Analysis and Correction of Pressure Wave Distortion in Fluid-Filled Catheter Systems

By Herman L. Falsetti, M.D., Robert E. Mates, Ph.D.,
Robyn J. Carroll, Ramji L. Gupta, M.S.,
and Adam C. Bell, Sc.D.

SUMMARY
Dynamic characteristics of a variety of catheters and their dependence on various operating parameters are presented. Careful flushing of the catheter with degassed water or saline considerably improves the performance of these systems. The operating temperature, number of catheter uses, and average transmural pressure difference do not have a significant effect.

The error due to catheter distortion in commonly used left ventricular performance indices (end diastolic pressure, peak systolic pressure, maximum $dp/dt$ and $V_{max}$) was assessed. On the basis of these results, it is shown that the natural frequency of the catheter system must be greater than 40 Hz to produce results accurate to 10%.

The experimental data were used to develop a semi-empirical model for the catheter transducer system. This model was used in the design of an analog compensator to further improve the dynamic characteristics of the catheter transducer system. The compensator requires only two parameter settings, catheter natural frequency and damping ratio.

Additional Indexing Words:
Frequency response Cardiac catheter Pressure compensation LV pressure Rate of pressure rise

The ideal pressure recording system should have a linear response which is independent of frequency over the range of interest. Currently used manometer systems have a low damping ratio and low natural frequency which can introduce significant error in left ventricular pressure measurements and those contractile indices which depend on the rate of left ventricular pressure rise ($dp/dt$). A general discussion of this problem has been given by Shirer.1 Several investigators2-8 have studied the effects of catheter length, diameter, material composition, and miniature air bubbles on the performance of fluid-filled catheter systems. The purposes of this report are to:

1) present dynamic characteristics of commercially available catheters, 2) quantitate the errors attributable to limited dynamic frequency response, and 3) propose methods for correcting those errors in a routine clinical situation.

Methods
In this study, catheters commonly used to measure left ventricular pressures were tested. The characteristics of these catheters are listed in table 1. Their frequency response was tested with a dynamic calibration device which generated a sinusoidal pressure input of varying frequency. Figure 1 is a block diagram of the system used. The sine wave pressure generator was a simple electromechanical device and is described in detail elsewhere.9 Sinusoidal pressure amplitudes of 10 mm Hg at frequencies up to 150 Hz were applied to the chamber along with an adjustable bias of 0 to 150 mm Hg. This calibration device had a flat frequency response to over 125 cycles per second. Two Statham P23Db transducers were used; one in the dome of the pressure chamber (reference transducer) and one attached directly to the hub of the catheter tested. Fluid temperature could be varied from 75 to 100°F. The catheter was inserted into the chamber, flushed with fluid, and allowed to equilibrate to chamber temperature. The catheters were tested at increments of 10 Hz and a detailed frequency response curve was obtained. The natural frequency ($F_n$) and

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From the Departments of Medicine and Mechanical Engineering, State University of New York at Buffalo, Buffalo, New York.

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Address for reprints: Dr. Herman L. Falsetti, Director, Hemodynamics Laboratory, Department of Internal Medicine, University of Iowa Hospital, Iowa City, Iowa 52242.

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damping ratio (B) of an equivalent second order system were determined, where:

\[ B = \frac{1}{2(\text{amplitude ratio at } F_n)} \]

a reasonable approximation for B < 0.2.

These studies were carried out under a number of conditions which included: 1) repeated catheter usage; 2) a 20°F temperature change (body temperature versus ambient temperature); 3) a 150 mm Hg change in intramural pressure (the effect of the catheter being within the arterial system) and 4) various flushing techniques.

The frequency response characteristics were used to estimate the percentage error in end diastolic pressure, peak systolic pressure, maximum \( \frac{dp}{dt} \) and \( V_{\text{max}} \) caused by a typical catheter system. Fourier analysis was used to determine the frequency content of left ventricular pressure, measured with a cannula. The wave form chosen for analysis had an end diastolic pressure of 10 mm Hg, a peak systolic pressure of 120 mm Hg, and a pulse rate of 70 beats per minute. The catheter frequency response was simulated using a fourth order model, and the resulting pressure curve was reconstructed using 20 harmonics. Typically, the amplitude of the tenth harmonic was 1% of the fundamental.

Signal distortion may be corrected by Fourier analysis techniques, which usually requires a computer, or by analog compensation. Fourier analysis is a rather complex mathematical treatment and usually cannot be performed on line. Analog compensation has the advantage of simplicity and direct accessibility and requires only that the frequency response curve be expressed mathematically in terms of known parameters. An analysis of this problem from our laboratory, including the design and evaluation of an analog compensator, is presented elsewhere. This study revealed that the commonly used single second order circuit overcompensates most catheters below their natural frequency. Analysis of a number of lumped and distributed parameter models of the catheter system indicated that a cascade of two second order circuits produces an accurate compensator.

**Results**

The catheters tested are listed in Table 1. The catheters were initially flushed with CO₂ and then

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**Table 1**

<table>
<thead>
<tr>
<th>Catheter</th>
<th>French Size</th>
<th>Outside diameter (mm)</th>
<th>Inside diameter (mm)</th>
<th>Length (cm)</th>
<th>Material</th>
<th>N*</th>
<th>Natural frequency Mean</th>
<th>Damping ratio Mean</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gensini</td>
<td>7F</td>
<td>2.33</td>
<td>1.47</td>
<td>100</td>
<td>Teflon</td>
<td>25</td>
<td>59.8</td>
<td>.109</td>
</tr>
<tr>
<td>Transeptal</td>
<td>8.4F</td>
<td>2.80</td>
<td>1.50</td>
<td>70</td>
<td>Polyethylene</td>
<td>8</td>
<td>66.7</td>
<td>.158</td>
</tr>
<tr>
<td>Pigtail</td>
<td>8F</td>
<td>2.66</td>
<td>1.43</td>
<td>110</td>
<td>Polyurethane</td>
<td>26</td>
<td>50.8</td>
<td>.137</td>
</tr>
<tr>
<td>Femoral coronary</td>
<td>8F</td>
<td>2.66</td>
<td>1.37</td>
<td>100</td>
<td>Polyurethane</td>
<td>6</td>
<td>45.1</td>
<td>.216</td>
</tr>
</tbody>
</table>

*N* = the number of catheters tested.

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The catheter is inserted into the pressure generator. Two Statham P23Db transducers are used; the reference transducer is attached to the dome of the pressure generator and the other transducer to the hub of the catheter to be tested. Their signals are amplified and recorded.

**Figure 1**

Block Diagram of Calibration System. The catheter is inserted into the pressure generator. Two Statham P23Db transducers are used; the reference transducer is attached to the dome of the pressure generator and the other transducer to the hub of the catheter to be tested. Their signals are amplified and recorded.
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![Graphs showing frequency response and phase angle](image)

Figure 2

Frequency Response of a Catheter System. The upper panel is a log-log plot of amplitude ratio versus frequency. The lower panel is a semi-log plot of phase angle versus frequency.

with degassed saline. A typical frequency response is shown in figure 2. The catheter response is qualitatively similar to that of an underdamped second order system and can be characterized in terms of a natural frequency and damping ratio. It has been shown that a fourth order model better represents the measured response. Table 1 also shows the frequency response range for the catheters tested. With similar flushing and test conditions the range of the natural frequency and damping ratio for each type of catheter did not vary greatly. Several of the reusable catheters (Gensini and Kifa) were followed for multiple usage and did not show an appreciable change in frequency response characteristics over ten uses.

The standard deviations presented in table 1 are for a number of catheters with the same specifications (type, size, length). Repeated calibrations of a single catheter after repeated uses and resterilizations showed a much smaller variation in frequency response characteristics, typically of order of a few percent, in natural frequency and damping ratio.

The effects of a 20°F change in temperature (body temperature versus ambient temperature) did not make an appreciable difference in the frequency response. This is illustrated in the left panel of figure 3. The six catheters tested at room temperature and body temperature show no significant change.

The effect of transmural pressure (0 to 150 mm Hg) is shown in the right panel of figure 3. This

Figure 3

Left) Effect of Temperature on Catheter Characteristics. The natural frequency and damping ratio are plotted for a catheter at room temperature (open triangles) and again at body temperature (closed triangles). There appears to be no significant trend. Right) Effect of Transmural Pressure on Catheter Characteristics. The natural frequency and damping ratio of five catheters with an average transmural pressure of zero (open circles) and 150 mm (closed circles) is plotted. The natural frequency is not significantly changed; however, increased transmural pressure decreases the damping ratio.

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change was produced by calibrating with the entire catheter inside the chamber and again with only the tip inside. Transmural pressure always produced a decrease in the damping.

The two most important factors in maximizing the fidelity of the system are 1) elimination of miniature bubbles and 2) minimizing the length of the connections between the catheter and transducer. The left panel of figure 4 shows the excessive distortion introduced by a catheter when flushed with saline equilibrated in room air for two hours from which miniature air bubbles have evolved. The right panel shows pressures recorded with the same catheter flushed with degassed saline. The addition of a polyethylene connecting tubing between the hub of the catheter and the transducer had a similar effect.

Figure 5 illustrates the same result in terms of frequency response. There is a decrease in the natural frequency from 70 Hz to 20 Hz with a corresponding shift in the phase angle for the poorly-flushed catheter. The change in the damping ratio is minimized.

Figure 6 summarizes the results of a large number of frequency response measurements, including catheters flushed with degassed saline and with saline equilibrated with air. There appears to be no fixed relationship between natural frequency and damping ratio. Prior CO₂ flushing reduced the time required for degassed saline flushing to obtain optimal response.

Figure 7 is a plot of the percent error in end diastolic pressure caused by a limited system response. The distortion in the end diastolic pressure is expressed as a percentage of the true end diastolic pressure for natural frequencies up to 40 cycles per second.

Figure 8 demonstrates the estimated error in peak systolic pressure. Once again the error is calculated from the Fourier analysis of the measured pressure modified term-by-term for catheter distortion. The error in peak systolic pressure measurements is significant for natural frequencies below 20 cycles per second.

Figure 9 demonstrates the percent error in maximum dp/dt caused by a limited dynamic response of the catheter system. It can be seen that for natural frequencies below 30 Hz there is a large error in peak dp/dt. There are a number of contractile indices (V_{max}, peak velocity of contractile element, V_{CE} at peak stress, etc.) which are dependent on dp/dt. Plots of error versus natural frequency for these indices are very similar to figure 9.

**Figure 4**

Effect of Catheter Flushing on Left Ventricular Pressure. The left panel shows true ventricular pressure (LV cannula) and the distorted signal obtained by a poorly flushed Kifa catheter. In the right panel the indicated pressure signal has been improved by repeated catheter flushing with degassed saline.

**Figure 5**

The Effect of Flushing on Catheter System Frequency Response. The upper panel is a log-log plot of amplitude ratio versus frequency for an 8F Cordis Pigtail catheter. Phase response is shown in the lower panel. The well-flushed system (closed circles) shows a natural frequency greater than 50 Hz with a minimal phase shift of 50 Hz. The poorly-flushed system (open circles) shows a marked decrease in the natural frequency.
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Figure 6
Relationship Between Damping Ratio and Natural Frequency. The frequency response characteristics of 75 catheters are presented. Several commercial catheters were tested. There appears to be no relationship between damping ratio and natural frequency.

Figure 10 shows the significantly improved frequency response obtained by analog compensation. The compensated response of a well flushed catheter system is flat to approximately 85 Hz.

Figure 11 shows the compensator performance on line. In this experiment a short, wide bore cannula was placed directly in the left ventricle of an open-chest dog. A 8.4 Kifa transeptal catheter was also placed directly across the wall of the left ventricle. Both cannula and catheter were held by a special lucite stand to eliminate catheter movement. The catheter was attached to a strain gauge via a 40 cm connecting tube. The natural frequency and damping ratio of the catheter system were measured immediately before and after the experiment and did not change. These measurements were used to set the analog compensator. The signal from the catheter system was recorded and also fed into the compensator. It can be seen that the uncompensated catheter signal has lightly damped oscillations.

Percent Error in End-Diastolic Pressure Caused by Inadequate Frequency Response. The error is calculated from a Fourier analysis of the measured pressure, modified term by term for catheter distortion. Increases in natural frequency and damping ratio (B) reduced the error.

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of low frequency distorting the left ventricular pressure signal. The compensated signal shows marked improvement and is in good agreement with the signal obtained from the LV cannula.

**Discussion**

Left ventricular pressure and its derivative are commonly used in physiologic studies. Unfortunately there is little detailed information available concerning the effect of various operating parameters on the accuracy of the pressure recording. This has led to controversy in the acceptance of data recorded with fluid-filled catheter systems. Some previous studies have reported very limited frequency response of catheter systems, making them unsuitable for clinical evaluation of dp/dt.

Some laboratories have abandoned the use of fluid-filled catheters for the measurement of high fidelity left ventricular pressure in favor of miniature solid state or strain-gauge transducers mounted on the tip of the catheter. Although catheter tip manometers introduce little or no distortion into the pressure signal, a number of practical problems restrict their routine clinical use. The transducers are expensive, and their fragility limits the number of uses for a single catheter. They exhibit DC electrical drift, requiring the use of a fluid-filled lumen or separate catheter to obtain absolute values of left ventricular pressure. There have been at least two reported instances of mechanical failure of the catheter tip, introducing additional clinical hazards. Thus, it seems worthwhile to attempt to improve the performance of fluid-filled systems to make them suitable for accurate left ventricular pressure measurements.

Refinements in catheter-flushing techniques have been proposed to improve this response of fluid-filled catheters. This study quantitates the errors attributable to catheter frequency response and proposes methods for correcting these errors. It demonstrates that flushing with CO₂ and degassed saline improves the frequency response. Longer flushing with degassed saline alone has a similar effect.

The effect of other operating parameters appears to be small. There is no significant difference between catheter characteristics at ambient and body temperature. The average intramural pressure also has little effect. We were also impressed that the frequency response of reusable catheters did not change over ten uses and gas sterilizations.

The constant frequency response exhibited by a single catheter makes it possible to perform dynamic calibration of the catheter prior to sterilization, avoiding additional procedures in the catheterization laboratory. As described in detail elsewhere, a simple table hook-up is used to tune the analog compensator to the frequency characteristics of a particular catheter. It is essential that the catheter be carefully flushed with degassed saline after insertion since the presence of small bubbles will significantly affect the response.

Catheter distortion errors in end diastolic pressure, peak systolic pressure, and peak dp/dt are shown to depend strongly on frequency response.
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Figure 11

On-line Compensation of Left Ventricular Pressure. An uncompensated Kifa transeptal catheter and connecting tube placed directly in the left ventricle of an open-chest dog distorts left ventricular pressure signal by lightly damped oscillations compared to a high fidelity record of left ventricular pressure (LV cannula). On-line compensation (compensator output) markedly decreases the oscillation in the signal.

Characteristics. A natural frequency of greater than 40 Hz is required to limit errors to 10%.

While these results are believed typical for normal left ventricular pressures, caution must be used in attempting to draw quantitative conclusions from them. The shape of the LV pressure wave form will clearly influence the amount of distortion introduced. Peak systolic pressure will always be overestimated using a catheter with inadequate frequency response. The direction of the error in end diastolic pressure and peak dp/dt will depend on exactly what point in the distorted signal is chosen to represent end diastolic pressure and peak dp/dt. The values reported here were obtained by choosing the same time point in the cycle for each combination of natural frequency and damping ratio. Estimation of true end diastolic pressure from a badly distorted wave form (natural frequency < 20 Hz) is almost impossible. In addition to the shape of the wave form, the mean left ventricular pressure will also influence the percentage errors. Since mean pressure itself is unaffected by catheter distortion, increase in the mean pressure will tend to reduce the percent error, although not the absolute error in the measured pressures.

If the frequency response characteristics of the system are known, the output can be corrected by either digital or analog compensation. Digital compensation (Fourier analysis) requires computer facilities and is time consuming. Analog compensation is a more useful approach since the signal processing can be done on line.

Several studies10-13 have reported contractile indices which are dependent on the accurate measurement of left ventricular pressure. Pressures measured with a fluid-filled catheter system always include some degree of error due to signal distortion. The work reported here presents a systematic evaluation of these errors as well as methods for minimizing them. Catheter frequency response requirements will vary according to the measurement being made (see figures 7-9). In general, a fluid-filled catheter system should have a natural frequency greater than 40 cycles/sec and a damping ratio greater than 0.10 to accurately record left ventricular pressure. It is possible to achieve these values with most commercial fluid-filled catheter systems by the use of proper flushing techniques. Analog compensation can be used to further improve the frequency response characteristics of cardiac catheters, thereby reducing distortion errors to a negligible level.
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HERMAN L. FALETTI, ROBERT E. MATES, ROBYN J. CARROLL, RAMJI L. GUPTA
and ADAM C. BELL

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