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DIASTOLIC GALLOP SOUNDS, THE MECHANISM OF PRODUCTION^{1, 2}

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In a study previously reported from this laboratory, the mechanism of gallop sounds was studied with the aid of the electrokymograph (1). A wave of rapid lateral movement of the left ventricular wall was repeatedly demonstrated in each of the 28 patients with hypertension and heart failure with either a protodiastolic or presystolic gallop sound. The gallop sound occurred during this wave and not after its completion. The abnormal left ventricular border kymogram disappeared with the regaining of compensation and subsidence of the gallop sound in these patients. It was felt that these observations supported the views of Potain (2), Ohm (3), Wolferth and Margolies (4), Orias and Braun-Menendez (5), and Mannheimer (6) that an impact or sudden stretching of the ventricular wall is the chief mechanism of production of the gallop sound.

On the other hand, Hirschfelder (7), Gibson (8), Thayer (9), Sewall (10), Lewis and Dock (11), Brady and Taubman (12), and Dock, Grاندell, and Taubman (13) supported the theory of reflux closure of the atrio-ventricular valves as the mechanism for the production of the gallop sound on the basis of studies of apical impulse, jugular vein pressure pulse, left ventricular kymogram and ballistocardiogram.

The development of right and left heart catheterization (14, 15) and, particularly, the development of techniques to secure an accurate simultaneous recording of the atrial and ventricular

pressure pulses (15) have made it possible to further the investigation of the origin of the gallop sound. In this study the temporal relationships of the gallop sound to the atrial, superior vena caval, and external jugular pulses of the same subject were determined. Apex cardiograms were also studied in this series of patients. The recording characteristics of the piezoelectric pick-up and the Lilly capacitance manometer employed in the study were compared.

MATERIAL AND METHODS

Two groups of patients were used in this investigation: a) Left heart catheterization was performed to evaluate 10 patients with chronic rheumatic mitral valvular disease for cardiac surgery. Clinical evidence of a predominant mitral insufficiency, and that of a complicating aortic lesion were indications for the pre-operative left heart study. b) Right heart catheterization was performed on 4 patients with signs and symptoms of severe right heart failure to help establish the etiological diagnosis of the heart disease.

Right heart catheterization was performed according to the technique of Cournand and Ranges (14) and by the use of a small double-lumen catheter. Pulmonary "capillary" pressure was recorded by the method described by Lagerlöf and Werkö (16) and by Hellem, Haynes, and Dexter (17). For left heart catheterization a technique developed by Schnabel, Blakemore, Kuo, and Langfeld (15) for the simultaneous recording of pressures in the left atrium and left ventricle was used. Atrial and ventricular pressures were recorded simultaneously using two Lilly capacitance manometers either through a No. 7 double lumen Cournand catheter or through two small plastic catheters (18). The time lag of the small catheter system was 0.002 second or less. The apex impulse was obtained by the use of a glycerine capsule end-piece attached alternately to a) a piezoelectric pick-up, and b) a Lilly capacitance manometer. A specially constructed multichannel Hathway recorder which includes a phonocardiographic channel was used for all the recordings in this study. All records were taken at a paper speed of 75 mm. per second.

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³ This work was done during the tenure of a Research Fellowship and the tenure of an Established Investigatorship of the American Heart Association.

⁴ Markle Scholar in Medical Sciences.

⁵ Scholar in Cancer Research.

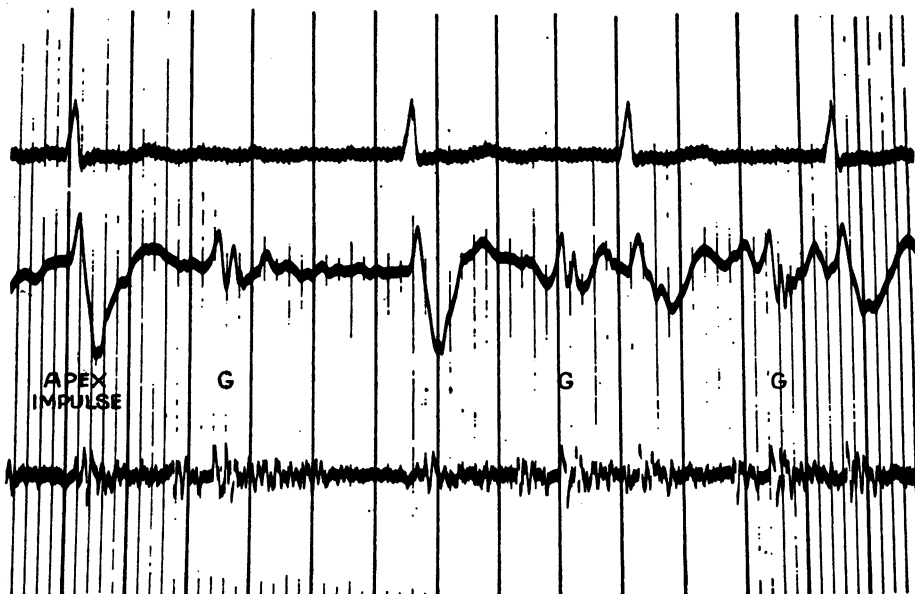


FIG. 1. APEX IMPULSE RECORDED WITH A PIEZOELECTRIC PICK-UP ON A PATIENT WITH MITRAL INSUFFICIENCY AND LOUD PROTODIASTOLIC GALLOP SOUND (G)

A sharp downward dip (inflection) following an initial upswing is recorded both during ventricular systole and at the time of the protodiastolic gallop sound.

RESULTS

Correlation of the apex impulse to the gallop sound

Apex impulses of this series of 14 patients with protodiastolic and presystolic gallop sounds were recorded both through a piezoelectric pick-up and

through the amplifying system of the Lilly manometer. A typical example of the apical impulse obtained through a piezoelectric pick-up from a patient with a protodiastolic gallop is shown in Figure 1. In this case the apex impulse starts to move upward (outward) about 0.04 second before the onset of the gallop sounds (G in Figure

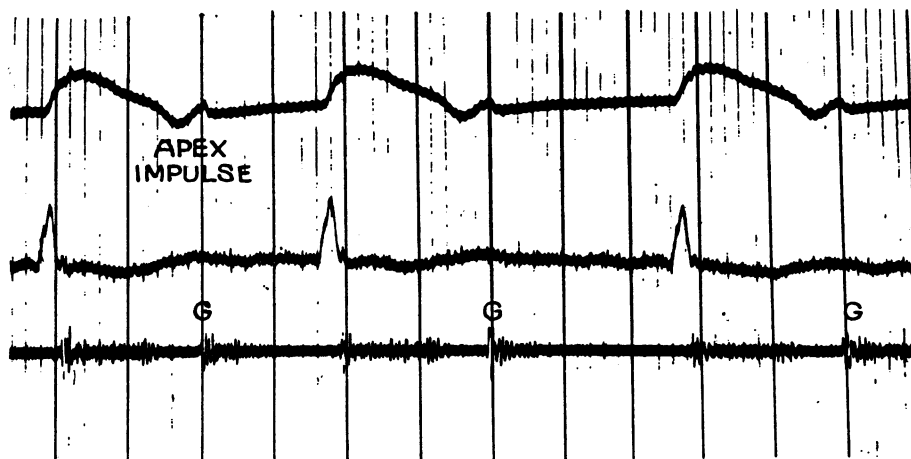


FIG. 2. APEX IMPULSE RECORDED WITH A LILLY CAPACITANCE MANOMETER ON A PATIENT WITH MITRAL INSUFFICIENCY AND A PROTODIASTOLIC SOUND (G)

Both the systolic and the diastolic out-thrusts are well sustained and they do not show the sharp inflections and other extraneous vibratory movements.

1). It rises sharply to the peak of outward thrust in 0.04 to 0.06 second, and is followed by a sharp downward dip (inflection). Similar sharp upward and downward swings in the apex cardiogram are seen with each apical thrust during ventricular systole. Finger pressures of varying abruptness and firmness were applied to the end-piece of the piezoelectric pulse wave pick-up to simulate apical out-thrusts. These maneuvers produced upward swings of varying sharpness not unlike the systolic and diastolic apex beats recorded in Figure 1. Each of the upward swings is followed by a sharp dip (inflection) of varying depth, which in turn is followed by a few after-vibrations.

Apex impulses were then taken on these patients by attaching the glycerine capsule end-piece to the Lilly manometer. The systolic and diastolic apical thrusts taken by this method are shown in Figure 2. In this tracing well-sustained systolic and diastolic apical out-thrusts are recorded. The extraneous movements are almost entirely eliminated, and an "inflection" wave is not seen either during ventricular systole or in protodiastole.

Correlation of the gallop sound with jugular vein pulse curve

The practices of using the jugular pulse curve to time various mechanical events of the cardiac cycle and of correlating these events to the onset of the gallop sounds were investigated by simultaneous recording of the right atrial and jugular vein pulse pressures in 4 patients with right heart failure and right-sided gallop sounds. The delay in the transmission of pulse wave from the mid-portion of the right atrium to the jugular vein at the level of the middle of the neck was found to range between 0.14 to 0.20 second in these patients.

In a patient with severe right heart failure and a right-sided presystolic gallop sound, the pulse pressures of the right atrium, superior vena cava, and external jugular vein were recorded sequentially with phonocardiogram and electrocardiogram. By selecting beats with approximately equal cycle lengths from the three tracings and then by carefully aligning the P waves in one tracing with the other two, we were able to obtain: 1) the respective time relationships between the "a" wave, as recorded with a catheter in the right atrium, in the superior vena cava, and in the external jugular vein, and the P wave in the elec-

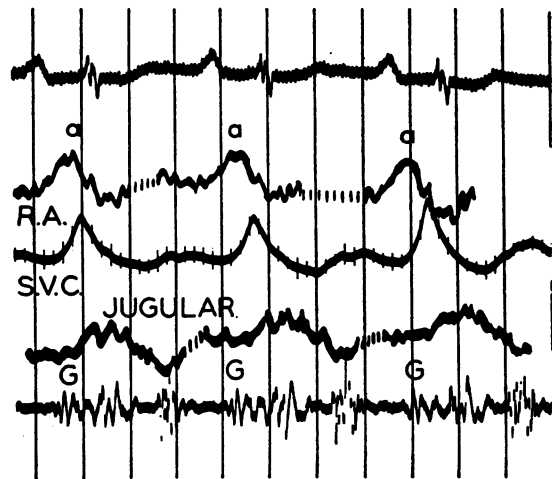


FIG. 3. TRACING ILLUSTRATES A PROGRESSIVE DELAY OF THE "a" WAVE WITH RESPECT TO THE P WAVE IN THE ELECTROCARDIOGRAM AS THE CARDIAC CATHETER IS WITHDRAWN FROM THE RIGHT ATRIUM TO THE JUGULAR VEIN

trocardiogram, and 2) the time relationships of these "a" waves obtained from different sites, with respect to one another. Figure 3 shows a progressive delay in the occurrence of the "a" wave in reference to the P wave in the electrocardiogram as one moves the catheter from the right atrium to the jugular vein. This delay may be as much as 0.14 to 0.20 second. For this reason the presystolic gallop which falls in good alignment with the peak of the right atrial "a" wave might well be related erroneously to some part of the "V" wave in the preceding cardiac cycle, if a jugular pulse curve were used for the purpose of timing.

Correlation of the pulmonary "capillary" pressure with left-sided gallop

Both right and left heart catheterizations were performed in 3 of the 10 patients with left-sided gallop sounds and predominant mitral insufficiency. Successful wedging of the catheter in one of the smaller branches of the pulmonary artery was achieved in all 3 patients.

A slight delay in the transmission of the "a" and "V" waves (amounting to only 0.01 to 0.03 second) was observed in the pulmonary wedge pressures of these 3 patients compared with their respective left atrial pressure curves obtained subsequently by left heart catheterization or by direct puncture of the left heart chambers during cardiac surgery. The length of the pulse wave

transmission time seemed to be dependent upon the distance from the heart at which the tip of the catheter happened to be wedged.

Right atrial and ventricular pressures in patients with right-sided gallop sounds

Simultaneous right atrial and ventricular pressure pulse curves were obtained in two patients with primary pulmonary hypertension, one patient with an interatrial septal defect, and one patient with idiopathic myocarditis. All 4 patients had normal sinus rhythm and all of them had moderate to severe degrees of right heart failure with prominent right-sided gallop sounds. The records showed that in each case the gallop sound began near the peak of the atrial "a" wave. In these patients, the gallop sounds occurred while the right atrial pressure was 3 to 11 mm. Hg higher than that of the right ventricle. The highest atrio-ventricular pressure differential was observed in a patient with idiopathic myocarditis who had a P-R interval of 0.32 second and a summation gallop. Examples of the right heart pulse pressure studies are presented in Figures 4a and 4b, 5a and 5b. Figure 4a was obtained from patient L.A. who had a large interatrial septal defect with a predominant left to right shunt, congestive heart failure, and a loud gallop sound (G) as recorded in the phonocardiogram. The gallop was best heard and was easily felt at the region of the

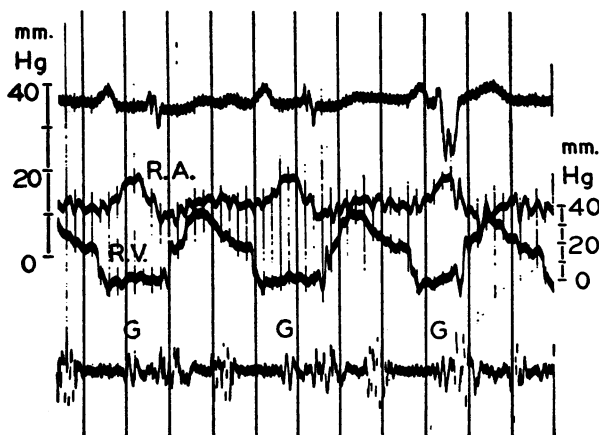


FIG. 4a. SIMULTANEOUS RIGHT ATRIAL AND VENTRICULAR PRESSURE CURVES OBTAINED FROM A PATIENT WITH INTERATRIAL SEPTAL DEFECT, RIGHT HEART FAILURE AND A RIGHT-SIDED GALLOP SOUND

The gallop (G) is recorded at the peak of atrial systole.

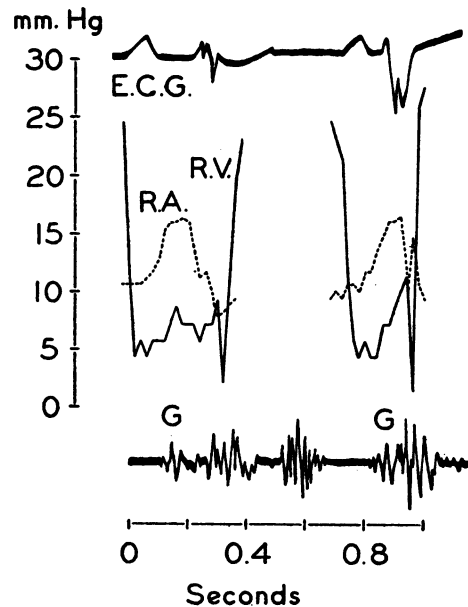


FIG. 4b. REPLOTTING THE ATRIAL AND VENTRICULAR PRESSURE CURVES OF THE SECOND AND THIRD HEART BEAT IN FIGURE 4a ON A COMMON BASE LINE AND ON THE SAME SCALE SHOWS THE RIGHT ATRIAL PRESSURE TO BE HIGHER THAN THAT OF THE RIGHT VENTRICLE FOR ABOUT 0.5 SECOND IN DURATION

The gallop sound (G) starts near the peak of the atrial "a" wave.

xyphoid cartilage. The tracing shows that the gallop sound occurs at the peak of the atrial "a" wave. Replotting of the right atrial and ventricular pressures of the second and third heart beat in Figure 4a on an equal and expanded scale and from the same base line (Figure 4b) gives a graphic demonstration of the relationship of the gallop sound to the intracardiac pressures. The atrial pressure was 8 to 9 mm. Hg higher than the ventricular pressure when the gallop sounds appeared. This pressure gradient across the tricuspid valve was not maintained to the point immediately prior to the rise of right ventricular pressure. No tricuspid stenosis was found during cardiac surgery.

Figures 5a and 5b were made from patient M.H. who had idiopathic myocarditis. A routine right heart catheterization was performed on him 3 years ago. The findings obtained in that study were within the range of normal. In the interim the patient went into congestive heart failure and developed a loud right-sided summation gallop. He was readmitted to the hospital for study. Be-

cause of X-ray evidence of an enlarged left atrium and the obscure nature of the cardiac lesion, a left heart catheterization was done to rule out mitral valvular disease. Simultaneous left atrial and ventricular pressure measurements showed no

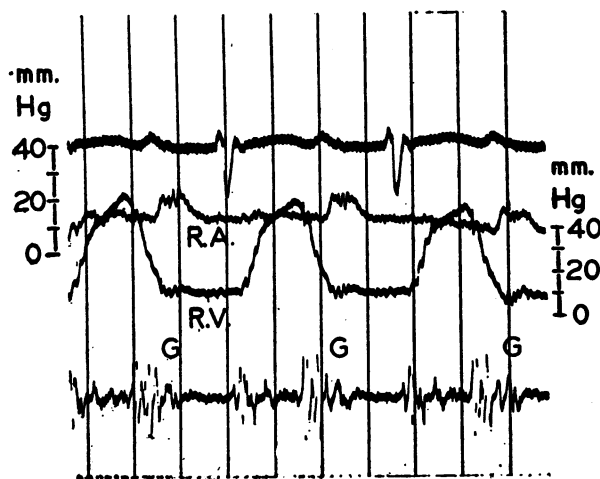


FIG. 5a. SIMULTANEOUS RIGHT ATRIAL AND VENTRICULAR PRESSURE CURVES OBTAINED FROM A PATIENT WITH IDIOPATHIC MYOCARDITIS, CONGESTIVE HEART FAILURE, AND A RIGHT-SIDED SUMMATION GALLOP (G)

Gallop sound G is recorded near the peak of the atrial "a" wave.

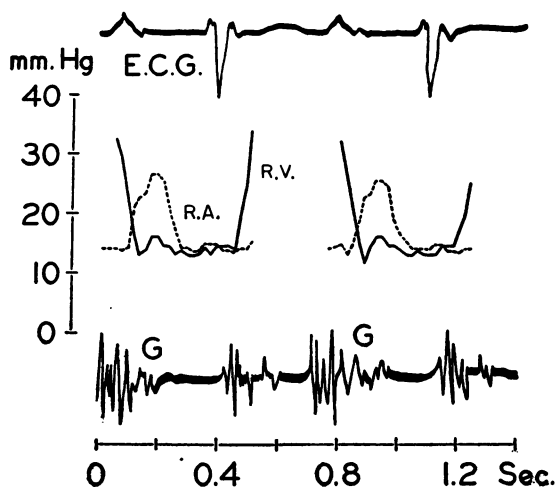


FIG. 5b. REPLOTTING OF THE ATRIAL AND VENTRICULAR PRESSURE CURVES IN FIGURE 5a ON A COMMON BASE LINE AND ON THE SAME SCALE SHOWS AN ELEVATION OF THE ATRIAL PRESSURE OVER THAT OF THE VENTRICULAR PRESSURE FOR ABOUT 0.4 SECOND

The summation gallop (G) occurs near the peak of the atrial "a" wave where the atrio-ventricular pressure differential is at its peak value.

diastolic gradient across the mitral valve. Recatheterization of the right heart (Figure 5a) showed elevation of the right ventricular systolic and diastolic pressures at this time. A summation gallop (G) was recorded at the peak of the right atrial pressure curve, which, on account of the markedly prolonged P-R interval, occurred in protodiastole. Coarse vibrations were recorded in both the atrial and ventricular pressure curves at the time the gallop sound was being recorded. Replotting of the atrial and ventricular pressure curves on the same scale and from the same base line shows a large atrio-ventricular pressure differential of 9 to 11 mm. Hg during atrial systole and at the time of the summation gallop (Figure 5b).

Left atrial and ventricular pressure in patients with left-sided gallop sounds

Simultaneous recordings were obtained by left heart catheterization of the left atrial and left ventricular pressures through two separate catheters in 10 patients with mitral insufficiency and gallop sound. In 7 of the 10 patients a protodiastolic gallop was recorded while the left atrial pressure was 6 to 18 mm. Hg higher than that of the left ventricle. In three patients with presystolic gallop the sound was recorded when the left atrial pressure was 3 to 6 mm. Hg above the left ventricular pressure. The left heart pressure curves obtained from a patient, M.H., with mitral insufficiency are shown in Figure 6a. The left atrial pressure curve shows: 1) a small rise in early ventricular systole due most likely to the closure of the A-V valves, 2) a sharp rise in pressure during late ventricular systole due to mitral insufficiency, and 3) the timing of the gallop sound to the lower third of the descending limb of the sharp "V" wave. No vibration of any kind was recorded in the left atrial pressure curve either during or after the occurrence of the gallop sound. On the other hand, a marked increase in coarse vibrations is seen in the left ventricular pressure curves in early diastole. The diagnosis of mitral insufficiency was confirmed at operation and was subsequently proven at autopsy. When the left atrial and ventricular pressure curves are plotted from the same base line and on a common scale, it is clear that the left atrial pressure is 12 to 13 mm. Hg higher than the left ventricular pressure



FIG. 6a. SIMULTANEOUS LEFT ATRIAL AND VENTRICULAR PRESSURES OBTAINED FROM A PATIENT WITH MITRAL INSUFFICIENCY, HEART FAILURE, AND A PROTODIASTOLIC GALLOP SOUND (G)

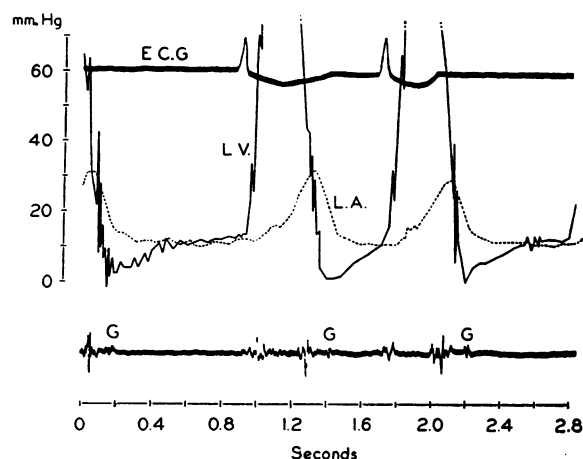


FIG. 6b. REPLOTTING OF THE PRESSURE CURVES IN FIGURE 6a ON A COMMON BASE LINE AND ON THE SAME SCALE SHOWS THE GALLOP SOUND (G) OCCURS AT THE LOWER THIRD OF THE DESCENDING LIMB OF THE EXAGGERATED "V" WAVE

The atrial pressure is higher than the ventricular pressure before, during and after the protodiastolic gallop sound.

at the moment the gallop sound occurs (Figure 6b).

DISCUSSION

Those investigators, who in their attempts to marshal evidence in support of the theory of reflux closing of the atrio-ventricular valves as the mechanism for the production of the gallop sound, have repeatedly emphasized the importance of apical impulse recordings in the study of pa-

tients with protodiastolic gallop (11-13). They have contended that the momentary retraction or the "sharp inflection" recorded in the tracing following the initial outward thrust is supportive of the assumption that the gallop sound is invariably accompanied by a reflux of blood in the direction of the atrium. In the present investigation, however, it was demonstrated that when a piezoelectric pulse wave pick-up with A-C coupling and a very short time constant is used to record the apical impulse, a sharp inflection is almost always recorded following the initial upswing. Indeed, these artificial retraction waves were recorded when direct finger pressure was applied to the end-piece of the recording set. Apical impulses obtained in these patients with gallop sounds by using the amplifying system of a Lilly manometer which has a steady time constant failed to show the retraction wave after the initial out-thrust.

The proponents of the valvular theory of the gallop sound also look for support in the study of the jugular venous pulsations (7, 8, 11-13). The demonstration of a delay of 0.14 to 0.20 second in the transmission of the venous pulse from the right atrium to the jugular vein clearly invalidates its use in an attempt to correlate gallop sound with certain events within the heart. The delay in venous pulse transmission time coupled with differences in the diastolic interval (the heart rate) between patients can also explain the controversies raised in the current literature with regard to whether the gallop sound should fall on the peak or on various points along the descending limb of the venous "V" wave.

It has been further suggested that an "h" (7) or "b" (8) or "f" (19) wave may be identified as an upward peak of venous reflux in the jugular pulse curve which follows the "V" wave in early diastole; and that the V-h trough is synchronous with the third heart sound. A careful study of the pulse wave recorded directly from the left atrium, however, did not reveal any sign of an upward peak in early diastole which could be considered as the possible origin of the so-called venous reflux wave observed in the jugular pulse curve (Figure 6a). In this connection it is pertinent to observe that when separate catheters are used to record the left atrial and left ventricular pressure curves, little or no extraneous vibration is recorded in the atrial curve while many coarse vibrations are

seen in the ventricular curve at the time of the occurrence of the gallop sound (Figure 6a). We are in agreement with the suggestion (20) that a "pure" jugular-venous pulse is difficult to obtain technically. It is more than likely that the wave of venous reflux observed in some patients with protodiastolic gallop rhythm is due to the inclusion in the venous pulse of certain parts of the carotid or aortic pulsations.

The hypothesis of a summation gallop as advanced by Wolferth and Margolies (4) has been repeatedly confirmed by numerous clinical observations. The large atrio-ventricular pressure differential recorded in one of the patients who had a minor grade A-V heart block and right-sided gallop further affirms the summation concept in the production of gallop sounds.

Comparative study of the wedge pressure and left atrial pressure curve obtained from the same patient either by left heart catheterization or by direct puncture of the left atrium during cardiac surgery shows a comparatively short delay in the pulse wave transmission time. Hence, in the absence of a true left atrial pressure, the pulmonary capillary pressure (wedge) is best suited for timing certain left-sided intracardiac events.

The simultaneous measurement of atrial and ventricular pressures on the side of the heart where the gallop sound originates shows that at the time of occurrence of the gallop sound the atrial pressure is invariably higher than the ventricular pressure. It is unlikely that the A-V valves could close and vibrate with the existing pressure relationships between these two cardiac chambers. These observations further support the view that an impact or sudden stretching of the ventricular wall is the basic mechanism of production of the gallop sounds.

SUMMARY

1. A sharp dip following an initial upswing is often recorded in the apex beat by using a piezo-electric pick-up which has a short time constant. The artificial wave of apical retraction can be eliminated by the use of the amplifying system of the Lilly manometer.

2. The temporal relationships of the atrial, vena caval, and jugular "a" wave to the P wave in the electrocardiogram and between one another have been studied and compared. The data indi-

cate that a delay in the venous pulse wave transmission from the atrium to jugular vein may amount to 0.14 to 0.20 second.

3. Comparing the pulmonary wedge pressure with the left atrial pressure obtained in the same patient, a small delay in the pulse wave transmission time is demonstrated. The delay is only about 0.01 to 0.03 second.

4. A venous reflux wave is not demonstrated in the pressure curves taken directly either in the right or left atrium at the time the gallop sound occurs. Therefore, the upward deflection which comes immediately after the "V" wave in the jugular venous pulse is probably due to the inclusion in the venous pulse of some components of the arterial pulse.

5. Simultaneous atrial and ventricular pressure measurements made on the side of the heart where the gallop sound originates show that the atrial pressure is invariably higher than the ventricular pressure at the time of the gallop sound. These observations further support the view that a sudden impact or stretching of the ventricle is the basic mechanism involved in the production of gallop sounds.

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