this is true, then the auscultatory systolic level is most likely an index of the central aortic pressure rather than the peripheral pressure in the vessel at the site of measurement. In the light of the foregoing assumptions an increase in general peripheral resistance is primarily registered by direct recording methods, whereas the indirect auscultatory observations are affected only secondarily by the increased work load on the heart resulting in an increased systolic pressure thrust.

Such a relationship might account for some of the discrepancies between direct and auscultatory readings encountered in this study. We make particular reference to our findings in the young hypertensive patients. In this group, usually, the arteriolar bed maintains a high degree of tonus. It seems reasonable to assume that such a state would augment the summation effect of the reflected wave upon the central wave resulting in a peripheral intra-arterial pressure higher than that obtained with the auscultatory method.

The findings in the young hypertensive group pose some interesting possibilities. If the auscultatory method is frequently in error in a young patient with moderate systolic elevation, an intra-arterial measurement may well be an indicated procedure in the investigation of such an individual. Early detection of some cases destined to develop a severe hypertension syndrome may be facilitated. It is also possible that information gained from such direct measurements might be of value in estimating the degree of hypertension, as a guide in the evaluation of therapy and in the formulation of a prognosis.

Conclusions

1. Direct and indirect determinations of blood pressure are compared in 70 patients in the immediate postoperative state, and the results of statistical analysis of these data are presented.

2. These studies demonstrate a frequent discrepancy between the direct and indirect readings.
3. The greatest discrepancy is found in the young hypertensive group. The possible clinical value of this finding is considered.

4. The decreasing order of accuracy for indirect methods of measurement is shown to be: oscillometric, auscultatory and palpatory.

5. The drift of indirect readings is to fall increasingly below the direct measurement as blood pressure rises.

6. The usual practice of employing one indirect technic only is not subject to criticism if the observer regards such a pressure estimation as an index to the true intra-arterial pressure. Changes in blood pressure can be detected by such a method but no conclusion should be drawn concerning absolute values.

7. An attempt is made to explain some of the factors contributing to the variable error by which auscultatory readings underestimate the true intra-arterial pressure.

**Sumario Español**

1. Determinaciones de presión arterial directas e indirectas son comparadas en 70 pacientes en el estado postoperatorio inmediato, y los resultados de un análisis estadístico de estos datos se presentan.

2. Estos estudios demuestran una frecuente discrepancia entre las lecturas directas e indirectas.

3. La mayor discrepancia se encuentra en el grupo hipertenso joven. El posible valor clínico de este hallazgo se considera.

4. El orden descendente de precisión para los métodos indirectos de medir la presión ha mostrado ser; oscilométrico, auscultatorio y palpatorio.

5. El rumbo de las lecturas indirectas es el de caer progresivamente por debajo de las lecturas directas a medida que la presión arterial aumenta.

6. La práctica usual de emplear una técnica indirecta solamente no esta sujeta a la crítica si el observador considera tal estimado de la presión como un índice de la presión intra-arterial verdadera. Cambios en presión arterial se pueden determinar por este método pero una conclusión sobre los valores absolutos no se debe aceptar.

7. Un atentado se hace para explicar algunos de los factores contribuyentes al error variable por el cual lecturas auscultatorias indirectas resultan más bajas que la presión verdadera intra-arterial.

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