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.

Additional Indexing Words: Fourier analysis Catheter-tip manometers Cardiac catheterization

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.

From the Departments of Pediatrics and Biomedical Engineering, The Johns Hopkins University School of Medicine and The Children's Medical and Surgical Center, The Johns Hopkins Hospital, Baltimore, Maryland.

Supported in part by NIH Grants HL-13679-03, HL-14207-01, Research Career Development Award 5K03-HL 09761-08, and the General Clinical Research Centers Program of the Division of Research Resources (RR-52), National Institutes of Health.

Address for reprints: Dr. L. Jerome Krovetz, Department of Pediatrics, University of Virginia Hospital, Charlottesville, Virginia 22901.

Received May 10, 1974; revision accepted for publication July 19, 1974.
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 recordings were considered suitable for further analysis.

Frequency response characteristics were determined either by the step response method or a sine wave oscillation chamber. Pressure recordings 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 a slightly better approximation of the CTM tracing, 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 0.20. 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>Table 1</th>
<th>Mean Errors of Conventional Catheter System Compared to Catheter-Tip Manometer for Pulse Pressure of Original and Resynthesized Waveforms</th>
</tr>
</thead>
<tbody>
<tr>
<td>Damped natural frequency (fd)</td>
<td>Number</td>
</tr>
<tr>
<td>7 - 10 Hz</td>
<td>19</td>
</tr>
<tr>
<td>11 - 15</td>
<td>12</td>
</tr>
<tr>
<td>16 - 25</td>
<td>18</td>
</tr>
<tr>
<td>26 - 50</td>
<td>11</td>
</tr>
</tbody>
</table>

*\(P < 0.05\) compared to corrected using measured \( \alpha \) & \( \alpha \).
†\(P < 0.05\) compared to original.
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.\(^{1,2}\) 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 semi-log 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>

Harmonic correction has reduced the 12% overshoot in early systole to 1%. The errors in $\frac{dp}{dt}$ increased from 1% to 22%.

---

**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.

---

**Figure 2**

Original (-----)  Corrected (-----)  Catheter-tip Manometer (-----)

DOG 95 12/1/69  LEFT VENTRICLE  ALPHA = 200  DNF = 15  HARMONICS UTILIZED = 12

Harmonic correction has reduced the 12% overshoot in early systole to 1%. The errors in $\frac{dp}{dt}$ increased from 1% to 22%.

---

**Figure 4**

![Figure 4](http://circ.ahajournals.org/)

LIMITATION OF PRESSURE WAVE CORRECTION

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).

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. 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
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

\[
\text{Table 3} \\
\text{Mean Percent Deviation of Conventional Catheter-Manometer Systems Compared to Catheter-Tip 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 (34%)</th>
<th>Corrected using (f_d) &amp; (\alpha) (50%^*) (worse)</th>
<th>Corrected using (f_d) &amp; (\alpha) from graph (44%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>7 - 10 Hz</td>
<td>19</td>
<td>34%</td>
<td>50%*</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 \(\alpha\).

Circulation, Volume 50, November 1974
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 multiple 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.

### Acknowledgment

The authors wish to thank Mr. Horace Brown for his invaluable technical advice and assistance. Also, we express sincere appreciation to Mrs. Olga Carr for her aid in the preparation of this manuscript.

### References

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

L. JEROME KROVETZ, RUFUS B. JENNINGS, JR. and STEPHEN D. GOLDBLOOM

Circulation. 1974;50:992-997
doi: 10.1161/01.CIR.50.5.992
Circulation is published by the American Heart Association, 7272 Greenville Avenue, Dallas, TX 75231
Copyright © 1974 American Heart Association, Inc. All rights reserved.
Print ISSN: 0009-7322. Online ISSN: 1524-4539

The online version of this article, along with updated information and services, is located on the World Wide Web at:
http://circ.ahajournals.org/content/50/5/992

Permissions: Requests for permissions to reproduce figures, tables, or portions of articles originally published in Circulation can be obtained via RightsLink, a service of the Copyright Clearance Center, not the Editorial Office. Once the online version of the published article for which permission is being requested is located, click Request Permissions in the middle column of the Web page under Services. Further information about this process is available in the Permissions and Rights Question and Answer document.

Reprints: Information about reprints can be found online at:
http://www.lww.com/reprints

Subscriptions: Information about subscribing to Circulation is online at:
http://circ.ahajournals.org//subscriptions/