Development of a New Catheter-tip Pressure Transducer

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Two major disadvantages of the conventional catheter-tip transducer have been incapability to calibrate baseline pressure and to adjust sensitivity after insertion. A vast majority of conventional catheter-tip transducers are classified as gauge type. Due to their structure they are inherently incapable of recalibrating after insertion. We have overcome this problem by developing a new differential type catheter-tip transducer equipped with a lumen that connects a small chamber at the backside of the transducer to another external port. This lumen is capable of pressure passage. The output of this type depends on the difference between the two imposed pressures. This passage makes a baseline standard possible, when the end of the lumen is exposed to atmospheric pressure. When pneumatic pressure is imposed to the end of the lumen using a syringe, for example, the transducer output shifts up and down in accordance to that pressure, enabling baseline pressure recalibration and verifying the degree of sensitivity after insertion. By obtaining the following data, we confirmed the stability and availability of this transducer: Baseline drift less than 0.04 mmHg/8 hour, frequency characteristics flat up to 60 Hz, and common mode rejection ratio more than 46 dB.

Key words : Catheter-tip transducer, Differential transducer, CV catheter, Baseline drift, Frequency characteristics

INTRODUCTION

Anesthesiologists and clinicians requiring accurate, continuous monitoring of intravascular pressures such as those of radial artery, pulmonary artery, and central vein regard direct measurement to be of fundamental importance. A pressure measuring system includes a transducer, which converts mechanical pressure movement into an electrical signal. The transducer is usually connected to a fluid-filled catheter in which pressure waveform travels down from a blood vessel to the transducer. Also, the catheter-tip transducer system is used to avoid the use of a fluid-filled system. In this paper, we deal with the development of a catheter-tip transducer manometer system.

A catheter-tip transducer is comprised of a miniature transducer attached to the peripheral end of an intravascular catheter, which consequently, can be introduced directly into a blood vessel. Since this system does not need fluid-filled catheters, its frequency response is high and can be well used in high-fidelity pressure measurement. However, the disadvantages of these transducers are that they are expensive and fragile with unstable baseline drift. Although improvements in this field of instrumentation have been made, performance remains unsatisfactory. The problems lie in the structure of the transducer.

To eliminate the above-mentioned problems, we have introduced a new type of differential transducer that is capable of shifting the baseline by applying appropriate pressure via the external port.

Structure of differential type catheter-tip transducer

Figure 1 shows the structure of a conventional gauge type catheter-tip transducer [1, 2]. Applied pressure distorts a diaphragm and a piezo element connected to the diaphragm converts the distortion into an electrical signal consisting of small voltages proportional to the pressure. Calibration of baseline and sensitivity adjustment are carried out by exposing the diaphragm to

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atmospheric pressure and then to a static pressure within the physiological range. Therefore, this procedure can not be done after introduction of the catheter into a blood vessel.

Figure 2 shows the fundamentals of our proposed new transducer structure. The small chamber at the backside of the piezo element connected to a passage of pressure lumen has an opening at the hand side of the catheter. As depicted in the figure, we attempted to control the pressure in the chamber at the backside of the piezo element. The transducer output is proportional to the difference between the two pressures applied to the diaphragm and to the lumen opening. Thus it is referred to as a differential type transducer.

Figure 3 shows the differential type catheter-tip transducer made from a commercially available multi-lumen CV catheter of 20 cm long and 7.5 French in diameter (KS7.5FR-3W, Kawasumi, Japan). The internal diameter of the lumen connected to the chamber is 0.9 mm. A hub is attached to the opening of the lumen to facilitate pneumatic pressure application using a syringe or another specially designed instrument.

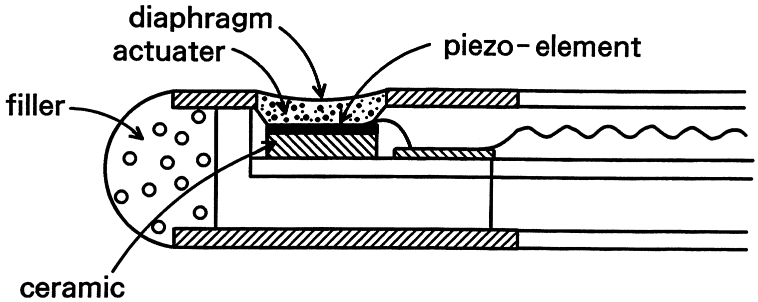

Fig. 1 Gauge type transducer: An applied pressure distorts a diaphragm and a piezo element mounted on the ceramic stand. Distortion of the element is converted into an electrical signal.

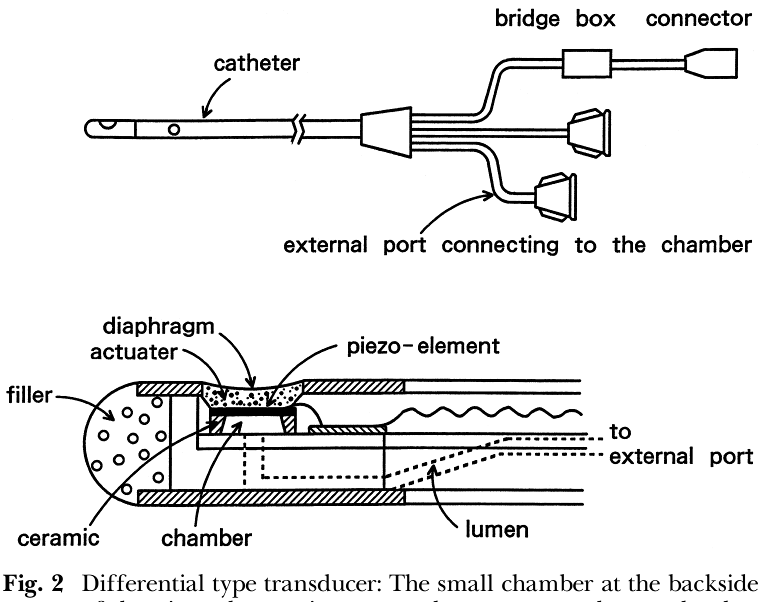

Fig. 2 Differential type transducer: The small chamber at the backside of the piezo element is connected to a pressure lumen that has the opening at the hand side of the catheter. The output of transducer is proportional to the difference between two applied pressures to the diaphragm and to the lumen.

METHOD

The differential type transducer functions in the same way as a conventional gauge type transducer when the opening of the lumen is exposed to atmospheric pressure, thus providing a high fidelity baseline level. Furthermore, applying an appropriate pressure to the opening enables compensation of baseline drift and removal of the DC component (i.e. the mean pressure) in order to expand the dynamic range of small pressure signals.

On the other hand, it is not clear whether or not the chamber and lumen at the backside of the piezo element enlarges baseline drift or reduces frequency characteristics of the transducer. Detailed inspections concerning these functions have been carried out using the following methods.

(1) Baseline drift

The baseline drift was measured under conditions where the differential type transducer was kept in a contained air environment to minimize the effect of airflow. The opening of the lumen also was released to the same environment. The transducer output was connected to the Servo recorder (U-255MD, Pantos, Japan) via the bridge amplifier (AP601G, Nihon Kohden, Japan). Its maximum 8-hour baseline deviation was measured and evaluated by comparing it to that of a conventional gauge type transducer (CVPS, Kawasumi, Japan).

(2) Differential characteristics

The differential type transducer was fixed, with sealing tape, to a disposable transducer dome (1295c, Hewlett-Packard, USA) and its output was connected to the Servo recorder as mentioned above. In order to measure the applied pressure to the transducer, a pressure transducer (TNF-R, Ohmeda, USA) was connected directly to the dome. Pneumatic pressure ranging from 0 mmHg to 50 mmHg was applied simultaneously to both the dome and the opening of the lumen. Common mode rejection ratio (CMR) was calculated as maximum output deviation/applied pressure ratio. CMR indicates whether or not, the performance of the output remained unchanged when signals in the common mode were applied to the two

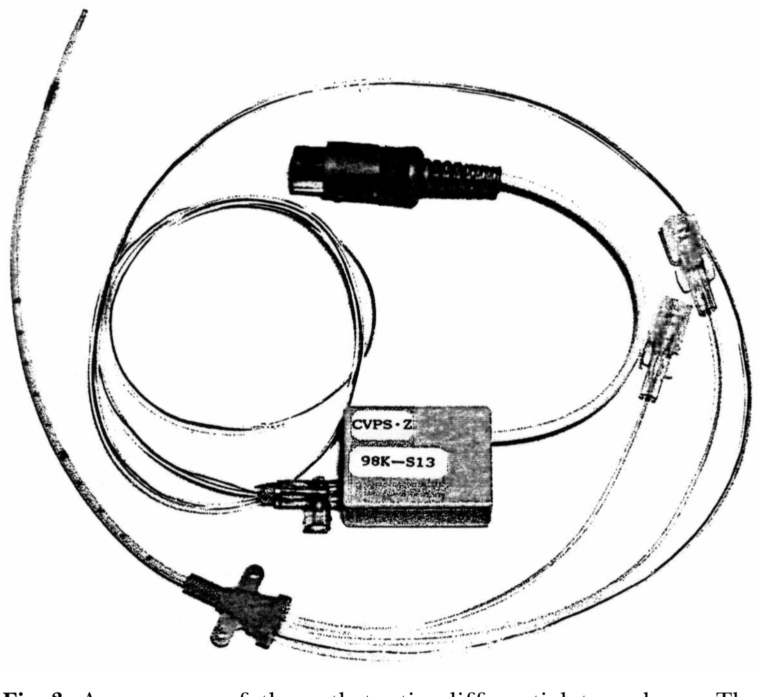

Fig. 3 Appearance of the catheter-tip differential transducer: The photo shows the catheter-tip transducer which is 20 cm long and 7.5 French in diameter. The wiring indicates the output of the transducer. One of the hubs is attached to the opening of the lumen connecting to the chamber.

inputs, thereby allowing differential characteristics to be evaluated. The smaller CMR value results in more desirable differential characteristics [3].

(3) Frequency characteristics

The chamber and lumen at the backside of the element appeared to be frequency-dependent, hence influencing frequency characteristics of the catheter-tip transducer. To assess the degree of influence, frequency characteristics of the differential type transducer were measured using the experimental apparatus shown in Figure 4. The output of the programmable oscillator (OSC-2L, Japan circuit design, Japan) controlled by a computer (PC9801, NEC, Japan) was connected to a loudspeaker (P5160, Fostex, Japan) via a custom-built amplifier. The speaker generates a sinusoidal pressure waveform of 1-60 Hz into the dome by oscillating a built-in diaphragm. The catheter was fixed to the dome, with the opening of the lumen kept at atmospheric pressure. For pressure reference, a pressure transducer was connected directly to the dome as mentioned above, and the dome was filled with Ringer lactate solution. Outputs from the two transducers were simultaneously read into the computer. By changing the frequency to progressively higher values, the ratio of the two pressure signals was calculated at each frequency, and a characteristics chart was constructed. Similar frequency characteristics of a gauge type transducer (CVPS, Kawasumi, Japan) and an ordinary CV (central venous) catheter without a transducer (1001, Ohmeda, USA) were also measured for comparison. The CV catheter was filled with Ringer lactate solution. Normal care was taken to fill the system slowly and ensure the absence of air bubbles. Thereafter, the natural frequency (fn) and the damping coefficient (ζ) were calculated as follows [4]:

$$fn = fr/(1-2\zeta^2)^{1/2}$$
$$\zeta^2 = \{1-(1-1/Ar^2)^{1/2}\}/2$$

Where fr is the resonant frequency and Ar is the peak amplitude at resonant frequency. Higher natural frequency and lower damping coefficient result in better waveform fidelity and less time lag [5, 6].

RESULTS

(1) Baseline drift

Figures 5 (a) and (b) show the baseline drifts of the differential type and gauge type transducers, respectively. Maximal deviations are 0.04 mmHg and 0.1 mmHg, respectively. Both transducers comprise the same piezo elements made by the same manufacturer, therefore, the differential type structure improved the baseline drift by one-half compared to that of the gauge type structure.

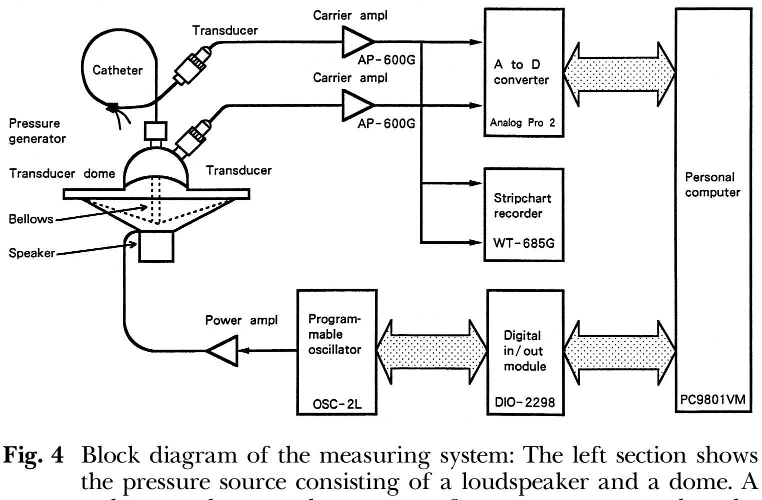

Fig. 4 Block diagram of the measuring system: The left section shows the pressure source consisting of a loudspeaker and a dome. A catheter and a transducer as a reference are connected to the dome, and two pressure signals are read into a computer simultaneously. A frequency characteristics is constructed by calculating a ratio of the two pressure signals at each frequency.

(2) Differential characteristics

Figure 6 shows the output variation of the differential type transducer when static 5 mmHg increments and decrements of pressure ranging from 0 to 50 mmHg was applied simultaneously to both the diaphragm and the opening of the lumen. A linear correlation was observed between the transducer output and applied pressure. A negligible amount of hysteresis was also observed. CMR (common mode rejection ratio) is indicated by the constant ratio

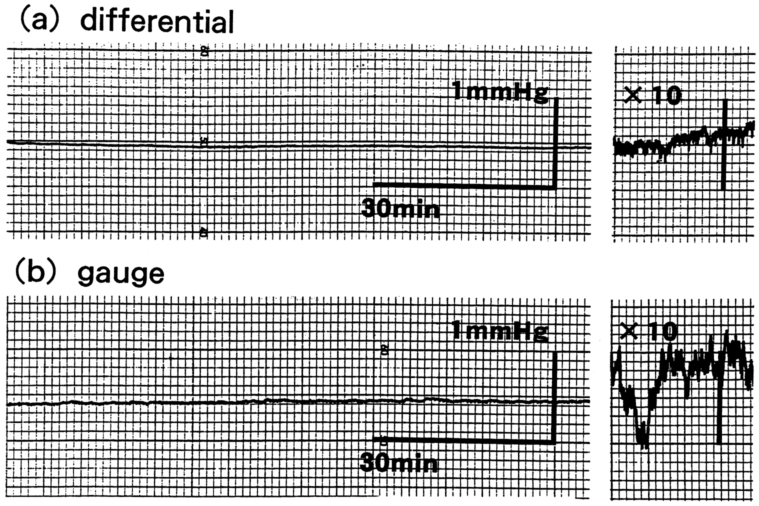

Fig. 5 Baseline drifts: Maximum deviations are 0.04 mmHg (upper trace) and 0.1 mmHg (lower trace). The differential type transducer improved the baseline drift by one-half compared to that of the gauge type.

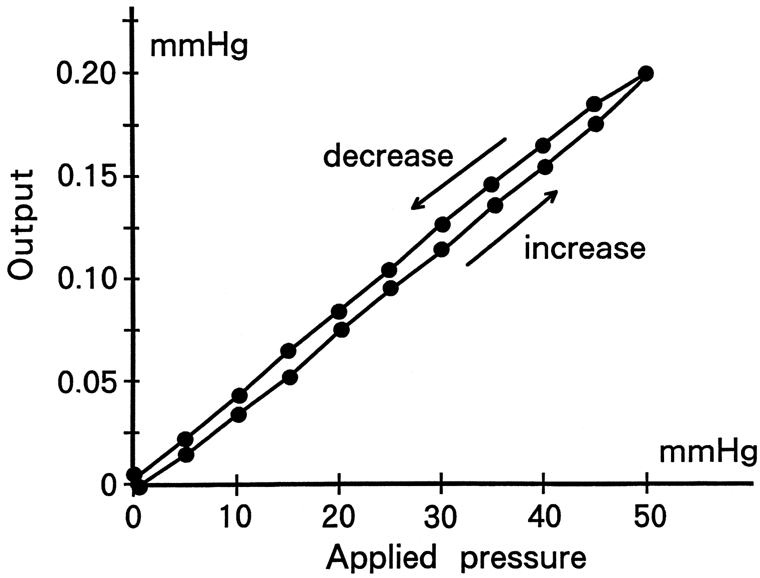

Fig. 6 Differential characteristics: The output is approximately proportional to the added pressure. A narrow hysteresis loop is also observed. In this case, the slope indicates CMR (common mode rejection ratio) and is calculated as -46 dB. See text for further details.

between them. The maximal output deviation was 0.25 mmHg when a pressure of 50 mmHg was applied. Therefore, CMR can be calculated as 0.25/50 = 0.005, determined as -46dB (decibels, calculated as 20 · log 0.005).

(3) Frequency characteristics

Figure 7 shows the frequency characteristics of 3 types of catheters; (a) differential, (b) gauge, and (c) normal CV catheter without transducer. The ordinate indicates the amplitude ratio between applied (A_0) and output (A) pressures. No trace difference was detected between (a) and (b). Their frequency characteristics showed little frequency dependency and were flat up to 60 Hz. Trace (c) showed frequency dependency; 7.1 Hz of resonant frequency, and 1.4 of resonant amplitude, resulting in 8.4 Hz of natural frequency (fn) and 0.38 of damping coefficient (ζ), obtained by using Equation [1] and [2]. By plotting these values into the evaluation chart [7], the highest frequency, i.e. the highest frequency component with which the catheter can derive with fidelity was determined as 2.2 Hz.

DISCUSSION

Employing a differential type transducer may eliminate problems that occur in the use of conventional gauge type transducers.

The baseline drift of the differential type transducer was reduced to one-half compared to the gauge type. This result agreed with expectations since the differential type had a high level of baseline fidelity. Generally the intravascular transducer works at body temperature, so baseline drift caused by temperature changes may not affect measurement errors. However, transducer calibration is performed before vessel insertion, and insertion may result in a temperature rise of approximately 10 degrees. Thereby, baseline drift of a few mmHg may be inevitable. The differential type transducer can solve this problem by recalibrating after insertion, as mentioned above.

As shown, CMR of the differential type transducer was 1/200, indicating that sensitivity difference between the diaphragm and the lumen was less than 1 %, and that the transducer can be recalibrated through the lumen instead of the diaphragm. For example, when a transducer is suspected of baseline shift and shows a pressure of P1, the magnitude of the baseline shift is determined as P1-P2 when pressure P2 is applied through the lumen so as to keep the output at zero. Therefore, transducer output may be corrected by applying pressure P2-P1 through the lumen using a device such as a syringe. Also, when higher sensitivity or expanded dynamic range is required in order to measure small pressure changes, the DC component or mean pressure component should be temporarily eliminated by adding the corresponding pressure from the lumen. The sensitivity of the transducer can be confirmed as follows: when two different pressures, (for example when P1 and P2 are applied in turn through the lumen and the corresponding transducer outputs) yield the changed portion of ⊿P, sensitivity can be calculated as ⊿P/(P2-P1). Also, linearity can be checked easily by changing P1 or P2.

It was feared that the differential type transducer may have frequency-dependent behavior. Fortunately, the influence of the lumen was not extreme. As shown, frequency characteristics of the differential type transducer were flat and proved to be similar to those of conventional gauge type transducers. Frequency components of a CV pressure waveform are estimated to be up to 7 Hz or less [8, 9]. Frequency characteristics of both the differential and gauge type transducers are wide enough to satisfy CV pressure waveform bandwidth requirements. On the other hand, the frequency response curve of a normal CV catheter without transducer had a resonant peak of 7.1Hz within the above mentioned frequency bandwidth, resulting in pressure waveform distortions. Although no actual distortions occurred, waveform delay time is prolonged, and errors in timing and the relationships of certain cardiovascular signals may result [5, 7, 10]. An example of waveform delay is demonstrated in Figure 8. The lower trace derived by a normal CV catheter showed not only waveform distortion but also 76 milliseconds of delay time from the upper trace derived by the catheter-tip transducer. This led us to conclude that the catheter-tip transducer should be used in the field of high-fidelity manometry.

Why does the lumen at the backside of the piezo element seem to have no effect on frequency characteristics? This lumen acts as inertance, i.e. as the impedance element whose magnitude is proportional to the frequency. Therefore, the impedance of the lumen increases with frequency and the higher the frequency rises, the harder the lumen becomes. Of course, transducer sensitivity of zero frequency is sufficient, so consideration of the influence of the lumen on the frequency characteristics is unnecessary.

Several commercially available PA (pulmonary artery) catheters with the catheter-tip transducer also have similar problems as the above-mentioned CV catheters [11]. Furthermore, they are quite expensive. The same concept introduced in this paper concerning differential type transducers might also be applied to PA catheters. High-fidelity PA pressure waveforms can perhaps be obtained with ease. Thus, the evaluation of PA catheters can expect a dramatic increase. However, there still remains the problem of considerable expense.

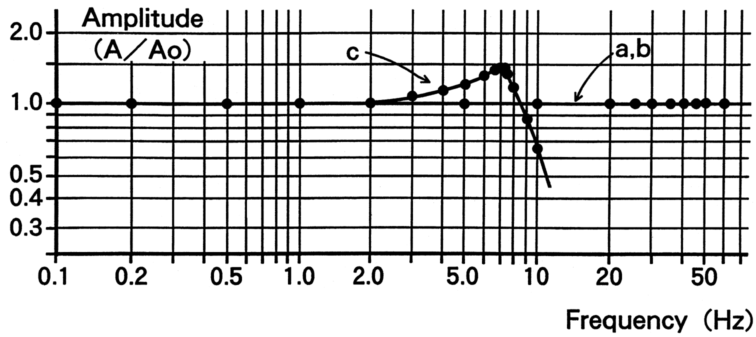

Fig. 7 Frequency characteristics: Trace (a), (b) and (c) show frequency characteristics of the differential type, gauge type, and normal CV catheter, respectively. Traces (a) and (b) are flat up to 60 Hz. Trace (c) has 7.1 Hz of the resonant frequency, and 1.4 of the resonant amplitude. See text for further details.

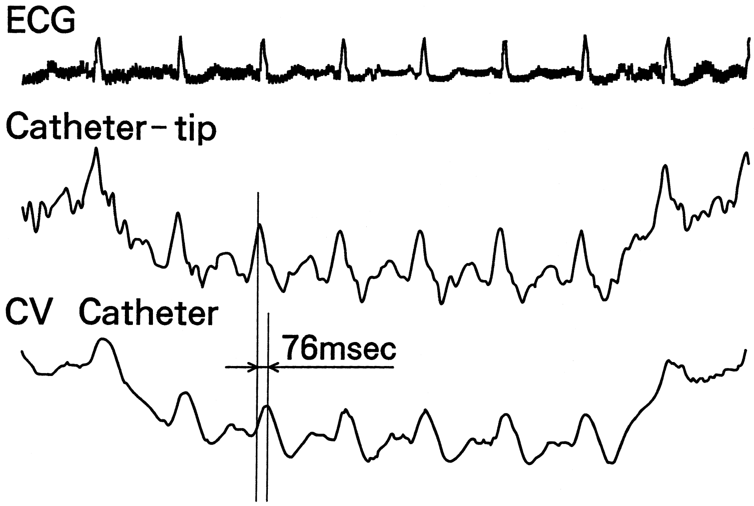

Fig. 8 Waveform distortion and time lag caused by a normal CV catheter: The lower trace derived from a normal CV catheter had 76 milliseconds time lag compared to the upper trace derived from the differential type transducer. Occurrence of time lag is inevitable for a fluid-filled catheter manometer system.

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