THE APEX CARADIOGRAM: ITS NORMAL FEATURES EXPLAINED BY THOSE FOUND IN HEART DISEASE

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Received October 2, 1962

The recording and interpretation of the low frequency movements at the cardiac apex have received little attention in recent years, when compared with the emphasis placed on the arterial and venous pulses in the neck. We are of the opinion that close scrutiny of the apex cardiogram, i.e. the record of these low frequency præcordial movements, is of great value, not only as a reference tracing in phonocardiography, but as a diagnostic aid in itself.

Marey first recorded the apex cardiogram experimentally in 1863, and in 1885 he recorded it in man, using a Marey capsule and a mechanical recording system. Mackenzie (1902), Müller (1906), Hay (1909), and Dressler (1937) used similar methods, and the published records are of good quality. Photographic recording, using a light beam reflected from a Frank capsule, was used by Hess (1915), Weitz (1922), Routier and Van Bogaert (1934), and Orias and Braun Meñendez (1939), while Crehore had used a comparable method in 1911.

All these methods of recording depended upon air displacement in a system of tubes leading to a membrane, only the method of inscription being fundamentally different. Taquini, Massell, and Walsh (1940) and Rappaport and Sprague (1942) used a piezo-electric microphone (Miller and White, 1941) activated by air displacement in a system of tubes leading from the area of pulsation that it was wished to record. Johnston and Overy (1951), Luisada and Magri (1952), and Luisada (1953) obtained similar apex cardiograms using both an electromanometer and a piezo-electric microphone. Hartman (1956) and Hartman and Snellen (1960) revived interest in the diagnostic value of the apex cardiogram, and it was after a visit to see Hartman's work that we started the routine recording of the apex cardiogram in this unit in 1958.

Since then further studies have been reported by Benchimol *et al.* (1960); Benchimol, Dimond, and Carson (1961) and Benchimol and Dimond (1962). Schneider and Klunhaar (1961) used a special transducer to record localized præcordial displacement, and their tracings bear some resemblance to the apex cardiogram.

All the records referred to above are displacement curves that record the relative movements between the heart and the chest wall. Eddleman *et al.* (1953a, b); Eddleman and Willis (1953); and Eddleman *et al.* (1957) described another type of displacement curve, the kinetocardiogram also recorded with a piezo-electric microphone. This gives information about total præcordial movement relative to a fixed point away from the chest wall. Harrison, Coghlan, and Prieto (1961) and Prieto, Coghlan, and Harrison (1961) analysed the kinetocardiogram in more detail and gave experimental evidence showing its relation to the velocity of blood flow in the cardiac chambers. Beilin and Mounsey (1962) have also described similar total movements of the chest wall using a photoelectric pick-up device instead of a piezo-electric microphone.

Mounsey (1957, 1959), using an accelerometer that recorded rate of change of velocity, described a type of apex pulse differing in form from the kinetocardiogram and apex cardiogram, but still recognizably demonstrating the same events. Groom *et al.* (1956) and Hollis and Vidrine (1959) have used a direct contact electronic pick-up to record low frequency vibrations. Their tracings closely resemble those of Mounsey (1957).

The movements of the præcordium are produced by a combination of factors, including cardiac movements, changes in the volume and consistency of the heart, and pulsation of the great vessels. In the dorsal decubitus position cardiac movement, produced by muscle contraction and relaxation, and by rotation of the heart, is best recorded at the apex. Volume changes, decreasing in systole and increasing in diastole, are best seen at the parasternal area, while the great vessel movements are best recorded at the base of the heart.

Since 1959 we have been using a piezo-electric microphone (Cambridge Instrument Company) as our recording apparatus (Fig. 1), and the apex cardiogram is now part of the routine phonocardiographic practice of this unit.

This paper is mainly concerned with the normal apex cardiogram, its recording, formation, appearance, and its time relations. Reference has been made in the text to its various abnormalities, particularly where they are relevant to the description and formation of the various phases of the normal apex cardiogram.

We have restricted our comments to the left ventricular apex cardiogram, as we have not so far

FIG. 1.—The apparatus used for pulse wave recording: 1. Piezo-electric microphone. 2. Polythene tubing. 3. Funnel pick-up device.

been satisfied that information of diagnostic value has been obtained from tracings from the right ventricle.

SUBJECTS AND METHODS

Thirty normal subjects were studied, in whom cardiac and pulmonary disorders had been excluded. There were 27 men and 3 women, and the ages ranged from 17 to 45 years.

The recording of the apex cardiogram in these subjects was performed in a similar fashion to the routine phonocardiographic practice of this unit. Using the piezo-electric microphone to record the pulse wave forms, and a crystal microphone to record the heart sounds, this latter microphone was placed in succession on the second right interspace parasternally (2R); the fourth right interspace parasternally (4R); the second, third, and fourth left interspaces parasternally (2L, 3L, and 4L); at the apex beat and midway between the apex and 4L which corresponds to the position of electrocardiogram lead V3. Any other area was recorded when necessary, and simultaneous mid and low frequency records were taken.

With each recording of the heart sounds, a simultaneous electrocardiogram (usually lead II), and an indirect carotid pulse using the piezo-electric microphone were taken as reference tracings. All the records were taken at a paper speed of 100 mm./sec., and with respiration halted in mid expiration.

For the pulse wave tracings, a reference electrocardiogram, again usually lead II, was accompanied by a phonocardiogram, usually at position 4L and a mid-frequency record. With a paper speed of 50 mm./sec. careful tracings of the carotid and jugular pulses were made, and using the same pick-up, the pulsations at the apex beat were recorded, both in the dorsal and the left lateral position. Monitoring of the tracings, using an oscilloscope, was essential, so as to obtain satisfactory tracings. Identification of the underlying ventricle was accomplished by placing the unipolar electrocardiogram chest lead in the position of the piezo-electric pick-up, and recording the electrocardiogram. With practice, a complete record can be made in less than 20 minutes.

It is important to note that the carotid, jugular, and apex pulse tracings are all obtained by using the simple robust apparatus shown in Fig. 1. The pick-up is a simple funnel, made of any suitable material, and with an internal diameter at its widest point, of approximately 1.5 cm. enabling it to fit into the average intercostal space. This funnel is connected to the piezo-electric microphone by a length of rigid plastic tubing less than 1 metre in length. The frequency response of the piezo-electric microphone is virtually linear from near zero to several hundred cycles per second, and it records changes in pressure at the pick-up funnel, the speed of response being limited only by the recording galvanometer. The amplifier controls of the galvanometer are similar to those used for the electrocardiogram, the sensitivity control being extremely simple to use.

To record the apex cardiogram the patient is propped up at an angle of 45° and the point of maximal cardiac impulse is determined by palpation both in the dorsal and in the left lateral position. The pick-up funnel is placed over the point of maximal pulsation and held firmly but not heavily in position, to prevent movement between it and the chest wall. Slight changes in position are often necessary before a suitable wave-form is seen on the oscilloscope, but the technique is not difficult, and we have now recorded many hundreds of these tracings.

With this apparatus, the difference in timing between the pulse wave recording through the piezo-electric microphone, and the sound recording through the crystal microphone, is less than 0.005 sec., less than the error involved in measuring the wave forms.

DESCRIPTION OF THE NORMAL APEX CARDIOGRAM

The normal apex cardiogram can be divided into four main phases, three of which are diastolic events. These are shown in Fig. 2, phase 1 representing the "a" wave; phase 2 the systolic wave which has many normal variations; phase 3 the early ventricular filling wave (EFW); and phase 4 the slow ventricular filling.

Point "O" represents the nadir of the apex cardiogram, between phases 2 and 3, and point "F" the end of the early ventricular filling phase, between phases 3 and 4. The diagram in Fig. 2 shows that the "a" wave in the apex cardiogram begins at about the apex of the P wave of the electrocardiogram, and the upstroke of the apex cardiogram begins with the QRS complex. The downstroke begins before the end of the T wave, but the phonocardiogram is a better reference tracing than the electrocardiogram particularly for diastolic events.

The first heart sound occurs on the main upstroke of the apex cardiogram, and the second sound (the aortic or pulmonary component, depending upon which ventricular pulsation is to be recorded) can be seen to occur on the downstroke of the main systolic wave. Both first and second sounds, therefore, are included in phase 2 of the apex cardiogram.

FIG. 2.—The normal apex cardiogram (ACG), showing the different phases of the wave form, and their relation to the phonocardiogram (PCG) and electrocardiogram. Phase 1=atrial wave. Phase 2=ventricular systole. Phase 3=rapid ventricular filling. Phase 4=slow ventricular filling. The numbers, 1, 2, 3, and 4, below the PCG indicate the four heart sounds, O is the nadir of the wave form and indicates the position of the opening snap. F is the end of the rapid filling wave, and "a" indicates the atrial wave.

left ventricular, and apex cardiogram pulse tracing, and it can be seen that the "a" waves all occur together. Accepting that the fourth heart sound is associated with atrial contraction, the "a" wave of the apex cardiogram immediately precedes this sound.

Moreover, if the A-V valve is so obstructed that flow and pressure changes through it are much slowed, then it would be expected that the "a" wave on the apex cardiogram would diminish and disappear. This in fact happens in mitral stenosis (Fig. 6). Similarly, if the atrium has to hypertrophy because of a rise in the end diastolic pressure in the ventricle, then the "a" wave of the apex

The point "O" at the end of phase 2 coincides with the opening snap of the appropriate atrio-ventricular valve, to within 0.01 sec., and the end of phase 3, that is the end of early ventricular filling, coincides with the third heart sound if this is present. The fourth sound occurs near the apex of the "a" wave in the apex cardiogram.

To consider the form of the apex cardiogram in more detail, we have described the four separate phases, together with their relation to the heart sounds. Table I shows the various measurements made on the 30 normal subjects. Both the mean and range of values are given for each parameter.

Phase 1 is the "a" wave representing late ventricular filling produced by atrial contraction. That it is in fact caused by atrial activity can be shown by its disappearance in atrial fibrillation, by its early appearance when there is prolongation of the P-R interval, and, as is shown in Fig. 4 and 5, by its complete dissociation from the main ventricular wave in cases of complete heart block. A similar pattern in this case is shown by direct recording of the right ventricular pressure wave at cardiac catheterization. Fig. 3 shows superimposed left atrial,

TABLE I

	Range (sec.)	Mean (sec.)
Onset of apex cardiogram to M1	0.021-0.082	0.044
Onset of apex cardiogram to A2	0.300-0.410	0.374
M1 to A2 interval	0.263-0.385	0.331
A2 to point "O" interval . . .	0.053-0.110	0.087
Point "O" to peak of "F" wave .	0.071-0.150	0.101
A2 to peak of "F" wave	0.155-0.247	0.188

All the time intervals have been corrected for heart rate using the Bazett formula.

FIG. 3.—A composite record of left atrial (LA) and left ventricular (LV) pressure curves together with the apex cardiogram. The records were taken from a male patient, age 32, with coarctation of the aorta, and a blood pressure of 180/110 mm. Hg in both arms. Left heart catheterization was performed for angiographic purposes, and the LA and LV pressure curves were recorded in turn, each simultaneously with the electrocardiogram and apex cardiogram, suitable complexes then being superimposed. It can be seen that the "O" point on the apex cardiogram just precedes the cross-over point of the LA and LV pressure curves. The "F" point coincides with the nadir of the early diastolic dip on the LV tracing. a, c, x, and y have their usual connotation with regard to the atrial pulse, and the pressure scale on the figure does not, of course, apply to the ACG.

cardiogram should increase in size, and again this can be seen to occur in aortic stenosis (Fig. 7), in systemic hypertension, and to a less extent in mitral regurgitation.

Phase 2 is the main systolic wave, and is produced by ventricular contraction. This wave has many variables, but it usually consists of an initial rapid upstroke, followed by a descending or ascending plateau, and a rapid descending wave, which may be preceded by a second, smaller peak.

The initial upstroke is probably produced by an increase in tension in the muscle, altering the shape of the heart, and by forward rotation of the apex beat. The initial upstroke is often interrupted by small vibrations which represent the first heart sound, and as shown in Table I the time interval from the onset of phase 2 to the first sound varies from 0.021 to 0.082 sec., with an average of 0.044 sec. As left ventricular volume decreases with ejection of blood, the plateau part of the curve is formed, and with changing heart shape a second peak may occur, to be followed by the rapid descent of ventricular relaxation. On this rapid descent, small vibrations representing the second heart sound may be seen.

Measuring the height of the upstroke from the end of the slow filling phase, the first sound occurred at about two-fifths of the way up to the summit; and using the point "O" as a reference on the descending limb, the second sound occurred at just more than half of the way down. The lowest point on the descending limb (point "O") occurs where the atrio-ventricular valves open, and blood

FIG. 4.—Record taken from a woman aged 19, with complete heart block, showing the relation between the P waves of the electrocardiogram, and the “a” waves of the apex cardiogram, and their dissociation from ventricular activity. Each “a” wave is associated with a fourth heart sound; the wide splitting of the second sound is associated with the right bundle-branch block.

FIG. 5.—The catheter tracing from the right ventricle of the same patient as in Fig. 4. It demonstrates the atrial waves, dissociated from the ventricular complexes as are the “a” waves of the apex cardiogram in Fig. 4.

begins to flow into the empty relaxing ventricle. It coincides very closely with the opening snap in mitral stenosis, but it does not represent the point at which the intraventricular pressure is lowest, rather the point at which pressure in the atrium exceeds that in the ventricle. This is well shown in Fig. 3, where the nadir of the apex cardiogram (point “O”) immediately precedes the intersection of the atrial and ventricular pressure curves, which from then on fall together to a lower level.

The time interval between the aortic second sound and the point “O” varied between 0.053 and 0.110 sec., with an average of 0.087 sec. (Table I).

Phase 3 begins at point “O”, and ends at the point we have designated “F”. It represents the sudden inflow of blood into the empty relaxing ventricle, and the steep rise of the curve is known as the early filling wave (EFW) or rapid filling wave (RFW). With this rapid inflow, the atrio-ventricular valves float towards each other, stretching the chordæ. This movement may be palpable, and is almost certainly the cause of the small peak at the end of the rapid filling phase. It is at least partly responsible for the third heart sound which occurs at this time.

If the mitral valve is stenosed, there cannot be rapid flow through it in early diastole, so that the EFW is either much slowed, or obliterated altogether (Fig. 6). On the other hand, if the valve is incompetent, the early ventricular filling produced by the increased volume of left atrial blood is both deep and steep, and often causes a sharp peak at point "F" (Fig. 8).

In the normal subject, the time interval between point "O" and "F" varied from 0.071 to 0.150 sec., with a mean of 0.101 sec.

FIG. 6.—Records from a woman aged 21, who had severe mitral stenosis, the valve diameter being assessed at operation as being 1 cm., split to 4.5 cm. On left: the pre-operative tracing, showing absence of both "a" waves and rapid filling waves. On right: the post-operative tracing, showing that both the "a" waves and the rapid filling waves are now clearly defined.

Phase 4 follows the rapid filling phase, with the curve of the pulse wave abruptly becoming much more shallow. This represents the late phase of passive diastolic filling, and ends at the next "a" wave, or at the onset of the next main systolic wave. This slow filling is readily seen in the normal, and in mitral regurgitation, but is merged into phase 3, the differentiation between two phases (3 and 4) often being indistinguishable in severe mitral valve stenosis.

It is probable that point "F" on the apex cardiogram—that is the end of rapid ventricular filling—coincides with the annular ascent point of Radner (1957, 1958) and almost certainly is the point at which intraventricular pressure begins to rise, i.e. is the point of the early diastolic "dip" of intraventricular pressure tracings (Fig. 3).

DISCUSSION

For more than 70 years the apex cardiogram has been used as a reference tracing to time events in the cardiac cycle. Many investigators recorded simultaneous pulse waves from the jugular veins, the radial pulse, and cardiac apex, and related the wave forms to cardiac haemodynamics (Mackenzie, 1902; Hay, 1909). Much of the original work on the third heart sound depended on the relation of this sound to the diastolic events recorded at the cardiac apex (Müller, 1906; Thayer, 1908, 1909; Bridgman, 1915; Hirschfelder, 1918; Routier and Van Bogaert, 1934).

Henderson (1906) demonstrated experimentally by cardiac plethysmography that left ventricular filling takes place rapidly and almost completely in the early part of diastole once the mitral valve

FIG. 7.—From a man, aged 17, with severe aortic stenosis. LV pressure 320/25 mm. Hg, peak systolic gradient across the aortic valve 200 mm. Hg. The apex cardiogram shows tall “a” waves, and deep early ventricular filling waves. Third and fourth sounds are visible on the phonocardiogram, the third sound coinciding with point “F”, and the fourth sound with the downstroke of the “a” wave. The second heart sound precedes point “O”, and a loud ejection sound (ES) coincides with the peak of the systolic wave of the apex cardiogram.

has opened. This phase of rapid filling is then followed by a more gradual filling phase which he termed diastasis and which is in turn followed by the wave of atrial contraction. Most modern textbooks of physiology consider that 60 to 70 per cent of ventricular filling takes place during the early diastolic phase of rapid ventricular filling (Best and Taylor, 1961; Wright, 1961).

Harrison *et al.* (1961) and Prieto *et al.* (1961) recorded simultaneous intracardiac pressure pulses and velocity tracings in dogs and compared them with the kinetocardiogram in man. The velocity records from the left ventricle of the dog are very similar to the plethysmographic tracings of Henderson (1906) and show a rapid movement of blood into the left ventricle immediately the mitral valve has opened, which is then followed by a slow filling phase.

These phases of left ventricular filling can readily be demonstrated by the apex cardiogram. The rapid filling wave on the apex cardiogram appears to be related to the phase of rapid inflow in the early part of diastole following isometric relaxation of the ventricle. The “F” peak which signals the end of the rapid filling phase is associated in time with the physiological third heart sound or the pathological third heart sound in protodiastolic gallop rhythm or mitral regurgitation (Müller, 1906; Thayer, 1908, 1909; Bridgman, 1915; Hirschfelder, 1918; Routier and Van Bogaert, 1934; Orías and Braun Menéndez, 1939; Taquini *et al.*, 1940).

Mounsey (1957; 1959) showed a similar phase of rapid filling with the præcordial accelerometer.

Simultaneous apex cardiogram and left atrial pressure pulse tracings show that the “F” wave occurs at the same time as the annular ascent wing described by Radner (1957; 1958) and by Nixon (1961) (Fig. 3). Radner attributed the annular ascent wing to the ascent of the mitral valve annulus and consequent partial closure of the mitral orifice. At the same time the mitral cusps and chordæ are tensed by the ascent of the annulus as the ventricle continues to fill.

FIG. 8.—The apex cardiogram of a woman, aged 20, with severe mitral regurgitation, showing a steep early filling wave that “overshoots” to produce a tall peaked “F” wave. The PCG shows the two components of the second sound, preceding a soft opening snap which is coincident with point “O”, and a clear third heart sound occurring at, and shortly after, the peak of the “F” wave.

Dock, Grandell, and Taubman (1955) have shown by means of simultaneous phonocardiography and roentgenkymography that ventricular expansion is almost completed at the time of the third heart sound and that there is a momentary reversal of outward movement of the apical impulse probably caused by traction on the papillary muscles during the ascent of the annulus. They also noted that loud third heart sounds as in protodiastolic gallop rhythm were frequently associated with a headward or rightward thrust of the body in ballistocardiograms. The latter motion almost certainly corresponded to the præcordial “F” wave on the apex cardiogram. An audible third heart sound is often associated with a palpable “F” wave particularly in these patients when they are placed in the left lateral position (Thayer, 1908, 1909; Hirschfelder, 1918).

The time relation between a third heart sound and the “F” wave is of great value in differentiating it from an opening snap. The opening snap, as previously mentioned, is related to point “O” at the nadir of the downstroke of the systolic wave of the apex cardiogram whereas the third heart sound is related to point “F” at the peak of the rapid filling wave (Fig. 2). Both components of the second heart sound precede point “O”.

At first sight, the rapid filling wave on the apex cardiogram appears to resemble the early diastolic dip with succeeding pressure rise, seen on the left ventricular pressure pulse. These two events are in fact dissimilar and should not be confused. Simultaneous records of the left ventricular pulse wave and the apex cardiogram show that the left ventricular pressure is still falling at the time of the ascent of the rapid filling wave to the “F” peak on the apex cardiogram (Fig. 3).

The left atrial pressure falls rapidly from the “v” peak to the “y” trough after the mitral valve has opened. This fall is contiguous with the terminal part of the left ventricular pressure pulse and hence with the phase of rapid left ventricular filling (Orias and Braun Meñendez 1939; Braun-

wald *et al.*, 1955). The left ventricular pressure only begins to rise at about the time of the "F" point on the apex cardiogram: presumably at this point the left ventricular diastolic volume is at or near its maximum and with further inflow there is a rise of pressure in the left ventricle (Braunwald *et al.*, 1955; Nixon and Wooller, 1961). The velocity curves recorded from the left ventricle in the dog by Prieto *et al.* (1961) and Harrison *et al.* (1961) also demonstrate that the left ventricular pressure is still falling during the phase of rapid early filling.

The apex cardiogram records both cardiac movements and the changes in the volume of the left ventricle. The velocity of blood flow is probably also of some importance in the formation of the pulse contour, which is in fact a composite tracing, and care is necessary in its interpretation. Many factors affect the amplitude of the apex cardiogram, including the pressure used in applying the funnel to the chest wall, the amount of subcutaneous tissue, and the proximity of the heart to the thoracic cage. It is often difficult to record in obese or emphysematous patients. The information it provides is qualitative rather than quantitative.

We have now had an extensive experience in the recording of the apex cardiogram and find that it has three main uses. First as a reference tracing in phonocardiography and particularly in timing left-sided events in the cardiac cycle. In this respect, it is superior to the jugular pulse which only reflects right-sided events. There is no transmission delay in recording the apex pulse, other than that inherent in the apparatus, and this is one of its advantages over the indirect carotid pulse wave. Secondly it is of value in assessing patients with mitral valve disease and particularly in deciding whether mitral regurgitation or stenosis is dominant in those patients with mixed lesions. We propose to consider this subject in detail in a separate communication.

The third use of the apex cardiogram lies in the post-operative assessment of patients who have had a mitral valvotomy. It provides objective information as to what has been achieved. Following successful operation it is usually possible to demonstrate a rapid filling wave and "F" peak which were not present before (Fig. 6). If significant mitral incompetence has been produced at operation then a large "F" wave will be recorded on the apex cardiogram.

The use of the left lateral decubitus position for recording the apex cardiogram was first suggested by Pachon (1902) and later referred to by Thayer (1909), Manoukhine (1914), Hirschfelder (1918), Pachon and Fabre (1934), Benchimol *et al.* (1960), and Hartman and Snellen (1960). This is often the only way of obtaining a sustained systolic wave form in a normal subject and in the absence of left ventricular hypertrophy.

When the patient is turned on to the left side, the heart remains in contact with the chest wall throughout the cardiac cycle and the apex cardiogram is then dominated by the volume and velocity changes in the left ventricle: the effects of cardiac movement and rotation are thus reduced to a minimum. An adequate apex cardiogram can usually be obtained in the dorsal decubitus position when the left ventricle is hypertrophied, probably owing to the closer contact of the hypertrophied ventricle with the chest wall.

The value of this technique lies in its relative simplicity. No special additional apparatus is necessary and the equipment is the same as that used for the routine recording of the carotid and jugular pulse waves. With practice a left ventricular apex cardiogram can be recorded on almost every patient as part of the routine phonocardiographic study. The apex cardiogram is unique in that it is the only indirect method available for assessing diastolic events on the left side of the heart.

SUMMARY

The apex cardiogram is a record of the relative movements between the heart and the chest wall. Its mode of production has been discussed, and the recording technique described, emphasizing the simplicity of this technique employing apparatus used for recording indirect carotid and jugular pulse forms. It is the only simple indirect method of assessing diastolic events on the left side of the heart.

The four phases of the normal apex cardiogram have been described. Three of these phases are

produced by diastolic events, and are of considerable value in the interpretation of these events on the left side of the heart.

The time relations of the heart sounds to the apex cardiogram have been described, with particular emphasis on its use in differentiating between the opening snap and the third heart sound.

REFERENCES

- Beilin, L., and Mounsey, P. (1962). The left ventricular impulse in hypertensive heart disease. *Brit. Heart J.*, **24**, 409.
- Benchimol, A., and Dimond, E. G. (1962). The apex cardiogram in ischaemic heart disease. *Brit. Heart J.*, **24**, 581.
- , —, and Carson, J. C. (1961). The value of the apexcardiogram as a reference tracing in phonocardiography. *Amer. Heart J.*, **61**, 485.
- , —, Waxman, D., and Shen, Y. (1960). Diastolic movements of the precordium in mitral stenosis and regurgitation. *Amer. Heart J.*, **60**, 417.
- Best, C. H., and Taylor, N. B. (1961). *The Physiological Basis of Medical Practice*, 7th ed. Ballière, Tindall, and Cox, London.
- Braunwald, E., Moscovitz, H. L., Amram, S. S., Lasser, R. P., Sapin, S. O., Himmelstein, A., Ravitch, M. M., and Gordon, A. J. (1955). The hemodynamics of the left side of the heart as studied by simultaneous left atrial, left ventricular, and aortic pressures; particular reference to mitral stenosis. *Circulation*, **12**, 69.
- Bridgman, E. W. (1915). Observations on the third heart sound. *Heart*, **6**, 41.
- Crehore, A. C. (1911). A study of tracings from the region near the apex of the heart. *J. exp. Med.*, **14**, 351.
- Dock, W., Grandell, F., and Taubman, F. (1955). The physiologic third heart sound: its mechanism and relation to protodiastolic gallop. *Amer. Heart J.*, **50**, 449.
- Dressler, W. (1937). Pulsations of the wall of the chest. *Arch. intern. Med.*, **60**, 225.
- Eddleman, E. E., Hefner, L., Reeves, T. J., and Harrison, T. R. (1957). Movements and forces of the human heart. I. The genesis of the apical impulses. *Arch. intern. Med.*, **99**, 401.
- , and Willis, K. (1953). The kinetocardiogram: III. The distribution of forces over the anterior chest. *Circulation*, **8**, 569.
- , —, Christianson, L., Pierce, J. R., and Walker, R. P. (1953a). The kinetocardiogram: II. The normal configuration and amplitude. *Circulation*, **8**, 370.
- , —, Reeves, T. J., and Harrison, T. R. (1953b). The kinetocardiogram: I. Method of recording precordial movements. *Circulation*, **8**, 269.
- Groom, D., Underwood, A. F., Bidwell, J. B., and Lindberg, E. (1956). The recording of heart sounds and vibrations. I. Historical review and description of a new electronic direct-contact vibration pickup. *Exp. Med. Surg.*, **14**, 239.
- Harrison, T. R., Coghlan, C., and Prieto, G. (1961). The movements of the heart during ejection. *Amer. Heart J.*, **62**, 804.
- Hartman, H. (1956). Differentiation between the influence of the right and of the left ventricle in the phonocardiogram with the aid of pulsation curves. Second European Congress of Cardiology, Stockholm. Abstracts, p. 127.
- , and Snellen, H. A. (1960). Proceedings of the Third European Congress of Cardiology, Rome, 1960. Communications, p. 711.
- Hay, J. (1909). *Graphic Methods in Heart Disease*, 1st ed. Oxford University Press, London.
- Henderson, Y. (1906). The volume curve of the ventricles of the mammalian heart, and the significance of this curve in respect to the mechanics of the heart-beat and the filling of the ventricles. *Amer. J. Physiol.*, **16**, 325.
- Hess, C. (1915). Untersuchung der Bewegung des normalen und pathologischen Herzens, sowie der zentralen Gefaesse, mit der Frankschen Apparat. *Ergebn. inn. Med. Kinderheilk.*, **14**, 370.
- Hirschfelder, A. D. (1918). *Diseases of the Heart and Aorta*, 3rd ed., p. 173. Lippincott, Philadelphia.
- Hollis, W. J., and Vidrine, A. (1959). Time relations of the subaudible low-frequency precordial thrust-impacts and electro-mechanical events of cardiac contraction and systolic ejection. *Exp. Med. Surg.*, **17**, 234.
- Johnston, F. D., and Overy, D. C. (1951). Vibrations of low frequency over the precordium. *Circulation*, **3**, 579.
- Luisada, A. A. (1953). *The Heart Beat*, chap. 4, p. 64. Lewis, London.
- , and Magri, G. (1952). The low frequency tracings of the precordium and epigastrium in normal subjects and cardiac patients. *Amer. Heart J.*, **44**, 545.
- Mackenzie, J. (1902). *The Study of the Pulse, Arterial, Venous, and Hepatic, and of the Movements of the Heart*. J. Pentland Young, Edinburgh and London.
- Manoukhine, J. J. (1914). Le cardiogramme en décubitus latéral gauche dans les affections valvulaires du coeur. *Arch. Mal. Cœur.*, **7**, 107.
- Marey, E. J. (1863). *Physiologie Médicale de la Circulation du Sang*. Delahaye, Paris.
- (1885). *La Methode Graphique dans les Sciences Expérimentales*, 2nd ed. Masson, Paris.
- Miller, A., and White, P. D. (1941). Crystal microphone for pulse wave recording. *Amer. Heart J.*, **21**, 504.
- Mounsey, P. (1957). Precordial ballistocardiography. *Brit. Heart J.*, **19**, 259.
- (1959). Precordial pulsations in relation to cardiac movement and sounds. *Brit. Heart J.*, **21**, 457.
- Müller, F. (1906). Ueber Galopprhythmus des Herzens. *Münch. med. Wschr.*, **53**, 785.
- Nixon, P. G. F. (1961). The third heart sound in mitral regurgitation. *Brit. Heart J.*, **23**, 677.
- , and Wooler, G. H. (1961). Rapid left ventricular filling and stasis in mitral regurgitation. *Brit. Heart J.*, **23**, 161.

- Orias, O., and Braun Meñendez, E. (1939). *The Heart-Sounds in Normal and Pathological Conditions*. Oxford University Press, London.
- Pachon, V. (1902). Contribution à la technique cardiographique chez l'homme. *C.R. Soc. Biol. (Paris)*, **54**, 884.
- , and Fabre, R. (1934). *Clinical Investigation of Cardiovascular Function*, trans. J. F. Halls Dally. Kegan Paul, London.
- Prieto, G., Coghlan, C., and Harrison, T. R. (1961). Movements of the heart during the period between the onset of relaxation and the beginning of ventricular filling. *Amer. Heart J.*, **62**, 528.
- Radner, S. (1957). Left atrial pressure curve: significance of annular ascent wing. *Acta med. scand.*, **159**, 219.
- (1958). Extended suprasternal puncture technique for flow studies in 135 cases of mitral valvular disease. In *Circulation: Proceedings of the Harvey Tercentenary Congress, London, 1957*, ed. J. McMichael, p. 250. Blackwell, Oxford.
- Rappaport, M. B., and Sprague, H. B. (1942). The graphic registration of the normal heart sounds. *Amer. Heart J.*, **23**, 591.
- Routier, D., and Van Bogaert, A. (1934). Contribution à l'étude clinique du bruit du galop. *Arch. Mal. Cœur*, **27**, 588.
- Schneider, H., and Klunhaar, E. W. J. M. (1961). Precordial low-frequency displacements of the thoracic wall. Method of recording and registration. *Amer. Heart J.*, **61**, 670.
- Taquini, A. C., Massell, B. F., and Walsh, B. J. (1940). Phonocardiographic studies of early rheumatic mitral disease. *Amer. Heart J.*, **20**, 295.
- Thayer, W. S. (1908). On the early diastolic heart sound. *Boston med. surg. J.*, **158**, 713.
- (1909). Further observations on the third heart sound. *Arch. intern. Med.*, **4**, 297.
- Weitz, W. (1922). Studien zur Herzphysiologie und pathologie auf Grund kardiographischer Untersuchungen. *Ergebn. inn. Med. Kinderheilk.*, **22**, 402.
- Wright, S. (1961). *Applied Physiology*, 10th ed., revised by C. A. Keele and E. Neil. Oxford University Press, London.