Influence of Heart Rate on the Phases of the Left Heart Cycle in Exercise

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The phases of the left heart cycle have been studied in young athletes at rest and after exercise utilizing vibrocardiographic and electrocardiographic data. The periods under study included electromechanical lag, isometric contraction, ejection, isometric relaxation, rapid filling, and diastasis. When compared to the length of the heart cycle (R-R interval) these periods were found to diminish linearly with decreased cycle length and the range of the periods was such that the duration of each phase could be predicted from cycle length. At cycle lengths shorter than 370 msec. (160 heart rate), the electromechanical lag, isometric contraction, isometric relaxation and rapid filling periods were found to plateau, the period of diastasis was completely eliminated and the period of ejection was found to shorten more markedly. It was suggested that a physiologic limit in heart rate is reached at this level.

INTEREST in the phases of the heart cycle was greatly stimulated by Wiggers¹⁾ who studied the duration of cardiac events in animals and attempted to determine how they were altered in various physiological states. In the human subject, observations on the duration of cardiac phases have been limited by the lack of reliable techniques to determine these periods externally. Heart catheterization studies have contributed most of the information but normal subjects are rarely studied and severe exercise loads cannot be imposed.

Precordial vibrations have come into use in recent years for the study of cardiodynamic phases. Apex cardiograms²⁾⁻⁴⁾ and kinetocardiograms⁵⁾ have demonstrated the ability to measure the durations of the phases of left ventricular systole and diastole in the human. These same correlations have been established in the animal with vibrocardiography.^{6),7)} Although hemodynamic correlations with vibrocardiograms have not been made in the human subject,* the close relationship of vibrocardiograms to apex or kinetocardiograms⁸⁾ as well as the close similarity of vibration wave forms between the human and animal⁷⁾ permits the use of these correlations in the human subject.

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* Since this article was written, vibrocardiograms have been recorded at human heart catheterization simultaneously with left ventricular pressure curves. The same hemodynamic correlations were found as reported for dogs.

This study was undertaken to determine the effects of alterations in heart rate induced by exercise on the phases of the left heart cycle as determined from vibrocardiographic and electrocardiographic data.

METHOD

Fifteen subjects were chosen for this study. Their ages ranged from 17 to 41 and averaged 26.2 years. All of these subjects were actively engaged in strenuous competitive athletics. They were screened by physical examination, electrocardiogram, blood pressure, chest x-ray and history.

The transducer for recording vibrocardiograms was a Ling-Temco-Vought condenser microphone with a frequency response of 1.5 to 3,000 cps, ± 3 DB.⁸⁾ The recording instrument was an Electronics-for-Medicine photographic recorder with a paper speed of 100 mm. per sec. The microphone was attached to the subject's chest by means of an elastic strap at the fourth left parasternal area⁹⁾ and a dipolar chest lead affixed at the midaxillary lines near the fourth to fifth intercostal spaces for recording electrocardiograms.

The exercise test consisted of pedalling on a bicycle ergometer at a rate of 20 Km. per hour with no load for a period of 2 min. The load was then increased step-wise at 2 kilopond (KP) levels until a maximum of 4 KP was reached. The speed of the ergometer was held constant at 20 Km. per hour. The test was terminated when the subject's heart rate reached 200 or began to plateau.

Records were obtained of vibrocardiograms and electrocardiograms at rest and during 3 to 4 successive levels of exercise. Measurements of the phases of the left heart cycle were made directly from the oscillographic records of the vibrocardiograms and electrocardiograms. The periods of the left heart cycle which were measured are described below and illustrated in Fig. 1 and 2.

Period 1. Period 1 was measured from the onset of the QRS complex of ECG to the H point of the vibrocardiogram. This period represents the electromechanical lag period and is the period between excitation and pressure rise in the ventricle.

Period 2. Period 2 was measured from the H wave to the J₂ wave of the

Fig. 1. Correspondence of the vibrocardiographic waves to the phases of the left heart cycle.

Fig. 2. Vibrocardiographic wave forms at rest and after exercise.

vibrocardiogram. This period corresponds to the isometric contraction period.

Period 3. Period 3 was measured from the J_2 wave to the L wave of the vibrocardiogram and represents the ejection period.

Period 4. Period 4 was measured from the L wave to the N wave of the vibrocardiogram and represents the period of isometric relaxation.

Period 5. Period 5 was measured from the N wave to the R wave of the vibrocardiogram and represents the rapid filling period.

Period 6. Period 6 was measured from the R point of the vibrocardiogram to the onset of the QRS complex of ECG and represents the period of diastasis or slow filling.

RESULTS

Table I presents the durations of the 6 intervals measured at rest and during exercise in 15 subjects. The duration of the previous cardiac cycle is given as the cycle length.

The mean values for each of the 6 periods are presented in Table II with the corresponding previous cycle length (R-R interval) shown in the first column and the duration of the subsequent cycle in the "total" column. It can be seen that there is negligible difference between these 2 values.

In Fig. 3 the electromechanical lag period (QH interval) is presented as a function of cycle length. Under resting conditions this period ranged from 39 to 50 msec. and 25 to 37 msec, after exercise. The average decrease of the interval from rest to exercise was 13 msec. Although there is a wide range both at rest and after exercise, there is a definite trend toward shortening as heart rate is increased. The maximum shortening occurred at cycle length of 370 msec. (160 heart rate). After this level the electromechanical lag period either remained the same or tended to increase slightly.

Fig. 4 shows the isometric contraction period ($H-J_2$) as a function of cycle length. A linear change of this interval can be seen with cycle length.

Table I. Duration of Each Period Before and After Exercise in msec.

Case No.	Name	Age	Condition	Period						
				R-R	I	II	III	IV	V	VI
3	F. K.	21	Control	930	43	56	287	74	120	410
			Ex. 1	560	35	52	190	62	70	150
			2	400	37	46	155	—	—	—
			3	390	36	45	132	67	53	40
7	B. P.	41	Control	1200	39	69	308	82	133	466
			Ex. 1	470	33	48	149	72	67	82
			2	360	30	46	128	58	62	41
8	T. M.	17	Control	1300	44	65	280	90	130	480
			Ex. 1	380	35	50	160	65	55	20
			2	340	37	52	145	60	55	0
9	T. R.	27	Control	1010	45	60	285	72	125	405
			Ex. 1	380	38	47	145	65	50	70
			2	310	32	48	105	60	70	22
13	K. K.	17	Control	980	43	60	275	75	120	430
			Ex. 1	440	30	53	160	65	60	80
			2	380	28	50	138	60	70	30
			3	350	32	45	115	55	60	40
			4	330	35	44	105	65	65	0
14	D. M.	17	Control	910	40	60	255	80	115	360
			Ex. 1	580	35	50	200	65	70	160
			2	500	35	50	180	65	70	115
			3	320	28	50	130	55	50	25
15	B. H.	32	Control	850	40	60	268	70	95	300
			Ex. 1	600	30	50	210	60	70	170
			2	460	30	50	180	55	70	90
			3	380	27	48	115	55	60	30
16	R. C.	27	Control	750	40	60	280	85	100	250
			Ex. 1	420	35	45	160	50	70	70
			2	320	35	47	135	55	60	30
			3	300	35	48	115	60	60	10
17	D. M.	17	Control	940	42	55	272	85	135	370
			Ex. 1	390	30	47	172	55	55	30
			2	330	32	46	130	55	55	25
			3	300	28	46	105	52	50	25
18	H. F.	27	Control	910	50	62	280	69	125	340
			Ex. 1	530	35	53	184	60	60	80
			2	370	25	50	140	50	50	55
			3	340	25	45	140	50	50	10

Continued Table I.

Case No.	Name	Age	Condition	Period						
				R-R	I	II	III	IV	V	VI
19	T. S.	37	Control	800	43	60	275	70	100	270
			Ex. 1	430	30	50	163	55	60	75
			2	350	30	45	130	55	57	50
			3	330	30	47	130	50	60	30
20	C. P.	27	Control	820	48	57	250	80	110	280
			Ex. 1	450	35	50	148	55	80	55
			2	380	33	47	128	50	65	50
			3	340	30	50	115	70	65	0
22	B. H.	32	Control	860	42	55	245	90	130	295
			Ex. 1	420	32	45	145	70	80	50
			2	350	35	45	115	55	70	20
			3	340	—	—	105	55	65	0
23	W. B.	23	Control	940	41	60	300	65	115	418
			Ex. 1	390	32	50	168	50	60	65
			2	350	25	50	130	47	50	45
			3	330	25	50	110	45	50	30
24	D. W.	31	Control	900	42	55	270	70	110	320
			Ex. 1	600	32	50	200	60	90	163
			2	420	28	48	145	55	75	60
			3	360	30	45	136	53	60	40

Table II. Mean Value of Each Period in msec.

Cycle length	Period						Total
	I	II	III	IV	V	VI	
300	31	47	105	55	57	0	295
400	31	48	155	57	62	50	404
500	33	50	185	60	71	105	504
600	35	52	210	64	81	160	602
700	38	54	240	68	92	215	707
800	41	57	255	71	102	275	801
900	42	59	270	75	113	335	894
1000	43	61	285	79	123	400	991
1100	43	64	295	83	134	475	1094
1200	43	66	300	86	144	550	1189

The resting isometric contraction values ranged from 55 to 69 msec. with an average of 60 msec. At peak exercise the isometric contraction range was from 45 to 52 msec. with an average of 47 msec. The isometric contraction period

Fig. 3. Duration of the electromechanical lag period (Period I) as a function of cardiac cycle length (R-R interval).

Fig. 4. Duration of the isometric contraction period (Period II) as a function of cardiac cycle length (R-R interval).

Fig. 5. Duration of the ejection period (Period III) as a function of cardiac cycle length (R-R interval).

reached a maximum shortening at a cycle length of 370 msec. (160 heart rate).

Fig. 5 presents the ejection period (J_2 -L) as a function of cycle length. Under resting conditions the ejection period ranged from 240 to 300 msec. with an average of 260 msec., and at peak exercise ranged from 110 to 170 msec., with an average of 140 msec. There was a progressive shortening of the ejection period with diminished cycle length which became more pronounced at intervals of less than 370 msec. (160 heart rate).

Illustrated in Fig. 6 is the isometric relaxation period (L-M) as a function of cycle length. The range at rest is from 62 to 85 msec. and at peak exercise from 50 to 70 msec. The mean values were 78 and 52 msec., respectively. There is a progressive shortening to the ejection period with diminished cycle length which became more pronounced at intervals of less than 370 msec. (160 heart rate).

Fig. 6. Duration of the isometric relaxation period (Period IV) as a function of cardiac cycle length (R-R interval).

Illustrated in Fig. 6 is the isometric relaxation period (L-M) as a function of cycle length. The range at rest is from 62 to 85 msec. and at peak exercise from 50 to 70 msec. The mean values were 78 and 52 msec., respectively. There is a progressive shortening of the isometric relaxation period with diminished cycle length with a plateau at 370 msec. (160 heart rate).

The rapid filling phase (N-R) is shown as a function of cycle length in Fig. 7. A decrease of this interval is noted with shortened cycle length. The resting values for this period ranged from 100 to 140 msec., with a mean value of 120 msec. At peak exercise the range was 50 to 80 msec. with an average value of 60 msec. The maximum shortening was reached at a cycle length of 370 msec. (160 heart rate).

In Fig. 8 the period of diastasis is presented as a function of cycle length.

Fig. 7. Duration of the rapid filling period (Period V) as a function of cardiac cycle length (R-R interval).

Fig. 8. Duration of the diastasis period (Period VI) as a function of cardiac cycle length (R-R interval).

Fig. 9. Mean durations of the phases of the left heart cycle as a function of cardiac cycle length.

There is a linear shortening of this period with diminished cycle length. At rest, diastasis ranged from 280 to 420 msec. with an average of 320 msec. At peak exercise it ranged from 0 to 100 msec. with an average of 30 msec.

The mean values of the 6 periods are summarized in Fig. 9 which shows the overall relationships of these intervals to cycle length and to heart rate.

DISCUSSION

There has been greater attention given to the study of the phases of the heart cycle in humans because of the ability of external techniques to determine these periods reliably. However, data are limited primarily to studies on total systole and diastole. Few attempts have been made to measure the subdivisions of these major phases.

The data obtained in these studies compare favorably with those obtained by others using direct and indirect methods. Braunwald,¹⁰⁾ who studied the electromechanical lag period using intraventricular pressure curves, found this period to average 52 msec. but made no conclusions regarding the relationship of this period to heart rate. Harrison,⁵⁾ who studied this period using the kinetocardiogram, found it to average 38 msec. He stated that limitations in his measurement accuracy did not permit any conclusions on alterations of this interval with heart rate. Coghlan¹¹⁾ et al. also found the same values using intraventricular pressure curves. De Palma¹²⁾ who studied this interval in cats, found that it was shortened with increased heart rates.

The data obtained in our resting subjects compare favorably with those of Harrison. The heart rate range in this study was of a much greater magnitude than either that of Harrison or Braunwald, thus explaining our findings of changes in the electromechanical lag period with heart rate.

Braunwald¹⁰⁾ studied the isometric contraction interval in humans and found it to average 61 msec. Harrison⁵⁾ obtained a 68 msec. average and concluded that the interval was not affected by heart rate in the resting subject. The resting values obtained in our studies compare well with those of Braunwald and Harrison. However, it was our finding that the isometric contraction interval shortened with increases in heart rate an average of 13 msec.

All of the available studies on ejection time show that this interval is a function of heart rate.¹³⁾ Although the absolute value of ejection time may vary according to the technique used, the changes with heart rate in normal subjects have been shown to be the same. Our data show a progressive decrease of ejection time with increases in heart rate up to maximal heart rate levels.

The isometric relaxation period has been studied by Benchimol et al.³⁾

using the apex cardiogram and was found to range from 40 to 80 msec. No conclusions were made regarding changes in this interval with heart rate. Harrison⁵⁾ has also studied this interval and found that there was an inverse relationship between heart rate and the isometric relaxation period. Our data show a similar range of this period and also indicate a progressive shortening with increased heart rate.

The only available data on the period of rapid filling have been obtained by Benchimol et al.³⁾ They found that this period ranged from 40 to 120 msec. and was directly related to the total diastolic period. Our data indicate that the range of this period is similar and confirm the findings that it is directly a function of the total diastolic period (Fig. 10).

There were no studies found concerning the period of diastasis in the normal human subject.

The close agreement between the durations of cardiac events obtained in this study and those obtained by other methods lends further support to the use of vibrocardiograms for timing the events of the heart cycle.

The variations of the 6 periods of the left heart cycle which were summarized in Fig. 9 illustrate the finding that the period of diastasis is affected to a greater extent than the other cardiac phases by changes in heart rate. The electromechanical lag, isometric contraction, isometric relaxation and rapid filling phases change minimally throughout the heart rate range. It is interesting to note that above a heart rate of 160 the period of diastasis is completely eliminated. At this heart rate level, the other phases also undergo variations. The electromechanical lag period tends to plateau or increase slightly, isometric contraction tends to plateau or increase slightly, ejection tends to shorten markedly, and isometric relaxation and rapid filling plateau or increase slightly. These findings suggest that a physiologic limit in heart rate is being achieved.

SUMMARY AND CONCLUSIONS

The phases of the left heart cycle have been measured in athletes at rest and during exercise utilizing vibrocardiographic and electrocardiographic data. Six periods were studied which corresponded to electromechanical lag, isometric contraction, ejection, isometric relaxation, rapid filling, and diastasis. These periods were compared with the total length of the left heart cycle at heart rates ranging from 50 to 200 beats per min. The range of these intervals was such that the duration of any cardiac phase could be predicted from ventricular cycle length.

The 6 periods of the left heart cycle all diminished linearly with cycle length up to heart rates of 160. After this level, the electromechanical lag and

isometric contraction periods remained unchanged, the ejection period shortened more markedly, and the isometric relaxation and rapid filling periods did not change. The period of diastasis demonstrated a marked shortening and was found to be completely eliminated above heart rates of 160. It was suggested that a physiologic limit of heart rate is achieved near this level.

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