An Intracardiac Manometer: Its Evaluation and Application

By Eugene J. Ellis, M.D., Otto H. Gauer, and Earl H. Wood, M.D., Ph.D.

The miniature intracardiac manometer supplied a method for recording artefact-free pressure tracings from the heart and great vessels of man and the intact animal. This instrument has been applied to the procedure of cardiac catheterization. It has also been used to demonstrate that if motion artefacts can be minimized, the central pulse can be recorded with reasonable accuracy by means of manometric systems with relatively poor dynamic response. Illustrations of pulse waves within the heart and great vessels of man and dogs and the effects of varying the dynamic response of the recording system are included.

The widespread acceptance and application of cardiac catheterization in diagnosis of congenital heart disease has required the accurate recording of changes in intracardiac pressure. In spite of the physical difficulties of recording through a long, narrow-bore cardiac catheter, it has been found that manometer-catheter systems with reasonably adequate dynamic response can be evolved.1-3 Even when such manometer-catheter systems are used, the recordings of pressure obtained from the right ventricle and pulmonary artery of human beings are often obviously distorted by artefacts.1,2

The artefacts are, for the most part, produced by pressures generated in the lumen of the catheter by the acceleration and deceleration of the contained column of fluid, associated with movements of the catheter imparted by the heart beat.1,2

This type of motion artefact can be minimized if the movable mass coupled to the manometer is very small so that the reactive forces and consequent pressures generated by movement are correspondingly reduced.

A manometer made sufficiently small to be attached to the intracardiac end of a cardiac catheter would have this characteristic. It would also avoid other serious difficulties associated with recording through a long narrow plastic tube, such as damping factors, entrapped air bubbles and variation of physical characteristics of the catheter which accompany change of temperature.

Gauer and Gienapp4,5 designed such an instrument according to the principles first outlined by Wetterer.6 The manometer as applied in cardiac catheterization is illustrated in figure 1. The brass housing of the miniature manometer accommodates two transformers, the secondary coils of which are wound in opposite directions. The relative coupling of the coils varies with the movements of a soft iron core mounted on the base of a tiny piston which is pressurized by the intracardiac or vascular pressure. The manometer is attached to an 8F. cardiac catheter and projects 1.2 cm. beyond its woven tip. Amplification of approximately 150,000 to 1 is required and carrier-wave amplifiers have been used.

Methods

A dynamic pump or pistonphone, described by Lambert and Jones, was employed to analyze the responses of this new manometer.1,2 This device generates equal amplitude pressure variations of variable frequency, by means of a piston moving in a small glass cylinder over a column of air and fluid. The piston is driven by means of an eccentric coupled to a variable speed electric motor. The manometer to be evaluated is fitted to the chamber which contains fluid by means of suitable airtight adapters.

An electromagnetically driven pressure oscillator,7 simpler in construction and easier to use than the instrument just described was employed for a portion of these studies. This instrument consists of a cylindrical lucite chamber filled with liquid, one
end of which consists of a stiff, brass diaphragm coupled to a magnetic pen motor which imparts a sinusoidal movement to the membrane. A strain-gage manometer is coupled directly to the opposite end and serves to monitor the variations in pressure produced in the chamber. The pen motor is driven by an electrical sine-wave oscillator. This type of dynamic testing device has three times the frequency range, approximately 1,000 cycles per second, of the piston type, but either device is satisfactory for evaluation and testing of manometers used for most physiologic recordings.

In addition to the previously described dynamic oscillators, square-wave or step responses were also employed to establish the physical characteristics of the manometric systems. A modification of the exploding balloon technic, originally described by Frank, was employed.8

In order to evaluate the applicability of the intracardiac manometer to catheterization of human beings four large adult dogs under light pentobarbital sodium anesthesia were employed.9 The manometer was passed through the external jugular vein into the chambers of the right side of the heart and into the pulmonary artery, and, by way of the carotid artery, into the aorta and left ventricle. After pressures were recorded from the intact animal the thorax was opened and respiration maintained by means of a pump. Pressures within the chambers of the heart were then recorded with a high-fidelity strain-gage system by direct puncture, and simultaneously with the intracardiac manometer.

Additional animals were subjected to extensive catheterizations of the right side of the heart and killed in three days to determine the extent of endocardial damage produced by catheters tipped with the Gauer-Gienapp manometer as compared to that produced by standard Courand catheters.

### Results

The miniature intracardiac manometer has a natural frequency in excess of 1,000 cycles per second. It is relatively undamped, but, when coupled with an appropriate galvanometer (Heiland type G†), will give a response of equal amplitude from 0 to 50 cycles per second without peaks thereafter (table 1; see also top panel, fig. 7).

The manometer is relatively insensitive to temperature. A zero or base-line shift corresponding to 6 to 7 mm. of mercury occurred with the change from room temperature (23 °C.), to body temperature (37 °C.). Such a zero shift did not affect the magnitude of the static or dy-

### Table 1.—Dynamic Response of Strain-Gage and Gauer-Gienapp Manometers in Per Cent of Static Sensitivity

<table>
<thead>
<tr>
<th>Strain gage with 15 gage needle, per cent</th>
<th>10</th>
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<td>97</td>
<td>98</td>
<td>106</td>
<td>124</td>
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| Gauer-Gienapp manometer, per cent        | 102| 105| 103| 97 | 84 | 74 | 62  |     |     |

In addition to the previously described dynamic calibrations and was avoided in practice by calibrating the instrument in a water bath at body temperature before and after insertion into the body.

Sensitivity of the manometer depends on the gain available in the amplifier. In these studies

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* Animal experiments conducted with the assistance of Dr. H. E. Essex, Institute of Experimental Medicine, Rochester, Minnesota.

† Manufactured by the Heiland Research Corporation, Denver, Colorado. Natural frequency 150 cycles per second, sensitivity 0.43 microampere per millimeter at 1 meter; damping used was approximately 200 per cent of critical.
a range of deflection from 0.3 to 2 mm. per millimeter of mercury was employed.

Hysteresis is negligible with the Gauer-Gienapp manometer, being less than 0.01 per cent.

The artefact which results from motion is almost absent with this manometer as illustrated in figure 2. A conventional 8 F. cardiac catheter, attached in an optimally damped strain-gage system (response within ±5 per cent of 28 cycles per second with no peaks thereafter), and a Gauer-Gienapp manometer were bound together so that they were subject to identical motion and the pressures generated by various motions were recorded at the same sensitivity. The absence of artefact with the Gauer-Gienapp manometer during circular, to-and-fro, pendular, side-to-side and rotating motion was evident. Numerous pressure recordings from the heart and great vessels of man and dogs were uniformly free of recognizable artefact of this type when the intracardiac manometer was used (figs. 3 to 6, 8 and 10).

Figure 3 demonstrates characteristic contours of the central pulse waves recorded with the Gauer-Gienapp manometer in intact dogs. The systolic summits in the left ventricle are noted to be of a slowly ascending or plateau type, while those of the right ventricle are peaked with a rapidly descending slope.

The catheter has been passed from the carotid artery down the aorta into the iliac artery in intact dogs and continuous pressure tracings have been taken as the manometer was slowly drawn back into the carotid artery. Figure 4 shows such a recording and illustrates the marked variations in the contour of the pulse waves recorded with the micromanometer at
Fig. 3. Pressure pulse contours recorded with the Gauer-Gienapp intracardiac manometer in the aorta, left and right ventricles in 2 intact dogs.

Fig. 4. Continuous recording of pulse waves in the intact dog while slowly withdrawing the Gauer-Gienapp manometer from the iliac artery through abdominal and thoracic aorta to the carotid artery.
Fig. 5. Tracing from human being during the withdrawal of the catheter from the pulmonary artery through the pulmonic valve into the right ventricle. The top tracing was obtained with the Gauer-Gienapp manometer and the bottom tracing from the same patient by means of an optimally damped system with the strain gage attached to the external end of a conventional Courand catheter, size 8. The apparent artefact in the midportion of the upper tracing is due to the position of the manometer within the pulmonic valve. The distortion of the lower tracing is due to the artefact produced by the motions of the catheter imparted by the heart beat.

Fig. 6. Tracings from pulmonary artery of human being during inhalation of air, 10 per cent oxygen, air and 100 per cent oxygen. The inserts showing the contours of pulse waves are from simultaneous records photographed at a faster speed. The arrows indicate the identical pulses on the fast and slow speed recordings.
Fig. 7. Response of the Gauer-Gienapp intracardiac manometer to equal amplitude pressure variations imparted by the pistonphone pressure oscillator. The three damping conditions illustrated were employed to record the pressure tracings shown in figure 8.

Fig. 8. The effect of rapid interchange of manometric systems with different characteristics of dynamic response (fig. 7) on the contours of pulse waves recorded from the right ventricle, left ventricle and arch of the aorta in an intact dog. Top panels recorded with a system with a dynamic response flat to 50 cycles per second, middle panels recorded with system flat to 30 cycles per second and bottom panels recorded with system flat to 5 cycles per second. Although the sensitivity of the three systems varies slightly there is little apparent or measurable change in the pulse contours obtained from the ventricles or the aorta.
different positions in the arterial tree. These results are similar to those obtained by Hamilton and Dow\textsuperscript{9} by individual pressure tracings recorded after direct punctures at different sites in the arterial tree.

Figure 5 shows pressure tracings from a human being recorded during slow withdrawal of a conventional cardiac catheter and of a catheter with the Gauer-Gienapp manometer attached from the pulmonary artery into the right ventricle. The artefacts induced by the motion of the fluid column in the conventional catheter are evident. This serves to emphasize the importance of the distortion produced by motion of the catheter.

The inhalation of various gas mixtures was associated with definite changes in the contour of the pulse wave in the pulmonary artery of human subjects as well as changes in the systolic and mean pressures (fig. 6). The effect of inhalation of low oxygen mixtures on systolic and mean pressures has been reported by others.\textsuperscript{10-13} The Gauer-Gienapp manometer makes it possible in addition to demonstrate effects on the contour of the pulse wave in the pulmonary artery.

The ability to obtain accurate artefact-free tracings with the Gauer-Gienapp manometer, supplied a direct approach to the problem of the dynamic characteristics necessary in a manometer to reproduce the central pulse accurately. This could be accomplished readily since variation in the resistance of the shunt across the galvanometer, that is, electrical damping, produced immediate, easily reproducible changes in the dynamic response of the over-all manometric system. The dynamic responses of the three systems used are illustrated in figure 7. The three systems were immediately interchangeable by flicking a switch. The dynamic response of the first system as determined by the pressure oscillator was uniform to 50 cycles per second but was reduced to 84 per cent at 60 cycles per second; the next was uniform to 30 cycles per second and down to 65 per cent at 60 cycles per second, and the last was uniform to but 5 cycles per second and was reduced to 32 per cent at 60 cycles per second. Rapid interchange of these recording systems in the dog with closed thorax produced little apparent change in the contour of the pulse wave (fig. 8). Although the sensitivity of three systems varies slightly there is no measurable change in the systolic, diastolic or mean pressure.

It is realized that the shift in phase or delay in time is increased in a highly overdamped system (lower panel, fig. 7) but still it is of small magnitude. The electromagnetic oscillator with monitoring strain gage made it possible to record the actual sine-wave pressure which occurred within the oscillator simultaneously with that being recorded through the manometric system (fig. 9). It can be seen that in the optimally damped system there was a constant delay through the range of equal amplitude response, the magnitude of which was negligible for practical purposes (left 3 panels, fig. 9). In the overdamped system the delay in time was greatest at low frequencies and decreased with higher frequencies (right 3 panels, fig. 9). The magnitude of the delay was, however, relatively
small: approximately 0.01 second at 10 cycles per second and about 2 milliseconds at 50 cycles per second. Because of the apparent low fundamental frequencies in the normal central pulse and because the actual delay in time was so small, little distortion was evident between the tracings obtained with these two systems of widely different dynamic responses.

This type of comparison also was employed in dogs with open thorax. The pressure tracings from an intracardiac micromanometer were monitored by simultaneous pressure recordings from the same cardiac chamber obtained by means of a special strain gage attached to a 15 gage needle introduced into the chamber by direct cardiac puncture. The strain-gage system had an equal amplitude response to 100 cycles per second and a peak response of 124 per cent at 170 cycles per second (table 1). Figure 10 does not demonstrate any appreciable differences in the appearance of pressures from the pulse waves recorded with the two different systems.

In the dogs on which necropsy was performed to determine the degree, if any, of endocardial damage produced by cardiac catheterization, it was found that the catheters tipped with the micromanometer produced no more and in some instances even less damage than the conventional 8 F. catheter.14, 15

**Comment**

It has been shown that reasonably satisfactory manometric systems can be obtained for recording from the external end of a conventional cardiac catheter, but that the artefact due to motion of the catheter produced by the heart beat is of such magnitude as to compromise seriously pressure recordings obtained therefrom. In application of the miniature intracardiac manometer, emphasis has been placed on the elimination of this motion artefact since it is one of the major considerations in obtaining satisfactory pressure tracings from the human being during cardiac catheterization.

![Simultaneous recordings from the Gauer-Gienapp intracardiac manometer and a special strain-gage system recording by direct intracardiac puncture in a dog with thorax opened.](image)

Fig. 10. Simultaneous recordings from the Gauer-Gienapp intracardiac manometer and a special strain-gage system recording by direct intracardiac puncture in a dog with thorax opened. The strain-gage manometer system had essentially an equal amplitude response to sine-wave pressure variations of from 0 to more than 100 cycles per second (table 1).

With the provision that optimally or overdamped manometric systems capable of reproducing sine-wave pressure variations of more than 5 cycles per second are used, the degree of fidelity of response to higher-frequency pressure variations is of less importance in obtaining accurate pressure recordings from a catheter than is the artefact due to motion of the catheter. Such artefacts may amount to 20 mm. of mercury (fig. 2), as compared to the little measurable or detectable difference in the tracings of central pulse waves recorded with widely divergent dynamic systems (fig. 8). Apparently in the dog, in which the normal heart rate is more rapid than that of man, the static and dynamic components of the central pulse can be reproduced.
faithfully with a considerably poorer dynamic system than is usually deemed necessary.\textsuperscript{16}

The analysis of the manometers used was carried out with dynamic pressure oscillators of two types, the pistonphone and the electromagnetic oscillator. These instruments are useful in determining the actual responses of manometers to rapidly oscillating pressure changes, such as are present in the vascular system. Evaluation of recording manometric systems in this manner would supply a much needed base line for comparison of the pressure tracings obtained from various laboratories which use different manometric systems, the dynamic responses of which are often poorly defined.

**SUMMARY AND CONCLUSIONS**

The application of a new miniature intracardiac manometer has been demonstrated in the catheterization of animals and human beings. Artefact-free, high-fidelity tracings of pulse waves were obtained.

The results indicate that the contour and magnitude of the central pulse can usually be recorded with reasonable accuracy with a manometric system which possesses a uniform sensitivity out to 5 cycles per second but only 32 per cent response at 60 cycles per second.

The dynamic response is of less importance than the artefacts associated with motion of the catheter in producing the poor intracardiac pressure tracings usually obtained with conventional cardiac catheter-manometer systems.

Recordings obtained from the pulmonary artery of human beings indicate that inhalation of gas mixtures of different oxygen content may be associated with changes in the contour of the pulse wave of the pulmonary artery as well as changes in the systolic, diastolic and mean pressures in the pulmonary artery.

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