Limitation of Correction of Frequency Dependent Artefact in Pressure Recordings Using Harmonic Analysis

By L. Jerome Krovetz, M.D., Ph.D., Rufus B. Jennings, Jr., M.D., and Stephen D. Goldbloom

SUMMARY
Frequency dependent phase and amplitude distortion may theoretically be minimized using correction formulae derived from a model which assumes that water-filled catheter-manometer systems are analogous to an oscillating mass attached to a spring and damping pot. This study defines the practical limits of this correction technique using harmonic analysis of simultaneously recorded water-filled and catheter-tip manometer systems.

Some improvement was obtained in tracings recorded with underdamped, high frequency response systems. In no case were exact duplications of the catheter-tip tracings obtained. Divergence of measured in vitro frequency response from actual in vitro frequency response was one source of these discrepancies. Loose coupling of the components of the system also changed the behavior from that of the assumed simple mechanical model and at times prevented adequate correction.

Catheter-tip manometers, in spite of their expense and relative fragility, still appear to be the best means at present of obtaining accurate pressure tracings, particularly at high heart rates or where time derivatives are to be computed.

CATHETER-MANOMETER SYSTEMS with a high natural frequency almost invariably are underdamped and resonance amplification of catheter movement artefact may be a significant problem. Water-filled catheters and transducers have been assumed to act upon the pressure pulse in a manner analogous to an oscillating mass attached to a spring and damping pot. The mathematics of these concepts have been described in previous publications.1, 2

Further, since damping may increase during the catheterization due to fibrin deposition, as a practical countermeasure there is a tendency to start with little or no damping. Hydraulic damping chambers increase the damping but decrease natural frequency.3, 4

Tuned circuits and electrical filters have been used to correct for underdamping. The amplitude and phase changes effected with these devices are difficult to match to the particular catheter system, however.5, 6

Recently the use of air-filled catheters to reduce catheter movement artefact7 has shown some promise. Catheter-tip manometers are now available which have excellent frequency and phase response characteristics and are capable of reproducing physiologic events with a high degree of accuracy.8 These have the disadvantages of higher initial cost, lower signal levels, and fewer shapes which limit maneuverability compared to conventional cardiac catheters and external pressure transducers.

In 1928, Wiggers suggested the use of harmonic analysis to eliminate frequency dependent pressure wave distortions.9 Although this technique has been employed for correction of pressure pulse waves,10 we have been unable to find reports establishing its practical limits. Simultaneously obtained data from a conventional catheter-external manometer and a catheter-tip manometer were compared to the waveforms corrected by harmonic analysis. This type of analysis also allows the study of frequency response characteristics of the catheter-manometer system at the instant of the pressure curve recording.

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LIMITATION OF PRESSURE WAVE CORRECTION

Methods

Pressures were recorded from catheter-tip manometers (Statham SF-1) and from either the water-filled lumen or a separate catheter which was connected to a Statham P23De transducer. Pressure waves were recorded on magnetic tape simultaneously from both systems in various chambers of the heart and great vessels in 3 dogs and in 18 patients during the course of diagnostic catheterizations. In three series of experiments the frequency response of the system was deliberately altered by adding varying lengths of PE50 polyethylene tubing between the catheter lumen and the external pressure gauge. A total of 60 pairs of pressure tracings were considered suitable for further analysis.

Frequency response characteristics were determined either by the step response method or a sine wave oscillation chamber. Pressures were recorded on magnetic tape and subsequently converted to digital format at 200 samples/sec. Sampling rate dependent aliasing was minimized by filtering the analog signal with an active filter with a corner frequency of 100 Hz and a 12 dB/octave rolloff.

Following conversion of the pressure tracing to digital format, each tracing was subjected to harmonic analysis. During resynthesis, harmonics which were higher in number than one-half the number of samples obtained for each pressure wave were eliminated. Modulus amplitudes and phase angles were corrected for frequency dependent distortion for each harmonic frequency and the curve was then resynthesized. Each set of pressure tracings of the pressure as recorded by the external transducer, the corrected and resynthesized curve, and the catheter-tip manometer curve was plotted on a graphic display terminal (Tektronix 4010) for easier comparison.

Time derivatives of the original, resynthesized and catheter-tip waveforms were computed using the derivative of the Lagrangian interpolation polynomial of degree two for successive triplets of points (IBM Scientific subroutine DET3). The program also computed systolic and diastolic pressures, pulse pressures, and peak first derivatives, as well as the percent deviation of each from that obtained using the catheter-tip manometer.

Results

A simultaneous display of brachial artery tracings of catheter-tip manometer (CTM), original and resynthesized pressure curves for a system with a damped natural frequency (fd) of 8 Hz and damping ratio (α) of 0.36 is shown in figure 1. The systolic peak is amplified and delayed in the conventional curves compared to the simultaneously recorded catheter-tip tracing. The original pulse pressure was 27% greater than that of the CTM and this error was reduced to 9% in the resynthesized curve. The corrected waveform is only a fair approximation of the curve. The corrected waveform is an approximation of the curved waveform, especially at the time of the dicrotic notch.

As the frequency response of the conventional manometer system was increased, in general, deviations between the original and the catheter-tip manometer systems decreased. In addition, the amount of correction obtained from the resynthesis increased (table 1). Figure 2 is an example of an arterial pressure tracing recorded with the catheter-manometer system having a fd of 15 Hz and α of .20. Comparison with figure 1 shows that the original wave is a slightly better approximation of the CTM tracing while the resynthesized curve is virtually identical to the CTM tracing.

Since the reproducibility of frequency response determinations have been shown to vary as much as 30%, the ratio of the moduli of the catheter-manometer system to the CTM were plotted as a method of determining the characteristics of the catheter-manometer during the time of recording the pressure wave. In figure 3 it may be seen that there is a small resonance peak at the 4th harmonic which corresponds to resonant frequency of 10 Hz. Using the maximum value obtained at this peak, the damping factor is calculated to be .42. These values are

Table 1

<table>
<thead>
<tr>
<th>Damped natural frequency (fd)</th>
<th>Number</th>
<th>Original</th>
<th>Corrected using measured fd &amp; α</th>
<th>Corrected using fd &amp; α from graph</th>
</tr>
</thead>
<tbody>
<tr>
<td>7 – 10 Hz</td>
<td>19</td>
<td>12.5%</td>
<td>10.8%</td>
<td>6.2%*</td>
</tr>
<tr>
<td>11 – 15</td>
<td>12</td>
<td>9.5%</td>
<td>5.5</td>
<td>3.6</td>
</tr>
<tr>
<td>16 – 25</td>
<td>18</td>
<td>6.9%</td>
<td>2.6†</td>
<td>3.3</td>
</tr>
<tr>
<td>26 – 50</td>
<td>11</td>
<td>4.0%</td>
<td>2.8</td>
<td>2.1</td>
</tr>
</tbody>
</table>

*P < 0.05 compared to corrected using measured fd & α.
†P < 0.05 compared to original.

Figure 1

Simultaneous display of catheter-tip manometer and original and corrected waveforms from a catheter-external manometer system. Note that the original waveform overestimates pulse pressure by 27% while the resynthesized waveform is only 9% higher. Conversely, dp/dt was only 1% different for the original waveform but 17% less for the corrected waveform.

Circulation, Volume 50, November 1974
strikingly different from those measured by the step response method at the conclusion of the procedure, namely \( f_d = 29 \) and \( \alpha = 0.22 \).

There was only fair agreement between catheter characteristics as measured by step response or sine wave generator and that measured by mapping the ratio of uncorrected to catheter-tip moduli. The correlation coefficient for undamped natural frequency was 0.82 but was significantly poorer for the damping ratio, namely 0.33.

Figure 4 illustrates resynthesized waveforms obtained using the damped natural frequency measured from the step response and also from the ratio of uncorrected to catheter-tip manometer moduli (fig. 3). In this instance, marked improvement may be seen when the frequency response and damping used for resynthesis were those that existed at the time when the pressure was actually being recorded.

Figure 5 presents three typical graphs of the uncorrected to catheter-tip manometer moduli. In the left panel there is a single resonance peak, such as is predicted for a system having two degrees of freedom. In the middle panel a secondary resonance occurs well beyond the frequencies of interest, as shown in the moduli of the catheter-tip manometer tracing. It has little or no effect upon the reproduction of the waveform. The right panel represents a system with two resonance peaks, both of which occur at low enough frequencies to distort the pressure wave significantly. Satisfactory correction of both pulse pressure and first derivative could only rarely be obtained with this type of multiple resonance pattern. Another example of this phenomenon is shown in figures 6 and 7 which show the frequency response versus relative amplitude curve obtained with a #7 F 75 cm open-end catheter. Figure 7A shows the step response for this catheter-external manometer system and figure 7B is semilog plots of successive decay amplitudes. Two separate lines with markedly different slopes, each corresponding to one of the coupled systems, may be seen. We have found that such loose coupling is a not infrequent occurrence. Of 26 catheter systems, three were overdamped, seven had two resonance peaks, and five had three or more peaks. Only 11 (42%) had the expected single resonance peak. Fortunately, about half of the multiple resonances occurred at higher frequencies, when the moduli of the waveforms were quite small and exerted a minimal influence upon the pressure wave. Loose coupling is a major hindrance to the correction of waveforms. Furthermore, it may be difficult to eliminate, even with close attention to system assembly, flushing or using deaerated fluids to minimize air bubbles.

**Table 2**

<table>
<thead>
<tr>
<th>Damped natural frequency (Hz)</th>
<th>Number</th>
<th>Improved (&gt; 5%)</th>
<th>No change</th>
<th>Worse (&gt; 5%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>7 - 10 Hz</td>
<td>19</td>
<td>6</td>
<td>8</td>
<td>5</td>
</tr>
<tr>
<td>11 - 15</td>
<td>12</td>
<td>4</td>
<td>7</td>
<td>1</td>
</tr>
<tr>
<td>16 - 25</td>
<td>18</td>
<td>6</td>
<td>12</td>
<td>0</td>
</tr>
<tr>
<td>26 - 80</td>
<td>11</td>
<td>2</td>
<td>9</td>
<td>0</td>
</tr>
</tbody>
</table>

**Figure 3**

The ratio of uncorrected, original moduli to those of the catheter-tip manometer is a reflection of the distortions imposed on the pressure wave by the fluid filled system. The arrow points to a resonance peak at the 4th harmonic, which corresponds to 10 Hz. The amount of amplification was used to calculate the damping ratio (see reference 4 for details). Resonance peaks at the 16th and 18th harmonics are unimportant since the amplitude of the harmonic terms is so small.
LIMITATION OF PRESSURE WAVE CORRECTION

Examination of tables 1 and 2 shows distinct differences in the improvement obtained with the resynthesized waveforms with various damped natural frequencies. For the 19 resynthesized curves obtained in the frequency response range of 7-10 Hz, only six showed less deviation than the original curves from the CTM values while approximately the same number showed more deviation. Of the 41 tracings where the frequency response was above 11, only one tracing was worsened by correction, while one-third showed significant improvement.

The frequency response requirements for recording first derivatives are approximately six times greater than those required for recording the original waveforms. The first derivative, dp/dt, calculated from conventional catheter-manometer systems showed average errors of 34-36% when compared to CTM systems (table 3). Furthermore, there was no improvement in these errors with increases of \( f_d \), up to 80 Hz. Correction of the waveform showed that the deviation of the peak dp/dt from the CTM values was often increased by the resynthesis, particularly when the frequency response was less than 25 Hz (table 4).

Discussion

Water-filled catheter and external transducer systems are often assumed to behave analogously to a mass-spring and dash pot. \(^1\), \(^2\) It is further assumed that such a system acts upon the pressure wave causing frequency dependent distortions of amplitude and phase angle. In this study we attempted to correct for these distortions using harmonic analysis and correction formulae derived from the initial assumptions and compared the results to a catheter-tip manometer.

The systems tested frequently did not act as

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*Harmonic correction of brachial artery tracing using damped natural frequency (DNF) and damping (alpha) measured by step response is shown on the left hand side of the figure. Considerably better correction was obtained using the values obtained from the ratio of uncorrected to catheter-tip manometer moduli (fig. 3).*

*Three patterns of resonance are shown. The single peak shown in the top panel and the pattern in the middle panel where the second peak occurs higher than the important content of the pressure pulse (dashed line) can both be improved by harmonic resynthesis. In contrast, the distortion of 2 resonances as in the bottom panel cannot be eliminated.*

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Circulation, Volume 50, November 1974
Loose coupling may be caused by tiny air bubbles, leaky connections, or overly compliant plastic tubing used as a connector. The two separate systems then act to cause multiple resonance peaks and errors in recording. The width of the resonance area or distance between the amplitude peaks is determined by a coupling coefficient which may be mathematically defined.11

Correction difficulties encountered with loose coupling are related to the magnitude of the modulus values in the resonance areas, as well as the width of the resonance band. When loose coupling is present, with a large amount of catheter movement artefact and low damping, correction of pressure waveforms is usually not rewarding.

The mathematical model does not appear to be valid for frequencies much higher than resonance. If the frequency being recorded is more than 1.5 times the natural frequency,1,2 overcorrection occurs. This imposes serious limitations on correction of low frequency response systems. We have generally been unsuccessful with correction of systems with an undamped natural frequency less than 10 Hz (table 2).

Falsetti and co-workers designed an analog compensator to improve the dynamic characteristics of fluid-filled catheter transducer systems. Optimal use of their system is based on the constant frequency response exhibited by a single catheter which allowed them to perform a dynamic calibration of the catheter prior to sterilization and thus avoid additional procedures in the catheterization laboratory. However, they also noted that extremely small air bubbles, temperature changes, as well as changes in transmural pressure all affected the damping ratio and, to a lesser extent, the frequency response. Our earlier studies have shown changes in f_{d} when measured repeatedly using the step response method.12 The variation in f_{d} and \alpha in the present study suggests that the use of a

![Image](https://example.com/image.png)

Figure 6

Frequency relative amplitude for a water-filled open-end catheter demonstrating loose coupling. Frequency was set by a sine wave generator and transmitted to a pen motor which in turn drove a mylar diaphragm in the pressure chamber into which the catheter was inserted. The pressure in the chamber is monitored with a test gauge mounted in the chamber and is flat to over 200 Hz.

predicted by the simple mechanical model. One source of error is a lack of perfect periodicity of the cardiac cycle. For example, a 10% variation in pulse rate can produce a 3% error in harmonic terms that are 10% of the fundamental in magnitude.10

![Image](https://example.com/image.png)

Figure 7

A. In a step response test, a finger cot is inflated with the catheter tip held so that the pressure is sensed at the open end. The finger cot is then burst using a flame or scalpel blade and the resulting pressure waveform recorded. B. Semilogarithmic plot of amplitude vs. time for the step response shown in A. Note the marked divergence of the two slopes indicating loose coupling.

![Image](https://example.com/image.png)

Table 3

Mean Percent Deviation of Conventional Catheter-Manometer Systems Compared to Catheter-Manometers for Peak dp/dt of Original and Resynthesized Waveforms

<table>
<thead>
<tr>
<th>Damped natural frequency (f_{d})</th>
<th>Number</th>
<th>Original</th>
<th>Corrected using measured f_{d} &amp; \alpha</th>
<th>Corrected using f_{d} &amp; \alpha from graph</th>
</tr>
</thead>
<tbody>
<tr>
<td>7 - 10 Hz</td>
<td>19</td>
<td>34%</td>
<td>50%* (worse)</td>
<td>44%</td>
</tr>
<tr>
<td>11 - 15</td>
<td>12</td>
<td>34%</td>
<td>42</td>
<td>35</td>
</tr>
<tr>
<td>16 - 25</td>
<td>18</td>
<td>36</td>
<td>22</td>
<td>13†</td>
</tr>
<tr>
<td>26 - 80</td>
<td>11</td>
<td>34</td>
<td>24</td>
<td>22</td>
</tr>
</tbody>
</table>

*P < 0.05 compared to original.
†P < 0.05 compared to corrected values using measured f_{d} and \alpha.
Table 4

<table>
<thead>
<tr>
<th>Damped natural frequency (Hz)</th>
<th>Number</th>
<th>Improved (&gt; 10%)</th>
<th>No change</th>
<th>Worse (&gt; 10%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 - 10 Hz</td>
<td>19</td>
<td>0</td>
<td>8</td>
<td>11</td>
</tr>
<tr>
<td>11 - 15</td>
<td>12</td>
<td>2</td>
<td>4</td>
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<tr>
<td>26 - 80</td>
<td>11</td>
<td>5</td>
<td>4</td>
<td>2</td>
</tr>
</tbody>
</table>

single set of values to characterize a catheter system may result in significant errors for the correction process.

The problem of the correlation of frequency response data obtained in vitro at the end of catheterization and the actual in vivo frequency response characteristics at the instant of pressure curve recording is a real one. Frequently a considerable period of time has elapsed between these two events. Furthermore, the reproducibility of multiplex frequency response determinations has been shown to vary as much as 30% even when measured in rapid sequence. The tolerance for divergence between measured in vitro frequency response and actual in vivo frequency response is inversely related to the magnitude of the moduli near resonance.

The use of recording systems with high natural frequencies and optimal damping is important in obtaining reliable data, particularly if the resultant pressure wave is to be differentiated or with high heart rates.

Analysis of 81 representative pressure tracings recorded by catheter-tip manometers showed that the average number of harmonics needed to reproduce both the original pressure pulse and dp/dt varied widely at different sites ranging from an average of 3 for the iliac artery to 14 for the left atrium, as well as varying widely at each site. Differentiation increased the number of harmonics required, an average of sixfold. Furthermore in actual practice, frequency response requirements increase as the amount of damping in the system decreases.

The requirements for accurate recording of the first derivative are such that significant errors may be introduced by fluid-filled manometers. Catheter-tip manometers should be employed in subjects or patients with high or varying heart rates or for measurement of dp/dt. Harmonic analysis has some value in correcting resonance amplified catheter movement artefacts, frequently present in underdamped systems. The problems discussed above, however, may interfere with correction and resynthesis of even high frequency response systems.

Conclusions

Water-filled catheters with external transducers produce frequency dependent phase and amplitude distortions during pressure wave recording. Correction formulae, based on a simple mechanical model, are only moderately successful for underdamped high frequency response systems and generally unsuccessful for low frequency response systems. Divergence between actual in vitro response and measured in vitro frequency response, as well as in vitro deviations of the system from the mathematical description of the model, limited its effectiveness. Catheter-tip manometers are to be preferred when accurate phasic tracings are required.

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