CARDIOMETRIC STUDIES ON CHILDREN[1]

II. THE DURATION OF THE COMPONENT PARTS OF THE CARDIAC SOUND CYCLE

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Introduction

THE main characteristics of the heart sound patterns noted on the stethographic records of almost 1,500 children were described in the first paper of this series [Boone and Ciocco (1)]. The description given represents an attempt to synthesize the characteristics of pitch, duration, intensity, and quality, which together produce the pattern of the recorded sound waves. In addition to this synthetic view of the stethogram, and for further analysis of the records, each of these four characteristics should be examined in detail. The need for this additional analysis is evident since the auscultatory evaluation of cardiac function is largely founded on the association between pathological alterations of the heart and circulatory system, and variations in pitch, duration, intensity, and quality of the heart sounds as auditorily perceived. Of these characteristics, *duration* may be determined with the greatest relative ease on the stethogram. From the standpoint of physiology and pathology the durations of the cardiac cycle and its sound components have been considered valuable indications of the cardiac function by a number of investigators [*cf.* Lombard and Cope, 1926 (10)]. In the first place, the duration of the total cardiac cycle is an expression of heart rate and rhythm. In this respect, the relative lengths of the systolic and diastolic components in each cycle also have particular significance. In view of these facts, and as a further step toward a complete analysis of the stethogram according to the objectives outlined in the preceding paper, measurements on the duration of the cardiac cycle and its principal components have

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been made from the stethographic records of 1,465 children. The resulting biometric constants of these measurements are presented in this paper.

Material and Technique of Examination

The material for the first paper consisted of stethographic records on 1,482 white children attending one elementary and one junior high school in Hagerstown, Maryland. The records for seventeen children could not be used for the purposes of measurement primarily because the base lines of the graph were too rough and consequently the origin or termination of the sounds could not be clearly identified. The results presented in this paper are based, therefore, on 703 boys and 762 girls, a total of 1,465 children. The mean age of both boys and girls was 11.3 years. The children examined were in no way selected with regard to the presence or absence of heart disease; this sample, however, is not entirely representative of the general population of school children either from the standpoints of socio-economic status or of age. As discussed in the first paper, the sample contains a higher proportion of older children and of children from less well-to-do families than is expected in the general school population.

The technique followed in obtaining the stethograms has been described in detail in the first paper to which the reader is referred. Here it is pertinent to note the following main elements of the procedure:

1. The examination was conducted in a sound-insulated booth.
2. All the children were examined while in a semi-reclining position.
3. Records were made of the heart sounds at the mitral, pulmonic, and aortic areas. With reference to this item, only the tracings from the mitral area have been measured because the onsets and terminations of the sound waves appear more definite on the records taken at this area.

Method of Measuring Duration of Cardiac Cycle and Its Components

As described in the first paper and illustrated in Figure 1, the

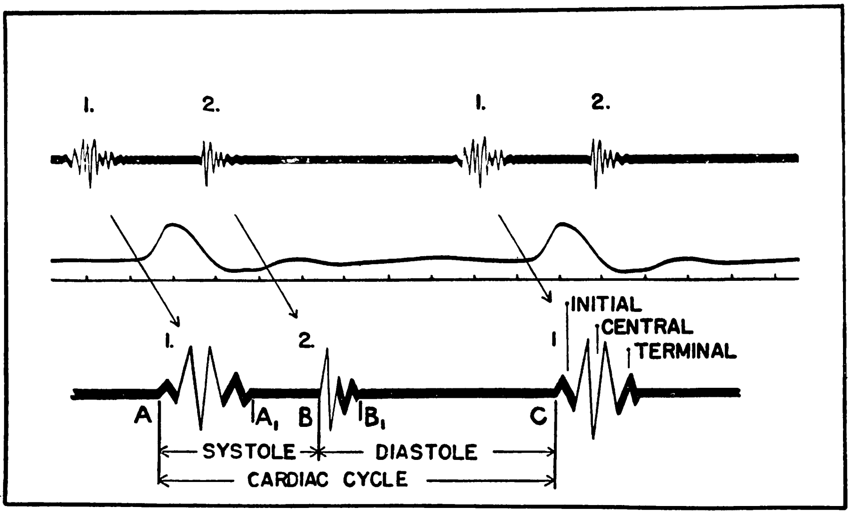

Fig. 1. Stethographic record of the basic pattern of the cardiac cycle and of its principal elements. Above is an actual tracing of two consecutive cycles and below a diagrammatic representation of the basic stethographic pattern of the cardiac cycle (AC), systole (AB), and diastole (BC). The first sound (AA_1) is indicated by 1, and the second sound (BB_1) by 2.

basic elements of the cardiac cycle are represented on the stethograph as follows:

1. A series of waves that corresponds to the first or systolic sound (AA_1, Figure 1),
2. A segment of smooth base line—the systolic interval of silence (A_1B, Figure 1),
3. A second series of waves that corresponds to the diastolic sound (BB_1, Figure 1), and
4. Another segment of smooth base line representing the diastolic interval or period of relative silence that terminates the cycle (B_1C, Figure 1).

The physiological significance of this major subdivision of the cardiac cycle is well recognized. As Lewis summarizes (9):

> The beginnings of the first and second heart sounds are used to signal the beginning and ending of the ventricular systole, respectively. When clear and sensitive records are obtained, these signals are amongst the most accurate which we possess for determining the times at which systole begins and ends; for, if they do not mark the closure, they mark

the immediately subsequent tension of the auriculo-ventricular or of the semi-lunar valves.

For purposes of the present paper, the duration of one cardiac cycle was defined as the interval of time between the initial wave of one systolic sound and the initial wave of the next systolic sound. In order to measure this duration it is first necessary to identify the systolic sound on the stethogram, and then to determine its initial deflection. The waves that constitute the systolic or first heart sound are in general distinguishable by their frequency and configuration from those of the diastolic or second sound. This is particularly true for stethographic records taken at the mitral area. Usually, the first sound is composed of three groups of waves, thus the first sound is introduced by waves of low frequency and low amplitude. The waves of the next group are of higher frequency and higher amplitude. The waves of the third group are of low amplitude but have about the same frequency as those of the second group. The diastolic or second sound is composed of two groups of waves both having approximately the same frequency but distinguishable by a difference in amplitude. It is not possible to rely exclusively on the configuration of the waves to distinguish the first and second sounds. A sure identification of these sounds can be made when in addition to the stethogram a simultaneous electrocardiogram or arteriogram is taken.

When an electrocardiogram is recorded simultaneously with the stethogram, the onset of the first heart sound takes place during the QRS complex, usually close to the peak of the R wave; the beginning of the second sound is found near the termination of the T wave. When a radial arteriogram is recorded simultaneously with the stethogram, the pulse wave is found to occur after the onset of the systolic sound and just prior to the diastolic sound. For the present study the left radial arteriogram was taken and the pulse wave was therefore utilized to identify the respective sound waves.

The onset of the waves representing a heart sound is taken to be that point where the initial wave of the group first deviates from the smooth base line. Occasionally, when some roughness of the base line is present, the onset of the initial wave may at first not be clearly evident. When some doubt arose, the use of a straight edge of opaque material was employed. The straight edge was placed parallel to and covering the base line, then moved slowly downwards until the small peaks of the roughened base line began to appear. By this procedure, the onset of the initial wave can be discerned as a definite break in the base line since the width of the initial wave is usually definitely greater than those of extraneous waves disturbing the base line. The same technique was of course employed in locating the termination of the sounds.[2]

The stethograms for this study were made on a bromide film moving at a uniform speed of 100 mm. per second. Linear measurements on the stethogram, taken in millimeters, can be converted into seconds when divided by 100. On the stethogram the measurements were taken to the last completed one-half mm. which means to the last completed .005 second. A pair of needle-pointed draftsman's dividers, a high-grade one-half millimeter rule, and a mounted reading glass lens for magnification were used for measuring. The points of the dividers were placed at the two extremes of the interval to be measured. The resulting spread of the dividers was then measured on the rule.

Although six to eight cycles were recorded at each precordial area, only one completed cycle on each individual stethogram taken at the mitral area was measured. The central or one of the two central cycles of the series was chosen for measurement.

The specific items that were measured on the cycle chosen, were

[2] If extra-vibrations follow the systolic or diastolic sound and there is an interval of smooth base line between the termination of the sound and the onset of the extra-vibration, no difficulty will be encountered in locating the ending of the sound. When, however, the extra-vibrations are continuous with the sound, then it will be observed that near the point where the termination of the sound would be expected the waves possess the least amplitude. The point of minimum deflection is taken as the termination of the sound.

the lengths of the total cardiac cycle, the lengths of systole and diastole, and the lengths of the first and second sounds.

Duration of the Cardiac Cycle and of Its Principal Components

The mean, median, standard deviation, and coefficient of variation of the duration of the cardiac cycle, systole, diastole, first and second sounds, respectively, computed from the measurements made on the stethographic records of the 1,465 children are presented in Table 1.

From this table the following facts appear noteworthy:

1. The mean duration of the cardiac cycle equals .722 seconds. This represents an average heart rate for this sample of children of 83 beats per minute.

2. The duration of diastole as measured here is one and one-half times as long as that of systole. The duration of the first sound is about one and one-half times that of the second.

3. The values of the median approximate very closely to those of the mean indicating that the frequency distributions of these durations are on the whole symmetrical.

4. The variability of the distributions, when measured by the standard deviation, is highest for the cardiac cycle. Of the components of the cardiac cycle discussed here, the largest standard deviation is found for the duration of diastole and the smallest for the duration of the second sound. However, the relative variability (coefficient of variation) is

Table 1. Biometric constants of the duration of the cardiac cycle, systole, diastole, first and second sounds measured on the stethograms of 1,465 children.

Sound Cycle Unit	Constants of the Frequency Distribution of Duration			
	Mean	Median	Standard Deviation	Coefficient of Variation
Total Cycle	.722 ± .0025	.721 ± .0031	.140 ± .0017	19.39 ± .25
Systole	.289 ± .0005	.291 ± .0006	.027 ± .0003	9.34 ± .12
Diastole	.433 ± .0020	.428 ± .0025	.113 ± .0014	26.10 ± .35
First Sound	.108 ± .0005	.105 ± .0006	.026 ± .0003	24.07 ± .31
Second Sound	.070 ± .0003	.069 ± .0004	.018 ± .0002	25.71 ± .33

least for the duration of the systole and highest for the duration of the diastole. It is also to be noted that the coefficients of variation obtained for the duration of the first sound and the second sound differ very little from the coefficient computed from the frequency distribution of duration of diastole.

The findings outlined in the last item deserve particular emphasis. In this sample, the differences among children relative to systole are much less marked than the differences relative to diastole or to the first and second sounds. Furthermore, since the first sound is a constituent of systole, from these observations it is to be inferred that the duration of the systolic interval (the interval between the end of the first sound and the onset of the second) is actually the most stable of the components of the cardiac cycle.

Following the first successful attempt made in 1892 by Hürthle [*cf.* Hürthle, 1895 (6)] to obtain permanent and objective records of heart sounds, the measurement of the duration of the cardiac cycle and that of its major components has been repeatedly the object of many investigations conducted by physiologists. The results obtained by the majority have been well summarized by Tigerstedt, [1921 (15)], Schütz [1933 (13)], and Oriás and Braun-Menéndez [1939 (11)]. A comparative study of the reported measurements reveals striking differences among the several series. In part this is probably due to differences in methods and techniques of recording the sound vibrations since at least ten, if not more, types of instruments have been constructed and utilized for the purpose. In part, the variation in the reported average measurements is due to the small number of observations on which they are based. Usually the data reported derive from measurements made on records of very few subjects, frequently only one or two persons. The duration of the cardiac cycle is found to vary from .628 seconds as reported by Ohm [*cf.* Tigerstedt, 1921 (15)] to 1.034 observed by Gerhartz [1910 (5)]. The duration of systole has been reported as low as .208 seconds also by Ohm and as high as .40 seconds by

Einthoven [1907 (3)]. The reported durations of the first and of the second sounds also vary considerably. Roos [1908 (12)] gave the duration of the first sound equal to .041 seconds, while the figure given by Einthoven [1907 (3)] is .176 seconds; the shortest second sound, equal to .024, was observed in the series of observations made by Gerhartz [1910 (5)] while the longest, equal to .104, by Einthoven [1907 (3)]. In view of the fact that these are observations based not on a series of records but on one or two individuals, and considering the value of the standard deviations in Table 1, the range reported could be due to chance. However, the method of recording and other factors such as age and sex must obviously play an important part in the duration of these cardiac events. This is seen when the data of Table 1 are compared with those of Table 2 which contains the results obtained by those investigators who measured the records of ten or more individuals. The comparison of the means of Table 1 with the data of Table 2 brings out the fact that the results obtained in the investigation reported here are somewhat lower than those reported by others, particularly by Lombard and Cope who have utilized the most extensive information to date.

The significance of differences in the examination is strikingly shown in Lombard and Cope's figures that indicate the effects of the standing, sitting, and recumbent positions on the duration of cardiac cycle, systole, and diastole. The duration of these cardiac phenomena is least when the subject is standing and greatest when the subject is recumbent. In addition, these same data point to a definite sex difference in the duration of the cardiac cycle, systole, and diastole, these all being longer in the males than in the females. It is to be noted also that with the exception of Bridgman's figures (2), the data concern adults. For systole, diastole, and cardiac cycle Bridgman's averages resulting from observations made on sixteen boys, 12-15 years old, are lower than Lombard and Cope's and Eyster's (4) but very close to those reported in the present paper.

Investigator	Total Cycle	Systole	Diastole	First Sound	Second Sound	Number of Observations
Eyster (1912)	.854	.307	.557	.128	.101	16 Adults, Average of 50 Cycles
Kapff (1914)	....	....	....	.08	.06	11 Adults
Bridgman (1915)	.731	.314	.417	.145	.089	16 Boys, Average of 10 Cycles
Kanner (1921)	....	....	....	.16	.10	10 Adults
Lombard and Cope (1926)	.7324	.2341	.4983	....	....	252 Tests, 176 Men, Average 15 Cycles Standing
	.8156	.2677	.5479	....	....	94 Tests, 91 Men, Average 15 Cycles Sitting
	.9453	.3003	.6450	....	....	64 Tests, 64 Men, Average 15 Cycles Recumbent
	.6932	.2467	.4485	....	....	72 Tests, 68 Women, Average 15 Cycles Standing
	.7477	.2693	.4784	....	....	58 Tests, 58 Women, Average 15 Cycles Sitting
	.8057	.3003	.5054	....	....	58 Tests, 58 Women, Average 15 Cycles Recumbent

Table 2. Mean duration of cardiac cycle, systole, diastole, first and second sounds reported by several investigators.

From these comparisons it appears that the duration of the cardiac phenomena discussed here are affected by a number of physiological factors unconnected with health or disease. Consequently before full use can be made of such data for purposes of detecting the cardiac status of children or of adults it is necessary to investigate further what factors other than pathological affect the durations of these cardiac phenomena. Even though the technique of examination relative to position, respiration, etc., of the subject is standardized as has been done in the present investigation, it still remains to arrive at a measure of the influence of other conditions, particularly of the age and sex, on the duration of the cardiac cycle and that of its components. These will be considered in the following sections.

Duration of Cardiac Cycle and of Its Major Components in Boys and Girls

Between males and females definite differences are manifest in relation to the mortality and probably to the morbidity from diseases of the heart and circulatory system. At all ages, the males exhibit a higher mortality from cardiovascular diseases except from chronic endocarditis which in certain age periods is more prevalent in the females. Differences between the sexes are observed also relative to the stethographic pattern of the heart sounds. As reported in the previous paper, variations from the basic pattern are found more often in boys than in girls. The one exception is the presence of a third heart sound noted more frequently in the girls.

Besides the differences mentioned it is a well-established fact that the pulse rate in the females is more rapid than in the males. It is to be expected, therefore, that the duration of the cardiac cycle, because of its reciprocal relation to rate, should be longer in the boys than in the girls of this sample. These expectations are borne

Table 3. Biometric constants of the duration of the cardiac cycle, systole, diastole, first and second sounds measured on the stethograms of 703 boys and 762 girls.

Sound Cycle Unit		Constants of the Frequency Distribution of Duration			
		Mean	Median	Standard Deviation	Coefficient of Variation
Total Cycle	Boys	.746 ± .0034	.748 ± .0043	.135 ± .0024	18.10 ± .36
	Girls	.699 ± .0031	.697 ± .0039	.127 ± .0022	18.17 ± .33
Systole	Boys	.292 ± .0007	.293 ± .0008	.026 ± .0005	8.90 ± .16
	Girls	.287 ± .0007	.288 ± .0009	.028 ± .0005	9.76 ± .17
Diastole	Boys	.454 ± .0030	.456 ± .0038	.117 ± .0021	25.77 ± .49
	Girls	.412 ± .0026	.405 ± .0033	.107 ± .0019	25.97 ± .48
First Sound	Boys	.112 ± .0007	.108 ± .0009	.027 ± .0005	24.16 ± .46
	Girls	.105 ± .0006	.102 ± .0007	.024 ± .0004	22.86 ± .41
Second Sound	Boys	.070 ± .0005	.069 ± .0006	.018 ± .0003	25.71 ± .49
	Girls	.069 ± .0004	.068 ± .0006	.018 ± .0003	26.09 ± .47

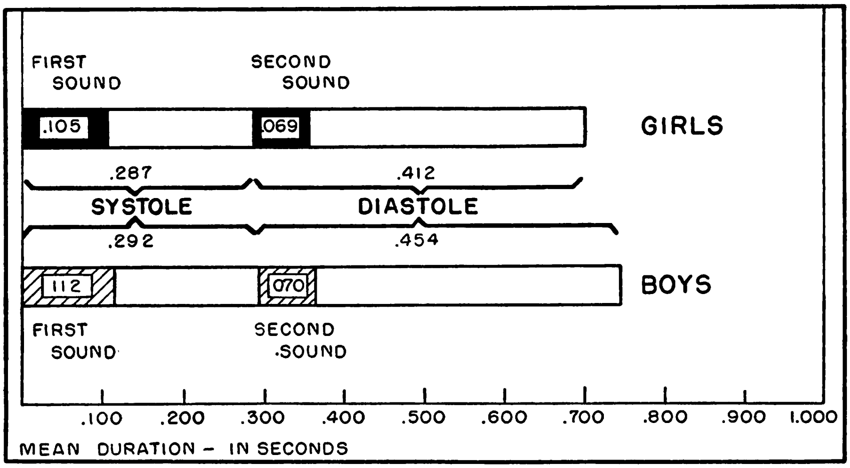

Fig. 2. Mean durations (in seconds) of the cardiac cycle, systole, diastole, first and second sounds obtained from measurements taken on the stethograms of 703 boys and 762 girls.

out by the observations presented in Table 3 and illustrated in Figure 2.

From both the figure and table it is apparent that the mean duration of the cardiac cycle and of each of the components studied is longer in the males than in the females. The mean duration of the cardiac cycle of the boys is .047 seconds longer than that of the girls. In terms of heart rate, this difference amounts to 5 beats per minute. The greater duration of the cardiac cycle in the boys being over ten times its probable error is statistically significant. This is likewise true for the other components of the cardiac cycle, the only exceptions being the duration of the second sound.

With regard to the median durations, the differences between the sexes are of the same order and directions as those of the arithmetic means.

The absolute variability of the distributions for the two sexes when measured by the standard deviations is not consistently greater or less for either sex, although the boys are more variable with regard to duration of cardiac cycle, diastole, and first sound. However, because the arithmetic means are all smaller in the case of the girls, the latter exhibit for almost all the measurements an insignificantly higher relative variability (coefficient of variation).

Lombard and Cope (*cf.* Table 2) have reported sex differences for adults in the mean duration of the total cardiac cycle, systole, and diastole. These investigators also indicate that systole, relative to duration of cardiac cycle, is longer in women than in men. The data of the present study indicate the same. It will be noted that while for the boys the mean duration of the cardiac cycle is 6 per cent longer, the mean duration of systole is only 2 per cent greater. In addition, the mean duration of the first sound is found to be slightly over 6 per cent longer in the boys while that of the second sound is only 1 per cent longer in the boys than in the girls.

Summing up, then, these data show definitely that the duration of the cardiac cycle and its principal components is greater in the boys than in the girls. However it can be inferred that in terms of duration of the cardiac cycle, the duration of systole and of the second sound is somewhat greater in the girls.

Duration of the Cardiac Cycle and of Its Principal Components in Relation to Age

The sex differences reported in the preceding section are present at each year of age in this sample of children. This is evident from the data on the mean duration of the cardiac cycle and of its components illustrated in Figure 3.

In Figure 3 it will be noticed that at each year of age, excepting 11 years, the duration of the cardiac cycle of the boys is longer than that of the girls. At 11 years of age, the mean cardiac cycle of the girls is .003 seconds longer than that of the boys. At this same age, the girls also exhibit a longer mean diastole by .005 seconds but at all other ages the diastole of the boys is longer on the average. The values for the mean duration of systole, first and second sounds are also higher in the boys in the majority of cases. Thus, it seems that the differences between the boys and girls are, on the whole, consistent at all ages, from childhood through adulthood. What signifi-

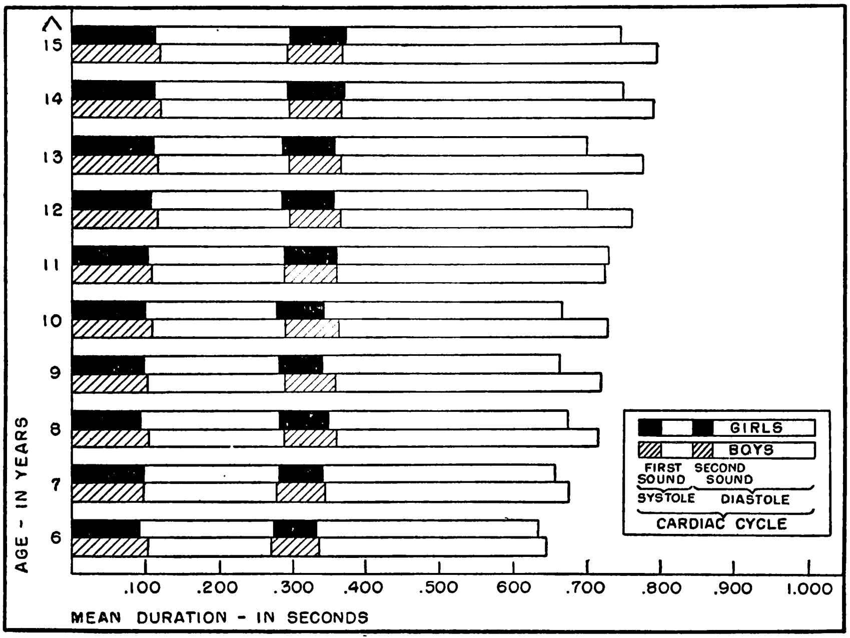

Fig. 3. Mean durations (in seconds) of the cardiac cycle, systole, diastole, first and second sounds obtained from measurements taken on the stethograms of 703 boys and 762 girls of stated age.

cance these differences may have relative to the sex differences in mortality and morbidity from heart diseases is not known. Yet these and other findings regarding the diverse pattern of behavior of the two sexes with respect to disease point to the direction which will lead to an understanding of some of the elements responsible for the breakdown of the cardiovascular system.

The data presented in Figure 3 also indicate that with advancing age, the expected increase in the duration of the cardiac cycle results from an increase in the duration of all the components discussed here. This is more clearly seen in Figure 4 in which the mean values at each age for both girls and boys together have been plotted on an arith-log grid. From Figure 4 it appears that between the ages of 6 and 15 years the mean duration of each of the cardiac events measured here increases annually at a rate which is almost uniform from year to year.

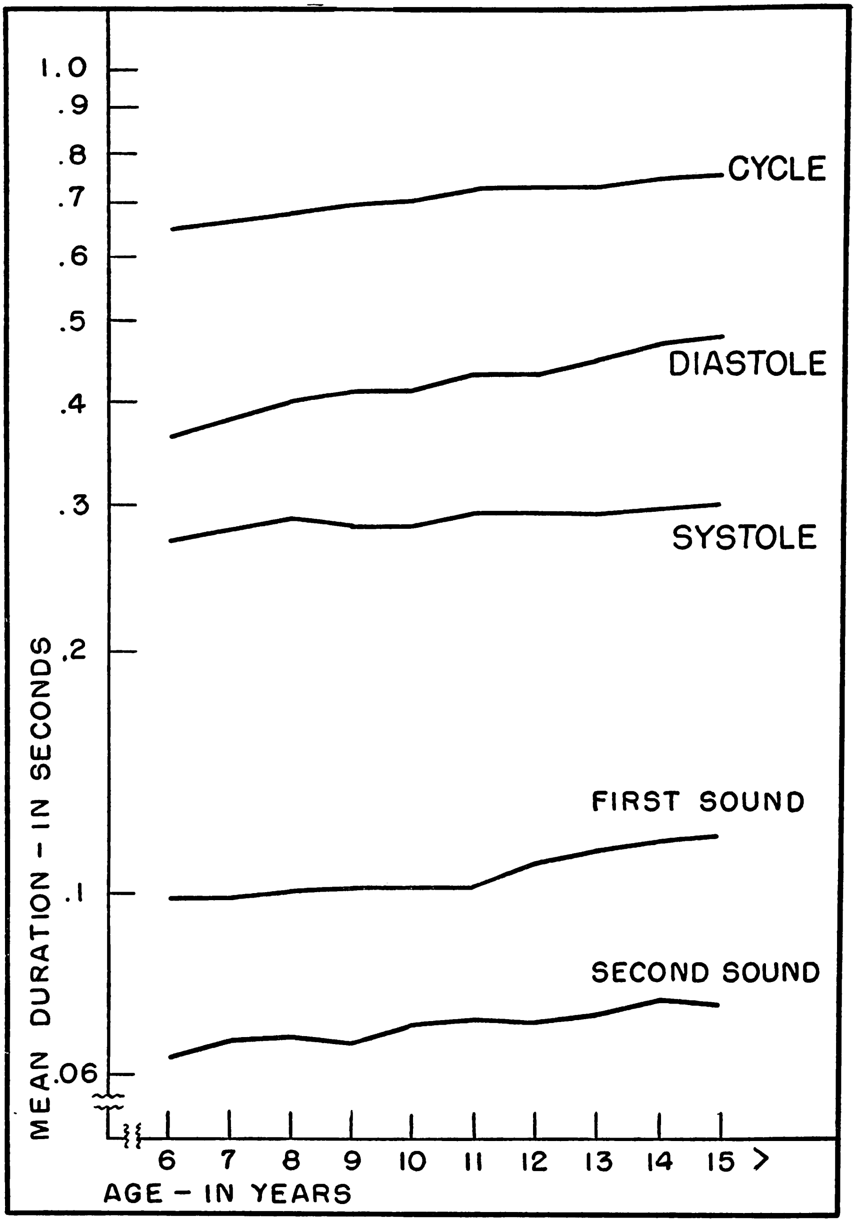

Fig. 4. The age trend of the mean durations of the components of the cardiac cycle plotted on arith-log. scale. The measurements have been obtained from the stethograms of 1,465 children.

Since the values of the arithmetic means are plotted on a semilogarithmic graph their slopes are directly comparable. An examination of the age trends reveals that apparently the rate with which diastole lengthens in duration as age increases is more rapid than that of the systole. The duration of systole also increases more slowly than that of the cardiac cycle. On the other hand, both the first and the second sounds apparently increase at a rate almost the same as that of the diastole. It seems then that with advancing age, the increase in the duration of the cycle results from an increase in the length of both systole and diastole, but the major portion of the increment is due to the lengthening of diastole. This together with the other facts presented in the present paper show that the duration of diastole is more variable than that of systole and therefore variation in the total duration of cycle, the summation of systole and diastole, results to a greater degree from the variation of diastole.

Although the duration of the cycle increases at practically a uniform rate between the ages of 6 and 15 years, it is to be realized that this is a short range of years and the rate observed holds good only within this range. It is a known fact that on the average the pulse rate decreases sharply from a high rate of about 130 beats per minute [*cf.* Vierordt, 1893 (16), also Sutliff and Holt, 1925 (14)] in infancy to one of about 105 at 3-4 years of age. It continues to decline until the rate of 72 is reached at 20 years of age. Thereafter the average rate of 72 is maintained with little change, throughout the remainder of life. The steady decline of the pulse rate from childhood to adulthood would lead to the expectation of the trend observed in the duration of the cardiac cycle (*cf.* Figure 4).

Furthermore, if the observations made on the present sample of children are expressed in terms of heart beats per minute (heart rate=60/ cycle duration) the age trend will be found to parallel that reported for pulse rate. In Figure 5 is illustrated a comparison of the average heart rate observed in these children with Sutliff and Holt's mechanical perequation of the average pulse rates measured under basal conditions and reported by a number of in-

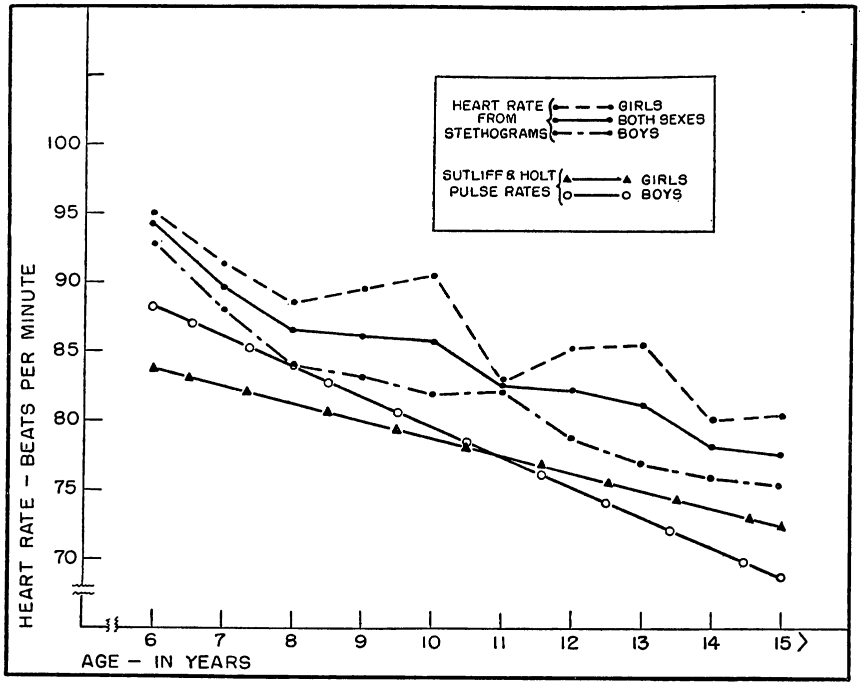

Fig. 5. Average heart rates obtained from the stethographic records (rate = $\frac{60}{\text{cycle length}}$) of 703 boys and 762 girls of stated age compared to the average pulse rates reported by Sutliff and Holt.

vestigators. From Figure 5 it appears that the average heart rates derived from the stethographic records are about 5 beats higher than the average pulse rates reported by Sutliff and Holt. Whether the higher rate found in this sample is due to the differences in the method of measuring or to the differences in the physical condition of the children of the two samples cannot be determined. It is interesting to note that in contrast to older data [*cf.* Vierordt, 1893 (16)] on pulse rate, Sutliff and Holt arrive at a higher rate for boys than for girls below the age of 11 years. The main point of the comparison of the two sets of data is, however, the age trend and in this there is remarkable agreement. Combining boys and girls it is found that Sutliff and Holt's data indicate an average decrease in pulse rate of 1.5 beats per minute for each year of age while the heart rate of the present sample decreases by 1.6 beats per minute on the average between the age of 6 and 15 years.

Summary

This paper describes the technique employed in measuring the duration of cardiac cycle, systole, diastole, first and second sounds from the stethographic records of 1,465 children. A statistical analysis of these measurements reveals:

1. For all the children the mean duration of the total cycle is .722 seconds which corresponds to a heart rate of 83 beats per minute. The mean duration of diastole equals .433 seconds and is about one and one-half times longer than the systole whose duration is .289 seconds. The mean duration of the first sound is .108 seconds while that of the second sound is .070 seconds.

2. The standard deviation of the frequency distribution of cycle duration is .140 seconds or 19 per cent of the mean. Therefore, within the area of the distribution curve limited by one standard deviation above and below the mean, a range containing roughly two-thirds of the children, the heart varies from 64 to 102 beats per minute.

3. Of the major components of the cardiac cycle, the duration of diastole is the most variable in absolute terms. The duration of the second sound is the least variable. However, relative to the mean value, the duration of systole differs the least from child to child while that of diastole varies the most.

4. The mean durations of the cardiac cycle, systole, diastole, first and second sounds are all longer in the boys than in the girls and this sex difference is to be observed generally at all ages.

5. The mean durations of the cardiac cycle and its components increase at a uniform rate from age 6 to 15 years. It is to be noted that the rate of increase is apparently not the same for systole and diastole; the former increases at a slower rate than the latter.

6. A comparison of the age trend of the stethographic heart rates

with data on pulse rates compiled by others reveals that during the age period under discussion the average annual rate of decrease is almost identical in the series compared.

The main objective of these cardiometric studies, as has been stated, is to arrive at a means of developing an objective "screening device" to select children who require special attention or care with respect to the heart and circulatory system. The analysis reported in the present paper has for its purpose to give a description of the stethographic pattern of the heart sounds in terms of their duration. From the data reported tentative standards can be set up for the evaluation of the cardiac status of children, but the results of repeated tests on the same children and of other clinical and laboratory examinations must be studied in connection with the present data before it is possible to determine definitely the significance of individual deviations from the values of duration obtained.

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