The purpose of this study was to examine the relationship of the time components of the left ventricle. Since one of the ways to investigate cardiac function is to analyze the time intervals between particular events of the cardiac cycle, various time intervals of systole and diastole of the left ventricle were measured from simultaneous recordings of the electrocardiogram, phonocardiogram, carotid pulse wave, and apex cardiogram. The relationship of the time components was determined by factor analysis. The results showed that the six nonoverlapping intervals, which included the (1) isovolumetric relaxation phase, (2) rapid filling phase, (3) slow filling phase, (4) electromechanical lag, (5) isovolumetric contraction phase, and (6) ejection phase, are relatively independent of each other and of cycle time (with the exception of the slow filling phase). They reflect the factors that account for the variance of all the time components of the left ventricle. These relationships among the intervals appear to be similar for different ages and sex. (RC)
One of the ways to investigate cardiac function is to analyze the time intervals between particular events of the cardiac cycle. Multichannel recording techniques have provided simultaneous information of electrical, acoustic, pressure, and mechanical events for the assessment of cardiac events. Following earlier work by Marcey (1860) and Garrod (1874), Wiggers (1922) divided the cardiac cycle into periods of systole and diastole. Both systolic and diastolic periods were subdivided into smaller phases. Katz and Feil (1923) and Blumberger and Meiners (1959) began the contemporary approach by use of the arterial pulse, electrocardiogram, and phonocardiogram to delineate systolic time phases. The diastolic time phases have been determined by adding the apexcardiogram (e.g., Benchimol, et al., 1961).

**Definitions and Measurement**

**Cycle Time**

The complete cycle time (CT), often reported as heart rate (HR) in terms of number of cycles per minute, has been widely used as one component of cardiac output. As such it has been utilized as an indicator of severity of stressors, and as one means of evaluating cardiovascular function at rest and in response to a standard sub-maximal work load. The maximum number of cardiac cycles per minute has also been used as one way to reflect "normal" aging trends, and as one of the measures which can form the basis for exercise prescription. The cycle time response to various levels of sub-maximal work has been used to estimate maximal oxygen uptake in practical field situations.

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1 Introduction to Symposium, Research Section, AAHPER, Atlantic City, March, 1975.
Introduction

Cycle time (CT) is defined as one complete cardiac cycle. It is measured from an event in one cardiac cycle to the same event in the next cycle. The peak of the QRS complex in the electrocardiogram (ECG) has often been used. The first major component of the second heart sound (S-2) of the phonocardiogram (PCG) is used in this paper since it marks the beginning of diastole (see Figure 1). The use of CT is preferred to HR since it is more precise, although the ease of obtaining HR makes it more feasible in field situations.

Diastole

The resting portion of the cardiac cycle, diastole (DIA) (Wiggers, 1922), is the time from the end of ejection to the beginning of excitation. Left ventricular DIA begins with the closure of the aortic valve and includes isovolumetric relaxation, rapid and slow filling (Wiggers, 1922)(see Figure 2).

Isovolumetric relaxation phase. The IRP is the first part of diastole, from the end of ejection to the beginning of filling. It is measured from S-2 (PCG) to C on the apexcardiogram (ACG) (Benchimol, et al., 1961). It has also

Diastole is selected for the beginning of cycle time because of the effects different amounts of filling apparently have on systole.

The mitral valve does not close until after Q, however, only minute filling takes place after Q. Since Q is the beginning of systole, it has arbitrarily been used as the end of diastole.
been called isometric or isovolumic relaxation.

**Rapid filling phase.** RFP is the time from the beginning of filling to the end of the phase in which the ventricle fills rapidly terminated by the resistance of the ventricle to further stretch (Yang, et al., 1972). It is measured from 0 to F on the ACG.

**Slow filling Phase.** SFP (Wiggers, 1922) is the largest portion of diastole, from the end of rapid filling to the onset of stimulation for the next systole. It is measured from F (ACG) to Q (ECG).  

**Systole**

The working portion of the cardiac cycle includes two pre-ejection intervals and the time for ejection (see Figure 3).

**FIGURE 3 about here**

Electromechanical lag. The EML (Harrison, et al., 1964) is the time from the onset of excitation to the beginning of contraction. It represents the electrical-mechanical delay found in muscles between stimulation and contraction. EML is measured from Q⁴ (ECG) to the first major component⁵ of the first heart sound⁶ (S-1) on the PCG (see Figure 4). EML has also been called electropressor latency or asynchronous period (Raab, 1966).

---

⁴Or the beginning of the QRS complex if there is not a Q.

⁵First major deflection (positive or negative) after peak of R (ECG) is used for S-1.

⁶The time for beginning of contraction may not correspond exactly with S-1, but it appears to be the best estimate from atraumatic methods. In addition, acute or chronic changes in the Q to S-1 interval would reflect primarily changes in EML.
Isometric contraction phase. The ICP (Rushmer, 1956) is the time from the beginning of contraction to beginning of ejection. It is measured from S-1 (PCG) to the onset of the steep ascent (C-1) of the carotid pulse wave (CPW) minus the pulse wave transmission time (T PTT) from the heart to neck. ICP is normally calculated by subtracting ejection period from the mechanical systole (S-1 to S-2). It has also been called isometric (Wiggers, 1922) or isovolumic contraction (Wallace, et al., 1962).

Tension period. TP (Frank and Kinlaw, 1962) is the time for both pre-ejection intervals. It is measured from Q (ECG) to C-1 (CPW) minus PTT. It is normally calculated EML + ICP, or total systole (Q to S-2) minus ejection period. TP has also been called excitation-ejection time (Harrison, et al., 1964), isometric tension period (Raab, 1966), or pre-ejection period (Weissler and Garrard, 1971).

Ejection Period. EP (Wiggers, 1922) is the time from beginning to end of ejection, and is normally measured from C-1 to the dicrotic notch (C-3) on the SPW (Weissler, et al., 1961) (see Figure 5). It can be divided into its percussion wave (rapid ejection) and tidal wave (reduced ejection) (Tavel, 1972). It has also been called left ventricular ejection time (Weissler and Garrard, 1971).

7PTT is measured from S-2 to C-3 which represent the end of ejection at the heart and neck respectively. The assumption is made that the PTT prior to ejection is the same as PTT after ejection.

8In studies dealing with various time components of the left ventricle, it seems somewhat redundant to include LV before ejection time, although it might be helpful if it were the only left ventricular variable used in the study.
Mechanical systole. MS (Weissler, et al., 1965) is the time from beginning of contraction to end of ejection, and is measured from S-1 to S-2 (PCG), or can be calculated ICP + EP.

Total systole. TS (Weissler, et al., 1965) is the time from onset of excitation to the time of ejection. It is measured from Q (ECG) to S-2 (PCG) or can be calculated EML + ICP + EP. TS has also been called electromechanical systole (Fardy, 1973).

Summary

Various time intervals of systole and diastole of the left ventricle can be measured from simultaneous recordings of the electrocardiogram, phonocardiogram, carotid pulse wave, and apex cardiogram (See figure 6). The cardiac events marking the beginning and ending of the

FIGURE 6 about here

INTERVALS ARE:

- end of ejection, S-2 on the PCG;
- onset of filling, O on the ACG;
- end of rapid filling, F on the ACC;
- onset of excitation, Q on the ECG;
- onset of contraction, S-1 on the PCG;
- onset of ejection, C-1 on the CPW minus PTT between heart and neck;
- end of rapid ejection, C-2 on CPW;
- end of ejection of next cycle, S-2.

The points on the indirect recordings do not always correspond precisely to the cardiac events (Luisada and MacCanon, 1972), although they appear to
be valid approximations (Harrison, et al., 1964; Spodick and Kumar, 1968; Weissler, et al., 1961). Some investigators prefer to refer directly to the points on the ECC, PCG, CPW, AND APCG (e.g., it would be Q-S-1 rather than EML; or S-1 to S-2 rather than NS) (e.g., see Fardy, 1973). This reference to the points on the recordings is more accurate, but it is also more cumbersome and is not as easily understood.

**Relationship to Cycle Time**

The correlations between each of the intervals and cycle time appears to be similar for males and females (Spitler and Franks, 1975) of different ages (Molnar, et al., 1971) (see Table 1). Even in those intervals which tend to vary in length with age and sex, the relationships among the intervals are quite similar. The correlation to cycle time is very high for DIA and S1P; moderately high for EP, MS, and TS; and low for EML, ICP, RFP, and IRP.

**Relationship Among Intervals**

The relationship among the intervals is demonstrated by the correlational matrix (see Table 2) and the factors derived from factor analysis (see Table 3).

The variance of all the intervals can be accounted for by two major factors and four "specific" factors (Franks, Wiley, and Cureton, 1969; Molnar, et al., 1971; Spitler and Franks, 1975). Factor one reflects primarily the slow filling phase.
Introduction

of diastole, with total diastole, cycle time, and heart rate also having high loadings. Factor two reflects primarily the ejection period, with mechanical and total systole also having high factor loadings. Intervals having high loadings on factor one have moderate loadings on factor two, and intervals with high loadings on factor two have moderate loadings on factor one. For example, DIA has a factor loading of .92 on factor one and .38 on factor two; whereas, EP has a loading of .92 on factor two and .35 on factor one. There are specific factors for IRP, RFP, and EML. TP loads with ICP on the same factor.

Concerning the use of HR (or CT), it is obvious that HR could be substituted directly for factor one. There could be only moderate success in predicting factor two (EP, MS, or TS) from HR alone, and HR would provide almost no information concerning the shorter intervals (RP, RFP, EML, ICP).

Other evidence of the relative independence of the intervals from each other and from CT includes their differential response to postural change (mental and physical stressors) (Franks and Cureton, 1968); and apnea and face immersion in water (Rodgers, et al., 1973).

Summary

The six non-overlapping intervals, IRP, RFP, SFT, FML, ICP, and EP, are relatively independent of each other and of CT. They would reflect the factors that account for the variance of all the time components of the cardiac cycle. These relationships among the intervals appear to be true for different ages and sexes.
References


Wiggers, C. J. Studies on the consecutive phases of the cardiac cycle, I. the duration of the consecutive phases of the cardiac cycle and the criteria for their precise determination. *American Journal of Physiology*, 1922, 56, 439-459.

Figure 2

Ejection

End of Rapid Filling

End of Relaxation

Diastole

S2

Isovolumetric

Slow Filling

End of Excitation

Rapid Filling

Onset of Filling

ACG

ONSET OF FILLING

RAPID FILLING

60 msec

320 msec

490 msec

110 msec

60 msec

ECG

Excitation
FIGURE 3

END OF EJECTION

TOTAL Systole

M E C H A N I C A L S Y S T O L E

T E N S I O N P E R I O D

E X C I T A T I O N

O N S E T O F EXCITATION

O N S E T O F CONTRACTION

I C P

50 msec

100 msec

320 msec

270 msec

370 msec

50 msec

ECG

S2

ECG

PCG

CPW (PTT)
Figure 4

1. ECG
2. PCG
3. Ejection
4. Isovolumetric contraction
5. Contraction
6. Ejection mechanical lag
7. Tension period

- PTT
- CPW
- CI
- QRS
- S1
- S2

50 msec
100 msec
FIGURE 5

CYCLE TIME

DIASTOLE

TOTAL SYSTOLE

MECHANICAL SYSTOLE

FILLING TIME

TENSION PERIOD

EJECTION TIME

ISOVOLUMETRIC RELAXATION

RAPID FILLING

SLOW FILLING

ELECTROMECHANICAL LAG

ISOVOLUMETRIC CONTRACTION

RAPID EJECTION

SLOW EJECTION

END OF ONSET OF END OF ONSET OF ONSET OF END OF END OF
EJECTION OF RAPID CONTRACTION EJECTION RAPID EJECTION EJECTION
FILLING FILLING

60 110 320

50 50 100 170

IRP RFP SFP EML ICP REP SEP

60 110 320 50 50 100 170
### TABLE 1
CORRELATION OF CYCLE TIME WITH LEFT VENTRICULAR INTERVALS

<table>
<thead>
<tr>
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<th>CYCLE TIME</th>
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<tbody>
<tr>
<td>1.</td>
<td>.99</td>
</tr>
<tr>
<td>2.</td>
<td>.26</td>
</tr>
<tr>
<td>3.</td>
<td>.10</td>
</tr>
<tr>
<td>4.</td>
<td>.55</td>
</tr>
<tr>
<td>5.</td>
<td>.77</td>
</tr>
<tr>
<td>6.</td>
<td>.76</td>
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<tr>
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<td>.23</td>
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<td>8.</td>
<td>.21</td>
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<td>9.</td>
<td>.32</td>
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<td>10.</td>
<td>.72</td>
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<td>11.</td>
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<tr>
<td></td>
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<td>-------</td>
<td>-----</td>
</tr>
<tr>
<td>1. Heart Rate</td>
<td></td>
</tr>
<tr>
<td>2. Cycle time</td>
<td>-.99</td>
</tr>
<tr>
<td>3. Diastole</td>
<td>-.98</td>
</tr>
<tr>
<td>4. Isovolumetric relaxation</td>
<td>-.26</td>
</tr>
<tr>
<td>5. Rapid filling</td>
<td>-.13</td>
</tr>
<tr>
<td>6. Slow filling</td>
<td>-.91</td>
</tr>
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<td>7. Total systole</td>
<td>-.75</td>
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<tr>
<td>8. Mechanical systole</td>
<td>-.69</td>
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<td>10. Isovolumetric contraction</td>
<td>-.07</td>
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<td>11. Tension period</td>
<td>-.24</td>
</tr>
<tr>
<td>12. Ejection period</td>
<td>-.65</td>
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TABLE 3
FACTORS FOR LEFT VENTRICULAR INTERVALS

<table>
<thead>
<tr>
<th>FACTORS*</th>
<th>1...Diastole**</th>
<th>2...Systole**</th>
<th>3...Isovolumetric contraction</th>
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</thead>
<tbody>
<tr>
<td>Slow filling</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Diastole</td>
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<td></td>
<td></td>
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<tr>
<td>Cycle time</td>
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<tr>
<td>(-) Heart rate</td>
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<table>
<thead>
<tr>
<th>SPECIFIC &quot;FACTORS&quot;</th>
<th>4...Electromechanical lag</th>
<th>5...Isovolumetric relaxation</th>
<th>6...Rapid filling</th>
</tr>
</thead>
</table>

*Variables which had highest factor loadings are listed under each factor. Virtually all the variance of the intervals was accounted for by these six factors.

**The variables listed under factor one had moderate loadings under factor 2 (e.g., diastole had a factor loading of .92 for factor one and .38 for factor two). The variables listed under factor two also had moderate loadings under factor one.

***Tension period had a moderate factor loading (.50) under factor 4.