SELECTION OF TECHNIQUES FOR THE MEASUREMENT OF LEFT HEART PRESSURES

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The technique of venous catheterization gives only indirect information about lesions of the left side of the heart. Analysis of mitral valve disease was made possible by the discovery that a venous pressure pulse could be obtained from a catheter wedged in a peripheral pulmonary artery (Lagerlöf and Werkö, 1949; Hellemis *et al.*, 1949). The form of the arterial pulse has been used for the indirect evaluation of aortic valve disease (Hancock and Abelman, 1957; Wood, 1958), and in recent years several techniques for direct measurement of left heart pressures have been introduced. Puncture of a cardiac chamber is usually necessary, and the risk of these methods is considerably greater than that of the right heart catheterization.

Whenever hæmodynamic study is thought necessary, the type of investigation to be performed must be decided with regard to the abnormality present and the information required. The value of the data to be obtained must be considered in relation to the morbidity of the procedure. Right heart catheterization alone is often decisive, and left heart pressure measurements should be reserved for situations in which they will provide critical information.

In the present study, emphasis is placed on the accurate measurement of the pressure gradient across the mitral or aortic valve, with simultaneous estimation of the cardiac output. Assessment of regurgitant flow by indicator dilution (Carleton *et al.*, 1960; Warner and Toronto, 1958) or angiocardiology (Björk and Lodin, 1959; Uricchio *et al.*, 1959) may require different techniques, but fundamentally similar considerations will apply.

METHODS

The methods used have been described previously (Davila *et al.*, 1959). Central arterial pressure was recorded continuously using the Seldinger (1953) method. Right heart catheterization was performed for the measurement of pulmonary arterial and wedge pressures. Left atrial pressures were obtained by transbronchial puncture using a slotted bronchoscope which could be removed leaving the needle in place. Left ventricular pressures were recorded by direct puncture through the anterior chest wall (Brock *et al.*, 1956) or by retrograde arterial catheterization using a Cournand catheter inserted in the right brachial artery (Voci and Hamer, 1960).

Simultaneous pressure measurements were made on either side of the mitral or aortic valves while cardiac output was estimated by the Fick method. Pressures were recorded with P23Db Statham strain-gauges and a 4-channel direct writing Sanborn Polyviso with optimal damping, and were replotted on the same scale without correction for phase lag. The base-line for all pressure measurements was the middle of the chest at the level of the second costal cartilage (Roy *et al.*, 1957). The Ry/v ratio (Owen and Wood, 1955) was calculated from left atrial pressures adjusted to a base-line at the level of the sternal angle. Blood oxygen contents were determined by the Van

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Slyke method. Valve areas were calculated by the standard orifice formula (Gorlin and Gorlin, 1951).

RESULTS

During a period of one year 139 patients with suspected mitral or aortic valve disease were catheterized and left heart study was attempted in 94 (Table I).

TABLE I
METHODS OF LEFT HEART STUDY EMPLOYED

Method	Attempted	Failed	Succeeded
Transbronchial left atrial puncture ..	37	4	33
Percutaneous left ventricular puncture ..	73	4	69
Retrograde arterial catheterization ..	39	22	17

Transbronchial left atrial puncture was successful in 33 of 37 patients with mitral valve disease. One patient could not be bronchoscoped, and in two only transient left atrial pressure records were obtained, the needle being dislodged as the bronchoscope was withdrawn. In another patient it seems likely that the needle was embedded in thrombus.

Pulmonary arterial wedge pressures were recorded at the same time as 24 of the successful left atrial punctures. The mean wedge and left atrial pressures agreed within 1 mm. Hg in each case, but the wedge pressure showed various degrees of reduction in amplitude of pulsation and distortion of wave form with superimposed artefacts (Fig. 1). The reliability of the wedge pressure was not related to the mean pressure level or to the pulmonary vascular resistance.

FIG. 1.—Simultaneous left atrial (LA) and pulmonary arterial wedge (PAW) pressures in three patients with mitral disease and atrial fibrillation. The wedge record shows a reduced amplitude of pulsation with loss of the c wave, slurring of the y descent, and artefacts due to valve closure. The diagnosis was confirmed at operation in each case; the estimated mitral valve areas are given in parentheses below.

From above downwards: (a) Moderate MS (1.0 cm.²), (b) More severe MS with moderate MR (0.8 cm.²), (c) Slight MS (2.0 cm.²) with severe AS. Similar values for the Ry/v ratio were obtained from the direct left atrial pressure in each case. MS = mitral stenosis, MR = mitral regurgitation.

There were 4 failures in 73 attempts at left ventricular puncture. In 2 of the 29 patients with mitral stenosis, pressure records were obtained but proved to be from the right ventricle, and in 2 of the 33 with aortic valve disease the left ventricular cavity could not be entered. Eight of the remaining patients had mitral regurgitation and 3 cardiomyopathy. Cardiac arrest occurred in one patient with severe mitral regurgitation, but he recovered after cardiac massage. Præcordial pain and prolonged hypotension were frequent, and minor degrees of hæmopericardium were sometimes found at subsequent operation, but cardiac tamponade sufficient to require paracentesis did not occur.

The success of retrograde catheterization of the left ventricle depended in part on the persistence of the operator. In general it was easier to enter the left ventricle if there was aortic valve disease, as the normal valve cusps tended to divert the catheter tip into the sinuses of Valsalva. The formation of a loop at the catheter tip facilitated passage through a normal valve. Coiling of the catheter in a dilated ascending aorta was often a problem, and it was difficult to pass through a tight aortic stenosis (Table II). In two patients with calcified aortic valves there was transient dysphasia after the procedure. In about a third of the patients the arterial pulses were lost distal to the arteriotomy, but there was no evidence of ischæmia in the arm or hand.

TABLE II
RETROGRADE ARTERIAL CATHETERIZATION

Valve lesion	Attempts	Ventricle entered
Isolated aortic stenosis	12	2
Mitral disease with normal aortic valve	10	4
Aortic stenosis with mitral stenosis	5	3
Aortic stenosis and regurgitation	5	3
Aortic regurgitation with mitral disease	7	5

The mean left ventricular diastolic pressure in 29 patients with predominant mitral stenosis ranged from 4 to 16 mm. Hg (average 10 mm. Hg). There was little variation with the severity of the lesion, mean diastolic pressures between 7 and 15 mm. Hg being found in 4 patients with tight stenosis and severe pulmonary vascular obstruction. Similar values were found in the majority of patients with mitral insufficiency (10 patients) or aortic valve disease (42 patients), but in 10 patients the mean left ventricular diastolic pressure was over 20 mm. Hg.

DISCUSSION

Pulmonary Arterial Wedge Pressure

There has been considerable controversy as to the value of the pulmonary arterial wedge pressure as an index to the left atrial pressure (Wiggers, 1953). It is generally agreed that the mean pressures are similar (Kaplan, 1959), but the wave form of the left atrial pressure pulse may be considerably damped in the course of transmission to the wedged catheter. The reliability of a wedge pressure wave form cannot be determined unless a left atrial pressure is recorded simultaneously for comparison. Even a clearly venous pulse may be considerably reduced in amplitude and the c wave is often obliterated (Fig. 1). The y descent in the pulmonary arterial wedge pressure (Owen and Wood, 1955) is difficult to interpret. Direct left atrial pressures frequently show a diphasic y descent, an initial rapid fall in pressure being followed by a slower decline, but this appearance is often lost in the pulmonary arterial wedge record (Fig. 1). Detailed study of left atrial pressure changes therefore requires left atrial puncture, but the simplicity and low risk of the pulmonary arterial wedge method make it preferable when the information it gives is adequate.

In our experience, analysis of the left atrial pressure pulse is of little value in the assessment of mitral valve disease when a pressure gradient persists across the mitral valve throughout diastole (Hamer *et al.*, 1959). The height of the v wave and the slope of the y descent are, of course, related

to the degree of mitral stenosis and of associated regurgitation, but many other factors are involved. Flow of blood into the left atrium from the pulmonary veins occurs mainly in systole, so variations in right ventricular stroke volume and in mitral regurgitation have similar effects on the left atrial pressure pulse. The pressure changes resulting from the flow of blood in and out of the tense left atrium depend on the volume of the chamber and the mechanical properties of its walls. The Ry/v ratio allows for the increase in rigidity of the left atrial wall as it is distended (Owen and Wood, 1955), but cannot correct for individual variations in the size and structure of the left atrium. Fig. 1 shows similar Ry/v ratios in three different hæmodynamic situations. Under these circumstances left atrial puncture for the accurate measurement of wave form does not seem justified except as a research procedure.

In mitral stenosis with a high left atrial pressure, the pulmonary arterial wedge pressure may be used to calculate the diastolic pressure gradient, as variations in left atrial pressure throughout the cardiac cycle are relatively small (Fig. 2). When the pressure gradient is small, phasic changes in left atrial pressure are of greater significance, and damping in transmission to the wedged catheter consequently more important. Phase lag, which seems to affect the a wave more than the v wave (Luisada and Liu, 1956), is a further complicating factor.

FIG. 2.—The mitral diastolic pressure gradient in severe mitral stenosis with normal rhythm using the pulmonary arterial wedge (upper) and left ventricular pressures (middle). In this and the subsequent figures simultaneous pressure records on each side of the valve are shown above, and in the lower part of the figure the pressures are shown replotted on the same scale for measurement of the gradient. When the mitral diastolic gradient is large little error results from using the pulmonary arterial wedge pressure as variations in left atrial pressure throughout the cardiac cycle are relatively small. Similarly the assumption of a mean left ventricular diastolic pressure of 5 mm. Hg will produce little error.

FIG. 3.—Left atrial (LA) and left ventricular (LV) diastolic pressures in severe uncomplicated mitral regurgitation with atrial fibrillation. The diagnosis was confirmed by subsequent operation. The superimposed facsimile tracings show that the left atrial pressure falls rapidly to the level of the left ventricular diastolic pressure when the mitral valve opens.

Pulmonary arterial wedge pressures are adequate for the assessment of uncomplicated mitral stenosis as a small gradient indicates a mild obstruction that does not require detailed study. However, in the presence of pulmonary vascular obstruction, tricuspid valve lesions, or myocardial disease (Fleming and Wood, 1959), significant mitral stenosis may be associated with a small diastolic pressure gradient as the cardiac output is reduced. Accurate measurement of the degree of stenosis in these circumstances requires left atrial puncture.

In mitral insufficiency a y descent falling rapidly to the level of the left ventricular diastolic pressure is clear evidence of the absence of stenosis (Fig. 3). Direct left atrial pressures are necessary to measure a small gradient accurately (Fig. 4) but, as a small mitral diastolic gradient may be found in pure mitral regurgitation (Harvey and Ferrer, 1959), left atrial puncture for this purpose is unjustified.

FIG. 4.—The mitral diastolic gradient in a patient with a combination of moderate stenosis and regurgitation with atrial fibrillation. The superimposed facsimile records from a different part of the same tracing show the diphasic y descent, some fall in left atrial pressure continuing throughout diastole. Accurate measurement of this small gradient requires left atrial puncture.

FIG. 5.—The mitral diastolic gradient in a patient with moderately severe mitral stenosis and considerable regurgitation with atrial fibrillation. Subsequent operation showed a mitral valve area approximately 0.6 cm^2 . Note that the pressure scales are different in the left atrial (LA) and left ventricular (LV) tracings. There is considerable respiratory variation in both pressures. The replotted tracing (bottom) shows a high mean left ventricular diastolic pressure (15 mm. Hg). Considerable error would result from calculations of valve area based on an assumed value of 5 mm. Hg.

Left Atrial Pressure

Hæmodynamic measurements are usually made under basal conditions. Natural variations, for instance the effects of anxiety, tend to disturb the basal state and may require mild sedation. In stenotic lesions the calculated valve area is not affected by an increase in cardiac output: in mild cases an increase in the pressure gradient may even be of value as errors of measurement are reduced. On the other hand, mitral regurgitation varies with the arterial pressure (Braunwald *et al.*, 1958).

Basal conditions are therefore desirable, and enable observations to be compared from case to case. Considerable disturbance is produced by the discomfort of transthoracic puncture or bronchoscopy and it may be difficult to interpret the data obtained under these circumstances.

Left atrial pressures may be obtained by transthoracic, transbronchial, suprasternal, or trans-septal puncture. Transthoracic left atrial puncture (Björk *et al.*, 1953) is often an uncomfortable procedure. Burning pain in the throat may occur as the oesophagus is penetrated, and a feeling of upper sternal pressure probably arises from the pericardium. Accidental aortic puncture may be dangerous. Minor hæmopericardium is found afterwards in most cases. Hæmothorax, pneumothorax, and hæmoptysis are frequent, and a period of hypotension often follows. In a recent review 15 deaths were reported in 2178 cases (Crymes *et al.*, 1959). Despite the technical difficulties satisfactory measurements of cardiac output can be made. Our previous experience with this technique (Gadboys *et al.*, 1957) with one fatality in 34 patients did not encourage its continued use.

In left atrial puncture by the bronchoscopic route (Facquet *et al.*, 1952; Morrow *et al.*, 1957), the aim is to enter the chamber extrapericardially. The only frequent complications are minor hæmoptysis and blood-staining of the pericardial fluid. The pulmonary artery or the aorta may be punctured if the left atrium is small. Only 2 deaths were reported with this method in 1472 cases reviewed (Crymes *et al.*, 1959). Davila *et al.* (1959) had 3 cases of severe bronchial bleeding with one death in 46 patients; they then modified the technique, using a smaller needle and a split bronchoscope that was withdrawn after the left atrium had been punctured. This method was used in the 35 cases reported here (Fig. 3 and 4). Scopolamine premedication, local anaesthesia, and bronchoscopy necessarily disturb the basal state: the patient is allowed to rest after the needle has been inserted, but tachycardia often persists.

Suprasternal puncture with a needle passing in front of the trachea to enter the left atrium (Radner, 1954 and 1955) has not been used extensively. The pulmonary artery and aorta are often penetrated and it seems likely that complications will occur (Fox, 1959). The use of a long thin needle makes it difficult to obtain undamped records.

Trans-septal left atrial puncture using a long curved needle inserted through the femoral vein has been introduced recently (Ross *et al.*, 1959; Nixon, 1960). The basal state is undisturbed, but there is a danger that the aorta or the tricuspid valve may be damaged or the atrial wall perforated. The technique is particularly easy if the left atrial pressure is raised, as the septum bulges into the right atrium, but is made difficult by right atrial enlargement.

Left Ventricular Pressure

Calculation of the valve area in mitral stenosis was originally based on the assumption that the left ventricular diastolic pressure averaged 5 mm. Hg with a base-line similar to that used in the present study (Gorlin and Gorlin, 1951). Our data in patients without left ventricular hypertrophy shows an average left ventricular diastolic pressure of 10 mm. Hg with considerable individual variation. Other workers have reported similar findings (Yu *et al.*, 1958). If the mitral diastolic gradient is large, the error produced by assuming a left ventricular diastolic pressure of 5 mm. Hg is small (Fig. 2).

A low pulmonary arterial wedge pressure indicates a mild lesion if the cardiac output is normal. If there are associated abnormalities, such as pulmonary vascular obstruction, tricuspid valve lesions, or myocardial disease, which tend to reduce the cardiac output, the gradient must be measured accurately and left ventricular pressures are required for precise assessment of the stenosis. Similar considerations apply if there is moderate elevation of the wedge pressure and definitive measurement of the stenosis is needed to determine whether operation is required.

Left ventricular pressures are also necessary in patients with serious mitral regurgitation, aortic valve disease, systemic hypertension, or cardiomyopathy, as these lesions may be associated with an increase in the left ventricular diastolic pressure (Fig. 5). In mitral regurgitation an elevated diastolic pressure may contra-indicate repair (Davila *et al.*, 1958). The diagnostic difficulties in

aortic stenosis are considerable (Wood, 1958; Hancock *et al.*, 1958) and left ventricular pressure measurement (Fig. 6) seems justified if there is any doubt as to the presence of severe obstruction.

In expert hands, left ventricular pressures can usually be obtained by transmitral catheterization after left atrial puncture. However, the procedure may be tedious, and the pressure records are often damped as a small catheter must be used (Björk and Malmström, 1959). Knotting or kinking of the catheter in the left atrium is an additional hazard. In the presence of mitral regurgitation it is often difficult to keep the catheter tip in the ventricle. In isolated aortic stenosis puncture of a small left atrium may be difficult, and although it is often possible to pass the catheter into the aorta this cannot be relied on. Simultaneous left atrial and ventricular pressures can be obtained, the left atrial pressure being recorded alongside the catheter, but a larger needle is required than for the left atrial pressure alone, and the risk of the procedure is probably increased.

FIG. 6.—The aortic systolic gradient (bottom) in aortic stenosis derived from proximal aortic and left ventricular (LV) systolic pressures.

Brock *et al.* (1956) used percutaneous left ventricular puncture to obtain left ventricular pressures in aortic stenosis. They reported 79 punctures without mortality, but 2 deaths occurred in 36 attempts to pass a catheter into the aorta through a larger needle (Fleming *et al.*, 1958). Sixty-nine left ventricular punctures were performed in the present study. Pericardial pain and hypotension were frequent complications, and cardiac arrest occurred in one patient. Dilatation of the left ventricle due to aortic or mitral regurgitation facilitates puncture, but it may be difficult to enter the small left ventricular cavity in isolated mitral or aortic stenosis, especially in obese patients. After operation the dangers may be less as the pericardial space is obliterated (Morrow *et al.*, 1960). The reliability and simplicity of left ventricular puncture recommend it, but the dangers are considerable. It seems likely that suprasternal left ventricular puncture will present similar difficulties.

Retrograde arterial catheterization (Zimmerman *et al.*, 1950; Carlotti *et al.*, 1951; Voci and Hamer, 1960) avoids puncture of a cardiac chamber and does not disturb the basal state. A fatality occurred in an early study (Zimmerman *et al.*, 1950), but recently several large series have been reported without serious complication (Grundemann *et al.*, 1958; Morrow *et al.*, 1960). Ischaemic changes in the limb used for arterial catheterization are clearly a potential risk, and care must be taken to avoid obstruction of a coronary artery. Transient dysphasia in two of our patients may have been due to embolism from fragments from the calcified aortic valves. In mitral valve disease, retrograde catheterization seems the best method for obtaining left ventricular pressures. Littman *et al.* (1960) report that a curved catheter tip will pass easily through a normal aortic valve. Retrograde catheterization is difficult in severe aortic stenosis, but is usually possible if there is associated regurgitation. The site of obstruction (Fleming *et al.*, 1958; Morrow *et al.*, 1959) can be demonstrated by this method.

Aortic Pressure

The pressure pulse in the proximal aorta is affected by the character of ventricular ejection and by the effects of aortic regurgitation, but the mechanical properties of the aortic wall and the timing of flow to the peripheral vessels (Warner *et al.*, 1953) also play a part. Analysis of the effects of aortic valve disease is, therefore, complicated by the presence of other variables. There is normally considerable distortion of the arterial pressure pulse as it is transmitted peripherally, the peak becoming later and more prominent and the dicrotic wave being accentuated (Wiggers, 1952). These changes are less evident in aortic stenosis (Wright *et al.*, 1956) but study of the peripheral arterial pulse in this condition has been found of little value (Hancock and Abelman, 1957). Analysis of the pressure changes in the proximal aorta (Wood, 1958) seems more rewarding, but in our experience the aortic pressure pulse has not provided decisive evidence of the haemodynamic situation in lesions of the aortic valve.

CONCLUSIONS

Left heart pressure studies have a considerable risk and should be reserved for situations in which they give information of decisive value. In isolated mitral stenosis a high pulmonary arterial wedge pressure is sufficient indication of a severe lesion and, in the absence of complicating factors, a low wedge pressure indicates mild stenosis. If there are associated changes reducing the cardiac output, a low pulmonary arterial wedge pressure is an indication for measurement of both left atrial and left ventricular pressures to assess the gradient and the degree of stenosis accurately. A moderate elevation of the wedge pressure or associated left ventricular hypertrophy require measurement of the left ventricular pressure, but if a considerable mitral diastolic gradient is found the pulmonary arterial wedge record is adequate as an index of the left atrial pressure. The severity of associated mitral regurgitation cannot be reliably determined from the form of the left atrial pressure pulse. In aortic stenosis left ventricular pressures are usually required.

The modified transbronchial technique was used in the present study as the least dangerous method available for obtaining the left atrial pressure. Trans-septal puncture produces less disturbance and allows catheterization of the left ventricle, but its dangers have not yet been fully assessed. The transthoracic approach is less satisfactory. Left atrial puncture with catheterization of the left ventricle may have a place in mitral stenosis when both left atrial and left ventricle pressures are required. In the presence of mitral regurgitation, rejection of the left ventricular catheter makes this method unsuitable.

Percutaneous puncture was often used to obtain left ventricular pressures in mitral valve disease. Retrograde arterial catheterization is probably less dangerous and is particularly easy if there is an associated aortic valve lesion. In severe aortic stenosis percutaneous puncture is necessary, but retrograde catheterization is preferable if there is significant aortic regurgitation or aortic stenosis of only moderate degree.

SUMMARY

Indications for direct measurement of left atrial and left ventricular pressures are defined and the available techniques reviewed in the light of experience with transbronchial left atrial puncture (33 cases), percutaneous left ventricular puncture (69 cases), and retrograde arterial catheterization of the left ventricle (17 cases).

The transbronchial route is preferred for left atrial puncture, but other methods may have a place when left ventricular pressures are also required. Retrograde arterial catheterization seems the best method for obtaining left ventricular pressures, except in severe aortic stenosis.

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