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# A STATISTICAL COMPARISON OF NORMAL BALLISTOCARDIOGRAMS RECORDED WITH A HIGH-FREQUENCY TABLE AND WITH VARIOUS INSTRUMENTS WHICH RECORD BODY MOTION DIRECTLY

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BALLISTOCARDIOGRAMS obtained with any one of several devices originally developed by Dock and Taubman[1] which record the motion of a bar placed across the shins qualitatively resemble tracings obtained with a high-frequency table of the type introduced by Starr.[2] In order to estimate the degree of resemblance quantitatively, we obtained measurements of certain wave segments of tracings of normal subjects recorded simultaneously with a high-frequency table and with each of three different types of Dock instruments. From this study we hoped to obtain specific information bearing on certain theoretical and practical aspects of recording body motion with these devices.

### MATERIALS AND METHODS

The high-frequency critically damped table used in this study has been completely described.[3] It utilizes a Statham strain gauge, the output of which is amplified by a Brush amplifier. The displacement tracing is recorded on one channel of a Brush recorder. The outputs of the three instruments utilizing direct body recording were amplified by a Sanborn Viso-Cardiette and recorded

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on the second channel of the Brush recorder. These instruments consisted of: (1) a photoelectric ballistocardiograph[4] manufactured by the Sanborn Company. When this instrument is in use, the light source, mounted on the crosspiece, moves with reference to a stationary photoelectric cell. It produces a displacement tracing. The built-in filter was used in all tracings to minimize undulations of the base line with respiration. (2) A piezoelectric ballistocardiograph[5] manufactured by the John Peck Laboratories. It measures body movements in terms of displacement. (3) An electromagnetic ballistocardiograph manufactured by J. Everett Hill. If unfiltered, such an instrument produces a velocity tracing. However, the instrument used in this study contains a filter in the form of a 20 microfarad capacitor which almost completely integrates the velocity trace into one of displacement type.[6] Comparison of simultaneous tracings obtained with this filtered instrument and with the bed showed homologous wave peaks to be in phase.

The table was standardized so that a 280 gram weight produced a displacement equivalent to a one centimeter deflection on the record. The amplifier (Viso-Cardiette) was adjusted so that the tracing obtained with one of the Dock type instruments showed an amplitude approximately equivalent to that of the tracing obtained with the table. This adjustment could not be made exactly, but the statistical studies were carried out in such a way as to eliminate variations in standardization as a source of error.

The statistical results to be reported are based on two groups of data:

A. Simultaneous tracings on ten normal individuals, four men and six women, aged 23 to 38.

B. Ten consecutive simultaneous tracings on one normal man.

In both A and B three sets of simultaneous tracings were obtained with the following: (1) table and photoelectric instrument; (2) table and piezoelectric instrument; (3) table and electromagnetic instrument. Figure 1 illustrates typical tracings obtained on a 27-year-old man.

In Part B, the direct-recording device was removed and replaced between each of the ten consecutive recordings, the sensitivity of the Viso-Cardiette remaining constant.

In Part A, the IJ and JK segments of 20 consecutive systoles were measured to the closest 0.5 mm. on each of the simultaneous records. The IJ and JK segments were chosen because they represent the prominent upstroke and prominent downstroke, respectively, of the normal ballistocardiogram. The ratio, JK:IJ, was also calculated for each of the complexes measured.

In Part B, the IJ and JK segments produced by twenty to twenty-five consecutive systoles were measured to the closest 0.5 mm. on each of the separate records. The measurements were started and stopped at the same point in the respiratory cycle as judged by the waxing and waning of the amplitude of the complexes. The same number of complexes was always measured in the two simultaneous tracings. The mean segment length for each individual record was determined. The mean IJ and JK segments were also expressed in the form of the mean JK:IJ ratio for each of the ten records. All measurements were made by the same individual.

Since all of the tracings obtained with the table were recorded simultaneously with the Dock type of instrument, it was obvious that the footboard of the table ordinarily utilized in routine ballistocardiography could not be used because it would damp the body motion picked up by direct recording. Therefore, all tracings obtained with the table were recorded without the footboard. This undoubtedly modifies the amplitude of waves recorded with the table. However, since this method of recording was constant for all tracings with the table, the basis for making comparative quantitative studies seemed sound. The maximum motion of the table is of the order of only 0.00015 inch.[3] Therefore, the ballistocardiographic table is, for practical purposes, as stable as any type of rigid table advocated for use with the direct-recording devices.

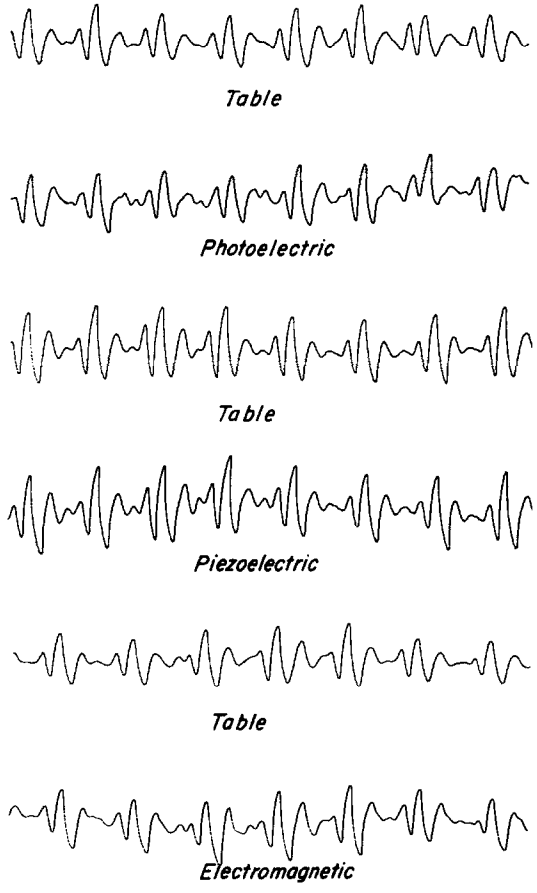


Fig. 1.—Normal man, aged 27. Typical comparative tracings obtained with a high-frequency ballistocardiographic table and with each of three types of instruments designed to record body motion directly. See text.

## STATISTICAL RESULTS

*Data From Part A.—*

1. *Correlation between the two general methods of recording*: Correlation coefficients were calculated between the segments or ratio of each of the Dock

type instruments and the corresponding segment or ratio of the table and tested for significance by means of Fisher's z transformation.[7] There was a high degree of correlation between the table and each of the direct-recording devices for both the IJ and the JK segments. All probability values were below the 0.001 level except in the case of the IJ segment of a single subject with the photoelectric instrument; this value was, however, below the 0.01 level.

In the case of the JK:IJ ratio, the individual correlations between the table and each of the direct-recording devices were not striking. Probabilities for such correlations exceeded 0.05 for four individuals with the photoelectric instrument, three individuals with the piezoelectric instrument, and three individuals with the electromagnetic instrument.

The correlations obtained for individual subjects were not averaged because significant heterogeneity of the coefficients ($P < 0.02$) was demonstrated* in all instances except three. These three, for which P ranged between 0.10 and 0.20, consisted of the JK segment and the JK:IJ ratio recorded with the photoelectric instrument and IJ segment recorded with the electromagnetic device.

2. *Differences in the degree of correlation between each of the three direct recording devices and the table*: Tests of significance of the difference between correlations of each of the pickups and the table were carried out by means of the z transformation to determine whether one correlation was significantly superior to another.

In the case of the IJ segment the piezoelectric instrument yielded a significantly better correlation than the photoelectric instrument in two individuals ($P < 0.01$, $< 0.02$). In one subject the piezoelectric device showed a significantly better correlation than the electromagnetic instrument ($P < 0.01$) and a correlation with the latter significantly exceeded that of the photoelectric pickup in one subject ($P < 0.01$).

For the JK segment, the piezoelectric instrument demonstrated a significantly better correlation than the photoelectric in one instance ($P < 0.02$); the electromagnetic instrument correlated significantly better than the photoelectric in one subject ($P < 0.05$); the electromagnetic instrument showed a significantly higher correlation than the piezoelectric in one subject ($P < 0.05$).

In the case of the JK:IJ ratio, the correlations obtained with the piezoelectric instrument significantly exceeded those obtained with the photoelectric in two subjects ($P < 0.01$, $< 0.02$), and a correlation of the electromagnetic device significantly exceeded that of the photoelectric on one occasion ($P < 0.01$).

Thus, in no instance did the photoelectric instrument give a significantly better correlation with the table for IJ and JK segments or the JK:IJ ratio than did the other two devices.

3. *Degree of constancy in normal subjects of the JK:IJ ratio*: The variance of the JK:IJ ratio obtained for the ten subjects with each of the instruments

*The chi-square test used to determine the probability that the several correlations were not drawn from the same correlation parameter is that described by Snedecor;[7] it may be represented by the equation:

$$\text{Chi square} = S\left\{(n-3)\,z^2\right\} - \bar{z}S\left\{(n-3)\,z\right\}$$

where the degree of freedom is one less than the number of correlations tested.

utilizing direct body recording was compared with the variance of this ratio for corresponding tracings obtained with the table. In all cases the variance of this ratio from subject to subject was less with the direct pickup than with the bed. However, the variance ratio[7] showed that none of these differences approached significance.

4. *Variation in amplitude of IJ and JK segments with respiration*: The variance of the amplitude of the IJ segments of each individual recorded with each Dock type instrument was compared with the variance of the amplitude of this segment recorded simultaneously with the table by means of a variance ratio. A similar test was carried out for the JK segment. In no subject did such variance ratios approach statistical significance indicating that the variation in amplitude of these segments with respiration could not be demonstrated to be significantly greater or smaller with the direct-recording device than with the table.

*Data From Part B.—*

*Reproducibility of consecutively recorded tracings with the instruments utilizing direct recording*: These studies were designed to give information concerning inaccuracies arising from inability to place the direct-recording device uniformly in the same position for repeated tracings. The variance of the segments and of the ratio for a given instrument was compared with the variance of the corresponding segment or ratio simultaneously recorded with the table. In all instances the variability of repeated tracings with the three devices was greater than the variability of those with the table. However, the variance of the piezoelectric instrument did not significantly exceed the variance of the table for either of the segments or the ratio. The variance of the electromagnetic instrument was significantly greater than the variance of the table for the JK segment ($P < 0.02$) but not for the IJ segment or the ratio. The variance of the photoelectric instrument was significantly larger than the variance of the table for both the IJ ($P < 0.02$) and the JK ($P < 0.002$) segments but not for the JK:IJ ratio.

The variances of the mean segments and ratio with the various direct-recording instruments were also compared with each other. The variation of these measurements recorded with the table is assumed to depend solely upon the variation of the patient's heart action from record to record and thus to provide a control for the correction of that particular portion of the total variation obtained with each instrument. This correction was obtained by dividing the mean segment or ratio obtained with the direct-recording device by the corresponding mean segment or ratio obtained with the table for each of the 10 repeated records. The resultant 10 quotients were utilized for the determinations of the variances used in the variance ratios. There was no significant difference in the variances of the IJ segment or the JK:IJ ratio of the three direct-recording instruments when subjected to variance analysis by the technique described. The probability falls just below the 0.05 point when the greater variance of JK obtained with the photoelectric instrument was compared with the variance of this segment recorded with the electromagnetic device.

## DISCUSSION

The excellent correlation between corresponding IJ and JK segments obtained with each of the direct-recording instruments and with the table suggests that these simple devices record the individual headward and footward movements of the body with an accuracy comparable to that of a stable, well-constructed, high-frequency table. The relatively poor correlations obtained for the JK:IJ ratio, however, indicate that significant differences may exist between the contours of ballistic complexes recorded with the two types of instrumentation, suggesting that qualitative impressions gained from inspection of the two types of records may not always closely coincide.

It is probable that any of the three pickups might be used as advantageously as a ballistocardiographic table in short term experiments involving comparison of individual segment length before and after the introduction of a factor, e.g., a drug to modify cardiovascular performance. It should be emphasized, however, that this statement, based on the correlations, would not hold true when in a given experiment it would be necessary to remove and replace the device between recordings. The varying amplitudes of deflections obtained with repetitive recordings at the same amplification sensitivity also indicate that none of the three devices tested may be used to quantitate initial cardiac force in a manner similar to the method used with a ballistocardiographic table.[8]

If it is possible to devise an instrument which may be accurately and independently standardized and which shows a relatively constant response with variations of placement greater than those encountered in routine use,* it is quite possible that recording of body motion directly may be at least as satisfactory as recording of motion imparted by the body to a table. As the result of these studies it is our feeling that the presence or absence of restraint, restoring force and damping inherent in a table does not significantly modify the individual segments of the ballistocardiogram. If such factors were of great importance, one would expect, in their absence, considerable "overshooting" in the larger segments of a record as compared with the smaller segments. Either such "overshooting" is not present to any significant degree or, if present, it is proportional to the force involved in the formation of the segment. If disproportionate "overshooting" occurred with direct recording it is unlikely that simultaneous segments recorded directly and with the table would show the excellent degree of correlation found in this study. Moreover, it seems unlikely that significant proportionate "overshooting" occurs. If this were present one would expect a significantly greater respiratory variation in IJ and JK segment size with the direct-recording devices than with the table. This was not demonstrated in any subject with any of the three instruments tested.

The statistical results suggest that the three instruments used in this study for direct recording may yield tracings for which normal wave ratio standards could be determined. These ratios would apparently not be unduly influenced by differences in placement of the instrument. It is also possible that standards for a high-frequency table which have been determined for the respiratory varia-

*The calibrated bar-magnet velocity meter recently described by Smith[9] may meet these criteria.

tion of the IJ segment[10] might be applicable to tracings recorded with any of these three devices. To test these possibilities would require careful evaluation with a larger group of individuals than that reported here and would also require study of a group of patients with cardiac abnormalities.

## SUMMARY

Normal ballistocardiograms obtained with three types of instruments which record the movement of a cross-bar placed across the shins were compared with tracings simultaneously recorded with a high-frequency table. Statistical studies yielded the following results:

1. A high degree of correlation exists between the IJ and JK segments recorded with the table and the corresponding segments simultaneously recorded with each of the instruments studied.

2. In the case of the JK:IJ ratio, significant correlations between tracings obtained with the table and with each of the direct-recording instruments were not always demonstrated in individual subjects.

3. The variation between the means of the JK:IJ ratio recorded in each of the ten subjects with the three instruments was not significantly different from the variation of the means of corresponding ratios recorded simultaneously with the table.

4. A significant difference could not be demonstrated in the respiration variations of the IJ and JK segments recorded with each of the three direct-recording devices and the respiratory variations recorded with the table.

5. The reproducibility of repeated tracings obtained with the instruments which record body motion directly was in general inferior to the reproducibility of tracings obtained with the table. This finding appeared to be particularly significant in the case of the photoelectric instrument.

The implications of these results, relating to certain theoretical and practical aspects of recording body motion with these devices, are discussed.

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