Time Relationship of Dynamic Events in the Cardiac Chambers, Pulmonary Artery and Aorta in Man

By Eugene Braunwald, M.D., Alfred P. Fishman, M.D. and André Courmand, M.D.

Exposure of the heart in the course of chest surgery affords a means of faithfully recording pressure pulses in the four chambers of the heart and in the large vessels of human subjects. This study in 13 individuals without any clinical evidence of cardiovascular disease, is concerned with the time relationship between electric and mechanical events and with the temporal sequence and respective characteristics of similar phases of the cardiac cycle in both sides of the heart. The results obtained by permutation of simultaneous pressure recordings confirm the classical observations made in dogs.

Pressure pulses have previously been recorded from the left side of the exposed heart in human subjects without any clinical evidence of cardiac disease, as well as in patients with mitral stenosis. The present study extends these observations by the simultaneous recording of blood pressures from both sides of the exposed human heart. The additional information gained by the present study falls into three broad categories: (1) The delineation of the temporal sequence of the various electric and mechanical events; (2) the definition of the respective and distinctive characteristics of right and left atrial pressure pulses, and (3) the contrast between electric-mechanical interrelationships in normal subjects and in two patients with incomplete right bundle branch block.

**Procedures**

Subjects: Pressure pulses were recorded in seven male and six female subjects, ranging in age from 15 to 50 years, who were undergoing resective surgery for localized pulmonary disease: 11 had pulmonary tuberculosis, one had a healed lung abscess and one a ruptured bullous cyst. Two of these patients had the electrocardiographic pattern of incomplete right bundle branch block, manifested by an RsR' pattern in the right precordial leads in association with a QRS duration of 0.08 sec. None of the 13 patients manifested clinical evidence of cardiovascular disease and the pulmonary artery pressure recorded during surgery was within normal limits in all instances.

Methods and Materials: Surgery was performed during ether-oxygen endotracheal anesthesia, occasionally supplemented by small amounts of cyclopropane. Patients with undue blood loss or lowering of systemic blood pressure were not used as subjects for this study. The pericardium was opened in order to puncture the cardiac chambers under direct vision.

The recording system included no. 20 gage needles, 3 inches long, connected to Statham pressure transducers (P23A) by means of thick-walled, vinyl plastic tubing, 122 cm. long, 1.9 mm. in internal diameter and of 6.6 mm. in external diameter. The natural frequency of this system was 60 cycles per second. The delay in the transmission of a pressure pulse through the plastic tubing-strain gage recording system was 0.005 sec. This time interval was subtracted from all measurements relating electrical to mechanical events. As reported by others, the contours of pressure pulses recorded through the vinyl plastic tubing and through lead tubing were identical.

Pressures were recorded simultaneously from the pulmonary artery and the aorta, from the ventricles and from both atria. In order to measure the duration of isometric contraction, simultaneous pressures were also recorded from the left ventricle and aorta, and from the right ventricle and pulmonary artery. In many instances, in order to complete the picture of hemodynamic events, pressures were recorded...
simultaneously from two cardiac chambers, the aorta and the pulmonary artery.

The zero reference point was visually set at the midlevel of the heart. The electrocardiographic lead for each tracing was selected on the basis of clear complexes and minimal electric interference. The pressures were recorded with a multi-channel, oscillographic, photographic recorder at paper speeds of 25 and 75 mm. per second.

Pressure and timing measurements were averaged for a minimum of 12 beats; whenever possible, respiration was arrested during the period of recording. The records taken at a paper speed of 75 mm. per second were used for measuring all time intervals. This made possible a reading accuracy of ±0.005 second. The mean value for at least 12 beats was calculated and expressed to the nearest 0.001 second. Differential pressures between the two atria were determined by calculating the pressure difference between simultaneously recorded left and right atrial pressures at 0.02 second intervals.

**RESULTS**

**Timing of Cardiac Events:** In table 1 are listed the average duration of various phases of the normal cardiac cycle and the number of cases from which each value is derived. Of particular interest is the asynchronism of the two sides of the heart. The onset of contraction of the right atrium preceded that of the left atrium by an average of 0.020 sec. However, left ventricular contraction began an average of 0.013 sec. before right ventricular contraction. In the left ventricle, isometric contraction lasted almost four times as long as in the right ventricle, with a rate of pressure rise approximately two and one-half times as rapid. The onset of right ventricular ejection preceded that of left ventricle (average = 0.035 ± 0.0097 sec.), and persisted longer (average = 0.028 ± 0.098 sec.) since the protodiastolic phase was difficult to recognize on most tracings, it was included with the ejection phase (fig. 1). This probably introduces only a small error since Wiggers has found that the total duration of protodiastole is 0.020 sec. on the left side of the dog heart. In spite of this possible small error, it appears that the duration of right ventricular ejection exceeds considerably that of the left ventricle (approximately by 0.060 sec.).

A schematic representation of the timing of electric and mechanical events during right and left atrial and ventricular systole, based on these data, is to be found in figure 2.

**Comparison of Right and Left Atrial Pressure Pulses:** In figures 2 and 3, various landmarks of the left and right atrial pressure pulses are compared in eight subjects in whom both atrial pressures were recorded simultaneously. The absolute pressure values were relatively high because of the presence of the open chest. As illustrated in figure 3A left atrial mean pressure exceeded the right in 6 of 8 subjects. A comparison of the components of the two atrial pressure pulses yielded the following additional

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**TABLE 1.** Temporal Relations of Electric and Dynamic Events in Normal Subjects

<table>
<thead>
<tr>
<th>Measurement</th>
<th>No. of Cases</th>
<th>Mean (sec.)</th>
<th>S.D. (sec.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Onsets P-Rt Atrial Systole</td>
<td>8</td>
<td>0.053 ± 0.0099</td>
<td></td>
</tr>
<tr>
<td>Onsets P-Lft Atrial Systole</td>
<td>12</td>
<td>0.055 ± 0.0087</td>
<td></td>
</tr>
<tr>
<td>Onsets Q-Rt Ventricular Systole</td>
<td>8</td>
<td>0.020 ± 0.0046</td>
<td></td>
</tr>
<tr>
<td>Onsets Q-Lft Ventricular Systole</td>
<td>9</td>
<td>0.065 ± 0.0087</td>
<td></td>
</tr>
<tr>
<td>Onsets Lft to Rt Ventricular Systole</td>
<td>7</td>
<td>0.013 ± 0.0043</td>
<td></td>
</tr>
<tr>
<td>Onsets Q-Rt Ventricular Ejection</td>
<td>10</td>
<td>0.080 ± 0.0079</td>
<td></td>
</tr>
<tr>
<td>Onsets Q-Lft Ventricular Ejection</td>
<td>12</td>
<td>0.115 ± 0.0117</td>
<td></td>
</tr>
<tr>
<td>Onsets Rt to Lft Ventricular Ejection</td>
<td>9</td>
<td>0.035 ± 0.0007</td>
<td></td>
</tr>
<tr>
<td>Onsets Aorta to Pul. Art. Incisure</td>
<td>10</td>
<td>0.028 ± 0.0008</td>
<td></td>
</tr>
<tr>
<td>Rt. Ventr. Isometric Contraction</td>
<td>8</td>
<td>0.016 ± 0.0040</td>
<td></td>
</tr>
<tr>
<td>Lft. Ventr. Isometric Contraction</td>
<td>11</td>
<td>0.061 ± 0.0121</td>
<td></td>
</tr>
</tbody>
</table>

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**FIG. 1.** Simultaneous aortic (AO) and pulmonary artery (PA) pressure pulses in a subject with normal circulation.

Paper speed, 25 mm./sec. on left, 75 mm./sec. on right. Time lines, 0.04 sec. apart. Arrows indicate beginning of ejection and end of protodiastole in the aorta and pulmonary artery.

Note differences in time between corresponding events in the two curves.
Fig. 2. Diagrammatic representation of the average timing of electrical and mechanical events on both sides of the heart during atrial and ventricular systole in normal subjects. 

(1) Onset of right atrial contraction. (2) Onset of left atrial contraction. (3) Onset of left ventricular contraction. (4) Onset of right ventricular contraction. (5) Onset of right ventricular ejection. (6) Onset of left ventricular ejection. (7) End of left ventricular ejection. (8) End of right ventricular ejection.

The striped areas represent ventricular isometric contraction. The stippled areas represent ventricular ejection.

Fig. 3. Relationships between simultaneously recorded left atrial (LA), and right atrial (RA), pressure pulses.

Center of each circle represents the pressure in mm. Hg in both atria of one subject. Squares represent the mean value obtained from all subjects.

Fig. 4. Relationships between simultaneously recorded left atrial (LA), and right atrial (RA) pressure pulses, and between left ventricular (LV), and right ventricular (RV) end-diastolic pressures.

Center of each circle represents the pressure in mm. Hg in both atria or ventricles of one subject. Squares represent the mean values obtained from all subjects.

Information: (1) The pulse pressure of the “a” wave was not consistently higher on either side (fig. 3B), (2) the average peak pressures of the “a” waves were identical in both atria (fig. 3C), (3) at the so-called “z” point, which marks the onset of ventricular contraction, the left exceeded the right atrial pressure in 6 of 8 subjects (fig. 3D), (4) the atrial pressure drop after the onset of ventricular contraction, the “x” drop, failed to show a consistent pattern, being greater in the right atrium in four subjects, greater in the left atrium in three, and equal in both atria in one (fig. 4A), (5) the “v” point pressure, i.e., the atrial pressure at the end of ventricular systole, was higher in the left atrium in 7 of 8 subjects (fig. 4B), and (6) the fall in pressure, immediately after the “v” point, the “y” drop, was also greater in 7 of 8 subjects in the left atrium (fig. 4C).
A left-to-right pressure gradient persisting throughout all, or nearly all, of the cardiac cycle with a peak at the "v" point; this pattern was observed in 4 subjects and is illustrated in figure 5. (2) A transient reversal of the left-to-right gradient during atrial contraction; this pattern, observed in three subjects, is illustrated in figure 6; the reversal is due to a higher "a" wave peak pressure on the right side than on the left. (3) A predominant right to left pressure gradient; this pattern was observed in one subject and is illustrated in figure 7.

**FIG. 5.** Simultaneous left atrial (LA), right atrial (RA), and differential atrial (DIFF.) pressure curves in a subject with normal circulation.

Note the high "v" point in the left atrial pressure pulse. The differential pressure curve demonstrates that left atrial pressure exceeds the right atrial throughout virtually the entire cardiac cycle.

**FIG. 6.** Simultaneous left atrial (LA), right atrial (RA), and differential (DIFF.) atrial pressure curves in a subject with normal circulation.

Note prominent atrial contraction wave in the right atrial pressure pulse, which briefly reverses the interatrial pressure gradient during each cardiac cycle.

The "v" point the highest point; the peak of the "a" wave in six and in the other two the peak of the "c" wave constituted the high points.

**Intra-atrial Pressure Gradients:** The interatrial differential pressures obtained in the eight subjects fell into three distinct groups: (1)
Ventricular End-diastolic Pressures: Simultaneous left and right ventricular pressures were recorded in 6 subjects. As may be seen in figure 4D, the left ventricular end-diastolic pressure exceeded the right in five subjects, and equaled the right in one.

Influence of RSR' Electrocardiographic Pattern in Leads from the Right Precordium on the Sequence of Electric and Mechanical Events: In two subjects with segmental pulmonary lesions, but free of evidence of heart disease or pulmonary hypertension, an RSR' pattern was obtained in electrocardiographic leads from over the right precordium; the duration of the QRS complex was 0.08 second in both subjects. A representative tracing is illustrated in figure 8 and some pertinent relations between electric and mechanical events are presented for these two subjects in table 2. In both, the onset of right ventricular contraction was delayed, exceeding the normal interval (table 1) between the onset of left and right ventricular contraction. Furthermore, the normal sequence of the onset of ventricular ejection was reversed, with ejection from the right ventricle beginning later than from the left. It appears, therefore, that in these two subjects, the RSR' pattern in conjunction with normal QRS duration, is associated with delayed conduction in the right bundle branch system.

DISCUSSION

The primary purpose of the present study was to compare, by means of simultaneous tracings using adequate manometric apparatus, electric and mechanical events on both sides of the heart in normal man. The observations gained from this study have thereby extended in three major directions those previously described in normal human subjects with open chest.

I. The Sequence of Electric and Mechanical Events on the Two Sides of the Heart. In general, the time relations between the various phases of the cardiac cycle are in accord with earlier observations on man. There is one point of discord with earlier observations, i.e., the time interval between the onset of atrial depolarization and of right atrial contraction; this interval averaged 0.09 second in a previous study from this laboratory using cardiac catheterization in closed-chest man and 0.065 second in the present study based on intracardiac puncture. The cause of this discrepancy has not been identified. However, the use of the cardiac catheter and the slower speed of the recording paper in the previous study, as well as the difficulty in delineating the exact onset of the P wave in all studies with remote electrocardiographic leads may be responsible. It would appear that a more adequate definition of this time interval could be gained by means of an atrial endocardial lead in order to sharply demarcate the onset of atrial depolarization.

The sequence of events which constitute the cardiac cycle in the dog and man is generally similar. Thus, the onset of right atrial contraction precedes that of the left. This is generally conceded to be due to the location of the sinoatrial node in the right atrium. The general similarity of sequence in man and dog extends to ventricular events with an earlier onset and an earlier termination of ejection; right ventricular ejection is consequently longer in duration than left. The longer duration of right ventricular ejection, which may be due to the lower pulmonary arterial resistance, implies that in a steady state, when the outputs of both ventricles are identical, the mean velocity of ventricular discharge must be greater on the left. A corollary of the difference in ejection times is that valve action is not synchronous on the two sides of the heart; the closure of the mitral valve precedes that of the tricuspid, whereas the pulmonic valve opens prior to, and closes after, the aortic valves.

II. The Atrial Pressure Pulse and Interatrial
Pressure Gradient. Opdyke and associates have emphasized the hemodynamic limitations of mean atrial pressures and have stressed the importance of measuring the atrial pressure at several specific points during the cardiac cycle. Various aspects of the atrial pressure pulse have been considered in some detail in this study. Thus, several features of the atrial \( v \) wave have been elucidated: These include: (1) the relative prominence in man, as in the dog, of the \( v \) point in the left atrial pressure pulse; (2) the higher level of the \( v \) point in the left than in the right atrium, and (3) the greater drop in the left than in the right atrial pressure after the \( v \) point. These, in accord with previous observations in dogs, suggest that the distensibility of the left atrium is less than that of the right atrium in man.

The atrial \( z \) point pressure is determined in large part by the distensibility properties of the entire veno-atrial ventricular system. The observations that the atrial \( z \) point pressure and the ventricular end-diastolic pressure are generally higher on the left than on the right side of the heart suggest that the distensibility of the left atrium is less on the left than on the right side. Accordingly, the absence of any consistent difference between the two atrial pressures at the onset of atrial contraction, between the \( a \) wave pulse pressures and between the \( a \) wave pressure peaks imply that right atrial contraction may be more vigorous than left atrial contraction.

Previous measurements of both atrial pressures in the same individual have been made by means of cardiac catheterization in patients with interatrial communications. These measurements have, in general, indicated that the mean pressure is higher in the left than in the right atrium. However, since respiratory pressure variations are quite large, relative to level of the atrial pressures, instantaneous interatrial pressure gradients could, therefore, not be calculated with any degree of accuracy in the earlier studies. These measurements became possible in the present study due to the availability of simultaneous pressure pulses from both atria. The results are remarkably similar to those obtained by Opdyke and associates in the dog with intact interatrial septum. These authors have also demonstrated that the experimental production of an atrial septal defect lowers the interatrial pressure gradient, but does not abolish it. Therefore, the interatrial pressure relationship observed in normal subjects may also obtain in patients with atrial septal defects.

III. The Influence of the Electrocardiographic Pattern of RSR' over the Right Precordium upon Cardiac Events: The presence of an RSR' pattern with a normal QRS duration in right precordial leads in two otherwise normal subjects provided the opportunity for determining whether or not a true conduction defect exists in such patients. In both patients the delay in the onset of right ventricular contraction and ejection indicate a defect in right ventricular conduction. These limited observations do not indicate the site of slowed conduction, nor do they imply that this particular electrocardiographic pattern is consistently associated with disturbed conduction.

SUMMARY

Pressure pulses from all four cardiac chambers and both great vessels were obtained by direct needle puncture at the time of thoracotomy in 13 subjects who were clinically free of cardiovascular disease.

The temporal relationships between corresponding hemodynamic events on the two sides of the heart were compared. The onset of contraction of the right atrium preceded that of the left atrium, while the onset of contraction of the right ventricle followed that of the left ventricle. Right ventricular ejection began earlier and was completed later than left ventricular ejection.

The contour of simultaneously recorded right and left atrial pressure pulses were compared. The atrial pressures at the onset and at the end of ventricular systole and the atrial pressure drop after the \( v \) point were generally higher on the left than on the right side of the heart. However, the pressure at the peak of the \( a \) wave, the \( a \) wave pulse pressure and the atrial pressure drop after the onset of ventricular contraction showed considerable variation between the two atria, without any consistent differences.
The instantaneous pressure gradients between the atria were plotted in eight subjects. In four, left atrial exceeded right atrial pressure throughout all, or virtually all, of the cardiac cycle.

Two cardiovascular normal subjects presented with the electrocardiographic pattern of RSR' over the right precordium. In these patients, a delay in the onset of right ventricular contraction and ejection was demonstrated.

**SUMMARY IN INTERLINGUA**

Pulsos de pression ab le quatro cameras cardiac e ambe vasos major esseva obtenite per directe acupuncture al tempore de thoracotomia in 13 subjectos qui esseva clinicamente sin morbo cardiovascular.

Esseva comparate le relationes temporal inter correspondente eventos hemodynamic al duo lateres del corde. Le declaration del contraction in le atrio dextere precedeva illo del atrio sinistre, durante que le declaration del contraction in le ventriculo dextere sequeva illo del ventriculo sinistre. Ejection dextero-ventricular comenciava ante e se terminava post le ejection sinistro-ventricular.

Esseva comparate le contornos de simultanea registrationes del pulsos de pression dextero- e sinistro-atrial. Le pressiones atrial al declaration e al termino del systole ventricular e le cadita del pression atrial post le puncto "v" esseva generalmente plus alte al sinistra que al dextera del corde. Tamen, le pression al culmine del unda "a", le pression differential del unda "a", e le cadita de pression atrial post le declaration del contraction ventricular monstrava considerable variationes inter le duo atrios, sed iste differentias monstrava nulle regularitate.

Le gradientes presional instantaneous inter le atrios esseva traciate graphicamente pro octo individos. In quatro de illes le pression sinistro-atrial exceedeva le pression dextero-atrial in one o quasi omne le cyclo cardiac.

Duo subjectos de normalitate cardiovascular habeva le configuration electrocardiographic RSR' supra le precordio dextere. In iste patientes un retardate declaration del contraction e ejection dextero-ventricular esseva demonstrate.

**REFERENCES**


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