Measurement of Pressures in Man by Cardiac Catheters

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Relationships between artefacts in recorded intracardiac pulses and the dynamic response and susceptibility of catheter-manometer systems to artefacts caused by motion of the catheter were investigated. Sine-wave motions of the catheter, resembling motion frequently seen when the catheter is in the pulmonary artery, produce sine-wave pressure variations with peak-to-peak amplitudes of 10 mm. Hg. Square-wave motions (impacts) produce high-frequency pressure variations, greatest (10 to 200 mm. Hg) when directed along the axis and much less when perpendicular to the axis of the catheter. High-fidelity records of pressure by conventional cardiac catheter-manometer systems are most unlikely when such catheters are threaded through the beating heart.

THE recording of pressures from the chambers and vessels of the right side of the heart in man usually must be done by means of a cardiac catheter connected to a manometer. For most purposes, the dynamic response of such a system can quite easily be made adequate for sufficiently accurate reproduction of the pressure pulses in question.[1-4] However, serious pressure artefacts caused by impacts on and motion of the catheter imparted by the heart beat practically preclude high-fidelity recording of pressure pulses by this method if conventional catheter-manometer systems are used.[2, 5] This study was carried out to obtain data concerning the optimal dynamic response characteristics of cardiac catheter-manometer systems for recording of pressure pulses by venous catheterization in man.*

METHODS

Pressure pulses and other physiologic variables were recorded during routine diagnostic cardiac catheterization[6] by a photo-oscillographic assembly described elsewhere.[7] In the majority of the studies, pressures were recorded via the catheter by means of a specially adapted strain-gauge manometer.[6] The over-all dynamic response of this catheter-manometer system could be varied instantaneously by a multiposition switch connected so as to allow recording of the pressure pulses interchangeably by three or four different galvanometers with natural frequencies of 5, 12, 25 and 150 cycles per second, respectively. During some of the observations, the catheter pressures were recorded interchangeably, by turning a stopcock, by either a high frequency Lilly capacitance manometer or the strain-gauge manometer (fig. 1). The resonant frequency and damping characteristics of the catheter-manometer assemblies used were determined at the conclusion of each catheterization procedure by recording the responses of the systems to square-wave and variable frequency sine-wave pressure variations generated by an electromagnetic hydraulic pressure oscillator described elsewhere.[7-9] Care was taken that the conditions of fluid filling and hydraulic connections between catheter and manometer were identical to the conditions pertaining during the actual observations.

The susceptibility of the catheter-manometer systems to pressure artefacts caused by motion of the catheter also was studied at the termination of each procedure soon after withdrawal of the tip of the catheter from the vein. The apparatus used consisted of a motor-driven cam that imparts either an approximate sine-wave or a square-wave motion to a shaft to which the tip or shaft of the catheter can be clamped (fig. 2). The sine-wave motions were at a frequency of two per second and at a peak-to-peak amplitude of 2 cm. The frequency of the square-wave impacts was one per second. The pressure artefacts generated when the catheter was subjected to these motions along the axis of the tip and perpendicular to the tip or the mid-shaft of the catheter were studied. It was found that these artefacts were closely similar irrespective of whether the tip of the catheter was immersed in water or in air.

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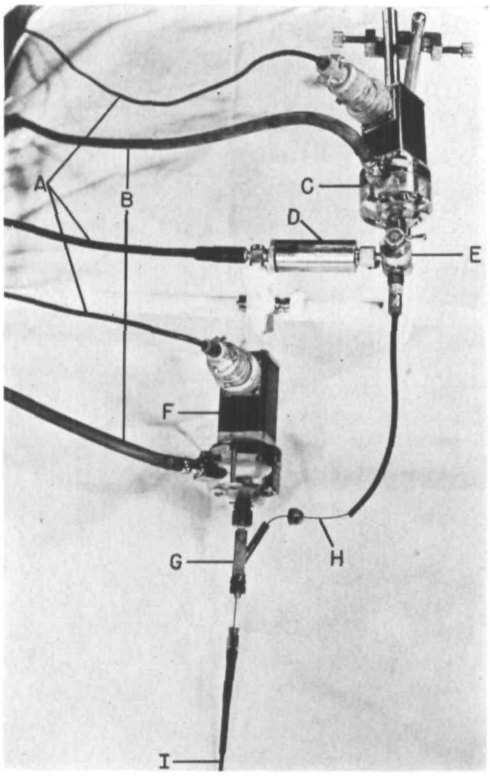

FIG. 1. Semiexploded view of cardiac catheter-manometer systems for incorporating a small polyvinyl plastic catheter (H) (145 cm. long, 0.6 mm. outside diameter and 0.3 mm. inside diameter) within the lumen of a conventional no. 6 French 120 cm. catheter (I). Specially designed low-compliance stopcock (E) for interchangeable recording of pressure pulses from either a strain-gauge (C) or a capacitance manometer (D). Special adapter (G) for making low-compliance connections between strain gauge (F) and lumen of cardiac catheter exterior to plastic catheter (H). Electric leads (A) to manometers; rubber-tubing connections (B) to pressurized wash bottle for flushing manometer-catheter systems with sterile heparinized saline solution.

RESULTS

Studies of this type have been carried out during 30 catheterization procedures using strain-gauge manometer systems only and in 17 procedures using the strain-gauge and capacitance manometers interchangeably. The patients had various types of cardiovascular abnormalities. The catheters used were of the Cournand type, either 100 or 120 cm. in length, and varied in diameter from size 4 to size 7 French.

In general, the dynamic response character-

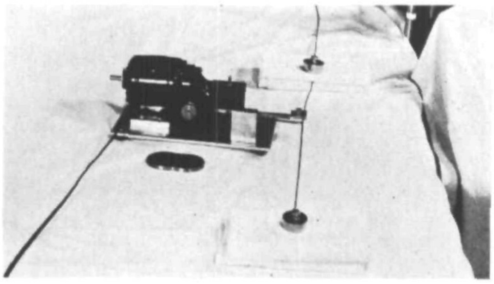

FIG. 2. Apparatus for subjecting cardiac catheters to reproducible sine-wave and square-wave (impact) motions. Catheter is clamped to motor-driven camshaft so that the motion is along the axis of the catheter tip or perpendicular to the catheter axis. Tension on coil spring attached to distal end of camshaft causes its proximal end to ride on cam wheel. Two interchangeable cam wheels were used to produce the camshaft motions: (1) a step-cut cam (in place on the apparatus) and (2) a cam (in foreground) cut to produce two approximately sine-wave motions of shaft for each revolution of cam wheel. Cam wheel was rotated at one revolution per second by means of a reduction gear train coupled to a 1,800-rpm synchronous motor.

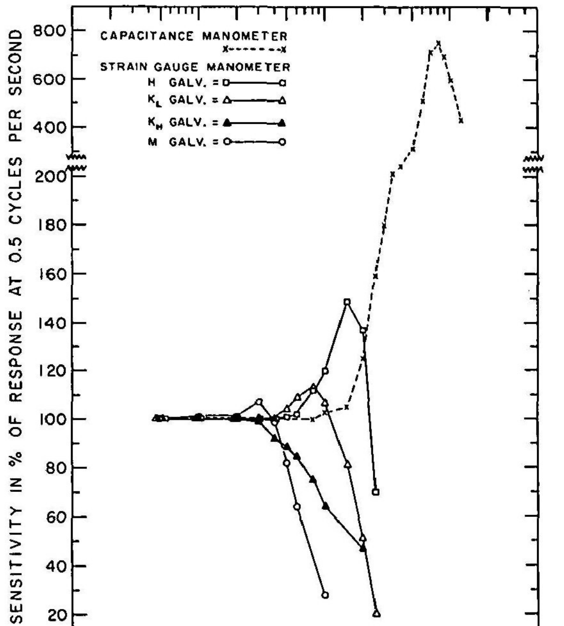

FIG. 3. Variations of sensitivity of cardiac catheter-manometer systems with the frequency of sine-wave pressure variations determined immediately after withdrawal of the no. 5 French 100 cm. catheter from the vein (see text for details).

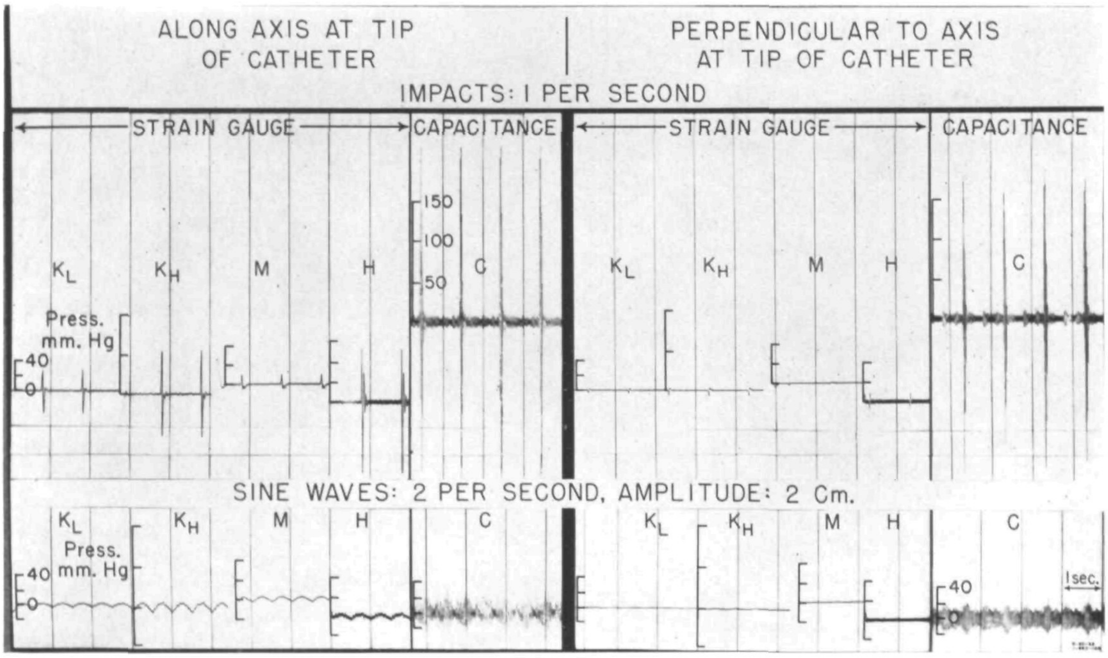

FIG. 4. Effect of variations in dynamic response of cardiac catheter-manometer systems on the pressure artefacts caused by motion of the catheter along the axis of its tip (left panels) and perpendicular to the axis at its tip (right panels). The motions of the catheter were produced by a motor-driven camshaft (fig. 2). Note that the lower frequency strain-gauge systems (K_H and M) record fewer high frequency artefacts than the 20-cycle system (H) and that the high-frequency undamped capacitance-manometer system records continuous high-frequency oscillations probably associated with induced mechanical vibrations in the catheter system. Note also that motions along the axis of the tip of the catheter produce greater pressure oscillations than do identical motions perpendicular to the axis of the tip and that the low frequency pressure artefacts produced by sine-wave motions are of approximately equal amplitude for all of the manometer systems used.

istics of catheters of a given size and length connected to the strain-gauge manometer were closely reproducible from procedure to procedure. This reproducibility was not obtained with the higher frequency capacitance-manometer system in spite of extreme care in attempting to insure minimal compliance of hydraulic connections and avoidance of entrapment of minute air bubbles.

Catheter-manometer systems with low dynamic response characteristics uniformly produced recordings of pressure pulses with less evident distortion by motion artefact than did the higher frequency systems. This difference was especially evident for pressure recordings from the pulmonary arterial wedge, pulmonary arteries and right ventricle.

Excellent correlation was noted between the degree of distortion of recorded pressure pulses by motion artefacts and the amount of motion artefact caused by sine-wave and impact motions of the catheter produced outside the body by the motor-driven cam apparatus. Figures 3, 4 and 5 show typical results illustrating these findings. These studies were carried out during and after cardiac catheterization of a 6 year old girl found to have pulmonic stenosis. Pressures were recorded via a 100 cm. no. 5 cardiac catheter from the pulmonary arterial wedge, pulmonary artery and right ventricle by a strain-gauge manometer coupled interchangeably to each of four different galvanometer systems designated as K_L, K_H, M and H, and by a high-frequency capacitance manometer (fig. 3).

The natural frequency of the capacitance-manometer system was 90 cycles per second, and that of the strain gauge-catheter system was about 20 cycles per second. By use of lower frequency galvanometers, the response of the strain-gauge system could be reduced interchangeably to about 10 or to less than 5 cycles per second (fig. 3). The susceptibility of these catheter-manometer systems to pressure artefacts caused by motion of the catheter is shown in figure 4. Since the major portion of the pressure artefacts is caused by the acceleration and deceleration of the fluid column within the catheter induced by motion of the catheter, it is to be expected that motions along the axis of the catheter generate greater reactive pressures than do motions perpendicular to the axis. Impacts along the axis of the tip of the catheter caused spikes of pressure varying from about 5 mm. Hg for the overdamped 5-cycle strain-gauge system to more than 200 mm. Hg for the underdamped 90-cycle capacitance-manometer system. Sine-wave motions at two per second of 2 cm. amplitude caused relatively smooth peak-to-peak variations in pressure of 10 mm. Hg in the 5, 10 and 20-cycle strain-gauge systems. Continuous noise of an amplitude of 10 to 20 mm. Hg practically obscured the low-frequency sine-wave pressure artefact recorded by the 90-cycle capacitance system. Catheter-manometer systems of higher frequency were uniformly more susceptible to the higher frequency motion artefacts induced by impacts on the catheter than were the low-frequency systems. However, as would be expected, all the systems were about equally susceptible to the low-frequency sine-wave pressure artefacts generated by sine-wave motions of the catheter.

Pressures recorded by these identical cathe-

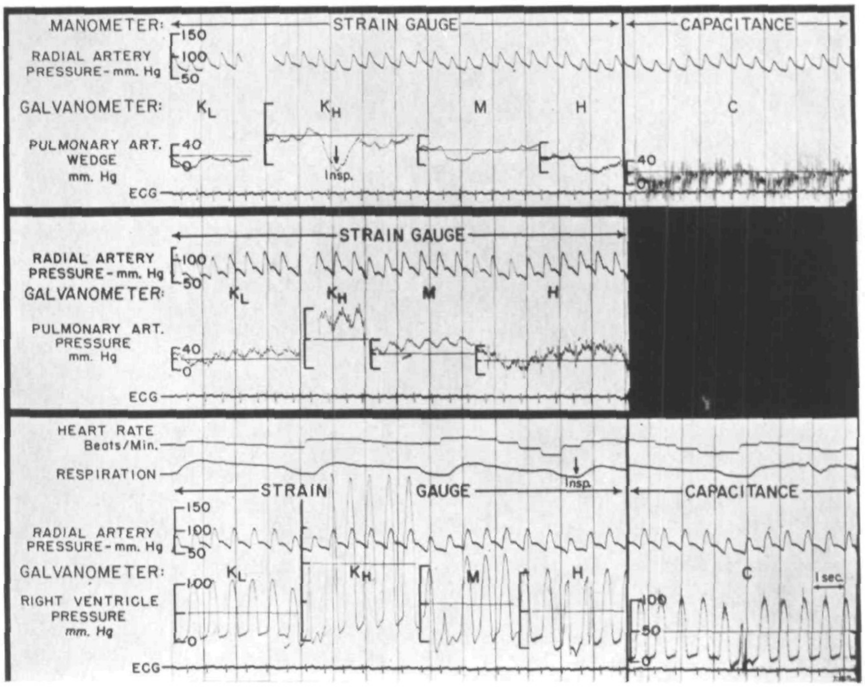

FIG. 5. Effects of variations in dynamic response of catheter-manometer systems on pressure pulses recorded from the pulmonary arterial wedge, pulmonary artery and right ventricle of a 6 year old girl who had valvular pulmonic stenosis. The dynamic responses of the strain-gauge and capacitance-manometer systems are shown in figure 3. Note that recordings from the lower frequency strain-gauge systems (K_H and M) show less evident distortion by artefact than do recordings from the 20-cycle system (H) and that when the catheter is threaded through the beating heart the pressure pulses in the capacitance-manometer recording are almost completely obscured by high-frequency artefact. Note also the correlation between the susceptibility of the various systems to motion artefact shown in figure 4 and the evident artefact in the pressure pulses recorded by these same manometer systems.

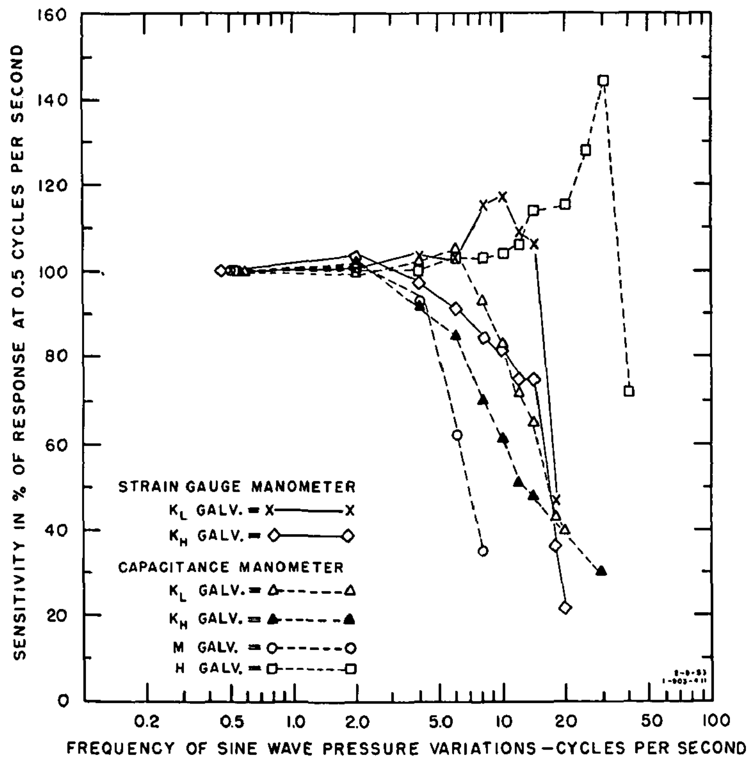

FIG. 6. Variations of sensitivity of cardiac catheter-manometer systems with the frequency of sine-wave pressure variations determined immediately after withdrawal of the no. 5 French 120 cm. catheter from the vein (see text for details). The catheter could be connected interchangeably to either a capacitance or a strain-gauge manometer. The dynamic response of the capacitance manometer could be altered interchangeably by connecting to any one of four different recording galvanometer systems designated H, K_L, K_H and M and that of the strain gauge by connecting to two different galvanometer systems, K_L and K_H.

ter-manometer systems from the pulmonary arterial wedge, pulmonary artery and right ventricle are shown in figure 5. Tracings most free from evident artefacts were obtained by the five-cycle system. When the catheter was threaded through the heart into the wedge position, the pressure pulses recorded by the 90-cycle capacitance-manometer system were obscured by artefacts.

Tracings obtained by the capacitance manometer can be improved by the damping provided by recording through low-frequency galvanometers so that the high-frequency response is limited to 5, 10 or 20 cycles per second (fig. 6). Capacitance and strain-gauge systems damped in this manner to similar high-frequency response are about equally sensitive to motion artefacts (fig. 7). Tracings of pressure pulses obtained from the pulmonary artery and right ventricle (fig. 8) show the least evident artefacts for the five-cycle system (M), most for the 20-cycle system (H) and intermediate and about equal artefacts for the 10-cycle capacitance and strain-gauge systems (K_L and K_H).

It has been suggested that motion artefacts would be reduced if extremely small catheters were used or, better still, if pressures were recorded by a small catheter threaded through cardiac catheters of standard size. In our laboratory, this has been found not to be the case. The small catheter used was of the Peterson type (145 cm. in length, 0.3 mm. in inside diameter and 0.6 mm. in outside diameter).* For recording pressures from the heart it was threaded through a conventional 120 cm. Cournand no. 6 cardiac catheter using the

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* Manufactured by Albert E. Afford Co., 226 Williams Avenue, Barrington, New Jersey.

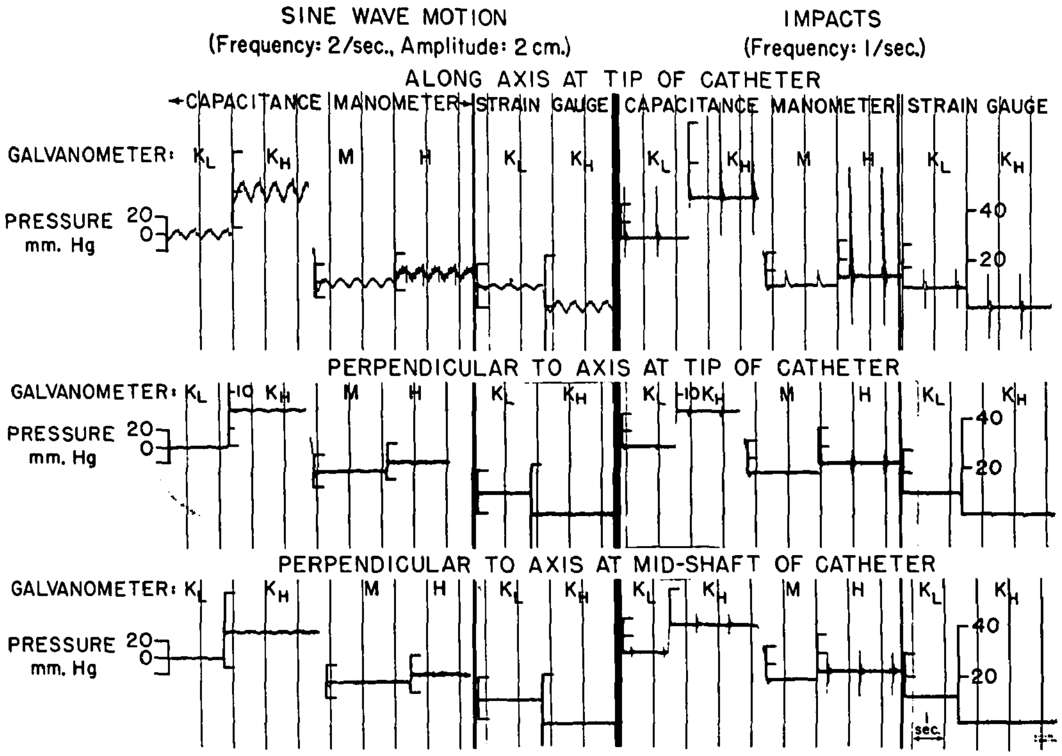

FIG. 7. Effect of variations in dynamic response of cardiac catheter-manometer systems on the pressure artefacts caused by motion of the catheter along the axis of the tip of the catheter (top panels), perpendicular to the axis at its tip (middle panels) and perpendicular to the axis at the midshaft of the catheter (bottom panels). Effects of sine-wave motions on the left-hand panels and of square-wave motions (impacts) on the right. The motions were produced by a motor-driven camshaft (fig. 2). Dynamic responses of capacitance and strain-gauge manometer systems shown in figure 6. Note the following: (1) The sine-wave motions along the axis of the tip of the catheter produce sine-wave pressure variations with an amplitude of approximately 10 mm. Hg. This type of motion, when perpendicular to the catheter shaft produces only minor pressure variations. (2) Impacts produce high-frequency (more than 10 cycles per second) pressure variations of greatest magnitude when the impact is directed along the axis of the catheter tip. (3) Amplitudes of recorded low-frequency pressure artefacts induced by sine-wave motion are approximately equal and are independent of the frequency response of different catheter-manometer systems used. (4) Amplitudes of the recorded higher frequency pressure artefacts induced by square-wave motion of the catheter (impacts) are inversely related to the frequency response of catheter-manometer system, being least for the lowest (M) and greatest for the highest frequency system (H).

adapter assembly shown in a semiexploded view (fig. 1).

The dynamic response of these systems is shown in figure 9. The resonant frequency of the 0.3 mm. catheter-capacitance system was about 30 cycles per second. For recording of pressure pulses, the system was damped down to 10 cycles per second, similar to the standard catheter-strain gauge system. The strain-gauge system recording from the cardiac catheter containing the small catheter was the most overdamped of the three systems, having a uniform response out to only two cycles per second.

The susceptibility of these systems to motion artefacts is shown in figure 10. The overdamped strain-gauge system exhibits the smoothest tracing, while the small catheter-capacitance manometer system is intermediate between that and the standard catheter-strain gauge system. Actual tracings of pressure pulses from the pulmonary artery of the same patient show similar results (fig. 11). Evident motion artefacts on the small catheter-capacitance

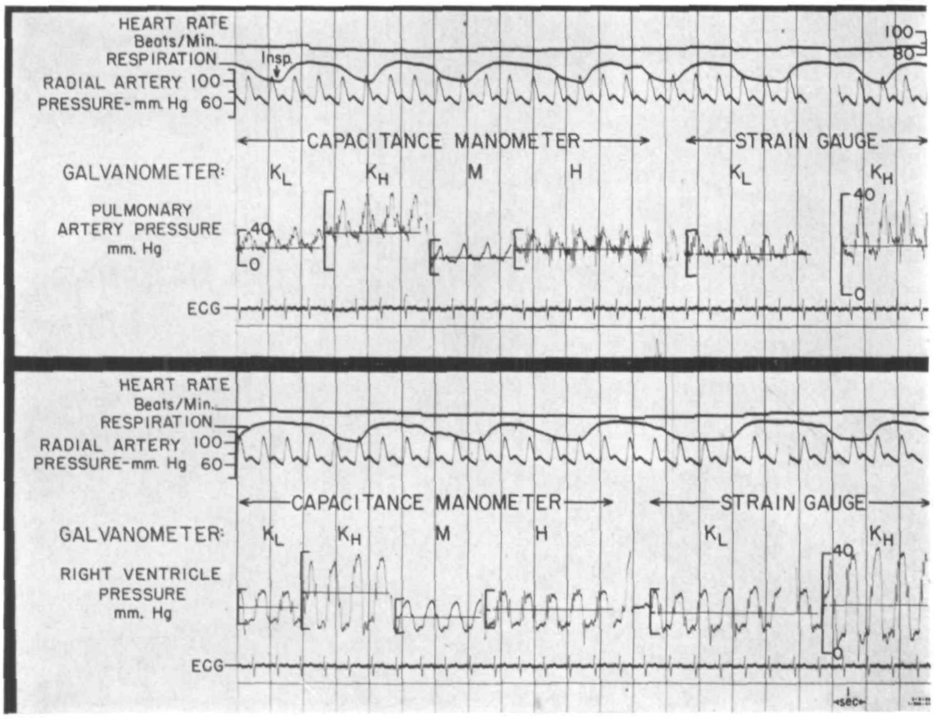

FIG. 8. Effects of variation in dynamic response of catheter-manometer systems on pressure pulses transmitted by no. 5, 120 cm. catheter. Records from the pulmonary artery and right ventricle of a 43 year old woman with atrial septal defect. Note close correlation between evident distortion of pressure pulses recorded by various systems and their susceptibility to pressure artefacts generated by catheter motion outside the body (fig. 7).

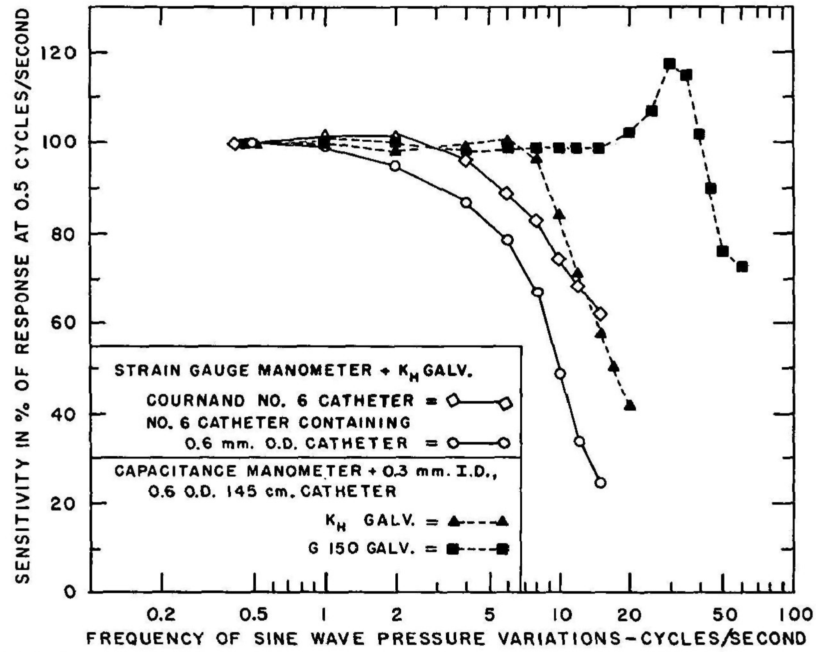

FIG. 9. Variations in sensitivity of the cardiac catheter-manometer systems shown in figure 1 with the frequency of sine-wave pressure variations.

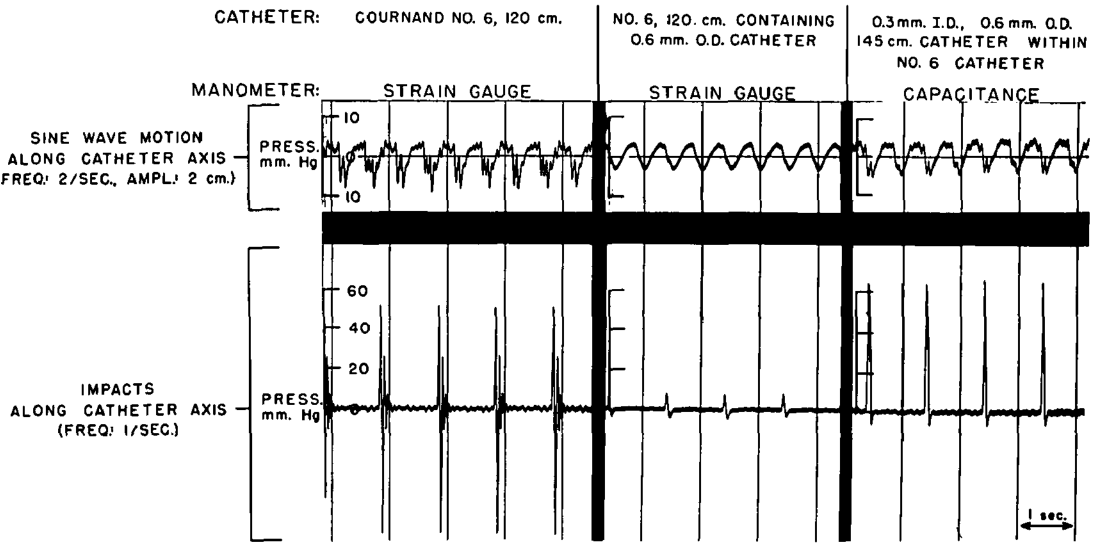

FIG. 10. Susceptibility of three catheter-manometer systems to pressure artefacts caused by sine-wave motions along the axis of catheter tip (top panels) and of square-wave motions (impacts) in same direction (bottom panels). Dynamic responses shown in figure 9. Note that amplitude of the low-frequency sine-wave pressure artefacts induced by sine-wave motion of the tip of the catheter approached 10 mm. Hg in all three systems.

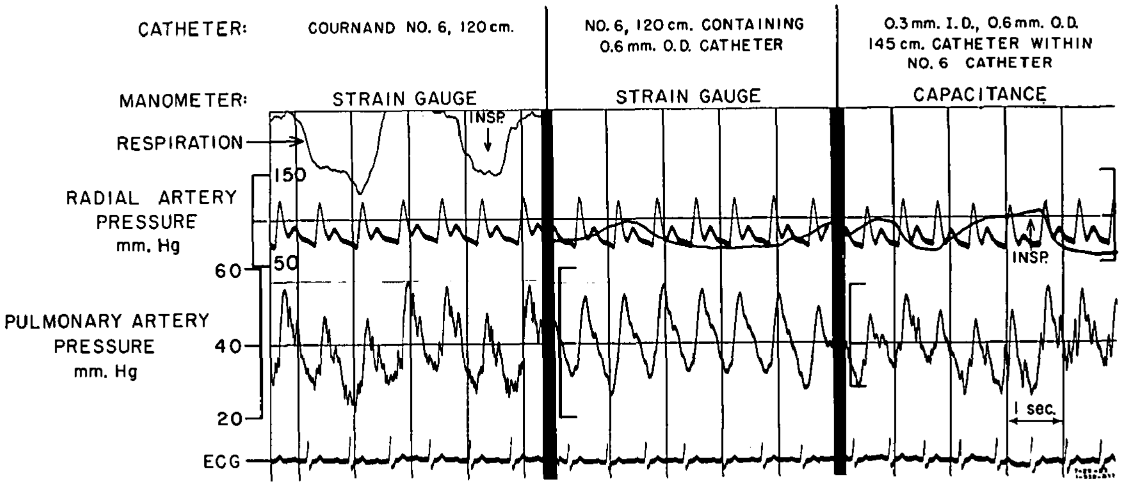

FIG. 11. Comparison of pulmonary arterial pressure pulses recorded by different catheter-manometer systems from a 23 year old woman with mitral insufficiency. Dynamic responses and susceptibility to motion artefacts of these three manometer systems shown in figures 9 and 10. The small plastic catheter was protected from impacts due to the heart action by the no. 6 cardiac catheter through which it was threaded into the pulmonary artery. Pressure pulses recorded by this system (right panel) are nevertheless still badly distorted by evident artefacts, although somewhat less so than recordings from conventional catheter-strain gauge system (left panel). Frequency response of the overdamped system (strain gauge connected to the no. 6 cardiac catheter containing the small plastic catheter) is probably too low (fig. 9) for accurate recording of intracardiac pressure pulses, although tracings obtained (middle panel) show the least evident distortion.

manometer tracing are intermediate between those seen on the tracings from the two strain gauge-catheter systems.

COMMENT

These and similar studies have led us to conclude that it is highly improbable that high-fidelity tracings of pressure pulses can be recorded via conventional catheters threaded into the beating heart. The degree of evident distortion by high-frequency artefacts can be reduced by using relatively low-frequency recording systems with a sharp cutoff in sensitivity to higher frequencies, which thus selectively discriminate against the relatively higher frequency motion artefacts. This requirement is, however, mutually antagonistic to the recording of cardiac pressure pulses, since complete elimination of evident motion artefact required such a low-frequency system that adequate reproduction of the pressure pulses in question may not be possible. Indeed, motions of the catheter at the frequency of the heart beat induce pressure artefacts at the frequency of the cardiac cycle that may be relatively smooth in contour and fused with the actual pressure pulse in such a way as to be unrecognizable as an artefact. Since the fundamental frequency of this type of artefact is identical to that of the cardiac cycle, frequency discrimination cannot be used as a means of selective attenuation of artefact with these characteristics.

The only solution to this problem known to us at present is the use of a miniature manometer attached to the intracardiac tip of the catheter. Such a manometer has been made by Gauer and Gienapp,[10] after Wetterer's design. Since its moving element has a mass of only 15 mg., reactive forces to acceleration and deceleration of the tip of the catheter are extremely small; hence, this catheter-manometer system is practically free of motion artefacts when the catheter is moved outside the body.[3] Pressure pulses recorded from the heart and great vessels similarly are practically devoid of artefact.[3]

SUMMARY AND CONCLUSIONS

The relationships among evident artefacts in the recording of intracardiac pressure pulses and the dynamic response characteristics and the susceptibility of cardiac catheter-manometer systems to pressure artefacts caused by motion of the catheter outside the body have been investigated.

An electromagnetic hydraulic pressure oscillator was used to study the dynamic response characteristics and a motor-driven cam apparatus was used to study the pressure fluctuations (artefacts) caused by reproducible sine-wave and square-wave motions of cardiac catheters connected to strain-gauge or capacitance-manometer systems. These studies were carried out immediately after use of these identical systems for recording of intracardiac pressure pulses during 47 diagnostic cardiac catheterizations in patients who had various types of cardiovascular abnormalities. The following conclusions were reached.

1. Sine-wave motions along the axis of the tip of the catheter at a frequency of two per second and a peak-to-peak amplitude of 2 cm. produce sine-wave variations of pressure at this frequency and with a peak-to-peak amplitude of about 10 mm. Hg. This motion of the tip of the catheter resembles that usually seen to some degree at cardiac catheterization, especially when the tip is in the pulmonary artery. Identical sine-wave motions perpendicular to the axis of the catheter do not produce significant variations in the pressure recorded from the catheter.

2. Square-wave motions (impacts) produce high-frequency (more than 10 cycles per second) pressure variations of greatest magnitude when the impact is directed along the axis of the tip of the catheter and of much less magnitude when the motion is perpendicular to the axis of the catheter. The amplitude of the recorded pressure variations induced by square-wave motion of the catheter (impacts) varied inversely in the range from 200 to 10 mm. Hg with the frequency response of the catheter-manometer systems used.

3. Close correlation was demonstrated between the susceptibility of cardiac catheter-manometer systems to the higher frequency pressure artefacts induced by motion of the catheter outside of the body and the degree of

evident distortion by artefact of pressure pulses recorded by the same catheter system from the beating heart.

4. Catheter-manometer systems with a uniform dynamic response out to 5 to 10 cycles per second with a sharp cutoff in sensitivity to higher frequencies were least susceptible to the higher frequency pressure artefacts induced by square-wave motions (impacts) of the catheter outside the body and likewise produced recordings of pressure pulses from the heart and great vessels with the least evident distortion by artefacts.

5. This type of frequency discrimination cannot be used as a means of selective attenuation of the low-frequency pressure artefacts induced by sine-wave type of motions along the axis of the tip of the catheter, since the fundamental frequency of the artefact due to this type of motion (usually seen to some degree at cardiac catheterization, especially when the tip of the catheter is in the pulmonary artery) may be identical to that of the pressure pulse being recorded.

6. Detailed analyses of the amplitude and contour of pressure pulses recorded by conventional catheters threaded through the beating heart should be regarded with a high index of suspicion, since the lower frequency artefact induced by motion of the catheter synchronous with the heart beat may be of such character and be fused with each pressure pulse in such a manner as to be unrecognizable as artefact.

7. Recording of pressures by a small catheter (0.3 mm. in inside diameter) threaded through a conventional cardiac catheter reduces slightly but not to a sufficient degree the evident artefact present in recordings of pressure pulses from within the heart. The responses of this catheter system to sine-wave motion along the axis of the catheter indicate, however, that there would be no practically significant attenuation of the low-frequency pressure artefact produced by this type of motion within the body.

8. It is most unlikely that high fidelity recordings of pressure can be obtained by conventional cardiac catheter-manometer systems when such catheters are threaded through the beating heart.

REFERENCES

[1] Wood, E. H.: Study of minimal dynamic response characteristics of manometer systems required for adequate recording of peripheral arterial pressure pulses in man. (Abstr.) Am. J. Physiol. **163:** 762, 1950.

[2] —: Physical response requirements of pressure transducers for the reproduction of physiological phenomena. Tr. Am. Inst. Elec. Engineers. (In press.)

[3] Ellis, E. J., Gauer, O. H., and Wood, E. H.: An intercardiac manometer: Its evaluation and application. Circulation **3:** 390, 1951.

[4] Wood, E. H., Leusen, I. R., and Warner, H. R.: Comparison of aortic pressure pulses recorded by strain-gauge and capacitance manometer-catheter systems in man. (Abstr.) Am. J. Physiol. **171:** 780, 1952.

[5] Lambert, E. H., and Jones, R. E.: The characteristics of a resistance-wire manometer for measuring blood pressure in cardiac catherization studies. Proc. Staff Meet., Mayo Clin. **23:** 487, 1948.

[6] Wood, E. H.: Special technics of value in the cardiac catheterization laboratory. Proc. Staff Meet., Mayo Clin. **28:** 58, 1953.

[7] —: Special instrumentation problems encountered in physiological research concerning the heart and circulation in man. Science **112:** 707, 1950.

[8] Isaacson, James, and Jones, R. E.: An electromagnetic hydraulic transducer for studying response characteristics of manometer systems to square wave and sine wave pressure variations of variable frequency. (Abstr.) Am. J. Physiol. **163:** 722, 1950.

[9] Jones, R. E.: Design and reciprocity calibration of a hydrodynamic pistophone. Thesis, Graduate School, University of Minnesota. March, 1952.

[10] Gauer, O. H., and Gienapp, Erich: A miniature pressure-recording device. Science **112:** 404, 1950.