Electrokymographic Studies in Insufficiency of the Aortic and Pulmonic Valves

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The following paper describes the results of electrokymographic studies performed on patients with proved aortic insufficiency. Alterations in the shape of the aortic ejection curve were found and were accompanied by a diminution or absence of the incisura in the presence of insufficiency of the aortic valves. Alterations in heart border motion of the ventricles were also found. The possible dynamic factors responsible for these changes are discussed and the clinical application of the electrokymograph to aortic and pulmonic valvular disease is pointed out.

Since Corrigan's description of the water-hammer pulse of aortic insufficiency in 1832, numerous studies of the alterations in circulatory dynamics have been reported. In human beings, MacKenzie recorded, by means of the polygraph, the characteristics of the peculiar pulse present in association with this disease. Feil, using optical methods of recording, has obtained recordings of the arterial pulse wave in patients similar to those recorded by MacKenzie. By means of the roentgenkymograph, records of the border motion of the heart and great vessels have been obtained in patients with aortic valvular disease. The roentgenkymographic method has certain inherent limitations, however, including the relative crudeness of the method of recording, and the difficulty of obtaining accurate measurements of the duration of various portions of the cardiac cycle for any given chamber or vessel. Although careful studies, utilizing optical means of recording, have been made of the pressure pulses in the aorta and aorta of animals with artificially induced aortic insufficiency, such direct methods of recording have not been systematically recorded in the human patient.

Recently Henny, Boone, and Chamberlain have introduced an accurate method of recording the border motion of the heart and great vessels by means of the electrokymograph. Tracings of the ventricular border motion recorded optically with this instrument have revealed a marked similarity to volume curves of the heart obtained in animals by means of the cardiometer. Records of border motion of the great vessels closely resemble those obtained from intra-aortic pressure tracings.

It is the purpose of the present study to record the alterations from the normal in such tracings, obtained by means of the electrokymograph, in a group of patients suffering from insufficiency of the aortic and pulmonic valves. Evidence will be presented that tracings of the great vessels with insufficient valves reveal a characteristic contour, and that the records of ventricular border movements in some patients may also show certain alterations. In addition, data indicative of alterations in the duration of certain portions of the cardiac cycle will be presented. Finally, the ability to determine the site or origin of a parasternal diastolic murmur (i.e., to ascertain whether insufficiency of the aortic or pulmonic valve exists) by means of such electrokymographic tracings will be illustrated.

Method and Material

The apparatus used consisted of the 931-A GE photo-electron multiplier tube and potentiometer (as described by Henny and co-workers), Cambridge electrocardiograph (with sound and pulse recorder), and a fluoroscope with a tilting table. Eighty kilovolts and 4 milliamperes were used, and the electrocardiograph paper was run at 50 mm. per second. The galvanometer string was standardized so that 1 millivolt gave a 2-cm. deflection. The coarse adjustment of the potentiometer was set at 5 while the setting of the fine adjustment was varied for the individual. The tracings were recorded in the posteroanterior, left anterior oblique, and right
RESULTS OF ELECTROKYMографIC TRACINGS

Aortic Insufficiency

Ascending Aorta. The tracings of the ascending aorta were satisfactorily obtained in 15 patients and are described in the following paragraphs according to contour and to duration of the ejection phase.

The majority of the tracings showed a moderately rapid, smooth, and continuous upswing of the first major upward deflection, followed by a rounded or somewhat flat peak, and terminating in a downward direction with the beginning of the phase of reduced ejection (fig. 1, C). The appearance of the early stages of ejection was, in many cases, not materially different from that of the normal tracing. However, in four of the tracings the initial rising limb was extremely thin and rose rapidly to a high summit (fig. 1, B).

The most constant and striking finding noted in these tracings was that there was marked diminution (fig. 1, B) to complete absence (fig. 1, C) of the incisural notches in all instances. In most cases this vestigial incisura occurred farther down on the descending limb than normally, as has been reported by other methods of investigation in animals.8, 10 In those cases in which the incisura was markedly diminished to absent, the descending limb of the aortic tracing revealed a rapid, smooth descent to the base line, beginning with the phase of protodiastole (fig. 1, C). When the rate of decline in aortic volume in diastole was observed in various cases, it appeared that the maximal decline occurred earlier in diastole in the phases of protodiastole and isometric relaxation in the patients with valvular insufficiency of the great vessels than in the normal subjects. In the normal group, aortic volume often appeared to decline to a greater degree in later diastole than in those patients with aortic or pulmonic insufficiency.

The phases studied were total, rapid, and reduced ejection. Since the incisuras of the aortic tracings were diminished or absent, this landmark for determining the end of systole was often not available. Total ejection in the ascending aorta, therefore, was determined by measuring the time consumed from the beginning of the rising limb of the tracing to the first vibration of the second sound.* Rapid ejection was measured as the period from the beginning of the rising limb to the summit of the tracing. Reduced ejection was measured from the summit to the second sound. It will be seen from figure 2 that the duration of the period of total ejection was prolonged in a majority of the patients with aortic insufficiency, when compared with the normal subjects. Rapid and reduced ejection were not selectively increased, either or both being prolonged in various instances.

The above findings were true in patients who had aortic insufficiency caused by either rheumatic fever or syphilis. There was no apparent close correlation with duration of the disease process, age of the patient, pulse pres-

* We have found the beginning of the second sound usually to be coincident with the beginning of closure of the aortic valves, with the beginning of the phase of protodiastole (the earliest phase of diastole), and thus with the end of ejection in the ascending aorta. Owing to ventricular asynchronism, in some patients the right ventricle may cease contraction first, and thus closure of the pulmonic valves would give rise to the earliest components of the second sound. In such cases the end of systole in the left ventricle would actually occur slightly later than the onset of the second sound would indicate. In such instances, however, measurements from the beginning of the ejection limb to onset of the second sound would give a value which might be slightly less than the true duration of total ejection, but would not give values that were greater than the actual duration. Hence total ejection may be measured with a fairly high degree of accuracy by this method.
Fig. 1.—Electrokymographic tracings of ascending aorta, with simultaneously recorded carotid pulse and sound tracing. Upward movement of EKY tracing indicates an increase in volume, downward movements a decrease in volume. (In each tracing, the lowest curve is the ascending aorta EKY, the curve above it the carotid sphygmogram.)

A, Normal subject. There is a moderately fast upswing of the rising limb of EKY tracing, with a well marked incisural notch (denoting closure of the aortic valves) followed by a large rebound wave, located high on the descending limb.

B, Patient with aortic insufficiency. Negro man, 45 years old, with evidence of marked left ventricular enlargement. Blood pressure 160/20, Corrigan type pulse. Loud, high pitched, blowing diastolic murmur audible at left sternal border and at first and second right interspaces. Reactions to Kline, Wassermann and Mazzini tests positive for syphilis. Note sharp, rapid increase in volume in early ejection phase, followed by a rapid decline in volume. There is a vestigial incisura located far down on the descending limb of the tracing. The incisural notch of the carotid pulse, although diminished in depth, is more easily distinguished than the incisura of the aorta in most pulse waves.

C, Patient with aortic insufficiency. Negro woman, 51 years old, with moderate left ventricular enlargement; vigorous, hyperactive carotid pulsations; moderately loud, high-pitched blowing diastolic murmur at left sternal border and at first and second right interspaces; rather harsh systolic murmur at first and second right interspaces. Reactions to Kline and Wassermann tests positive. There is a rather gradual rise of the pulse wave, with a fairly rapid decline after the summit. There is no clearly distinguishable incisural notch, on either aortic EKY or carotid pulse, to denote closure of aortic valves. (In tracings 1, B and 1, C, as in subsequent tracings, the diaphragm of the sound recorder has been placed laterally, over the apex of the heart, rendering the diastolic aortic murmur almost indistinguishable.)
sure, presence or absence of signs of congestive failure, or with the ingestion of digitalis.

Aortic Knob. The tracing of the aortic knob was satisfactorily obtained in 20 patients and these manifested definite changes from the normal. As was the case in the ascending aorta, the incisural notches were remarkably diminished (fig. 3, B) or entirely absent (fig. 3, C). The rising limb was not steep, as has been described above in several cases, but was as gradual as the normal. The peak was rounded but rarely flat as in some of the ascending aorta tracings.

Ventricle. There were 16 left ventricular tracings which were susceptible to analysis. The general contour of the systolic portion of the tracing was not altered. However, the diastolic section of the curves frequently showed aberrations from the normal. The periods of isometric relaxation, rapid filling, and diastasis usually show well-defined changes in gradient in the electrokymographic tracings of the ventricles of normal subjects (fig. 4, A). In place of the normal contour of the ventricular curve, there was frequently a rather smooth continuous upswing with poor delineation of the phases of rapid filling, diastasis, and auricular systole (fig. 4, B and C). The phase of diastasis was sometimes present provided the rate was sufficiently slow. It should be noted that while the curves of the ascending aorta were diagnostic, those of the left ventricle were less so. Although these left ventricular tracings were often altered as described above, in some patients their contour appeared normal.

Carotid Artery. The tracings of the carotid artery, obtained by placing a cup against the vessel and utilizing a segment capsule with optical recording, usually showed a contour similar to that of the aortic electrokymogram, with a diminished or absent incisura which frequently occurred low on the descending limb of the pulse wave. However, a point of some interest was the finding that in a few patients with aortic insufficiency incisural notches were sometimes present on carotid tracings even though they were completely absent on the electrokymographic tracings of the aortic knob (fig. 6, B). Although no explanation was apparent to account for this persistence of the carotid incisural notch under such conditions,
Fig. 3.—Electrokymographic tracings of aortic knob. (In each tracing, the lowest curve is the aortic knob EKY, the curve above it the carotid sphygmogram.)

A, Normal subject with well marked incisura denoting aortic valve closure.

B, Patient with aortic insufficiency; 38 year old woman. Blood pressure 140/62; marked left ventricular enlargement with loud blowing diastolic murmur audible at first and second right interspaces and at left sternal border. Numerous previous arm and hip injections for syphilis; reactions to serologic tests at time of examination negative. There is a poorly marked vestigial incisura seen on aortic knob EKY. The incisural notch is slightly better marked in the carotid pulse.

C, Patient with aortic insufficiency; Negro man, age 47 years. Admitted with acute polyarthritis diagnosed as acute rheumatic fever; history of "leakage of heart" known for twenty years. Blood pressure 180/80; diastolic blowing murmur at first and second right interspaces. Reaction to Mazzini test negative. Descending limb of EKY shows marked and abrupt decline in aortic volume with practically absent incisural notch. The greatest decline in aortic volume is seen to occur in early diastole. There is a well marked carotid incisura.

it would suggest that the aortic electrokymogram was a more reliable method of determining alterations in the pulse wave contour than was the carotid artery tracing obtained by these means. The periods of rapid ejection were variable on the carotid artery records, and their contour often differed considerably from that of the aortic tracings.
FIG. 4.—Electrokymographic tracings of left ventricle. Downward limb of EKY indicates a decrease in volume accompanying systole, upward movement indicates an increase in volume in diastole. (In each tracing, the lowest curve is the left ventricle EKY, the curve above it the carotid sphygmogram.)

A, Normal subject. Arrow denotes sharp and well defined increase in volume in rapid-filling phase of diastole, due to normal filling from auricle, followed by resting phase of diastasis and by terminal increase in ventricular volume probably due to auricular systole.

B, Patient with aortic insufficiency and previous congestive failure; Negro man, age 59 years. Moderate left ventricular enlargement, diastolic murmur audible at left sternal border and second right interspace. Blood pressure 120/56. Reactions to Kline, Wassermann and Mazzini tests positive. Phases of rapid filling and diastasis are poorly delineated with a somewhat smooth, continuous upswing in diastole. Note well defined incisural notch of carotid pulse.

C, Patient with aortic insufficiency; Negro man, age 40 years. Marked left ventricular enlargement, hyperactive carotid pulsations, blood pressure 150/76. Loud, blowing diastolic murmur at left sternal border and upper right sternal margin. Wassermann reaction 4+. As in the previous patient, the rapid filling phase and phases of diastasis and auricular filling are poorly marked and replaced by a rather gentle upward gradient of filling of the ventricle.
**Additional Findings.**

**Pulmonary Insufficiency.** In one patient whose clinical diagnosis was tetralogy of Fallot, a murmur heard at the base of the heart and along the left sternal border, with normal pulse pressure, and with no peripheral signs of aortic

Fig. 5.—Electrokymograms of pulmonary artery. (In each tracing, the lowest curve is the pulmonary artery EKY, the curve above it the carotid sphygmogram.)

A, Normal subject. Incisural notch, although normally located fairly far down on descending limb, is well marked, indicating closure of pulmonic valves.

B, Patient with congenital cyanotic heart disease. Clinical diagnosis: Tetralogy of Fallot complicated by pulmonary insufficiency. Cyanosis since infancy; patient frequently preferred squatting position. Moderate clubbing of fingers. Heart globular, normal size; rough, very loud systolic murmur at left sternal border, transmitted widely. Moderately loud diastolic blowing murmur at second left interspace. Lung fields showed relative diminution of lung markings and angiocardiography revealed stenosis of pulmonary artery with evidence of poststenotic dilatation. (Subsequent Blalock-Taussig procedure performed, with marked improvement in cyanosis and well-being.) Note complete absence of incisura on descending limb, with sharp and well defined incisura of carotid pulse. The electrokymographic tracings of the aorta in this patient (not shown) revealed a well defined incisural notch.

Additional Findings.

Pulmonary Insufficiency. In one patient...
while the tracings obtained from the aorta definitely exhibited these notches. Normal pulmonary artery tracings, as seen in figure 5, A, show a definite incisural notch. There appeared to be no doubt, therefore, that the murmur noted was due to insufficiency of the pulmonic rather than the aortic valves.

Aortic Stenosis. In 2 patients there was definite clinical evidence of aortic stenosis complicating the aortic insufficiency. In these two patients the rapid ejection period of the ascending aorta was divided into two separate phases—an initial rapid upswing ending abruptly in a much slower rise upward (fig. 6, A and B).

Fig. 6.—Patients with aortic stenosis and aortic insufficiency. (In each tracing, the lowest curve is the ascending aorta EKY, the curve above it the carotid sphygmogram.)

A, EKY of ascending aorta in 31 year old man with aortic stenosis. History of “inflammatory rheumatism” at age 9 years. Marked cardiac enlargement; very loud harsh systolic murmur at first right interspace transmitted into neck vessels, followed by blowing diastolic murmur in same area. After an initial ejection phase of rapid increase in volume there is a well defined change in gradient (indicated by arrows) with more gradual increase in volume to the summit. The descending limb shows no definite incisural marking. Immediately following the larger pulse waves are smaller ones due to premature ventricular contractions.

B, Patient with aortic stenosis and insufficiency; 64 year old white woman. Acute rheumatic fever in early adult life, recent congestive failure. Marked cardiac enlargement. Harsh systolic murmur at first right interspace, transmitted into neck vessels; blowing diastolic murmur in same area, also audible at left sternal margin. Separate harsh systolic and rumbling diastolic murmurs at apex. Reactions to serologic tests for syphilis negative. Note similar change in gradient of ascending ejection limb and poorly defined incisural notch of descending limb. In figure 6, B the incisural notch of carotid pulse is well defined.
Tracings of the central arterial pulse, recorded optically in patients with aortic stenosis, have shown a strikingly similar contour.8-14

**Discussion**

The electrokymograph has provided an easy and accurate method of studying many aspects of circulatory dynamics in patients. Many of these data are otherwise only obtainable by complicated procedures which are undesirable or involve some discomfort or hazard. Thus, although the registration of pressure pulse curves from the aorta, via catheterization of a peripheral artery, has been found possible in human beings, it is a relatively dangerous procedure.22

It should be realized that the electrokymogram provides information regarding the heart and great vessels through changes in volume, caused primarily by the movement of blood through the chambers of the heart and the great vessels. The electrokymogram has been shown to yield tracings closely resembling intra-aortic and intrapulmonic pressure curves obtained by the direct insertion of cannulas into the great vessels in animals or by cardiac catheterization in human beings.7-8

Electrokymographic tracings recorded from the ventricles have been shown to resemble closely ventricular volume curves provided by the cardiometer.7,8 Although positional movements of the heart and great vessels interpose some artefacts in the tracings from both instruments, nevertheless the general resemblance to records obtained by more direct means is striking, and the time relationships of the major events of the cardiac cycle are faithfully preserved.

The most striking alteration in aortic tracings obtained from patients with aortic insufficiency was the abolition or marked diminution in the incisural marking which normally accompanies the closure of intact aortic valves. Although a close correlation between the estimated degree of valvular insufficiency and the extent of obliteration of incisural marking was not possible, in general the more severe the evidence of valvular incompetency, the more completely this normal landmark was obliterated. This was accompanied by a rapid decline in aortic volume in the early phases of diastole.

The classic studies of Wiggers and his associates9-14 in animals, utilizing aortic pressure curves, have shown similar findings in experimental aortic insufficiency in animals. Their experiments have shown that the early diastolic decline in pressure increases significantly in experimental aortic insufficiency, and that the abruptness of the pressure decline increases with the size of the leak. Furthermore, these authors have shown that with larger leaks a progressively greater percentage of the regurgitated blood re-enters the ventricle earlier in diastole, in the protodiastolic phase. In this connection it should be pointed out that the percentage of blood that regurgitates per beat varies with the size of the leak, and estimates based on experimental data vary widely, ranging from an insignificant fraction to values of over 50 per cent of the stroke volume.

When the general contour of the aortic electrokymographic curves is considered, it is probable that many factors influence their general shape. In some instances the tracings revealed a sharp and abrupt discharge of blood in the early phases of systole (as in fig. 1, B), with a rather rapid decline in volume increase in later systole. This rapid ejection of a large volume of blood in early systole is due probably in part to the presence of increased initial tension existing at the onset of systole within the ventricle in patients with aortic insufficiency. However, a second factor which probably explains the rapidity of ejection of blood in early systole, is that ejection begins at a lower intraventricular pressure during systole, owing to the lower diastolic level of aortic pressure in most cases.9,10 In other instances (as in fig. 1, C) this early abrupt increase in volume was not noted, and the curves rose more slowly and declined in a similar fashion. In this connection it should be recognized that most of the patients were studied in hospital or clinic practice and revealed varying degrees of myocardial insufficiency, which probably influenced the velocity and type of ejection that occurred. Another factor which may determine the shape of such curves, and which Wiggers and Maltby10 thought to be of great importance in determining aortic pressure patterns, is the type of ventricular contraction exhibited by the ventri-
icle. Thus, in milder degrees of aortic valvular incompetency, the heart contracted usually in an "after loaded" fashion, and the ventricular and aortic pressure curves mounted rapidly and to greatest height in early diastole. In larger aortic regurgitant leaks, however, the ventricular pattern of response was of a "loaded" type with a more gradual slope in ascent and descent, and with the aortic pressure pulse strongly resembling the ventricular curves. This latter explanation may be the fundamental cause of the variations seen in the aortic electrokymograms. However, the possibility of "positional" movements also influencing the shape of these tracings cannot be excluded.

When the data regarding the duration of ejection are considered, although not finally conclusive, they indicate that the period of systole in patients with aortic insufficiency is usually prolonged beyond that of normal subjects. This is probably due to the increased volume of blood which the ventricle must expel. The attendant increased initial tension of the muscle is also probably of great importance in this connection. An increase in the duration of systole has been shown to accompany an increased initial intraventricular tension in experimental studies in animals. Since the initial ventricular tension is elevated in experimental aortic insufficiency, a similar mechanism is probably operative in prolonging the contraction phase in patients with such lesions. The possible effects of myocardial insufficiency in producing such a prolongation cannot be eliminated, however.

The most constant feature of the left ventricular electrokymographic tracings was a tendency to smooth over or eliminate many of the phases of rapid volume change. Thus the rapidly filling phase was not well marked in the majority of tracings of patients with aortic insufficiency. Similarly, even with slow rates the normal plateau of diastasis and the increase in ventricular volume due to auricular contraction were often poorly marked or absent. Although such tracings are admittedly not diagnostic in nature, they appear to be a deviation from the normal pattern. While a sudden marked in-
crease in ventricular volume in early diastole might have been anticipated in large leaks, this finding was not detectable in these tracings. "Positional" movements at the apex of the heart are often marked early in diastole and these may have obscured such a rapid increase in volume in some cases. However, it is more probable that the retention of residual blood in a dilated ventricle plus the early regurgitation of blood from the aorta has produced these alterations. These factors would combine to fill the ventricle to a considerable degree before the onset of rapid filling. In the case of a chamber of greater volume, the increment of a given amount of additional blood from the auricle would produce a smaller change in outward movement of the ventricular wall. There is reason to believe, from experimental work in animals, that the existence of aortic insufficiency, by filling the ventricle in the earliest phase of diastole, actually reduces the amount of blood which enters this chamber in the normal rapid filling phase, which occurs somewhat later. Hence the usual steep outward curve of movement normally seen in the rapid filling phase would be considerably attenuated and its slope diminished, under these conditions. The same factors would tend to obliterate or obscure the normal plateau of diastasis and also the terminal increase in volume due to auricular systole. This explanation appears to be the most feasible one to explain the alterations produced in the ventricular electrokymogram.

In an individual in whom the origin of a diastolic murmur is in doubt, the electrokymogram may be of considerable help in determining whether aortic or pulmonic valvular insufficiency exists. From the constancy with which variations in the electrokymographic tracings were obtained in patients with aortic insufficiency, it is probable that they will become a laboratory aid of corroborative value in the diagnosis of valvular insufficiency of the great vessels. No patient in the present group with definite signs of aortic insufficiency failed to show the characteristic alterations noted above in the aortic electrokymogram. Since
most of these patients manifested clinical signs of moderate to large regurgitant aortic leaks, it is possible that very slight degrees of aortic insufficiency might fail to show such aberrations. It also appears that electrokymographic tracings may be of aid in clarifying the diagnosis of aortic stenosis when systolic murmurs are found at the base of the heart.

**Summary**

1. Electrokymographic studies of the heart and great vessels were made in 22 patients with clinical signs of aortic insufficiency.

2. Variations from the normal were noted in all patients. These included: (a) A diminution or absence of the normal aortic incisural markings. This was a constant finding in all patients. (b) A rapid decline in volume in early diastole. (c) Alterations in the general shape and contour of the aortic tracings. (d) Prolongation of the duration of ejection (and hence systole) in most patients, compared with normal subjects. (e) Variations in the normal ventricular filling pattern of the left ventricle with a flattening and decrease in the normal changes in gradient in many patients.

3. One patient with pulmonic insufficiency revealed abnormalities of the pulmonic and right ventricular electrokymograms which resembled those seen in association with aortic insufficiency.

4. Two patients with aortic insufficiency complicated by aortic stenosis revealed definite alterations from the normal which are described.

5. The probable factors operative in causing these changes in the electrokymogram, and the diagnostic value of these patterns in patients are discussed.

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