The Normal Apex Cardiogram

Its Temporal Relationship to Electrical, Acoustic, and Mechanical Cardiac Events

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THE apex cardiogram was described in 1878 by Marey.[1] With the exception of its utilization in the timing of the opening snap of the mitral valve [2, 3] and in the identification of the third and fourth heart sounds,[4-6] it has been used only infrequently as an aid in timing cardiac phenomena. Technical difficulties in its recording have obstructed its more universal application and, more particularly, its use in timing systolic events of the cardiac cycle. There is no general agreement about the meaning of the apex cardiogram. It is still argued whether the tracing represents the recording of low-frequency vibrations of the precordium or of the actual movements of the heart.[3, 7-9] Furthermore, the normal configuration of the systolic wave of the apex cardiogram has not been determined with certainty. If a normal "systolic pattern" were established, deviation from this might be helpful in assessing certain pathophysiologic states.

It is the purpose of this report to analyze the normal configuration of the systolic wave of the apex cardiogram by comparing the apex cardiogram with the simultaneous recordings of the electrocardiogram, phonocardiogram, indirect carotid pulse, and left intraventricular pressure, and to compare the accuracy of the apex cardiogram with the jugular venous pulse as a reference tracing for timing right- or left-sided cardiac events.

Material and Methods

Twenty-five subjects without heart disease were studied in the basal state. The study group consisted of residents, medical students, or patients admitted to the Peter Bent Brigham Hospital with diseases unrelated to the cardiovascular system. Their ages ranged from 22 to 45 years. Eighteen were men and seven were women.

The electrocardiogram, phonocardiogram, and apex cardiogram were recorded simultaneously with the carotid pulse and later with the jugular venous pulse. The electrocardiographic extremity lead with the earliest QRS deflection was used. The phonocardiogram was recorded in the 100 cycles-per-second range from the fourth left intercostal space midway between the sternum and the apex. The carotid pulse and the jugular venous pulse were recorded on the right side of the neck. The apex cardiogram was taken with the subject in the left lateral position, so that the maximum apex impulse was thrown against the chest wall. All tracings were recorded in mid-expiration.

The equipment used * consisted of a 4-channel Poly-Beam recorder (Model 564) coupled to a Viso-Scope, which allowed the simultaneous visualization of the 4-channel signals. The electrocardiogram was recorded through an ECG-Preamplifier (Model 350-3200). Heart sounds were recorded with a Contact-Microphone (Model 350-1700-C10) and a Heart-Sound-Pre-amplifier (Model 350-1700 B). The carotid pulse, jugular venous pulse, and apex cardiogram were recorded with Crystal-Microphones (Model 374) connected through ECG-Preamplifiers (Model
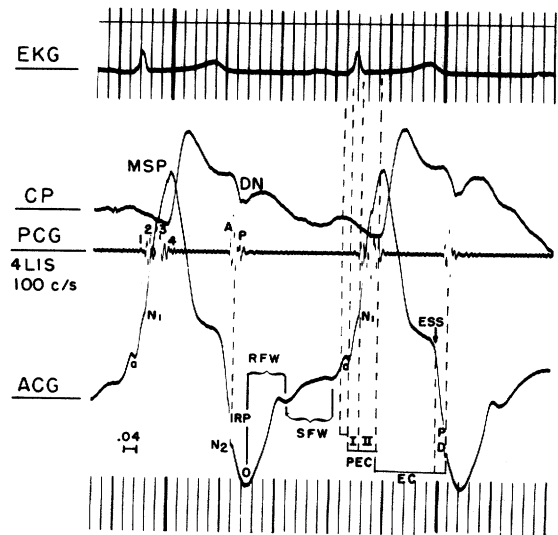
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* Manufactured by Sanborn Company, Waltham, Massachusetts.

350-3200). The electronic characteristics of the crystal microphone have been described by Miller and White.[10] It reproduces an electrical signal proportional to the change of pressure in the tubing. The frequency response of this microphone for pulse-wave recording is a constant between 1 and 1,000 cycles per second. A funnel type of cup applicator with a diameter of 2.5 cm. was used for the carotid pulse and apex cardiogram. The carotid pick-up was held in place with a 1-inch rubber band while the apex cardiogram pick-up was applied by hand. A double-rim suction piece was employed for the jugular venous pulse. The paper speed was 75 mm. per second. Vertical lines in the tracings represent time intervals of 0.04 second. Whenever time intervals were measured, the average

Figure 2

Simultaneous electrocardiogram, carotid pulse, phonocardiogram, and apex cardiogram. Normal subject.

of five consecutive cardiac cycles was taken.

In two patients with rheumatic valvular disease, simultaneous electrocardiograms, phonocardiograms, left ventricular pressure curves, and apex cardiograms were recorded. Ventricular pressures were obtained through a transseptal catheter, 72 cm. long, with a Statham P-23D manometer. Patient A.O. had mitral stenosis confirmed at cardiac catheterization and operation. Patient M.S. had mitral insufficiency documented by cardiac catheterization.

The following glossary of abbreviations is used in this study (figs. 1 and 2):

PCG: Phonocardiogram

S_1: First heart sound [comprising component 1, initial low-frequency-low-amplitude vibrations; component 2 (M_1), consisting of higher amplitude vibrations, commonly regarded as due to mitral valve closure; component 3 (T_1), similar to but following 2 and regarded as due to tricuspid valve closure; and component 4, the terminal low-frequency-low-amplitude vibrations].[11, 12]

S_2: Second heart sound (comprising A_2, aortic valve closure and P_2, pulmonic valve closure).

S_3: Third heart sound.
S_4: Fourth heart sound.
OS: Opening snap.
CP: Carotid pulse.
OSU: Onset upstroke.
DN: Dicrotic notch.

Figure 1

Schema of the sequential left-sided cardiac events relating electrocardiogram (EKG), phonocardiogram (PCG), carotid pulse (CP), and apex cardiogram (ACG).

A_2-DN: Time lag from onset of A_2 to the incisura of the dicrotic notch of the carotid pulse.

JVP: Jugular venous pulse (fig. 5).

  a wave: due to right atrial systole.

  x' descent: due to atrial relaxation.

  c wave: due to tricuspid valve closure.

  x descent: due to movement of atrio. ventricular ring toward the cavity of the right ventricle and continued atrial relaxation.

  v wave: due to right atrial filling (tricuspid valve opens at the summit of this wave).

  v descent: due to rapid emptying of right atrium.

ACG: Apex cardiogram

  EMI: electromechanical interval (from the onset of the QRS complex of the electrocardiogram to the onset of the systolic wave of the apex cardiogram).

Systolic wave:

  PEC-I: first pre-ejection component (from the onset of the systolic wave of the apex cardiogram to the onset of M_1).

  PEC-II: second pre-ejection component from the onset of M_1 to the onset of the upstroke of the carotid pulse).

  MSP: maximal systolic peak (the "E point" of Benchimol and Dimond).[13]

  EC: ejection component (from the MSP of the apex cardiogram to the onset of aortic valve closure (A_2) of the phonocardiogram or, alternatively, from the onset of the upstroke of the carotid pulse to the onset of A_2.

  ESS: end-systolic shoulder.

  PD: protodiastolic phase.

Diastolic wave:

  IRP: isometric relaxation period (from the onset of A_2 of the phonocardiogram to the O point of the apex cardiogram).

  O point: onset of the rapid filling wave (mitral valve opening).

  RFW: rapid filling wave.

  SFW: slow filling wave (diastasis).

  "a": left atrial contraction.

The Data and Their Implications

Atrial Wave. Atrial contraction was represented in the apex cardiogram (figs. 1 and 2) as a positive wave (*a* wave) occurring immediately before the systolic wave. The onset of the P wave of the electrocardiogram preceded the onset of the *a* wave by an average of 0.110 second (0.08 to 0.160 second).

The *a* wave of the apex cardiogram reflects left ventricular filling due to left atrial contraction. The peak of this wave coincides with the fourth heart sound of the left side.[14, 15] Since the right atrium contracts before the left atrium,[16] a fourth heart sound occurring before the peak of the *a* wave of the apex cardiogram must be a right-sided phenomenon and therefore must represent right ventricular filling due to right atrial contraction.

Systolic Wave, Pre-ejection Components. After the inscription of the *a* wave the tracing developed a rapid positive deflection that reached a maximal systolic peak at the point of the onset of the upstroke of the carotid pulse (aortic valve opening.) The interval between the onset of the QRS complex and the onset of the systolic wave of the apex cardiogram (EMI) averaged 0.021 second (table 1). The onset of the systolic wave occurred at an average of 0.035 second before the recording of the main vibrations of the first heart sound attributed to mitral valve closure.[11, 12] This interval is represented by the first pre-ejection component of the apex cardiogram (PEC-I, "pre-isometric phase")[17] of ventricular contraction (figs. 1 and 2, table 1). The

Table 1

Indirect Measurement of Electromechanical Interval (EMI), and Pre-ejection Components (PEC I and II) of the Apex Cardiogram in Normal Subjects

	EMI sec.	PEC-I sec.	PEC-II sec.
Mean ± S.E.	0.021 ± 0.002	0.035 ± 0.002	0.067 ± 0.003
S.D.	0.010	0.010	0.014
Extreme values	0.000 — 0.045	0.020 — 0.045	0.040 — 0.085

S.E., standard error; S.D., standard deviation.

initial low-frequency-low-amplitude vibrations of the first heart sound[3, 17, 18] (first component, numeral 1 of figs. 1 and 2) occurred during this portion of the pre-ejection component of the apex cardiogram. When simultaneous electrocardiogram, phonocardiogram, apex cardiogram, and left ventricular pressure curves were recorded (fig. 3), it was found that the onset of the systolic wave of the apex cardiogram actually preceded the systolic rise of left ventricular pressure. This means that the pre-ejection component of the apex cardiogram (PEC-I) started before and included the pre-isometric phase [18, 19] of ventricular contraction. Wiggers [19] defined the pre-isometric phase of ventricular contraction as that interval during which intraventricular pressure rises before effective closure of the atrioventricular valves.

Direct observation in this laboratory showed a lag of 0.007 second in the catheter-cable-manometer system. This accords well with the figure of 0.005 second found by Gordon et al.[20] In figure 3 the upstroke of the systolic wave of the apex cardiogram preceded the rise of left ventricular pressure by 0.025 second. Subtracting the 0.007-second lag period within the catheter-cable-manometer system, this portion of the systolic wave of the apex cardiogram still clearly preceded the onset of rise of left ventricular pressure. Depending upon the degree of lag of the intraventricular recording system employed, the apex cardiogram recorded by Benchimol and Dimond in a patient with mitral regurgitation would appear similarly to precede the onset of the upstroke of the right ventricular pressure curve (ref. 13, fig. 10).

It seems, therefore, that following the spread of electrical depolarization the apex cardiogram records the earliest portion of left ventricular contraction and that this occurs before there is any rise in intraventricular pressure. Furthermore, this early contraction occurs simultaneously with an acoustic event—namely, the initial low-frequency-low-amplitude vibrations of the first heart sound. It is suggested that both the first pre-ejection component (PEC-I) of the apex cardiogram
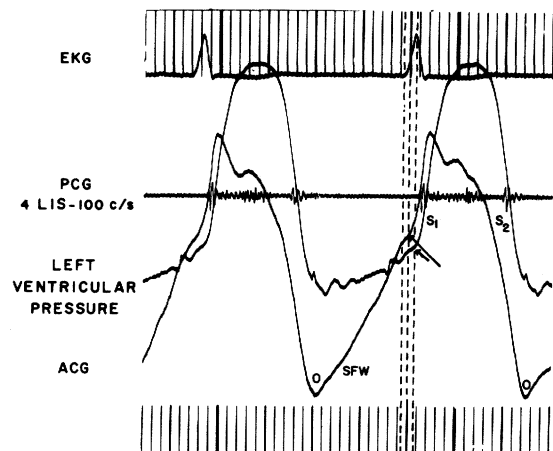

Figure 3

Simultaneous recording of electrocardiogram, phonocardiogram, left intraventricular pressure, and apex cardiogram in a patient with mitral stenosis. The beginning of the systolic wave of the apex cardiogram (large arrow) precedes the rise of left intraventricular pressure (small arrow) by 0.025 second and the onset of M_1 by 0.050 second. M_1 occurs 0.085 second after the onset of the QRS complex of the electrocardiogram and 0.025 second after the rise of left intraventricular pressure (delayed Q-M_1 interval).

and the simultaneous low-frequency-low-amplitude sounds may reflect the early contraction of the trabeculae carneae and papillary muscles described by Rushmer.[21]

The final portion of the ascending limb of the systolic wave of the apex cardiogram was inscribed between the onset of M_1 and the onset of the upstroke of the carotid pulse. This interval is represented by the second pre-ejection component of the apex cardiogram and corresponds indirectly to the isometric contraction of the left ventricle;* its average duration was 0.067 second (PEC-II, figs. 1 and 2, table 1). This figure is quite comparable to the direct measurement of 0.061 second found by Braunwald et al.[16] between the onset of left intraventricular systolic pressure and the onset of left ventricular ejection.[16] In the present study the principal

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* This interval is better called the isovolumetric contraction period.[34] Because of common usage, however, it is referred to here as the isometric contraction period.

vibrations of the first heart sound (M_1 and T_1) occurred before the maximal systolic peak of the apex cardiogram. In other words, these components occurred during the isometric contraction of the left ventricle. Exceptions to this relationship would be expected in the presence of delayed closure of the tricuspid valve (complete right bundle-branch block and severe tricuspid stenosis). Under such circumstances, T_1 would follow the maximal systolic peak of the apex cardiogram.

Systolic Wave, Ejection Component. The maximal systolic peak of the apex cardiogram, marking the end of the pre-ejection components, coincided with the onset of the upstroke of the carotid pulse and with the beginning of the fourth component of the first heart sound (numeral 4 of figs. 1 and 2).

Observations made in this laboratory indicate that there is virtually no lag between
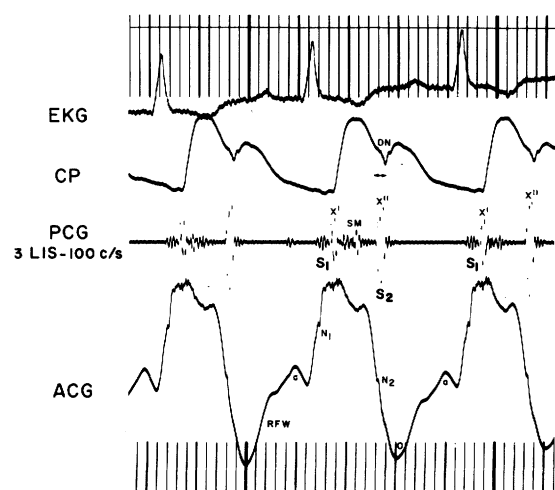
Figure 4

Electrocardiogram, carotid pulse, phonocardiogram, and apex cardiogram in a patient with aortic valve prosthesis. The ejection click (X') of the caged ball-valve coincides with the onset of the upstroke of the carotid pulse; the onset of the closure click (X'') of the caged ball-valve occurs 0.030 second before the incisura of the carotid dicrotic notch; and the notch N_2 coincides with the onset of the closure click (X'') of the caged ball-valve. Coarse vibrations interrupt the inscription of the maximal systolic peak of the apex cardiogram.

the onset of actual left ventricular ejection and the onset of the upstroke of the indirect carotid tracing. There is considerable lag (0.02 to 0.04 second), however, between recording of aortic valve closure (A_2) and the incisura of the carotid tracing. Direct and indirect evidence supports the above statement:

1. The phonocardiographic study of a patient in whom an aortic cage-ball prosthesis [22] was inserted showed two high-frequency, large-amplitude clicks during the period of left ventricular ejection (X' and X'', fig. 4). The first of these clicks (X') may be presumed to have occurred at the instant of impact of the silicone rubber-covered ball against the inner surface of the stainless-steel cage constituting the outer portion of the valve. Similarly, the second click (X'') presumably occurred at the instant at which the ball returned to and struck the circular base of the same cage. Whereas X' coincided with the onset of the carotid tracing, there was a delay of 0.035 second between X'' and the incisura of the carotid pulse.

2. The interval between the onset of M_1 and the onset of the upstroke of the carotid pulse (PEC-II, table 1) was 0.067 second in the present series and is comparable to that of 0.061 second found by direct measurement between the rise of left intraventricular pressure and the onset of left ventricular ejection.[16]

3. The QRS complex preceded the beginning of the upstroke of the carotid pulse by an average of 0.125 second in the present series, whereas the interval from the onset of the QRS complex to the point of onset of left ventricular ejection in Braunwald's series [16] was 0.115 second.

4. The onset of the upstroke of the carotid pulse and the maximal systolic peak of the apex cardiogram coincided with the terminal low-frequency-low-amplitude vibrations of the first heart sound (fourth component) in all cases in the present study.

The evidence presented suggests that there is a negligible lag in the inscription of the onset of the upstroke of the carotid pulse

but a definite lag in the inscription of the incisura. It is suggested that this discrepancy is attributable to the rapid propagation of the pulse wave in the arterial wall [23] at the onset of left ventricular ejection, contrasting with a relatively slow retrograde pulse wave occurring at the end of ejection. It is to be emphasized that aortic valve opening, as timed by the click (X', fig. 4), which is assumed to be due to the impact of the ball against the cage of the prosthesis, coincides with the onset of the upstroke of the carotid pulse and therefore that this point of the carotid tracing has virtually no time lag and may be used as a reliable reference point for timing the opening of the aortic valve and the onset of left ventricular ejection.

From the maximal systolic peak, at the onset of left ventricular ejection, the systolic wave of the apex cardiogram showed a rapid descent and reached a plateau at midsystole. This initial systolic descent of the apex cardiogram showed a close reciprocal relationship with the carotid pulse. As the carotid pressure curve rose rapidly the apex cardiogram tracing descended at a similar speed until the above-mentioned plateau was reached. This plateau in turn gave way to a secondary rapid descent. In the majority of cases a rounded shoulder marked the transition. In eight cases a small dome-like bulge was inscribed instead of a smoothly sloping shoulder. The end-systolic shoulder preceded the onset of aortic valve closure by an average of 0.036 second. This interval is comparable to that of 0.040 second measured by Wiggers by direct means [9] and represents in the apex cardiogram the protodiastolic phase described by this authority (PD, figs. 1 and 2).

Diastolic Waves. It was not always possible to identify the onset of diastole in the apex cardiogram. In 18 of the subjects studied it was ushered in by a notch (N_2) that coincided with the aortic component of the second sound. This notch, when recorded, interrupted the continuing secondary downstroke, signaling the end of the protodiastolic period and the onset of isometric relaxation.

Under special circumstances, such as the presence of systolic ejection murmurs arising in the right side of the heart and ending beyond aortic valve closure, or of reversed splitting of the second sound, the recognition of A_2, measured from the incisura of the carotid pulse, may be difficult. In these cases A_2 may be identified from its simultaneity with N_2 of the apex cardiogram.

The O point, which marks the opening of the mitral valve,[2, 3] was inscribed at an average of 0.091 second after the onset of A_2. This interval, from the onset of A_2 to the O point, measures indirectly the isometric relaxation phase of the left ventricle [14] (IRP, figs. 1 and 2).

Simultaneous apex cardiograms and pulmonary wedge pressure tracings have demonstrated that the O point of the apex cardiogram coincides with the peak of the *v* wave (opening of the mitral valve).[14] It is general-
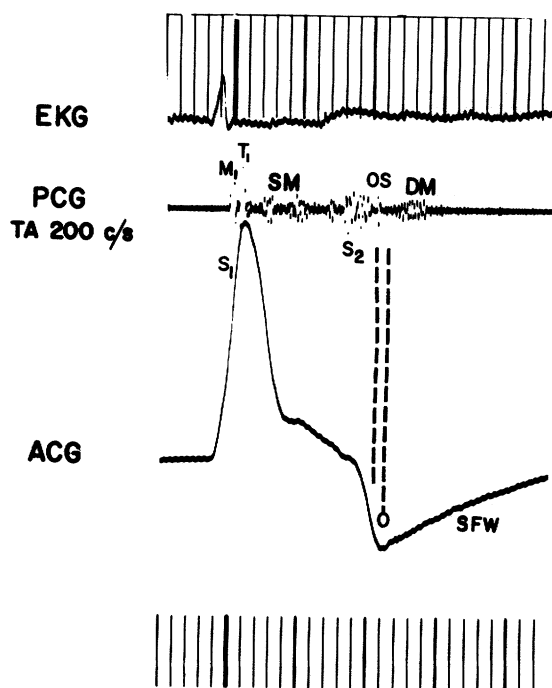
Figure 5

A tricuspid opening snap. Electrocardiogram, phonocardiogram (tricuspid area), and apex cardiogram in a patient with tricuspid stenosis demonstrated at cardiac catheterization. The opening snap (OS) occurs before the O point of the apex cardiogram.
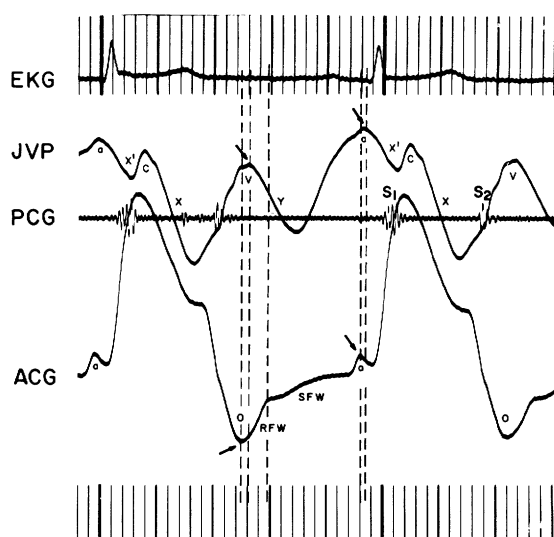
Figure 6

Electrocardiogram, jugular venous pulse, phonocardiogram, and apex cardiogram recorded simultaneously in a normal subject. The peak of the a wave of the JVP follows the peak of the a wave of the ACG; the summit of the v wave of the JVP follows the O point of the ACG. The nadir of the y descent of the JVP occurs long after the peak of the RFW of the apex cardiogram.

ly agreed that this point is useful in timing the opening mitral snap. From the present study it appears that the apex cardiogram may be of additional value in timing the opening snap of the tricuspid valve. By means of synchronous border electrokymograms of the left and right atrium Reinhold and Rudhe [11] have demonstrated that on the average the tricuspid valve opens 0.030 second before the mitral valve. This suggests that an opening snap occurring before the O point of the apex cardiogram is due to tricuspid valve opening (fig. 5). The succeeding rapid filling wave and the slow filling wave reflect the phasic filling of the left ventricle. The third heart sound occurs simultaneously with the peak of the rapid filling wave (fig. 7). The latter is therefore generally accepted as useful in timing the third heart sound and in separating it from the opening snap of mitral stenosis.

The diastolic components of the apex cardiogram have been amply described pre-

viously.[3, 6, 7, 14, 24] Diagnostic changes in the configuration, duration, and amplitude of the rapid filling wave in the presence of mitral stenosis and regurgitation as well as the timing of other diastolic phenomena have been emphasized by Benchimol et al.[13, 14, 25]

Temporal Relationship of the Apex Cardiogram with the Jugular Venous Pulse

Experience in this and other laboratories confirms the value of changes in configuration and amplitude of the waves of the jugular venous pulse in the differential diagnosis of various pathologic states. Examples include tall *a* waves in pulmonary hypertension, tricuspid and pulmonic stenosis;[26] ventricularization (c-v complex) in the presence of tricuspid regurgitation;[27, 28] and the differentiation between supraventricular and ventricular ectopic beats and between supraventricular and ventricular tachycardias.[28] But its value as a reference tracing for the phonocardiogram must be questioned.

A comparison of the components of simultaneous apex cardiogram and jugular venous pulse showed the following (fig. 6): (1) Even though, under normal conditions, tricuspid valve opening precedes mitral valve opening by 0.030 second[11] the summit of the *v* wave of the jugular venous pulse (tricuspid valve opening) was inscribed at an average of 0.066 second *after* the O point of the apex cardiogram (mitral valve opening) (fig. 6). (2) The nadir of the *y* descent of the jugular venous pulse reflects the end of rapid right ventricular filling, and the peak of the rapid filling wave of the apex cardiogram marks the end of the rapid left ventricular filling phase. Although the former event, namely, right ventricular filling, is known to occur *before* left ventricular filling, the peak of the rapid filling wave of the apex cardiogram *preceded* the nadir of the *y* descent of the jugular venous pulse. (3) Despite the fact that normal right atrial contraction *precedes* left atrial contraction by 0.020 second,[16] the peak of the *a* wave of the jugular venous pulse followed the peak of the *a* wave

of the apex cardiogram by an average of 0.031 second. Similar relationships have been found by previous investigators.[2, 6]

The reason for this apparent reversal of the normal asynchrony in the two sides of the heart, obtained from the simultaneous jugular venous pulse and apex cardiogram, is the delay in the transmission of the "actual" right atrial pressure waves into the neck veins. Lagerlöf and Werkö[29] by recording direct atrial pressure and external jugular venous pulse simultaneously found a lag of 0.080 second between the *a* wave of the right atrium and the *a* wave of the jugular venous pulse. As there is no delay between an acoustic event and its recording in the phonocardiogram, this same simultaneity would be required of a reference tracing for the phonocardiogram. The jugular venous pulse does

not fulfill this requirement. Since the apex cardiogram has less time lag than the carotid pulse of jugular venous pulse it satisfies more closely the requirements of a reference tracing for the phonocardiogram.

"Right ventricular apex cardiograms" recorded at the junction of the fourth left intercostal space and the left sternal margin have been reported as useful in timing right-sided events.[14, 30] Since it proved difficult to record reproducible tracings over the right ventricle this problem was not pursued in the present investigation. The necessity for timing right-sided events by a right ventricular apex cardiogram is in part obviated, however, by the ability of the left-sided apex cardiogram to time certain right-sided events.
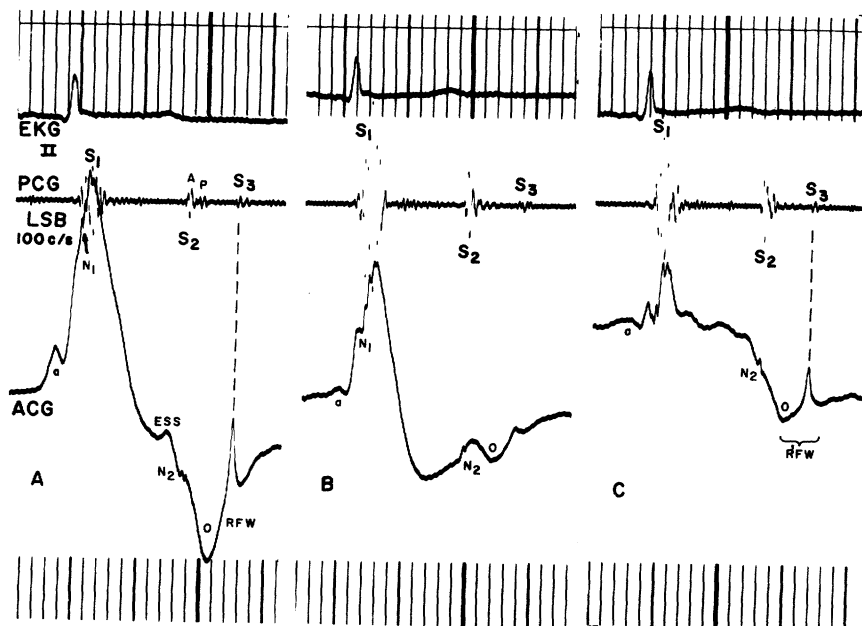
Discussion

The movements of the precordium at the

Figure 7

Apex cardiogram recorded sequentially. Tracing A demonstrates proper placement of the chest pieces of the ACG, all components clearly shown. Notch N_1 coincides with the onset of M_1; notch N_2 coincides with A_2 and the end-systolic shoulder (ESS) occurs before A_2. A prominent third heart sound (S3) corresponds with a peaked rapid filling wave (RFW). Tracing B shows an out-of-phase recording with a diminutive a wave and distorted ejection components and diastolic waves. Tracing C shows the apex cardiogram with proper placement of the chest piece but with attenuated amplification. Although the time relationship with the acoustic events is maintained, the configuration of the systolic components is distorted.

point of maximum impulse can be recorded in most normal subjects. These consist of systolic and diastolic components of definite and reproducible contour. The normal apex cardiogram has been the object of limited attention. The findings of the present investigation agree only in part with those reported in the few previous studies. The discrepancies can be explained partially by differences in technics. It has been demonstrated recently,[14] for example, that when the chest piece of the apex cardiogram is placed at a point other than the maximal apex impulse, an out-of-phase distorted pulse wave is inscribed (fig. 7).

Rappaport and Sprague[3] have stated that the apex cardiogram records primarily low-frequency vibrations. Because of its flat electronic response they considered it a linear phonocardiogram. According to these authors, it records accurately the first and fourth components (initial and terminal low-frequency-low-amplitude vibrations) of the first heart sound, but poorly, if at all, the vibrations of higher frequency and larger amplitude (the mitral and tricuspid components of the first heart sound). In the present study, with a similar crystal microphone for pulse wave recording[10] but with greater amplification and a smaller chest piece, notches coincident with the higher frequency, larger amplitude vibrations were well recorded. These were inscribed on the ascending limb of the systolic wave of the apex cardiogram coincident with the mitral (M_1, figs. 1 and 2) and tricuspid components of the first heart sound and on the descending limb of the systolic wave of the apex cardiogram coincident with the aortic component of the second sound (N_2, figs. 1 and 2). With the present recording technic, then the apex cardiogram registered small notches coincident with the higher frequency and larger amplitude components of the first and second heart sounds. No notches were inscribed that coincided with the initial and terminal vibrations of the first heart sound. It cannot be said with certainty wheth-

er these notches reflect acoustic or hemodynamic events.

In a most timely publication Coulshed and Epstein[31] see three principal uses in the apex cardiogram: (1) as a reference tracing in phonocardiography and particularly in timing left-sided phenomena; (2) in the evaluation of the relative role of stenosis and of regurgitation of the mitral valve; and (3) in the postoperative assessment of patients who have had mitral valve surgery. They consider that the apex cardiogram records both movements of the heart and changes in left ventricular volume but emphasize that it provides qualitative rather than quantitative information.

With these opinions we are in substantial accord. The apex cardiogram records motions of the chest wall which are, in large measure, produced by the heart. It reflects both the movements of the heart in the chest cavity and the intrinsic volume-pressure changes in the cardiac chambers—principally phasic contraction and emptying of the left ventricle on the one hand and relaxation and filling of this ventricle on the other. The deflections recorded are not random. They are uniform and can be explained on the basis of the known physiologic sequence of the cardiac cycle.

The morphology of the apex cardiogram is consistent with the thesis that it is largely the movement of the heart or the first derivative of the movement of the heart[32] which is recorded. As the wave of excitation traverses the Purkinje system spreading over the endocardial surface of the ventricles, the trabeculae carneae and papillary muscles are the first structures of the heart to contract.[21] Hawthorne et al.[33] have shown that with the onset of this contraction, the internal length of the heart decreases as the mitral valve is pulled toward the ventricular cavity. Simultaneously there is an expansion of the circumference of the ventricular wall. The initial increase in circumference of the chamber appears to occur before there is any rise in intracavitary pressure. As intracavitary pressure is generated, the circumference contin-

ues to increase in size until the moment of aortic valve opening. This coincides with the maximal systolic peak of the apex cardiogram. During the ejection phase the circumference diminishes and a negative wave is inscribed in the apex cardiogram. The pressure in the ventricular cavity continues to decrease until the O point is reached, at which time filling from the atrium begins.

Mention should be made of some of the limitations in the recording of the apex cardiogram: thick chest walls precluding adequate contact of the chest piece with the point of the maximum apical impulse, e.g., obesity, large breasts, thick pectoral muscles; intrathoracic disease preventing contact between the heart and the chest wall, e.g., pulmonary emphysema, pleural and pericardial effusion; and abnormal rotation of the heart causing displacement of the left ventricle, e.g., right ventricular hypertrophy, kyphoscoliosis. Even in some of the above instances, adequate attention to the details of positioning the patient and proper placement of the recording chest piece will often permit the operator to record accurate and reproducible apex cardiograms. The small chest piece used in this study facilitated the recording of satisfactory tracings even in individuals whose prominent ribs would have prevented optimal contact of a larger pick-up.

Summary

The configuration of the apex cardiogram and its temporal relationship to the electrocardiogram, phonocardiogram, carotid pulse, and jugular venous pulse were analyzed in 25 normal subjects. In two patients with rheumatic valvular disease simultaneous electrocardiograms, phonocardiograms, left intraventricular pressure and apex cardiograms were obtained. In all cases the apex cardiogram showed a characteristic and reproducible contour in both its systolic and diastolic components. The curves of the apex cardiogram display all consecutive phases of the cardiac cyle; contraction-and-emptying and relaxation-and-filling. It bears a constant relationship to the phonocardiogram and is more useful as a reference tracing for acoustic events than the electrocardiogram, carotid pulse, or jugular venous pulse. The onset of the systolic wave of the apex cardiogram precedes the rise of left intraventricular pressure and mitral valve closure. The maximal systolic peak of the apex cardiogram occurs simultaneously with the onset of left ventricular ejection and the rise of the carotid pulse pressure. Small deflections are frequently inscribed on the apex cardiogram at the time of mitral, tricuspid, and aortic valve closure.

The wave form of the apex cardiogram is caused primarily by movements of the left ventricle against the chest wall. It is thus a translation of the sequence of hemodynamic events occurring in the underlying left ventricle. The inaccuracy of the jugular venous pulse for timing right- and left-sided cardiac events is emphasized.

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Research and Teaching

Original thinkers and investigators do not therefore represent the only type of university professor. They will always be the distinguished figures; theirs will usually be the most profound and far-reaching influence. But even universities, modern universities, need and use men of different stamp—teachers whose own contributions to learning are of less importance than their influence in stimulating students or their resourcefulness in bringing together the researches of others.—ABRAHAM FLEXNER, *Universities— American, English, German* (Oxford University Press, New York, 1930), p. 6.

Circulation

The Normal Apex Cardiogram: Its Temporal Relationship to Electrical, Acoustic, and Mechanical Cardiac Events

EMILIO TAFUR, LAWRENCE S. COHEN and HAROLD D. LEVINE

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