AN AIR FILLED CATHETER FOR BLOOD PRESSURE MEASUREMENT

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Accurate recordings of blood pressure changes are a prerequisite for the diagnosis of congenital heart diseases and for examination of physiological function of the circulatory system. However, the conventional catheterization method consisting of a catheter and a manometer system often yields erroneously distorted recordings of blood pressure. The distortion is partly due to the low frequency characteristic of the measuring system and is partly associated with the catheter motion caused by external forces.

In the previous paper, a simple method was described to improve the frequency characteristics of the manometer system. A small metal cylinder with lateral holes was attached to the tip of a catheter. The catheter lumen was filled with a fluid and its tip was covered with a thin silicon membrane. This procedure remarkably improved the frequency characteristics of the catheter: The resonant frequency shifted to higher cycles of about three times that of the conventional, non-covered catheter. Moreover, the covering made it possible to adjust the viscosity of the fluid filled in the catheter by an addition of glycerin in such a way as to attain an adequate damping. Therefore, the undesired peaking of the frequency-amplitude curve could be eliminated completely without electrical damping.

Although having a desirable effect on the frequency characteristics, the covering on the catheter tip failed to suppress the repercussion due to the catheter motion caused by external forces other than blood pressure. Such an undesirable repercussion was considered to be due to the motion of the fluid mass in the catheter lumen. In other words, if the movable mass in the lumen could be minimized by replacing the fluid by other light substances the above mentioned repercussion may be eliminated. Thus, the catheter manometer system was filled with air instead of fluid. As a result the repercussion was actually reduced sufficiently. Moreover, the suspicion previously mentioned that the compressibility of the air might bring some erroneous effects was not proved to be the case. Flat frequency characteristic was observed from

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0 to 100 cps. This means that the sensitivity of output to change in pressure is almost equal in this range of frequency. Thus it is presumed that the compressibility was well compensated for, by the reduction in the mass.

When the catheter is inserted into the vascular vessel, the silicon membrane at the tip moves to and fro according to the pressure change, and this is transmitted through the air along the catheter lumen to a pressure sensor which is connected to the end of the catheter. The theoretical treatment of the pressure transmission through air in a long narrow tube, such as in this case, was set forth by FRANK. Since FRANK, it has long been regarded that a catheter filled with air which is referred tentatively in this paper as the “air catheter” was unapplicable for pressure measurement because of the compressibility of air and high frictional resistance along the narrow tube. However, its applicability has been demonstrated clearly by an appropriate design of instruments and the recent developments in electronics.

**METHOD**

1) **Structure of the catheter tip.** In order to eliminate the temperature effect on the pressure output, the structure of the tip was designed as illustrated schematically in Fig. 1. A thin brass cylinder of about 3 mm in outer diameter was divided into two chambers of equal volume: One was blind and the other was rendered sensitive to pressure through lateral holes covered with a silicon membrane. The blind chamber was constructed by closing the open cylinder with a small rubber stopper. The cylinder with two chambers was attached to the tip of a double lumen catheter which was connected with a differential manometer at the other end. The pressures in both chambers were transmitted to the pressure transducer of the differential manometer in the opposite directions, in such a way that the temperature effect in both chambers could be counterbalanced. The blood pressure signal was obtained only through the pressure sensitive chamber.

The silicon membrane consisted of a silicon solution of R.T.V. silicon 501 (Dow Corning Co. U.S.A.) mixed with R.T.V. catalyst (A.R. BROWN McFarlane Co.) with a ratio of 95:5 in weight. A closed glass tube of 2.8 mm in diameter was immersed in the above solution and the solution adhering to the glass surface was dried at room.
temperature in such a way that the small sack which formed would cover the tip with a sufficient tightness. To obtain an appropriate thickness of about 0.27 mm the procedure of immersion and drying was repeated several times.

2) Manometry and recording. The pressure transmitted through the air catheter was recorded by two manometers: One was a differential capacitance manometer combined with a capacity detector of Decker type, D-11L, Densoku, Tokyo and the other was a foil gauge manometer of LPU-0.5, Nihonkoden, Tokyo. The former detector was designed according to the principle outlined by LION⁶ and it was capable of converting small capacity changes into large output voltages. In the present study the pressure signal obtained from both manometers was further amplified by use of an amplifier, RDH-2, Nihonkoden, Tokyo. The former manometer showed flat sensitivity to a sinusoidal wave pressure in a frequency range of 0 to 70 cps and the latter, in a range of 0 to over 100 cps. The schematic diagram of the entire system is illustrated in Fig. 2. The fluid catheter was connected with a foil gauge manometer, LPU-0.5, Nihonkoden and an amplifier, RP-2, Nihonkoden.

![Fig. 2. Schematic illustration of the entire arrangement of the air catheter-manometer system.](image)

The frequency characteristic of the air catheter-manometer system was analysed with respect to amplitude variation and phase displacement. The amplitude variation in the output which is dependent on the frequency was determined by recording the pressure signal on an oscilloscope against time as a sinusoidal curve. The phase displacement was observed as a Lissajous' loop in which the X axis reflected the motion of the crank of the pressure generator which was considered to be synchronous with the applied pressure and the Y axis, the output signal of the pressure. The motion of the crank was detected from the change in capacity between two parallel metal plates, one of which was fixed to the moving crank, the other, to the base plate of the generator. The change in capacity was transduced to an electrical signal by using the resonant characteristic at high frequency. The output signal from the moving crank was led to the X-axis of the oscilloscope, while the pressure signal from the catheter was led to its Y-axis. Thus, the phase difference was observed as a Lissajous' loop.

3) Pressure generator. The pressure generator consisted of a plastic cylinder of 45 mm in inner diameter and a 1 mm thick rubber membrane covering the upper cut end of the cylinder. The membrane was forced to oscillate by means of an eccentric cam coupled to a variable speed electric motor which generated an equal pressure amplitude over a range of 2 to 95 cps. The catheter to be tested was fitted to the cylinder chamber by use of a suitable air-tight adaptor.

In addition the following step response test was carried out to investigate the resonant frequency of the air catheter system: After the pressure in the cylinder chamber was elevated, a stop-cock fitted to the lateral bore of the cylinder was opened
abruptly. This caused a rapid fall of the pressure, which was recorded synchronously through the oscilloscope.

4) Animal experiments. Blood pressure measurements were carried out with mongrel dogs anesthetized by pentobarbital with a dose of 30 mg/kg. The air catheter was inserted into the vascular vessels from the femoral artery or vein. The blood pressure from the aorta, the left and right ventricles were recorded on a pen-recorder. The recorded curves were compared with those obtained through a fluid catheter at the same position.

RESULTS

1) Relationship between the manometer output and the static pressure. The relation between the applied pressure and its output was strongly affected by the tensility of the silicon membrane cover. When the covering was loose and the size of the holes was large, a linear relation between the two could not be obtained. With a suitable tightness of the membrane, the desired linear relationship was observed over a range of 0 to 300 mmHg. The air pressure in the catheter lumen was increased with the increase of the applied pressure at a rate of 8 mmHg/100 mmHg. The sensitivity to the pulsatile pressure change was little affected by temperature change, but the output level drifted slightly in accordance with the temperature change. The calibration was made in a water bath regulated at 38.5°C.

2) Effects of temperature. Generally speaking, temperature changes affect the air pressure in a catheter. When an air catheter of 125 cm length is inserted

![AIR CATHETER](image)

![FLUID CATHETER](image)

**Fig. 3.** Responses due to the catheter motion. Two catheters bound together, one an air and the other a standard catheter filled with fluid, were slightly tapped in the course of recording the sine wave. The fluid catheter produced distorted patterns.
by 40 cm into a water bath of 38.5°C at room temperature, 25°C, the air pressure inside the catheter shows an increase of 20 mm H$_2$O. This value corresponds to the pressure change which may be expected when a pressure of several hundreds mmHg is applied at the catheter tip under a constant temperature. Therefore, the temperature change might cause a remarkable shift in the manometer output, if this temperature effect is not counterbalanced by that of another catheter. Thus, in this experiment in order to eliminate the above described effect, the structure of the catheter tip was designed as shown in Fig. 1, where the temperature effect of the pressure sensitive catheter could be eliminated satisfactorily by the introduction of a blind catheter. The volume of the blind catheter which is very important for this elimination was adjusted by the rubber stopper inserted in the catheter tip.

3) **Repercussion due to external forces.** When a fluid catheter is disturbed by some external force, a corresponding oscillatory noise appears on the recorded pressure pattern. In the case of an air catheter, however, the above disturbances were sufficiently eliminated as shown in Fig. 3. In this experiment a fluid catheter and an air catheter were bound together in such a way as to receive identical disturbances and in the course of recording a sinusoidal pressure pattern, the catheters were tapped lightly in a direction perpendicular to the catheters. It was clearly shown that while the sine wave was disturbed considerably on the record from the fluid catheter, only a slight oscillation was detected on the record from the air catheter.

4) **Frequency characteristics.** The frequency characteristics obtained with a fluid 7F single
Fig. 5. Sinusoidal pressure output and its Lissajous' loop against the applied pressure of the uniform amplitude and various frequencies, obtained with an 8P double lumen catheter.
lumen catheter of 100 cm is shown in Fig. 4. The sinusoidal pressure pattern and the Lissajous' loop which showed the phase displacement between the input and the output pattern were recorded at five different frequencies from 4 to 19 cps respectively. The amplitude of the pressure wave showed its maximum at the frequency of 13 cps and decreased rapidly thereafter. Fig. 5 shows the records obtained by use of an 8F double lumen air catheter on waves of 10 different frequencies ranging from 4 to 85 cps. The Lissajous' loop became round at 45 cps. The amplitude of the pressure signal showed no obvious maximum. At a frequency range higher than 45 cps the amplitude turned to decrease only slightly. Figs. 6 and 7 illustrate graphically the rela-

![Graph for Amplitude-frequency characteristics](image1)

**Fig. 6.** Amplitude-frequency characteristics of the air and the fluid catheters.

![Graph for Phase-frequency characteristics](image2)

**Fig. 7.** Phase-frequency characteristics of the air and the fluid catheters.
tion of changes of amplitude and the phase delay respectively against the frequency of the applied sine wave pressure. In Fig. 6, the result of a 7F single lumen air catheter is illustrated for comparison against that of the 8F double lumen air catheter. As may be seen in the figure the amplitude of the pressure signal obtained with the 7F fluid catheter showed the highest and sharpest changes in response to the frequency changes while lesser responses were seen in the 7F single air catheter. It was noted that the change of amplitude was the smallest with the 8F double air catheter. At the point of the maximum amplitude i.e. near 45 cps, the phase displacement showed 90 degrees as is seen in Fig. 7. Therefore, it might be concluded that because of the lesser diameter of the 8F double lumen air catheter the catheter system showed a higher degree of damping.

5) **Step response test.** The step response test was performed using a pressure generator for the sake of convenience, in spite of the fact that it seemed to be less suitable for this purpose than the widely accepted balloon explosion technique. As seen in Fig. 8, the output of the air catheter decreased slightly faster than that of the fluid catheter and stopped abruptly at the atmospheric pressure level, when a lateral bore on the wall of cylinder of the pressure generator was opened. With the fluid catheter, however, a remarkable pressure oscillation appeared as shown in Fig. 8. This oscillation may strongly distort the record of the rapid change in the blood pressure.

6) **Animal experiments.** The arterial pressure patterns obtained by use of the air catheter and the fluid catheter are shown in Figs. 9-A and B. The patterns by the air catheter (A series) were somewhat rounded and resembled patterns reported by use of the direct puncture method and the micromanometer me-
FIG. 9. Arterial pressure patterns in dog aorta recorded with air and fluid catheters placed at the same positions; The positions of the catheter of each figure are from top to bottom, 40 cm (ascending aorta), 30 cm (descending aorta), 20 cm (abdominal aorta) and 10 cm (femoral artery) respectively from the incised part of the femoral artery. A: with the air catheter and B: with the fluid catheter.

Methods). The incisura was clearly recorded at the portion of 40 cm insertion (the ascending aorta), while it became smaller as the catheter was drawn out. The patterns obtained by use of the fluid catheter (B series), on the other
hand, showed sharp and elevated peaks while some free oscillations followed the main peaks. At the portion of 30 cm insertion (the descending aorta) the pressure pattern showed double plateaus which disappeared by further withdrawing the catheter. This fact was demonstrated in three of the four animals employed. Such a deformation in pressure waves can hardly be explained as a simple effect of propagation of pressure waves.

Fig. 10. Ventricular pressure patterns recorded simultaneously with air and fluid catheters.
Some records of ventricular pressure obtained simultaneously by use of the air and the fluid catheters are shown in Fig. 10. The systolic summits in the left ventricular pressure showed a slowly ascending slope while those in the right ventricle showed a sharply ascending slope. The fact is in a good agreement with reports by Ellis et al.\(^{1}\) and Barritt and Davies\(^{10}\). The fluid catheter, on the other hand, presented a markedly prolonged systolic rise for both the left and the right ventricles, as compared with the record with the air catheter. Especially, in the pressure pattern recorded in the left ventricle by the fluid catheter the peak of the curve was rather simple, while a plateau appeared in the record with the air catheter.

**DISCUSSION**

The catheter-manometer system is an oscillatory system which is characterized with both the inertia due to the mass of the fluid in the catheter lumen and the elasticity of the transducer membrane. The pressure applied to the tip of the catheter causes a slight motion of the fluid. The transducer membrane is displaced by the inertia of the fluid and thus an oscillation appears. Such an oscillatory system has frequency characteristics showing resonance which is dependent on the mass and elasticity as was shown by the mathematical treatments by previous investigators\(^{5,11}\). The widely used manometer and standard catheter systems show a maximum resonant amplitude of 250% at a frequency of 13 cps. Therefore, the frequency component corresponding to the resonant frequency which is to be involved in the blood pressure should be amplified through the manometer system. The introduction of a simple electric damping may certainly reduce the change of the amplitude at the resonant frequency and extend the frequency range showing a flat sensitivity. However, the use of a damping circuit will lower the resonant frequency, and thus the frequency range in which the pressure can be measured without distortion may be narrowed even more.

In addition, the mass of the fluid initiates another factor of distortion. Namely the catheter motion caused by external forces such as the heart beat and or rapid change in blood flow will be transmitted via the mass to the transducer membrane which will result in an oscillatory noise on the pressure signal. This can not be eliminated even by an optimum damping of the oscillatory system, and can only be eliminated by the introduction of mass of smaller inertia in the catheter lumen. A previous study by the author on the effect of a catheter tip cover upon the frequency characteristics suggested a favorable result by replacing the fluid in the catheter with air. Physical examination with the air catheter-manometer system revealed that it may be useful for recording the blood pressure, and the following results were obtained: Firstly the resonant frequency was found at 45 cps. Secondly its output was
not affected by the catheter motion caused by an external force. And thirdly the recorded contours of the blood pressure were characterized by rapid rises and smooth summits in comparison with those obtained by the fluid catheter.

In spite of the obvious advantages, the air catheter showed a serious drawback, namely the temperature effect. In other words, the output of the air catheter-manometer system, when lacking means to eliminate the temperature effect, showed a conspicuous drift with the temperature change. Thus a special device was introduced at the catheter tip in combination with a double lumen catheter to compensate for the drift.

Recently several types of micromanometers have been developed for precise recording of blood pressure. These can be attached to the tip of the catheter and transmit the pressure directly through the lead wires lying in the catheter lumen. However, the delicate structure of the micromanometer is, in general, open to accidental damages and moreover the lead wires are frequently broken when the tip is inserted into the ventricle or further into the pulmonary artery. The air catheter, however, contains no electrical transducer in its lumen and is free from the disadvantages such as encountered in the micromanometer method.

SUMMARY

It was demonstrated in the present paper that a heart catheter filled with air could transmit the blood pressure without distortion. The 8F double lumen catheter employed showed an almost uniform output amplitude over a range of 0 to 85 cps with a phase delay of 90 degrees at 45 cps. It showed no natural oscillation at the step response test and its output received no effect from catheter motion due to external force.

The arterial pressure patterns recorded in animal experiments with this air catheter showed rapid rises and smooth summits in comparison with those obtained by use of the standard catheter system. The recorded contours of the arterial pressure showed significant changes in the incisura and the form of the wave summits, when the catheter tip was moved down along the aorta from the ascending aorta to the femoral artery.

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REFERENCE
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