Dynamic Testing of Catheter Manometer Systems

To the Editor—The complex and elegant article by Hopkins et al.1 casts doubt on the principles of dynamic testing of monitoring systems. For those interested in these matters, this is a truly revolutionary paper, since it throws 40 yr of scientific investigation into serious question. However, we take issue with the validity of the authors’ conclusions. Firstly, they note a disparity between dynamic testing in vitro (by sine wave pressure generation) and testing in vivo (by fast-flush technique). From this the authors conclude that serious doubt must be cast on the validity of the fast-flush test.

The initial thing that stands out to us is that with addition of the Rose* damping device in vitro, the natural frequency (f0) decreases dramatically (25.9 vs. 8.5 Hz). In vivo, there is no change in f0 with addition of the Rose*. The authors claim that this is not surprising since the Rose* is not adjustable, and its impedance presumably did not match those of the systems used here.1 Actually, this is very surprising. If an impedance matching device gives a “perfect” match to the transducer, there will be no resonance; damping will increase; and f0 will remain the same (or actually increased).* If the match is less than perfect, as would be expected with the Rose*, damping will increase, though not as much as in a perfect impedance match, and there will be some resonance; however, in accordance with parallel damping theory, the f0 will remain the same. This was seen in in vitro testing of the Rose* itself.2 The data from the Rose* in vitro implies behavior of a series resistor rather than that of a “parallel damper.”* In addition, all of the fluid from the damping capillary tube in the Rose* must be evacuated (a procedure not as easy to do as it sounds) and filled with fluid; if it is not, there will be a decrease in f0.

Secondly, one of the pillars on which their conclusions of their paper stands is their definition of working heart rate. Working heart rate (fω) is, as they define it, the predicted heart rate up to which a system of given f0 and damping ratio (α) will record pressure to within ±5% of the real value.1 From classical manometry theory, one can generate a curve or family of curves which plot relative amplitude (A) versus relative frequency (τ). The relationship between A and τ can be expressed, as correctly shown by Hopkins et al.,1 as:

\[
A = \frac{1}{(1 - \tau^2)^{3/2} + (2 \alpha \cdot \tau)^{3/2}}
\]

Hopkins et al. then does something which, to the best of our knowledge, is unique to the scientific literature of manometry theory: they solve the above equation with respect to τ. With the equation solved for relative frequency, the authors then solve the equation for values of A = 1.05 and A = 0.95 for any given value of α. This defines the range of τ for which A is within ±5% of the real amplitude. From this, the fω is calculated as:

\[
f_{\omega} = \frac{[t_1.05 \cdot f_0 \text{Hz} \cdot 60]}{10 \text{ beats per min}}
\]

where \(t_{1.05}\) is the frequency at which the recorded pressure is equal to 105% of the actual pressure; 60 converts Hertz to beats per minute. The \(f_0\) describes the natural frequency of the monitoring system. Ten beats per minute is used because the conventional wisdom states that a pressure recording system should have an amplitude–frequency response up to the tenth harmonic of the fundamental frequency; i.e., a complex wave form such as an arterial pulse can be synthesized by the addition of the first ten harmonics.4 If the fundamental frequency or first harmonic has a frequency of the heart rate, then by dividing [(\(t_{1.05} \cdot f_0\)) - 60] by 10 will give the fundamental frequency, or in this case, the fω. The results in Hopkins et al.’s paper show a large disparity between the predicted behavior of a monitoring system, quantified by fω, and their measured performance in vivo—the difference in pressures between monitoring systems with fluid-filled catheters and extension tubing versus transducer tipped catheters. Since the calculation of fω involves the measurement of α and f0, this disparity leads the authors to conclude that, in fact, the whole process of dynamic testing (i.e., the measurement of f0 and α) is of dubious nature.

We think, however, that the problem may not lie in the process of dynamic testing but rather in the author’s definition of fω—their measure of the predicted behavior of a monitoring system. The assumption that ten harmonics are necessary for the accurate reproduction of a waveform is debatable. Certainly peak amplitudes of waves, or systolic peaks, can be reproduced reliably with less than ten harmonics. Hansen5 showed that the peak systolic pressure of an arterial pulse synthesized by six harmonics would come within 95% of the peak systolic pressure of the original. Patel et al.6 showed that in an ascending aortic pressure trace, the peak systolic pressure could reproduce the original with five harmonics and that only three harmonics would yield a peak systolic pressure of 105% of the original. Patel et al.6 also showed that the left ventricular (LV) peak systolic pressure could duplicate the original LV peak systolic pressure with only three harmonics. LV pressures are classically much harder to reproduce accurately than are peripheral arterial pressures.

Therefore, whereas one may need ten harmonics to accurately reproduce the shape of a wave form, probably many less are needed to accurately reproduce the systolic peak amplitude (or peak systolic pressure). It is amplitude distortion—specifically, peak systolic pressure artifact—that we are concerned about. We believe that the definition of fω is seriously flawed. The number ten, in fact, cannot be assumed. Probably much smaller numbers are indicated. If this is so, then the fω—the measure of predicted behavior—may not deviate that much from measured behavior in vivo. Hence, Hopkins et al.’s conclusion that dynamic testing of monitoring systems is not valid may be incorrect.

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In Reply:—In response to the letter of Kleinman et al., we would like to reemphasize our conclusion that with a wide variety of blood pressure monitoring systems, errors in and the variability of systolic pressure measurement can be reliably reduced if these systems include the Rose® resonance eliminator and/or an electronic filter such as the one in the Hewlett Packard® (HP) patient monitor. This conclusion is based on the direct comparison of pressures simultaneously measured with catheter-tip pressure transducers and catheter-manometer monitoring systems. The multiple regression analyses show that when the Rose® is included in a monitoring system, the errors in systolic pressure measurement are independent of heart rate, extension tubing length, or the type of recorder used. As such, the Rose® represents a simple solution to a complex problem and obviates the need for dynamic testing. We did not seek to determine the robustness of the Rose® in reducing errors due to poor technique; care should still be taken in setting up pressure monitoring systems.

Having established which systems recorded pressure accurately in vivo, we sought to determine whether classical manometer theory would also predict that these systems would behave satisfactorily. The calculation of working heart rate (fₘ₉) was undertaken to solve a particular problem in analyzing the dynamics of resonating single-degree-offreedom catheter–manometer systems: since the resonant frequency (f₀) and damping coefficient (α) of a given system can change independently, we sought to define a single term that relates f₀ and α, and expresses it in physiologic units. The choice of ten harmonics is somewhat conservative but there is still no real agreement as to what bandwidth is needed to record accurately different blood pressures. While Patel et al.¹ report that the modulus of the fifth harmonic of left ventricular pressure is only 4% of that of the first harmonic, they also showed that the "less demanding" right and left atrial pressure curves had flatter frequency responses, with the fifth harmonics 25 and 20% of the fundamental, respectively. Attinger et al.² report that while the modulus of the fourth harmonic of the mesenteric arterial pressure (dog) is 9.5% of the modulus of the fundamental, the sixth harmonic is 11% of the fundamental. Similar findings are reported by Gersh et al.³ From these reports it is clear that if the definition of fₘ₉ is to be made less conservative, five harmonics would be the minimum allowable value. Gardner⁴ suggests that systems with a "natural" frequency (presumably damped resonant frequency) of less than 10 Hz (=seven harmonics at 90 beats per min) will be marginal even with resonance elimination using the Accudynamic®. The choice of five harmonics would effectively double the fₘ₉ values we have reported; for example, the fₘ₉ of system 1 with HP would rise from 35 to only 70 beats per min, and the fₘ₉ of system 1 with Rose® would rise from 54 to 108 beats per min; both these systems gave excellent recordings at heart rates up to 160 beats per min.

The calculation of fₘ₉ is simply a manipulation of the accepted equations for the characterization of catheter–manometer systems and relies on those systems being of a single degree of freedom ("lumped" systems). The low values for fₘ₉ are surprising and indicate that, based on theory, most of the systems studied would be unsuitable for arterial pressure recording. This is in stark contrast to the more than adequate performance of those systems in vivo. For example, the fₘ₉ of system 1 with EMT was 32 beats per min and that of system 1 HP was 35 beats per min, and yet the error pressures recorded with the EMT were much greater and more variable than those recorded, at the same time, with the HP. Furthermore, the differences between the fₘ₉ calculated in vitro (sine wave) and in vivo (fast-flush) cast doubt on the validity of the fast-flush test (especially if one is attempting to "tune" the Accudynamic®). In the case of the in vitro tests there was no evidence of the multiple resonances that characterize systems of many degrees of freedom ("distributed") systems, but the bulk-flow nature of the fast-flush test is such that it is almost certain that we are dealing with distributed systems, during the test itself. Rothie and Kim⁵ report similar disagreement between the fast-flush test and other methods of dynamic testing. Billiet and Colardyn⁶ show that the dynamic characteristics of a given catheter–manometer system are influenced by the position at which the pressure is applied, and they conclude that the fast-flush method may not be used in testing catheter–manometer systems.

The major thrust of the study, stated in the last sentence of the Discussion, is that satisfactory recordings can be made despite the theoretical predictions. While modification of the theory to take into account only five harmonics will go some way toward reconciliation of theory and practice, it will explain neither the differences between the fast-flush and sine-wave tests nor the different in vivo performances of systems with similar f₀ and α.

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* Billiet E, Colardyn F: Personal communication. Biotechnical and Intensive Care Department, University Hospital Ghent, De Pintelaan 185, B-9000 Ghent, Belgium, March 1990

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